WINDSOR CONFERENCE 2016

MAKING COMFORT RELEVANT

MAKING COMFORT RELEVANT

Proceedings

9th International Windsor Conference

Cumberland Lodge, Windsor Great Park, UK

7th - 10th April 2016

Edited by

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Prof Fergus Nicol

Rev Prof Michael Humphreys

Published by NCEUB 2016
to order go online to www.nceub.org.uk

Proceedings of 9th Windsor Conference Making Comfort Relevant

Network for Comfort and Energy Use in Buildings http://nceub.org.uk
Cumberland Lodge, Windsor, UK, 7th-10th April 2016
Windsor Conference 2016 www.windsorconference.com

ISBN 978-0-9928957-3-0

WINDSOR CONFERENCE 2016

MAKING COMFORT RELEVANT

Preface to the Proceedings of the 9th Windsor 2016 at Cumberland Lodge, Windsor

For many the costs of providing acceptable indoor temperatures have become prohibitive. Around the world people already have to make stark choices on whether to spend money on heating and cooling or on eating. The science of comfort developed in the 20th century around the needs of the HVAC industry for whom comfort was a product, produced by machines to be sold to customers. Engineers and other building professionals needed target conditions to feed into their calculations to create comfortable or neutral environments for groups of people in diverse buildings. But simple comfort models based on physics and physiology and using heat balance assumptions was found to be inadequate to explain the dynamic environments found to exist in many buildings when investigated using field surveys. However, despite being valued for its ability to deal with variable conditions, the field study approach continued to concentrate on finding a 'comfort temperature' for a particular group or environment.

At the same time sophisticated simulations did not stop the construction of buildings that still too often overheat. The serious challenge of achieving reductions in energy consumption and carbon emissions must to be faced without too often compromising the comfort, health, well-being and productivity of building occupants. Where are the cost effective solutions? Better climatic design; de-mechanisation of buildings; more efficient equipment or the reshaping building regulations? Or is it changes in occupant behaviour? We live in a world of rapid cultural, economic, environmental and architectural changes. At the same time there is a growing imperative to reduce energy use and its related GHG emissions and to cope with extreme weather and power outages in buildings. If we also want to make indoor environments more delightful there is a pressing need for more research into the dynamic nature of comfort. Increasingly the insights of ergonomics, psychology and thermal physiology can inform research in this field.

The role of comfort researchers is to help design a new generation of resilient buildings that will mitigate climate change and withstand its impacts. How do we measure the costs and benefits of different approaches to the provision of comfort in 21st century buildings and their resulting economic impacts? The provision of reliable, safe and affordable thermal comfort in buildings is a core priority for designers as the costs of energy rise and the global impacts of its use become ever clearer on our landscapes and in our changing climate. How can the researchers help with this endeavour?

Traditionally the subject of thermal comfort was dominated by the physics and physiology of comfort and its language. The terminology used by comfort researchers has been that of engineering and physics – temperature, humidity and air speed, clothing insulation and watts of metabolic heat in $W.m^{-2}$. An increasing acceptance of the behavioural, or adaptive approach to comfort has opened the way for a more holistic and dynamic understanding of thermal comfort. The provision of comfort can no longer be seen in isolation – as an activity detached from cost or impact. There is a realisation that behavioural adaptation can lead to a widening as well as a narrowing of the temperatures people find comfortable, and can apply in all buildings not just those which are naturally ventilated.

It is 22 years since the Windsor Conference first came to Cumberland Lodge and in that time our own ideas and approaches to the field have changed radically and our discussions have also started to change the assumptions of the world around us. This year there were workshops exploring comfort models and clothing, thermal physiology and teaching, statistics and ventilation and our understanding of comfort as a personal choice or a negotiated reality. All this was on offer in addition to keeping in touch with the latest developments in related products and controls design and standards, guidance and legislation around the world.

The driving theme of the 9th Windsor conference was the need to make the results we obtain from comfort research more accessible and widely applied. How can we help architects and engineers design better, more comfortable buildings? Thermal comfort studies help us write specifications for International Standards, or size an AC system, but do they help us decide what type of building is best in a humid tropical climate or how much diurnal variability is desirable in a north European home? Where should we build using massive stonework or where from wood and cane? When to use shading and when to welcome in the sun? How different are homes from offices? We need tools to explore and answer such questions and then convert this understanding into advice, not in the terminology of physicists and engineers but that of architects and builders? Can we present our ideas to design students in a way which will excite them?

Such questions are the basis of the 93 papers contained in this volume. The papers were written by many of the 130 experts from 22 countries who attended the 7 plenary sessions and 9 workshops of the conference. Two keynote speeches were delivered by three leading experts. There was a quiz night this year as well as the usual table tennis and billiards. A meeting was called of the scientific committee and lifetime achievement awards were made to Michael Humphreys and Fergus Nicol in recognition of their contributions.

We would like to acknowledge the effort of Scientific Committee members for reviews of abstracts and papers presented here.

Hopefully this compilation of papers will become an essential source for academics, researchers, building designers and managers as well anyone interested in new knowledge, approaches and technologies.

Fergus Nicol, Susan Roaf, Luisa Brotas, Michael Humphreys April 2016

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Despoina Teli, University of Southampton (UK),
Paul Tuohy, University of Strathclyde (UK),
Terry Williamson, University of Adelaide (AU),
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Da Yan, Tsinghua University (CN),
Runming Yao, University of Reading (UK),
Yingxin Zhu, Tsinghua University (CN).

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Meshack Efeoma, University of Edinburgh (UK).

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TIMETABLE and ATTENDEES

9th International Windsor Conference

Cumberland Lodge, Windsor Great Park, UK

7th - 10th April 2016

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9th International Windsor Conference, 7th - 10th April 2016, Cumberland Lodge, Windsor Great Park, UK

9th Windsor Conference 2016

TIMETABLE

Thursday 7th April 2016

17:00 **REGISTRATION**

18:00 **WELCOME DRINKS: Courtesy of VELUX**

19:00 **DINNER**

After Dinner Talk - Invited Chair: Michael Humphreys

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Friday 8th April 2016

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10:05 **Fergus Nicol** 90
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10:20 **Marcel Schweiker and Andreas Wagner** 108
Exploring potentials and limitations of the adaptive thermal heat balance framework

10:35 **Discussion**

11:00 **COFFEE BREAK**

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Luisa Brotas
Michael Humphreys

SCIENTIFIC COMMITTEE

Michael Adebamowo (NG)
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Maria Kolokotroni (UK)
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Stefano Schiavon (US)
Fionn Stevenson (UK)
Shin-ichi Tanabe (JP)
Despoina Teli (UK)
Paul Tuohy (UK)
Terry Williamson (AU)
Peter Wouters (BE)
Da Yan (CN)
Runming Yao (UK)
Yingxin Zhu (CN)

SESSION 2: People, Behaviours and Ageing
Invited Chairs: Edward Ng and Fionn Stevenson

SESSION 3: Comfort in Buildings **14:00 - 16:00**
Invited Chairs: Yingxin Zhu and Maria Kolokotroni

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Invited Chairs: Risto Kosonen and Caroline Karmann

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Invited Chair: Fergus Nicol

20:30 **Elizabeth Shove**
The Concept of Comfort in a Changing Climate

ATTENDEES

Australia

Rachel Bills
The University of Adelaide

Lyrian Daniel
The University of Adelaide

Richard de Dear
The University of Sydney

Jungsoo Kim
The University of Sydney

Ashak Nathwani
University of Sydney

Thomas Parkinson
The University of Sydney

Mahsan Sadeghi
The University of Sydney

Ben Slee
The University of Sydney

Fan Zhang
The University of Sydney

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Peter Holzer
Institute of Building Research & Innovation

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Luciana Fernandes
State University of Campinas

Eduardo Krüger
Technological University of Parana

Roberto Lamberts
Federal University of Santa Catarina

Lucilla Labaki
State University of Campinas

Angélica Walsh
State University of Campinas

Saturday 9th April 2016

SESSION 4: Comfort in Hotter Climates — 09:00 - 11:00
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11:00 **COFFEE BREAK**

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12:45 **Discussion**

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P. R. China

Bin Cao
Tsinghua University

Hongzong Chen
Tsinghua University

Xiaohang Feng
Tsinghua University

Li Huang
Tsinghua University

Kevin Lau
The Chinese University of Hong Kong

Baizhan Li
Chongquing University

Min Li
Tsinghua University

Yanchen Liu
Tsinghua University

Edward Ng
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Hongli Sun
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Chuang Wang
Tsinghua University

Da Yan
Tsinghua University

Haiyan Yan
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Peng Yang
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Juan Yu
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Wuxing Zheng
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Yingxin Zhu
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Thravalou Stavroula
University of Cyprus

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VELUX A/S

Bjarne Olesen
Danish Technical University

Jørn Toftum
Danish Technical University

Finland

Risto Kosonen
Aalto University

Jarek Kurnitski
Aalto University

SESSION 6: Comfort and Climate — 14:00 - 16:00
Invited Chairs: Philomena Bluyssen and Jens Pfafferot

WORKSHOP 2.1: Domestic Comfort in Different Climates — 16:30 - 18:00, Flitcroft Room
Invited Chairs: David Shipworth and Hom Rijal

France

Venetia Grigorva
Saint-Gobain

Ariane Schumacher
Saint-Gobain

Germany

Peter Bröde
IfADo

Runa Hellwig
Augsburg University of Applied Sciences

Martin Möhlenkamp
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Jens Pfafferott
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Rajan Rawal
CEPT University

Rijildas Thayhathu Veetil
Indian Institute of Technology Roorkee

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Tri Harso Karyono
Tanri Abeng University

Ireland

Oliver Kinnane
Trinity College Dublin

Italy

Alessia Gadotti
University of Trento

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Craig Farnham
Osaka City University

Ryozo Ooka
The University of Tokyo

Hom Bahadur Rijal
Tokyo City University

Marina Takasu
The University of Tokyo

Masanari Ukai
kogakuin University

Noriko Umemiya
Osaka City University

WORKSHOP 2.2: Comfort Teaching, Tools and Techniques — 16:30 - 18:00
Invited Chairs: Runa Hellwig and Stefano Schiavon — Sandy Room

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After Dinner Event — 20:30 - 21:30
Invited Chairs: Dennis Loveday and Susan Roaf

20:30 Just Exactly How Cool are You? The Clothing Quiz

Netherlands

Atze Boerstra
BBA Binnenmilieu

Philomena Bluyssen
Delft University of Technology

Arjan Frijns
Eindhoven University of Technology

Boris Kingma
Maastricht University

Marije te Kulve
Maastricht University

Wouter van Marken Lichtenbelt
Maastricht University

Hannah Pallubinsky
Maastricht University

Jacob Verhaart
Eindhoven University of Technology

Stephanie Veselá
Eindhoven University of Technology

Michal Veselý
Eindhoven University of Technology

New Zealand

Julia Thompson
Victoria University of Wellington

Nigeria

Michael Adebamowo
University of Lagos

Adetokunbo Sangowawa
University of Lagos and KOA Consultants Ltd

Qatar

Madhavi Indraganti
Qatar University

Switzerland

Giorgia Chinazzo
Ecole Polytechnique Fédérale de Lausanne

Uganda

Mark Olweny
Uganda Martyrs University

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Invited Chairs: Da Yan and Atze Boerstra — Hodgson Room

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09:55 **Discussion**

10:30 **COFFEE BREAK**

United Kingdom

Michael Adaji
University of Kent
Abdulrahman Al Alshaikh
Heriot-Watt University
Rucha Amin
University of Southampton
Luisa Brotas
London Metropolitan University
Anna Coppel
ARUP
James Cornaby
Dyson
Asif Din
London Metropolitan University
Matthew Eames
University of Exeter
Meshack Efeoma
University of Edinburgh
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Rex Galbraith
University College London
Rajat Gupta
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University of Manchester
Fergus Nicol
London Metropolitan University
Daniel Fosas de Pando
University of Bath

SESSION 7: Future Facing Hot Topics **11:00 - 13:00**
Invited Chairs: Susan Roaf and Fergus Nicol

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11:00 **Haiyan Yan, Liu Yang, Wuxing Zheng and Daoyi Li** 1100
A new method to develop the adaptive thermal comfort model

11:15 **Craig Farnham, Lili Zhang, Jihui Yuan, Takeo Mizuno, Kazuo Emura and Alam Ashraful** 1117
Cooling Effect of a Mist Fan for Large Indoor Spaces

11:30 **Thomas Parkinson and Richard de Dear** 1131
Thermal pleasure and alliesthesia in the built environment

11:45 **Stefano Schiavon, Toby C.T. Cheung, Elliott T. Gall and William W Nazaroff** 1146
Real-time personal continuous monitoring of air temperature, relative humidity, carbon dioxide, and thermal and perceived air quality acceptability in Singapore

12:00 **Ryozo Ooka, Madhavi Indraganti and Hom B. Rijal** 1155
A Comparative Analysis of Thermal Acceptability in Offices in India and Japan

12:15 **Ben Slee and Richard Hyde** 1165
Improving the thermal performance and energy efficiency of NSW Demountable classrooms using a community led retrofitting strategy. A proposal for Broken Hill

12:30 **Matthew E. Eames and Edward M. Shorthouse** 1186
An exploration of the selection of design summer years to define the overheating risk of buildings

12:35 **Mark Olweny, Leslie Lubowa Mugagga and Tadeo Nedala** 1202
A study of thermal comfort and thermal preferences in the upland tropical climate of Uganda

12:40 **Christhina Candido, Jessica Zhang, Jungsoo Kim, Richard de Dear, Leena Thomas, Paula Strapasson and Camila Joko** 1214
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12:45 **Discussion: Key Themes and Thoughts to take forward – Discussion of the three days**

13:00 **LUNCH**

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Sumavalee Chindapol, John Blair, Paul Osmond and Deo Prasad 1252
Thermal Responses of the Elderly in Summer Hot-Humid Climates

Shamila Haddad, Paul Osmond and Steve King 1270
Relationship between children's comfort temperature and outdoor climate: some methodological issues

Salah Imam, David A. Coley and Ian Walker 1284
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Ommid Saberi and Prashant Kapoor 1325
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Ken Parsons
Loughborough University

Adrian Pitts
University of Huddersfield

Stephen Porritt
Loughborough University

Gary Raw
UCL Energy Institute

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WINDSOR CONFERENCE 2016

MAKING COMFORT RELEVANT

AFTER DINNER TALK

The history of international standardization for the ergonomics of the thermal environment

Bjarne Olesen and Ken Parsons

Invited Chair: Michael Humphreys

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

The history of international standardization for the ergonomics of the thermal environment

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Abstract
Standardisation in relation to the thermal environment goes back many years, where mainly national standards like ASHRAE 55 (thermal comfort, first issue 1966) and ACGIH established in 1962 the first Threshold Limit Values for industrial work places. Internationally the standardization work started in 1978 under ISO TC 159 Ergonomics; SC 5 Ergonomics of the Physical Environment formed a new Working Group WG1 Ergonomics of the thermal environment. This working group covers all aspects of the influence of the thermal environment on people like heat stress, cold stress, thermal comfort, physical and thermal physiological measurements etc. The first standard ISO 7243 was dealing with heat stress and the use of WBGT based on the ACGIH standard. This was soon followed by the most cited standard for thermal comfort ISO 7730. The presentation will include a historical overview of this work and the people involved.

Keywords: thermal environment, heat stress, cold stress, measurements, thermal physiology, standards

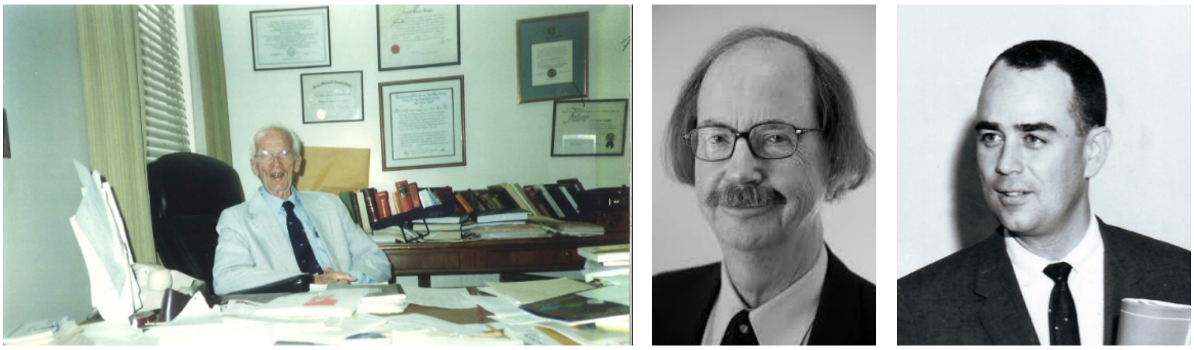
1 Introduction

The thermal environment is one of the crucial facets of living and working environments. In particular, the physiological response of people with respect to the thermo-hygrometric parameters affects the thermal sensation with its consequences in terms of comfort, well-being and productivity. In addition, its prediction or assessment is required to avoid health risks in extreme cold and hot environments. For this reasons thermal environments are usually classified into moderate, where the main goal is achieving thermal comfort conditions, and severe (cold and hot) where heat strains can occur and the workers safety and health has to be guaranteed.

2 History

During the 20th century three of the main contributors to the studies on thermal comfort were Pharo Gagge, Ralph Nevins and P. Ole Fanger (Figure 1), who gave the main contributions to the study of thermal comfort; but there were many researchers before them.

Since Antiquity, more or less complex theories have been developed to identify the essential functions responsible for life (e.g. respiration, heart, blood). Hippocrates believed that blood was warm at a fixed temperature by divine will, whereas Plato concluded that blood circulation was due to a fire diffusion. In the second half of the Second Century Galen ruled that – contrary to ematocentric and cardiocentric theories - there is no air in the blood vessels and theorized the existence of capillaries. In later centuries, other scientists devoted great attention to caloric theories and physiological studies, but only in the Modern Age were meaningful results achieved (d'Ambrosio and Lopardo, 2014).



Pharo Gagge
John B. Pierce Foundation, Yale University
1908 -1993

Ole Fanger
Technical Univ.
Denmark
1934-2006

Ralph Nevins
Kansas State Univ.
1924-1973

Figure 1 Three main contributors to the studies on thermal comfort.

Sanctorio Sanctorio obtained the first important results leading the way for the modern thermo-physiology at the beginning of the 1600. He was among the first to use physical measurements in medicine. By means of a scale of his invention, he postulated the existence of the *perspiratio insensibilis*, which is one of the mechanisms of heat exchange between man and environment.

A.L Lavoisier and P.S. Laplace are among the pioneers of the studies on the response of people to the thermal environment. Equipped with a special ice calorimeter, in 1780 they carried out experiments on the production of thermal energy in animals by finding a relationship between heat loss and breathing.

In 1865 Claude Bernard was the first to realize the idea of human body homeostasis reprised only in 1932 by W.B. Cannon.

Thanks to the evolution of knowledge in the field of physiology, in the first half of the twentieth century studies progressed quickly. In 1923 Yaglou, assisted by F.C. Houghten, formulated the Effective Temperature index ET based on the thermal sensation felt by a subject in movement between two conditioned environments. At the beginning, ET was referred only to a homogeneous environment and standard clothing conditions.

In 1924, the John B. Pierce Laboratory was founded in Yale , where under the guidance of C.E.A. Winslow – the first director – L.P. Herrington and A.P. Gagge began their studies on the energy flows between man and his surrounding environment, creating one of the most famous and prolific schools.

In 1941 the J.B. Pierce Laboratory's group (Gagge et al., 1941) formulated the most used (and incoherent with respect to SI) units for the metabolic rate and the clothing insulation: the *met* and the *clo*, respectively. In this paper are also mentioned two important issues: the reduction of clothing insulation due to wind and body movements (one on the most studied topics in the 80's), and the optimal temperature values as a function of metabolic rate and clothing insulation (still an open matter among researchers in the field).

In the same year, Burton in the UK formulated and validated experimentally the first mathematical model simulating the thermoregulatory response: the body is assimilated to a homogeneous cylinder and thermal field within it is obtained by Bessel's functions (Burton, 1941).

World War II and the Korean War pressed some US research centers to organize support to the troops who were engaged in military operations in none-temperate climatic areas (McIntyre, 1980). In fact, during those conflicts the US had significant human losses due to extreme weather conditions in which the troops were fighting. Consequently, J. B. Pierce and Natick's Base laboratories started to carry out a series of studies on the physiological response of the body to extreme conditions and on the role of clothing in protection against thermal stress (d'Ambrosio, 2012). These studies continued over the years (Belding et al. 1947a, 1947b) favouring the development of collateral researches as clothing.

In the 50s other players such as HVAC engineers were involved in research (d'Ambrosio and Lopardo, 2014) and several studies on comfort conditions in confined environments were carried out in cooperation with ASHRAE (American Society for Heating, Refrigeration, and Air Conditioning Engineering). This cooperation helped Gagge's team (Y. Nishi, in particular, Gonzales and Berglund) deepen moderate thermal environment theories and led to the formulation of ET* and SET indices.

ASHRAE decided to close its research laboratory, located in Cleveland since 1924, and invited interested organizations to bid on receiving its equipment. Ralph Nevins obtained from the state of Kansas $160,000 for a building and a like amount from the National Institutes of Health for installation and operation. He obtained the chamber and promised to carry on research in ASHRAE's interest for at least 5 years. The new facility was named the Institute for Environmental Research, and Dr. Nevins became its Director. Under his guidance researchers like Rohles and McNall did experimental studies and measured the impact of the thermal environment on peoples comfort. In this test facility the studies forming the basis for Fanger's PMV-PPD index were also made. Nevins accepted in 1973 the position of Fellow and Head of the Environmental Engineering Group and Member of the Executive Committee of the John B. Pierce Foundation Laboratory, New Haven, Connecticut.

ASHRAE has established the Ralph G. Nevins Physiology and Human Environment Award for young researchers under the age of 40, that has contributed to the knowledge on human physiology and comfort (Figure 2).

Figure 2. Together with Prof. Fanger recipients of the Ralph Nevins Award from left Jørn Toftum, Bjarne W. Olesen, P.Ole Fanger, Byron Jones, Shin-Ichi Tanabe and Ken Parsons.

European studies on moderate thermal environments were developed at the Technical University of Denmark, thanks to Ole Fanger who published in 1970 his famous book entitled “Thermal Comfort” (Fanger, 1970) where the definition of PMV and PPD indices are reported.

Studies on severe environments started during the wars of the twentieth century led to the definition of the IREQ index, for cold environments, and WBGT and SW_{req} for hot environments. Generally, indices can be classified into rational, - based on the heat balance on the human body – and empirical, derived on experimental base.

3 Standards’ development

Established in 1947, ISO (International Organization for Standardization) is the international body for regulations. It groups 162 National regulatory bodies. The European body CEN (European Committee for Standardization) in cooperation with CENELEC (European Committee for Electrotechnical Standardization) and ETSI (European Telecommunications Standards Institute) develops standards in force at European level. CEN cooperates with ISO thanks to the Vienna’s Agreement. National Standardization bodies (e.g. UNI in Italy, ANSI in US, DIN in Germany, BSI in the UK etc.) compulsorily accept within six months CEN Standards which are published as UNI EN (DIN EN, BS EN etc). If a CEN standard exist you cannot have a different national standard on the same topic. For ISO standards there is no obligation to use them, but they can be adopted by National bodies as national standards (e.g. in case of UNI) or used in contracts. However, National bodies can prepare and publish National standards not in conflict and non-overlapping with CEN.

All regulatory bodies are organized in Management Bodies and Commissions or Technical Committees (also Subcommittees if needed), composed by working groups who prepare the drafts to be discussed and approved by the Management Bodies.

3.1 International Standards in the field of the Thermal Environment

Since the 1980s, the working group ISO TC 159 SC5 WG1 (Ergonomics of the Thermal Environment) released a series of Standards aimed to regulate the field of the thermal environment. This working group has been chaired by three different conveners: 1978-1994 G. Aubertin, France; 1994-2015 Bjarne W. Olesen, Denmark and since 2015 Jørn Toftum Denmark. At CEN level, the TC 122 WG 11 (Ergonomics of the Physical Environment) was formed later and is also active and, apart from a couple of cases, they adopt the ISO standards for thermal environments as EN standards. Designers of HVAC systems have to be aware of these standards, which represent the basis required for the ergonomic assessment of environments where people live and work. This is also because they affect the values of thermo-hygrometric design parameters. In addition, the compliance with these standards strongly interferes with energy saving requirements. Therefore, it is more and more important to have a close cooperation among building and equipment designers, ergonomics and occupational health experts (d'Ambrosio Alfano et al., 2014a).

Figure 3. TC159SC5WG1 meeting at Danish Standard in 1980's.

Presently, the field of the Thermal Environment is regulated by a set of 21 Standards divided in categories according to Figure 1. The full list is reported in Table 1. A description of the background to the standards and current status is provided in Annex 2

Table 1. Standards presently under force. [a] Ergonomics of the Thermal Environment series. [b] Ergonomics of the Physical Environment series.

ISO / CEN Number	Year	Title
ISO 7243[a] EN 27243	1989 1993	Hot Environments - Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature)
ISO 11399[a] EN ISO 11399	1995 2000	Principles and application of relevant International Standards
ISO 10551[a] EN ISO 10551	1995 2001	Assessment of the influence of the thermal environment using subjective judgment scales
ISO 7726[a] EN ISO 7726	1998 2001	Ergonomics of the thermal environment - Instruments for measuring physical quantities
ISO 12894[a] EN ISO 12894	2001 2001	Medical supervision of individuals exposed to extreme hot or cold environments
ISO 13731[a] EN ISO 13731	2001 2001	Vocabulary and symbols
ISO/TS 13732-2[a]	2001	Methods for the assessment of human responses to contact with surfaces - Part 2: Human contact with surfaces at moderate temperature
ISO 15265[a] EN ISO 15265	2004 2004	Risk assessment strategy for the prevention of stress or discomfort in thermal working conditions
ISO 7933[a] EN ISO 7933	2004 2004	Analytical determination and interpretation of heat stress using calculation of the predicted heat strain
EN ISO 8996[a] ISO 8996	2004 2004	Determination of metabolic rate
EN ISO 9886 ISO 9886	2004 2004	Ergonomics - Evaluation of thermal strain by physiological measurements
ISO 7730 [a] EN ISO 7730	2005 2005	Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria
ISO 14504-2[a] EN ISO 14504-2	2006 2006	Evaluation of thermal environments in vehicles - Part 2: Determination of equivalent temperature
ISO 14504-3[a] EN ISO 14504-3	2006 2006	Evaluation of the thermal environment in vehicles - Part 3: Evaluation of thermal comfort using human subjects
ISO 13732-1[a] EN ISO 13732-1	2006 2008	Methods for the assessment of human responses to contact with surfaces - Part 1: Hot surfaces
ISO 13732-3[a] EN ISO 13732-3	2006 2008	Methods for the assessment of human responses to contact with surfaces - Part 3: Cold surfaces
ISO 11079[a] EN ISO 11079	2007 2007	Determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects
ISO 15743[a] EN ISO 15743	2008 2008	Ergonomics of the thermal environment - Cold workplaces - Risk assessment and management
ISO 9920[a] EN ISO 9920	2007 2009	Estimation of thermal insulation and water vapour resistance of a clothing ensemble
ISO 28802[b] EN ISO 28802	2012 2012	Assessment of environments by means of an environmental survey involving physical measurements of the environment and subjective responses of people
ISO 28803[b] EN ISO 28803	2012 2012	Application of international standards to people with special requirements

In truth, the first standard on the thermal environment was the American ASHRAE 55 (Conditions for thermal Comfort) issued in 1966 after two years of work and periodically revised until the last version dated 2013. Based upon Houghten's and Yaglou (1923) studies, it prescribed the Effective Temperature as a comfort index and, firstly, it defined the thermal comfort as a condition of the mind. Since 1975, the document has been often revised. The main innovation are the adoption of the two-node Gagge's model (Gagge, 1973), the New Effective Temperature index ET* (Gagge et al., 1971) and, finally, in 2004 the adoption of PMV/PPD index and local discomfort indices based on ISO 7730. Due to its authoritativeness, ASHRAE 55 is a reference worldwide.

At ISO level, the first Standard was ISO 7243, issued in 1982.

3.2 The Standards for hot environments

ISO 7243, the first standard in the field of the thermal environment was issued in 1982 and adopted by the CEN in 1993. It was based upon the WBGT (Wet Bulb Globe Temperature), an empirical index for the assessment of hot environments. The origin of the index WBGT is usually traced to 1957. Based on an investigation to control heat illnesses in training camps of the US Army and Marine Corps, Yaglou and Minard (1957) introduced the WBGT index, accepted by ISO and American Conference of Governmental Industrial Hygienists as a preliminary tool for the assessment of hot thermal environments (d'Ambrosio Alfano et al., 2014b).

This empirical index combines the measurement of two derived quantities, the natural wet bulb temperature and the globe temperature together with the air temperature and claims therefore to take into account the main heat transfer phenomena (evaporation, convection, and radiation) affecting the thermal sensation and strain. In 1989, the early version of the standard was revised. It is currently in advanced stage of review.

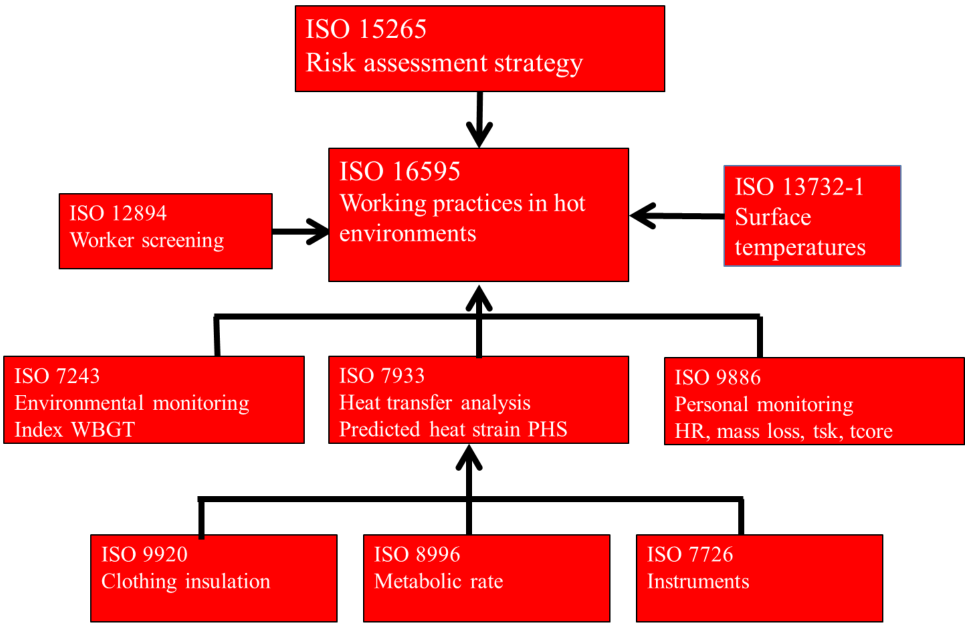


Figure 4. ISO Standards for the assessment of heat stress

In the same year ISO released the ISO 7933 entitled *Hot environments: Analytical determination and interpretation of thermal stress using calculation of Required Sweat Rate*. Published by the CEN in 1997 as EN 12515, the standard adopted the Required Sweat rate index SW_{req}. This is a rational index taking into account a simplified thermoregulation model and the heat transfer mechanisms within the body and between the outer surface of it and the surrounding environment.

Considering the major limitations of EN 15215, as well as the fact that this standard appeared to be little used in practice (Malchaire et al., 2001), a joint research project between some of the main European research teams in the field of thermal factors was started in the period 1996-1999. The European Union supported this project (entitled Assessment of the risk of heat disorders encountered during work in hot conditions) within the Program BIOMED II. As a result of this research a new model was developed: the *PHS* (Predicted Heat Strain) adopted since 2004 in the new version of ISO 7933 Standard. Formulated on a rational basis (Malchaire *et al.*, 2001, 2002) with new equations and boundary conditions, and robustly validated both in the field and under laboratory conditions, the *PHS* model provides results very different from those exhibited by the SW_{req} with high levels of reliability. Nevertheless, *PHS* exhibits some weaknesses (Wang et al., 2011): this is the reason why ISO 7933 is presently under revision.

3.3 The Standards for cold environments

As stressed by Leblanc (1975), the first studies devoted to the topic dealt with military operations or expedition activities and that only in the past years the interest has moved to the working both outdoors and indoors (freezer rooms, special kitchens or industrial operation carried out at lower temperature), and to the health safeguarding during the climatic cold waves. As a matter of fact, working in cold environments not only results in accidents and injuries but also affects the performances of work due to the required protective measures.

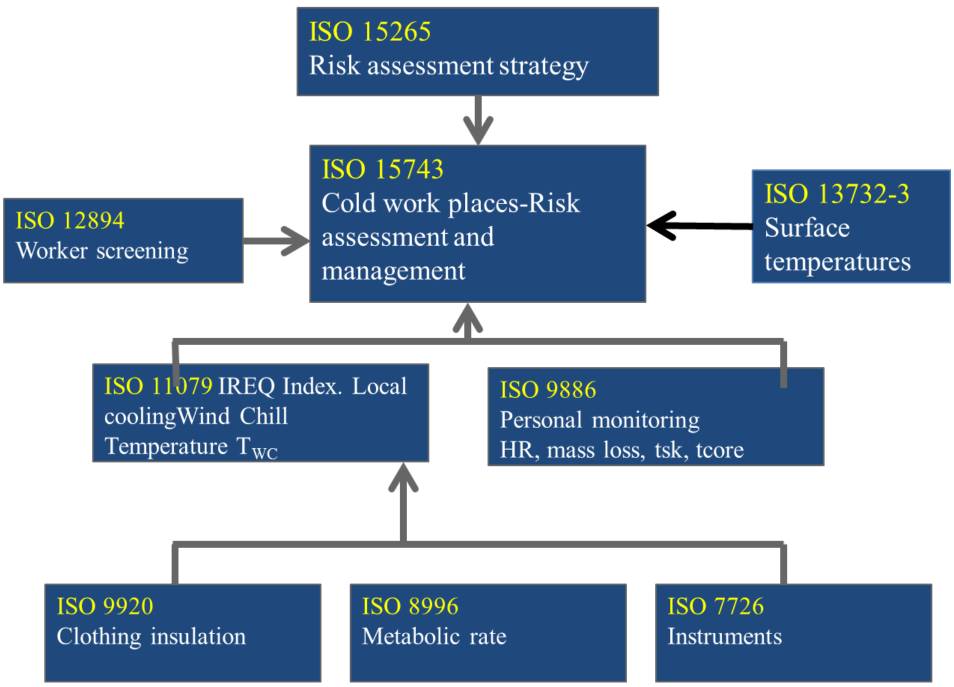


Figure 5 ISO Standards for the assessment of cold stress

The only standard devoted to the matter, is the ISO 11079, issued in 1993 as ISO/TR and entitled *Evaluation of cold environments: Determination of required clothing insulation (IREQ)*. It has been revised in 2007. The standard is based upon the studies conducted primarily in the US and in Scandinavia and defines the IREQ index for global cooling and a series of indices of local risk. IREQ model proposed by Holmér (1984) integrates the effects of air temperature, mean radiant temperature, relative humidity, air velocity, and metabolic rate and specified the required clothing insulation of the clothing ensemble consistent to the actual environmental conditions and activity of the body to maintain its thermal equilibrium.

3.4 The Standards for moderate environments

ISO 7730 was the first International Standard addressed to moderate thermal environments. Entitled *Determination of the PMV and PPD indices and specification of the conditions for thermal comfort*, it was published on August 15, 1984. The convenor of the ISO workgroup (TC159SC5WG1) on the thermal environments was led by Aubertin, while the work on ISO 7730 was led by Prof. Fanger. It was based on the use of PMV and PPD indices (for thermal comfort conditions for the body as a whole) formulated on a rational basis in the well know Fanger's book entitled Thermal Comfort. These indices depend upon four environmental parameters (air temperature, air velocity, relative humidity, mean radiant temperature) and two personal quantities (metabolic rate and clothing insulation). Concerning local discomfort ISO 7730 was based upon the draught rate model also reporting discomfort due to vertical difference of air temperature and radiant asymmetries. All the recommended criteria was based on studies with human subjects (Fanger et.al 1980, 1986, Olesen S. et. al. 1973, Olesen B.W, 1977a, 1977b, Olesen B.W et. al.,1979).

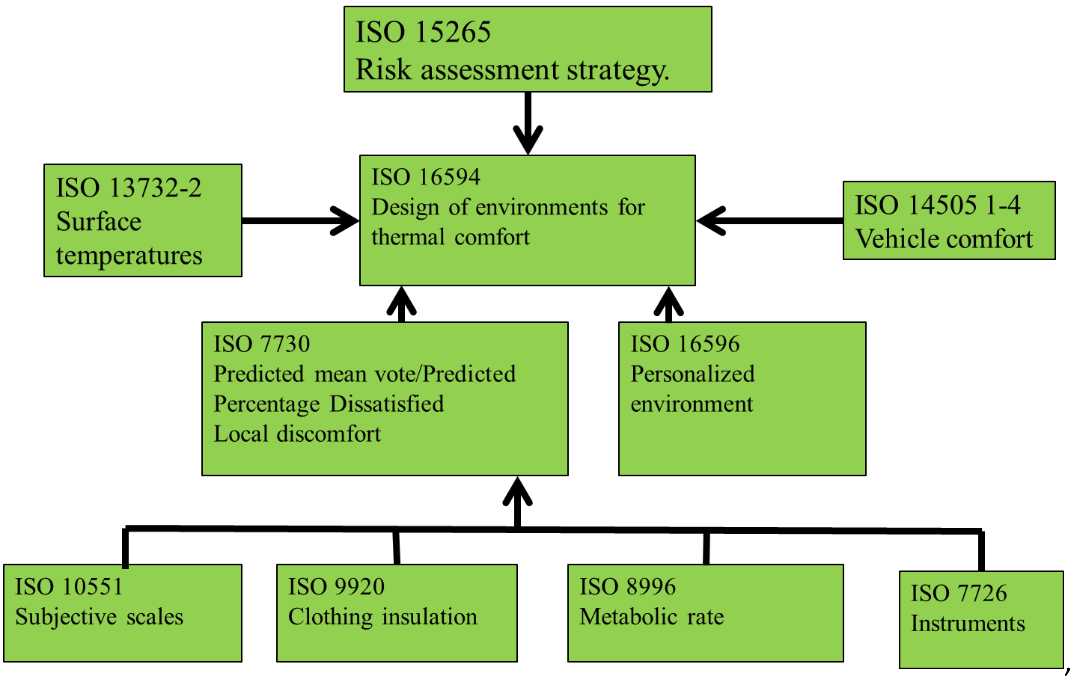


Figure 6 ISO Standards for the assessment of thermal comfort

The development of studies on comfort, in particular those concerning the naturally ventilated environment and on clothing, has led to some fundamental changes that can be found in the 2006 version presently in force (it also exhibit a different title as reported in table 1). In 2015, a new revision process has started accounting all observations arising from the practice (d'Ambrosio Alfano et al., 2014a) and the new scientific achievements in the field of moderate environments (Halawa and van Hoof, 2012).

According to ASHRAE's definition, thermal comfort is affected by the subjective perception of the environment. This is the reason why, as complementary approach to the objective assessment of thermal comfort (ISO 7730), ISO Standard 10551 was published in 1995. This document, also revised by CEN in 2001, defines the scales for the subjective evaluation of moderate thermal environments and gives important information for the formulation and the elaboration of questionnaires.

3.5 Standards for vehicles

Due to small volumes, wide transparent envelope and highly variable and non-uniform conditions all vehicles have to be considered as special environments. Consequently, it is not possible directly to use the PMV and PPD indices. To provide effective methods for their assessment, in 1996 started the European Program *Development of standard test methods for evaluation of thermal climate in vehicles*, whose results led to the publication of the ISO Standards 14505-2 and -3. The part 2 defines four Equivalent Temperature Indices (global, segmental, directional, and omnidirectional) and illustrates respective measurement methods, also based upon the use of thermal manikins. The part 3 provides a method to assess the thermal comfort performance of a vehicle under certain conditions on the base of questionnaires administered with special criteria.

3.6 Standards for people with special requirements

The first draft of the ISO 28803 Standard is dated 2007 and has required a long period of preparation. This high social value document is aimed to apply the Standards in the field of the Indoor Environmental Quality (as a result of thermal, visual, acoustic comfort and indoor air quality) to categories of subjects with particular requirements (e.g age, gender, disabilities). Consequently, it deals with many issues (e.g. the difference in thermal sensation generally felt by an elderly person compared to that experienced by a young person, changes in the temperature perception do to spinal cord diseases, etc.).

3.7 Standards for contact with surfaces

Since the early 2000s, there has been an increasing interest in the issues related to the temperature of surfaces the human body or its parts may come in contact with. Main results from the studies have merged into the ISO 13732 series of standards, which all are based on experiments, with some weaknesses.

3.8 Standards for the assessment of thermal environments

The increased interest in occupational safety and health gave rise to the update of legislation and the promotion of public awareness, education and investigation in this field (Council of the European Community, 1989). This approach resulted in the formulation of a special four-phase strategy called SOBANE (Malchaire et al., 1999), which resulted in a new standard ISO 15265 devoted to the evaluation of the risk for the prevention of constraints or discomfort under thermal working conditions. This Standard provides a protocol of analysis characterized by an in-depth analysis of the working conditions aimed to identify quick solutions for easy problems or special investigations in complex situations.

Some years later ISO Standard 15743, addressed to cold environment and inspired by the SOBANE's Strategy adapted to cold stress risks, was published.

These are very important documents especially because the assessment of non-residential environments as industrial workplaces or technical spaces of ships (Palella et al., 2016) should be assessed with special protocols to minimize health risks and accident (mainly for people with special requirements). It is important to highlight that both ISO and EN workgroups are preparing two other standards for the assessment of moderate and hot environment.

3.9 Supporting Standards

These documents are crucial because they provides basic input parameters for the measurement/assessment, the calculation of indices and, finally, for medical issues related to the assessment of thermal environments.

3.9.1 ISO EN 11399

The purpose of this document, issued in 1995, is to specify information to allow the correct, effective and practical use of all standards concerned with the ergonomics of the thermal environments. Despite several standards here mentioned have been revised and new standards have been published, this standard is now out of date.

3.9.2 ISO EN 13731

The first trace of this standard – issued in 2001 and presently under revision – is a document prepared by ISO/TC 159/SC 5/WG 1 in 1979. The peculiarity of ISO 13731 is the unification of terms and definitions adopted by the standards of the field. Consequently, users and workgroups who have the task of writing the rules have a clear picture on the name of the different quantities, their significance and the symbols. This is not easy, especially because the field of the thermal environment involves a wide variety of skills (e.g. ergonomists, architects, doctors, engineers) and creating a common language is the precondition for a mutual comprehension and a correct application.

3.9.3 ISO EN 9920

Clothing can be considered a behavioral thermoregulation factor: it affects the heat balance on the human body (in terms of thermal insulation and vapor resistance) and, consequently, comfort and stress indices (Alfano and d'Ambrosio, 1991).

The first version of ISO Standard 9920 appeared in 1995 with the title *Ergonomics of the thermal environment: Estimation of the thermal insulation and evaporative resistance of a clothing ensemble*. It was mainly based upon studies carried out in US at the Kansas State University (McCullough et al., 1982) and J.B. Pierce Laboratories (Nishi et al., 1975) and in Denmark at the DTU (Olesen et al., 1982).

The document has been strongly revised taking into account results from researches on the effects of body movements and wind (Havenith *et al.*, 1999; Parsons *et al.*, 1999; Havenith and Nilsson, 2004) and the characterization of thermo-physical properties of clothing (ASTM, 2010). The present version has issued in 2007, revised in 2008 ad adopted by the CEN in 2009. It is an exhaustive document about clothing, with more than one hundred pages and about 60 references. It reports the definition and the meaning of the whole of physical quantities involved in the thermo-physical characterization of clothing (e.g. air insulation, total insulation, basic insulation), the measurement methods, the formulas to be used for the correction of basic values and, finally, special tables reporting clothing thermal insulation and the water vapor resistance of garments and clothing ensemble with different levels of detail.

3.9.4 ISO EN 8996

Metabolic rate is one of the two personal parameters affecting the heat balance on human body and related comfort/stress indices. ISO Standard 8996, issued in 1990 with the title *Ergonomics - Determination of metabolic heat production*, it has been revised and published in 2004. At screening level, it provides the data to use for simply and easily characterizing the mean workload for a given occupation or for a given activity by means of special tables (mainly based upon studies carried out by Spitzer et al., 1982) at different detail. It is presently under revision.

3.9.5 ISO EN 7726

ISO Standard 7726, firstly issued in 1985, has remained unchanged since 1988. New advances of the research on instruments, measurement methods and more and more miniaturized sensors have leaded to a revision, presently under progress.

3.9.6 *ISO 12894* and ISO *9886* Standards

The application of ISO 12894 and ISO 8996 Standards is restricted to severe environments. The first deals with screening methods for persons exposed to hot and cold conditions, the second with measurement and interpretation methods of physiological quantities (e.g. skin temperature, core temperature, heart rate and gross body mass loss).

4 Future of standards related to human response to thermal environments

At the time of writing an integrated strategy is being developed internationally for standards in the area of Ergonomics (ISO TC 159) including physical environments (SC5) and thermal environments (WG1). This will identify progress so far and what standards are required and how they will integrate as a system in the future (next 10 to 20 years). For thermal environments existing standards are continually under review and revision, as new information and requirements become available. New participating countries such as China will bring their considerable expertise to support developments. Consideration is being given to thermal response to special environments (e.g vehicles including space, hypo- and hyper-baric environments, sustainable buildings etc) and special populations (people with disabilities, vulnerable people, children, elderly people, the sick and people from different regions and cultures). Energy use will be a driver for change. Standards for human performance and productivity provide new challenges. New methods including computer aided design, models of human thermoregulation and adaptive and behavioural approaches will be investigated for their contribution to standards. How standards are applied and integrated into user-centred organisations will also influence standards of the future for which there are many opportunities with much work to do in a changing and developing world.

5 Conclusions

Despite the history, standardization in the field of the thermal environment is quite young, it is very complex and in continuous evolution. This is mainly due to the progress in research and the impressive activity of ISO and CEN groups.

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Annex 1 Members of TC159SC5WG1

ISO TC159 SC5 WG1	Members-2016	Members 1980-90's	Affiliation
Country		Name	
Belgium	Malchaire	Malchaire	Univ. Catholique de Louvain
Brazil	Caetano		
Canada	White, Matthew		
China	Ran, Linghua		
	LI, Baizhan		
Denmark		Fanger	DTU
		Langkilde	DTU
	Olesen	Olesen	DTU
	Toftum		DTU
Finland		Ilmarinen	Inst. Occupational Health
		Kähkönen	Inst. Occupational Health
	Rintamäki, Hannu		Inst. Occupational Health
France		Aubertin	INRS
		Grivel	CRNS
		Candas	CRNS
		Gabay	RATP
		Muzet	CRNS
		Azar	Renault
Germany		Hettinger	Inst. Arbeitsmedizin
		Hahne	BAA
		Gebhart	Inst. Arbeitsmedizin
	Kampmann	Kampmann	Ruhrkohle AG
		Griefhan	UNI Dortmund
	Bröde		
	van Treeck		

	Wölki		
India	**Sen, Dibakar**		
	Iqbal, Rauf		
	De, Amitabh		
Israel	**Epstein, Yoram**		
Italy	**D'Ambrosio-Alfano** **Palella**	**Alfano**	**UNI. Napoli**
Japan		**Yoshida**	**Nihon Univ.**
		Tochihara	**Kyushu Inst. Design**
	Yokoyama	**Matsui**	**Nihon Univ.** **Sapporo Univ**
Korea	**Lee, Inseok**		
	Kwon, Ju-youn		
	Kwak, Jae Keun		
	Jang, Hyuk Jo		
Netherlands		**Lammers**	
		Havenith	**TNO**
Sweden		**Holmer**	**Inst. Occupational Health**
	Kuklane, Kalev		**Lund University**
UK	**Parsons**	**Parsons**	**Loughborough Univ.**
		Graves	
		McCaig	**Magdalen House**
		Crockford	**Inst. Tropical Medicin**
	Hodder		**Loughborough Univ**
	Havenith		**Loughborough Univ.**
	Graveling		**IoM Edinburgh**
United States		**Dukes-Dobos**	**NIOSH**
	Bernard		**Univ Southern Florida**

Annex 2 Background and current status

ISO TC159 SC5 WG1'Ergonomics of the Thermal Environment'
Background to development and current status of published and likely future standards.

Note 1. The 'parallel' European committee is CEN TC122 WG11. All work items and standards developed under the Vienna agreement with ISO lead.

Note 2. The experts identified as being involved in the development of standards are from the memory of the authors who have attended almost all of

the meetings of WG1. Many WG1 members contribute and we apologise if there are any omissions or misrepresentations.

Note 3. Standards are the responsibility of the whole working group and their acceptance is by international vote.

Note 4. Technical Reports (TR) and Technical Specifications (TS) are published documents but are not full international standards.

Note 5. The development of a standard is by progressive international vote on a New Work Item (NWI); Committee Document (CD); Draft International Standard (DIS) and Final Draft International Standard (FDIS). The process takes around 5 years. Standards are reviewed every five years and revisions of standards are made as required through a New Work Item and back to CD or DIS stage.

ISO standards related to human response to thermal environments

ISO 7243 (1989) (ED 2) Hot environments–Estimation of the heat stress on working man, based on the WBGT- index (wet bulb globe temperature).
Background: Frank Dukes-Dubos from the National Institute for Occupational Safety and Health (NIOSH) in the USA, led the work on producing an international standard for the assessment of heat stress based upon the WBGT index. The WBGT index was first proposed for the avoidance of heat casualties during outdoor military training in the USA, and is now used, world-wide, in industry, and for other applications such as sport. ISO 7243 was first published in 1982 and limit values were taken from the American Conference for Governmental Industrial Hygienists (ACGIH) annual publication on environmental limits. The values are reviewed and revised annually but the ISO standard still has the original limit values. The revision of the standard is being led by Ken Parsons from Loughborough University, UK and Tom Bernard from the University of Southern Florida, USA (supported by Jacques Malchaire from Belgium, Francesca D' Ambrossio-Alfano from Italy and Shin-itchi Sawada from Japan).

Current status: Proposed revision, ISO DIS 7243 was accepted in ballot with comments at both ISO and CEN level. WG1 considered proposed replies to comments and, after revision to take account of comments, will send ISO FDIS 7243 for a final vote. Note Japan's concern that the existing standard has been incorporated into Japanese regulations, so sensitive about unnecessary change. Hence negative vote by Japan. 15 of 16 countries voted positive at DIS level.

ISO 7726 (1998) (ED 2) Ergonomics of the thermal environment–Instruments for measuring physical quantities.

Background: This standard provides a specification of measuring instruments for the assessment of thermal comfort and heat and cold stress. The project was led by Bjarne Olesen from Denmark with support from Hans-Jurgen Gebhardt from Germany and Gaetano Alfano from Italy.

Current status: The revision is being led by Francesca d'Ambrosio-Alfano from Italy.

Revision will be under the Vienna agreement with ISO lead.

ISO 7730 (2005) (ED 3) Ergonomics of the thermal environment–Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria

Background: This standard is based upon the thermal comfort indices proposed by Professor Ole Fanger from Denmark who also led the project to produce the standard. A second editon was produced, led by Bjarne Olesen from Denmark, which added material on local discomfort and practical application.

Current status: A proposal has been made to revise the standard, led by Jorn Toftum from Denmark and supported by Boris Palella and Francesca d' Ambrosio-Alfano from Italy. Revision will be under the Vienna agreement with ISO lead?

ISO 7933 (2004) (ED 2) Ergonomics of the thermal environment–Analytical determination and interpretation of heat stress using calculation of the predicted heat strain

Background: proposed by Professor Bernard Metz and led by Jean-Jacques Vogt from Strasbourg, France, the Required Sweat Rate (index) was validated in a series of multi-national studies by the European Iron, coal and steel association and produced as an ISO standard in 1989. Limitations, many noted by the German coal mining industry and Bernhard Kampmann, were addressed in a European BIOMED project led by Jacques Malchaire from Belgium. A significant revision led to the Predicted Heat Strain method and current version of the standard.

Current status: Revision will be under the Vienna agreement with ISO lead and Jacques Malchaire as project leader. ISO TC159 SC5 WG1 has agreed to revisions and ISO DIS 7933 will be produced and sent for vote.

ISO 8996 (2004) (ED 2) Ergonomics of the thermal environment–Determination of metabolic rate

Background: Professor Thomas Hettinger from the University of Wuppertal in Germany led this project to provide values and methods to allow estimation of metabolic rate for different activities. It included results from his previous work as well as from the multi-national studies by the European Iron, coal and steel association. A second edition was led by Jacques Malchaire from Belgium, supported by Hans-Jurgen Gebhardt from Germany.

Current status: New revision will be under the Vienna agreement with ISO lead? ISO TC159 SC5 WG1 discussed revisions and ISO CD 8996 will be prepared by Jacques Malchaire and sent for vote.

ISO 9886 (2004) (ED 2) Evaluation of thermal strain by physiological measurements
Background: Where conditions are beyond the scope of methods proposed in standards, direct physiological measures can be used. This standard describes relevant methods and their interpretation. It can contribute to the development of personal monitoring systems. A number of experts contributed to this standard including Jacques Malchaire, George Havenith, Ingvar Holmer, Bjarne Olesen and Ken Parsons.

Current status: Standard accepted and no proposal for revision.

ISO 9920 (2007) (ED 2) Estimation of thermal insulation and water vapour resistance of a clothing ensemble
Background: This standard contains data concerning clothing properties mainly from the work of Elizabeth McCullough and Byron Jones from Kansas, USA for ASHRAE and of Bjarne Olesen in Denmark. It was led by Bjarne Olesen in the first edition and George Havenith (Netherlands/UK) added information for the second edition.

Current status: No new work item proposal for revision at ISO level. Action to consider whether a revision is required, in particular to complement the European initiative on Personal Protective Clothing and Equipment (CEN TC122 WG14).

ISO 10551 (1995) (ED 1) Ergonomics of the thermal environment–Assessment of the influence of the thermal environment using subjective judgment scales
Background: Subjective scales for use in the assessment of thermal environments. Led by Francois Grivel from Strasboug, France.

Current status: New work item for revision accepted at ISO level to cover all indoor environmental components, not just thermal. Revision will be through ISO TC159 SC5 WG4. ISO CD 10551 produced by project leader, Ju Youn Kwon from Korea. To be sent for vote at level of CD.

ISO 11079 (2007) (ED 1) Ergonomics of the thermal environment–Determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects
Background: A method for assessing cold environments using a new index proposed by Ingvar Holmer from the National Institute for Working Life in Stockholm, Sweden. Based upon a calculation of the clothing insulation required to maintain comfort and survival. As the index was new it was first published as a Technical Report, then as a standard. Project leader Ingvar Holmer who later moved to the University of Lund.

Current status: Revision about to begin. Project leader will be Kalev Kuklane from the University of Lund, Sweden.

ISO 11399 (1995) (ED 1) Ergonomics of the thermal environment–Principles and application of relevant International Standards
Background: Standard to describe the series of standards and how they can be applied. Often called the 'umbrella document'. Rod Graves from the UK initial project leader followed by Ken Parsons.

Current status: No new work item proposed. Action ISO TC 159 SC5 to consider revision at level of Ergonomics of the Physical environment. Under consideration by ISO TC159 SC5

WG4 (integrated environments). Current standard out of date but not withdrawn as considered of some use.

ISO 12894 (2001) (ED 1) Ergonomics of the thermal environment–Medical supervision of individuals exposed to extreme hot or cold environments

Background: Medical screening standard led by Ron McCaig from the Health and Safety Executive, UK.

Current status: Standard accepted and no revision proposed.

ISO 13731 (2001) (ED 1) Ergonomics of the thermal environment–Vocabulary and symbols

Background: Standard that provides definitions and symbols and ensures that standards are consistent with the use of terms across the series. Led by Gaetano Alfano and Francesca D'Ambrossio-Alfano from Italy.

Current status: Revision will be under the Vienna agreement with ISO lead. ISO DIS 13731 to be sent for vote. Francesca D'Ambrossio-Alfano is project leader.

ISO 13732–1 (2001) (ED 1) Ergonomics of the thermal environment–Methods for the assessment of human responses to contact with surfaces–Part 1: Hot surfaces

Background: CEN TC122 WG3 used British Published document BS PD 6504 and research by Harald Siekmann from Bonn, Germany, to produce European Standard EN 563 to support the European Machinery Directive. Much needed information on burns caused by contact between machines and hot surfaces. Later transferred to ISO 13732-1 with CEN lead and a more broad scope than just machinery. Harald Siekman project leader.

Current status: No new work item proposed. CEN TC 122 WG11 (having merged with WG3) decided no requirement for revision at meeting of CEN TC122 WG11 in Berlin, 2013. Widely used standard with information incorporated into product standards.

ISO/TS 13732–2 (2001) (ED 1) Ergonomics of the thermal environment–Methods for the assessment of human responses to contact with surfaces–Part 2: Human contact with surfaces at moderate temperature

Background: Japanese initiative led by Joseph Yoshida and later by Dr Matsui to establish thermal sensation when in contact with surfaces of moderate temperature. Later completed by Bjarne Olesen, convenor of WG1 and published as a Technical Specification (TS).

Current status: Technical Specification accepted and no revision proposed. Not CEN document.

ISO 13732–3 (2005) (ED1) Ergonomics of the thermal environment–Methods for the assessment of human responses to contact with surfaces–Part 3: Cold surfaces

Background: A multi-national European research project into skin reaction on contact with cold surfaces led to the production of this standard. The project leader was Ingvar Holmer from Stockholm, Sweden.

Current status: Standard accepted and no revision proposed.

ISO/TS 14505–1 (2007) (ED 1) Ergonomics of the thermal environment − Evaluation of the thermal environment in vehicles − Part 1: principles and methods for assessment of thermal stress.

Background: A multi-national European research project into vehicle comfort (EQUIV) identified the Equivalent temperature as a valid index for use in vehicle standards. This Technical Specification provides background material and was led by Ingvar Holmer from Sweden.

Current status: No CEN document. Series of standards on vehicle environments under review led by Christoph van Treeck from Germany.

ISO 14505–2 (2006) (ED 1) Ergonomics of the thermal environment − Evaluation of the thermal environment in vehicles − Part 2: Determination of Equivalent Temperature (see also ISO 14505–2 (2006)/Cor 1:2007: (ED 1) Technical Corrigendum 1.)

Background: A multi-national European research project into vehicle comfort (EQUIV) identified the Equivalent temperature as a valid index for use in vehicle standards. This standard provides definitions of Equivalent Temperature and how it can be determined. It was led by Invar Holmer from Sweden.

Current status: No CEN document. Series of standards on vehicle environments under review led by Christoph van Treeck from Germany. Discussed by WG1 with proposal to include the properties of the seat as a part of the index, in a future revision.

ISO 14505–3 (2006) (ED 1) Ergonomics of the thermal environment − Evaluation of the thermal environment in vehicles − Part 3: Evaluation of thermal comfort using human subjects.

Background: User performance method, using a representative group of passengers, for determining whether a vehicle environment can be considered comfortable. Led by Ken Parsons from the UK.

Current status: EN ISO 14505-3 published. No new work item proposed. Series of standards on vehicle environments under review led by Christoph van Treeck from Germany.

ISO 14505–4 Ergonomics of the thermal environment − Evaluation of the thermal environment in vehicles − Part 4: Determination of equivalent temperature using a numerical manikin.

Background: Detailed computer model of how to determine the Equivalent Temperature. For use in computer aided design. Led by Professor Kori from Japan.

Current Status: No standard or formal document to date. Discussion still in WG1. Series of standards on vehicle environments under review led by Christoph van Treeck from Germany.

ISO 15265 (2004) (ED 1) Ergonomics of the thermal environment − Risk assessment strategy for the prevention of stress or discomfort in thermal working conditions.

Background: Originally a risk assessment methodology for use in hot conditions, it has been adopted more widely as an underlying applications methodology. Led by Jacques Malchaire from Belgium as a practical method for performing risk assessment from simple assessments to the use of experts.

Current status: EN ISO 15265 published. No new work item proposed.

ISO 15743 (2008) (ED 1) Ergonomics of the thermal environment − Cold work places − Risk assessment and management

Background: Part of a series on working practices, where standards are used along with the risk assessment strategy (ISO 15265) in practical assessment (related to 'process standards'). Concerned with cold work places and led by Johani Hassi and Hannu Rintamaki from Finland.

Current status: Standard accepted. No new work item proposed.

ISO/TS 16418 Ergonomics of the thermal environment– Mathematical model for predicting and evaluating the dynamic human physiological responses to the thermal environment.

Background: New work item to develop an ISO model for use in computer aided design. Professor 'Shin' Yokoyama led the project. Successful CD vote but WG1 recommended publish as TS.

Current status: New document to be produced leading to a Technical Specidifcation. Led by Boris Pallela and Francesca d'Ambrosio-Alfano from Italy.

ISO/TR 16594 Working practices for moderate thermal environments

Background: Technical report on practical methods for achieving thermal comfort. Part of the process standards series. Led by Bjarne Olesen from Denmark.

Current status: Work progressing towards TR through ISO TC159 SC5 WG1. Document available and new project leader Jorn Toftum from Denmark.

ISO/TR 16595 Working practices for hot environments

Background: Part of the process standard series. Technical report based upon risk assessment standard (ISO 15265). Led by Jacques Malchaire from Belgium.

Current status: Document has been prepared by the project leader Jacques Malchaire. To besent for vote.

ISO/TR 16596 Personalized environment

Background: The development of workstations with individual control and other adaptive behaviour has led to a requirement for a specification of the range of conditions over which control can be achieved. Bjarne Olesen from Denmark is the project leader.

Current status: No new document has been produced so far, however a link with a separate committee concerned with buildings and indoor environments will provide a draft document. This will be led by Bjarne Olesen.

ISO 28802 (2012) Ergonomics of the physical environment–Assessment of environments by means of an environmental survey involving physical measurements of the environment and subjective responses of people

Background: Developed by ISO TC 159 SC5 WG4: Integrated environments. This standard includes methods for the assessment of thermal environments as well as other environmental components. It is a practical method and the project was led by Ken Parsons from the UK supported by Simon Hodder (UK) and Hiro Sato (Japan).

Current status: Standard accepted. No proposal for revision.

ISO 28803 (2012) Ergonomics of the physical environment–Application of International Standards to people with special requirements

Background: Developed by ISO TC 159 SC5 WG5: Environments for people with special requirements and based upon the document ISO TS 14515 that was led by Joseph Yoshida from Japan, through WG1. Developed to consider standards in physical environments, not just thermal. Project led by Ken Parsons from the UK with support from Hiro Sato, Kenji Kurakata and Ken Segawa from Japan. First standard in this area on accessibility for which there is now a 24500' series.

Current status: Standard accepted and no proposal for revision. Initially considered to be a transition standard as accessibility becomes progressively included in main standards and research leads to greater knowledge.

ISO/TR 15742 Ergonomics of the physical environment -- Determination of the combined effects of environmental components on people

Background: Technical Report to document what is known about how environmental components (thermal, light, noise etc) combine and interact to form responses to 'total' environments. Initial early attempt led by Ken Parsons did not reach CD due to lack of knowledge in the area. ASHRAE produced a 'Guide 10' based upon similar considerations.

Current status: ISO re-started work through ISO TC159 SC5 WG4 'integrated Environments' and led by Simon Hodder, UK.

SESSION 1

New Thinking and Hot Topics in Comfort

Invited Chairs: Richard de Dear and Luisa Brotas

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Re-constructing Thermal Comfort

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Abstract

"Thermal comfort" is a, socially- and culturally-determined construct widely used as the design basis of buildings intended for human occupancy. Design for thermal conditions and energy use dominate engineering design to meet consensus and regulatory building design guidelines. While early commentaries by meteorologists focused on human health impacts of thermal conditions, more recently, meteorology has focused attention on thermal comfort requirements and their contribution to increased atmospheric concentrations of greenhouse gases. Global warming concern has stimulated widespread engineering efforts to increase energy efficiency. Examination and refinement of the thermal comfort model is the subject of substantial research activity with conflicting and, at times, indicting results. Responses from mostly non-engineering stakeholders focus on examination of alternatives to the model with its flawed input data, virtual neglect of important factors, and the construct's implicit assumptions that drive building energy use. Commentators question the construct and the process by which it should be determined or applied. Exploration of the construct and alternatives have important implications for environmental policy as well as human relationships to the buildings we occupy. Application of the standard throughout the world is simply unsustainable. The time has come for re-evaluation of the construct "thermal comfort."

Keywords: Thermal comfort, construct, occupant control, climate change, sustainability

1 Introduction

"Comfort is a state of mind." (Rohles, 1988).

In this paper we inquire into the underlying problems associated with the construct of thermal comfort and the thermal comfort model, and we discuss alternatives based on suggestions by Cain. (2002) and Chappells and Shove (2005).

The thermal comfort model used in modern standards and regulations, primarily in "advanced economies" (or industrialized countries) was developed >45 years ago by P. Ole Fanger for use in centrally-controlled environmental control systems (e.g., HVAC) (Fanger, 1970; van Hoof, 2008). Refinements have been made in the data available for use of the model, but many problems still remain.

To be clear, the model and its application have little or no place in the buildings occupied by the vast majority of the Earth's population and primarily serve the wealthier 15% who live in the advanced, industrialized economies or the wealthier segment of developing economies.

> "Rather than figuring out more efficient ways of maintaining 21–23C in the face of global warming, society should be embarking on a much more searching debate about the meaning of comfort and the ways of life associated with it. In this way, it might be possible to exploit existing diversity and variety both in people's

expectations and in the built environment and so avoid a commitment to an unsustainably standardized future.” (Chappells and Shove 2005).

2 The thermal comfort Construct

Thermal comfort is a socially- and culturally defined construct (Cain, 2002; Chappells and Shove, 2005). In spite of its limitations, the “thermal comfort” construct remains the most widely-used and dominant basis for design of and research related to buildings intended for human occupancy. Reducing the construct to an engineering design equation ignores important matters of fact and differences in matters of values while addressing dominant political relationships.

2.1 Re-Examination of the construct

Among the concerns suggested by Chappells and Shove (2005) are the imposition of the model on a global scale through spreading standardization and its associated requirement for air-conditioning as well as the lack of participation by many stakeholders outside the HVAC research and manufacturing industry and their associations.

Adjustments to the model and the input data are partially addressed by establishment of standardized measurement systems, addition of the adaptation version for warmer environments, and additional data on clothing insulation values. Un-addressed or under-addressed are issues related to reliance on lab studies versus field studies; occupant control, changes in metabolic rates in the populations of Europe and North America during the last 55 years (since the referenced 1960s metabolic rate data were derived and published), and the dynamic nature of the indoor environment and occupant activity and human interactions with occupied buildings.

Many of the details of the model’s performance have been studied (van Hoof 2008; Kim et al, 2013; Humphreys and Nicol, 2003; Nakano, 2002; and Parsons, 2003). Issues related to the construct were raised by Cain (2002) and Chappells and Shove (2005). We will try to focus on the implications of the problems and issues in terms of future direction for thermal comfort research and building design/operation.

2.2 Occupant (User) Control

A fundamental and pivotal issue for occupant satisfaction is the question “who decides what for whom?” (Turner, 1972, 1976), ‘The only way to satisfy close to 100% of building occupants is to give occupants control over the microclimate in the spaces they occupy.’ (Stolwijk, 1984). If buildings enabled personal control, there would be no need to refine or re-evaluate the construct of thermal comfort.

In housing, the most important question is always ‘Who Decides What for Whom?’ (Turner, 1972; 1976). Turner showed that the occupants of housing are most satisfied with their housing to the extent that they control the decisions that are most important to them (Turner, 1972, 1976). Indoor environmental research in office workplaces has shown that a similar effect of control of important decisions is the key to occupant satisfaction (Boerstra, 2013).

User-controlled radiant heaters under the desk, small, desktop variable speed personal fans, and providing more latitude in clothing requirements in offices can enable users to control their own microenvironment with the promise of reaching a dissatisfaction level much closer to 0 % than any possible refinement of the thermal comfort equation, even with "perfect" implementation of the results. There is a large potential for energy saving simply through changes in residential building occupants' behavior without a loss of comfort or well-being. (Dietz et al, 2009).

2.3 Thermal comfort and health

The continuing move to engineered, "thermally comfortable" environments (maintaining a narrow temperature band) has negatively impacted human health by reducing the body's natural ability to respond to environmental challenges. (Marken Litchtenbelt, 2015). Humans' capacity to adapt to their thermal environment is quite large but shrinking among those in carefully managed thermal conditions. "…[A]llowing temperatures to drift may be healthy… and may contribute to a more sustainable built environment." Future thermal comfort models should include Physiology (body composition); individual differences; dynamic indoor environment; optimal comfort, NOT maximal comfort; health; and, other environmental factors (e.g., light/noise)" Marken Lichtenbelt, 2015).

Commentaries written in the 1940s by meteorologists focused on human health impacts of extreme thermal conditions (Brunt 1943, 1945). The human body is an "intricate heat engine, complicated by its possession of a nervous system…" A rise in internal body temperature of …[5°C] or a drop of …19°C can be fatal. The body is able to maintain an approximate equilibrium of temperature "…over a wide range of external conditions, and the body's internal temperature will be very nearly the same…when shivering with cold on a winter's day" or when sweating heavily on a summer's day." (Brunt, 1943).

2.4 Responses to Global Warming (Climate change)

Climate plays a new role: global warming focuses our attention on buildings' energy use and contribution to increased atmospheric concentrations of some greenhouse gases (Kingma, 2015; Girman, 2008; Levin, 2008). Concern over global warming stimulates efforts to reduce building energy use by engineering measures to increase energy efficiency (IPCC, 2015; Architecture 2030). Climate-sensitive design is an ancient practice (Olgyay, 1963) that is largely neglected today.

An alternative response focuses on examination of the construct's implicit assumptions and its power to drive building energy use. Exploration of the construct and alternatives have important implications for environmental policy as well as humans' relationships to our buildings (Cain, 2002; Chappells and Shove, 2005). Residences and non-residential buildings in the USA and UK consume on the order of one-third of their total energy use for heating and cooling. The fraction of actual building-attributed energy use is even greater for thermal control when non-building-related energy uses (e.g., kitchen and laundry appliances, televisions, etc.) in buildings are subtracted from the total.

2.5 Sustainability-focused engineering

The model's assumption of mechanically heated and cooled building environmental control is relevant to only a small fraction (ca. <1/4) of the Earth's inhabitants. A more widely relevant model will require a change in the reliance on air-conditioning with its installation and operational costs and the consumption of energy necessary for its implementation.

A more universally applicable model for thermal comfort control would rely on only natural (or passive) means of heating and cooling supplemented by centralized systems (where available) based on optimizing the trade-off between reducing the dissatisfied occupants and keeping GHG emissions within a small (e.g.,5%) of the minimum achievable with the best available thermal conditions control technology. High tech solutions implementing evolving sensor technology can be driven by real-time data on thermal conditions within and around a building and by occupant thermal sensation.

2.6 The role and refinement of Thermal Comfort standards

Because ASHRAE Std 55 and ISO 7730 are so widely adopted, (at least in advanced economies), there has been abundant research to try to refine/improve the comfort equation without questioning its alternatives such as passive thermal control - heating and cooling, user control, design responsive to local climate and culture, and healthier indoor environmental conditions. But the overall impact of this research has been to refine the model and reinforce its adoption (van Hoof, 2008) while becoming increasingly irrelevant to a sustainable future. (Chappells and Shove, 2005).

Fixing the PMV equation is a technical matter that has an extremely limited ability to create closer agreement between the PMV or PPD and empirical data gathered in the field. All the attention to uniform measurement instrumentation or to improvements in the data available for modeling in research or design do not address fundamental issues such as local climate, culture, and behavior. PMV is capable of modifications to greatly improve the validity of its predictions. (Humphreys and Nicol, 2002). The fundamental construct of thermal comfort is rarely discussed.

PMV yields predictions that are biased with respect to operative temperature, humidity, air movement, clothing insulation, and metabolic rate, and also with respect to the outdoor temperature. The ranges of the component variables that are consistent with the valid use of PMV are much narrower than those given in ISO 7730(Humphreys, 2002; Humphreys and Nicol, 2003).

In spite of its enormous impact on building design, the thermal comfort construct and model are used primarily for design and are not enforced by regulatory bodies in completed buildings. Facility managers may use the portions of the standards as guidance for facility operations.

During design, detailed information on building use is not always available. So, designers use “default assumptions” about building use (occupancy, activity, and operational hours) as well as average weather data in the thermal comfort model. The result is often a design of a highly-engineered, centrally-controlled building for an abstracted occupant and environmental context. Technology is extending the reach of automation and generalized design through automated control of residential thermal environments as part of the so-called “smart house.” Occupants are removed farther from control and awareness of their building’s technical systems. While the designs may be theoretically suitable for the average occupant any place in the world, in reality every occupant and place in the world is unique, and failure to achieve predicted thermal comfort is common.

Is it reasonable to believe that, technically the equation can be 'fixed' to work well everywhere in the world? Or are local climate and human physiological and cultural differences distinct enough to defy universally valid thermal comfort equations unless accurate local factors (climate, expectation, etc.) are introduced into the equation? (Nakano et al, 2002)

Even if the PMV worked well and worked everywhere, do we want to insist that all buildings all over the world have air conditioning? What are the energy and climate implications? Are they "acceptable" or will some of us be "dissatisfied" with the outcome?

3 Thermal comfort model – Why can't we get it right?

3.1 The ASHRAE PMV model and its PPD output

Guidelines for thermal comfort adopted by ASHRAE (2013) , European Committee for Standardization (CEN), and ISO (2005) are based on the simplified tabular and graphic

presentations of the Predicted Mean Vote (PMV model) and associated predicted percent dissatisfied (PPD) equations (Fanger, 1970; ISO, 2003; ASHRAE, 2013). The PPD is calculated from the PMV according to an equation also developed by Fanger (ASHRAE, 2013a, b).

Of the model's four environmental parameters (temperature, relative humidity, air velocity, and radiant temperature). and two human factors (metabolic rate associated with activity levels and the insulation value of clothing) (ASHRAE 2013a, b; ISO, 2005) only one (temperature) or two (temperature and humidity) of the environmental factors are used to operate buildings. The human factors are often assumed without regard to the actual variations that occur in time and space within and among real buildings and their actual occupants (van Hoof, 2008; Nakano et al, 2002).

The standards set targets for the percentage of occupants "dissatisfied" with their thermal environment. These subjective target values vary among the standards.

"[T]he biggest limitation" to the use of thermal comfort models may be "…the accuracy with which comfort perceptions can be related to the physiological variables simulated in the thermal models." (Jones, 2002)

Fanger's equation to calculate PPD from PMV is widely accepted as an essential element of the construct in spite of convincing evidence of its limitations. The ASHRAE *Fundamentals Handbook* shows the PMV-PPD relationship as symmetrical around the neutral value of 0 where the lowest number of dissatisfied occupants is approximately 5% based on the PMV translated into PPD. (ASHRAE 2013a).

Humphreys and Nicol (2003) found that responses were asymmetrical on the warmer and colder sides of neutral. (See Figure 1.) The results of their study using the responses in the ASHRAE database of field studies as a single distribution showed the PMV "free from serious bias," although they found underlying biases in relation to all contributing variables. These biases often combine to produce a substantial bias in PMV. In individual buildings, PMV often "…differs markedly and systematically from the actual mean vote…."in both naturally ventilated and air-conditioned spaces. They concluded that ISO 7730, "in its present form can be seriously misleading when used to estimate thermal comfort in buildings." The authors examined the biases in each of the variables in the equation at different values of PMV and calculated the effect on PPD of the errors in PMV. A plot of their findings is shown in Figure 1

A weak link in thermal comfort theory is the assignment of set values for satisfaction and dissatisfaction. Votes +2 and higher or -2 and lower are deemed indicative of dissatisfaction although there is little or no scientific basis for this. In fact a comparison of results obtained with the model and results obtained through other research methods shows a disturbing lack of correspondence between the PPD values and other expressions of thermal sensation or satisfaction with the thermal environment (Kim et al 2013) and the need for a more integrative view of the indoor environment. (Humphreys, 2002; deDear and Brager, 2002; van Hoof, 2008). Cultural and climate factors also affect thermal comfort votes (Maiti, 2013; Kim et al, 2013).

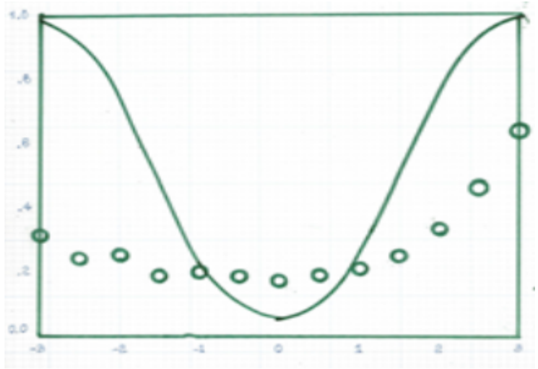

Figure 1 –). Effect of biases in the variables in the thermal comfort equation on the actual percentage of people dissatisfied (APD –open circles) with the thermal environment. Vertical scale is PPD, solid line (based on ISO 7730). Horizontal scale is thermal comfort votes on ASHRAE 7-point scale. (After Humphreys and Nicol, 2003)

There is abundant research testing the accuracy of predictions made with the PMV model that report discrepancies between model predictions and empirical data collected from building occupants. van Hoof's reviewed the results of thermal comfort model use and documented many of its shortcomings and many common criticisms of it (van Hoof, 2008). One explanation offered is that the model was developed in laboratory settings with primarily student subjects in well-controlled circumstances and standardized clothing and activities whereas the populations occupying "real" buildings in the extensive field studies vary in age, activity, clothing, and thermal comfort preference. An additional explanation is that thermal comfort votes used to calculate the average PMV for a population are influenced by the attitudes of the subjects toward their employer, salary, or co-workers. Others have found a stronger correlation with outdoor temperatures. Finally, some researchers have found problems with the details of the model that are discussed below.

Charles (2003) reviewed the thermal comfort model and concluded that the PMV model…

> "…is not always a good predictor of actual thermal sensation, particularly in field study settings. Discrepancies between actual and predicted neutral temperatures reflect the difficulties inherent in obtaining accurate measures of clothing insulation and metabolic rate. In most practical settings, poor estimations of these two variables are likely to reduce the accuracy of PMV predictions."

Some of the controversy reflected in the research associated with the PMV model is related to the model's poor performance in predicting occupant thermal comfort ratings, particularly in building without central thermal control systems ("free-running" or naturally ventilated building) (deDear and Brager, 2002).

3.2 Steady State Assumption

The thermal comfort model is used by engineers with the unrealistic assumption that conditions are at steady state in occupied indoor environments. Building HVAC systems are designed and programmed to be dynamic in their response to typically variable internal loads (usually heat loads, many of which are attributable to the normal ebb and flow of the presence and activities of occupants) and outdoor weather conditions, primarily temperature, wind, insolation, and (often) relative humidity.

Totally neglected in the thermal comfort model is time. The model does not account for changes in the building, the weather, or in occupant activity over time, and these changes can and often do dramatically alter the inputs to the model. Rohles considered time one of the 7 (not 6) factors on which the human response to the thermal environment depends (Rohles, 1981).

3.3 Clothing

Research has focused on reducing the uncertainty of some of the model's parameters, particularly the environmental parameters while the greatest uncertainty tends to be associated with the occupant variables, activity levels and clothing insulation values (van Hoof, 2008). Research results on clothing insulation values have been incorporated into the standard and the supporting handbooks and guidance, but this work largely ignores issues of clothing fit (looseness), fabric type and density, and the effect on the insulation value of the airspace.

An important aspect of occupant behavior that can neither be controlled nor reliably predicted is clothing. The details of clothing and its interaction with occupant activity (e.g., movement) affect the actual insulation value. The range of clo values associated with any type of clothing and the insulation value of the air gap between layers span such a large range that continually adjusting the values in the standard is unlikely adequately to cover all combinations and variations of the infinitely large number of ensembles, textiles, fit, and activity. By enabling occupants to modify their clothing or local environment modestly, a far larger fraction of occupants are likely to be satisfied with the thermal conditions of their environment.

3.4 Design versus Performance Standards

There is a fundamental difference between design standards and performance specifications as the basis of design. While ASHRAE and ISO thermal comfort standards appear to specify the thermal conditions that must be achieved, the standards' are used only for design - as they are required by regulations and codes in many jurisdictions. The actual control and operation of centrally-controlled buildings is almost universally done on the basis of only dry bulb temperatures, thus ignoring the other three environmental factors: relative humidity, air movement, and radiant temperatures and on the basis of overly simplistic and often incorrect assumptions about the human factors: activity level and clothing insulation values.

In spite of its enormous impact on building design, the thermal comfort construct and model are used primarily for design and are not enforced by regulatory bodies in completed buildings. During design, detailed information on building use is not always available, so, designers use "default assumptions" about building use (occupancy, activity, and operational hours) as well as average weather data in the thermal comfort model. The result is often the design of a highly-engineered, centrally controlled building for an abstracted occupant and environmental context. Technology is extending the reach of automation and generalized design through automated control of both commercial and residential thermal environments as part of the so-called "smart building" Trend, largely a marketing term for equipment manufacturers. Occupants are removed farther from control and awareness of their building's technical systems. While the designs may be theoretically suitable for the average occupant any place in the world, in reality every occupant and place in the world is unique, and failure to achieve predicted thermal comfort is common.

3.5 Model prediction accuracy

Abundant studies of research designed to assess the accuracy of predictions made with the PMV model report discrepancies between model predictions and empirical data collected from building occupants, with much of the literature reporting discrepancies conducted in climates and/or cultures that differ significantly from those of North America and Europe (Maiti, 2013), where the standards based on the PMV model are widely codified into regulations governing the design of buildings (Kim et al, 2013; Nakano et al, 2002). The model is a design tool and there is limited practical adherence to it in the operation of real buildings where operators adjust system settings to conserve energy or to reduce the level of occupant complaints about thermal conditions.

Figure 16, (in Chapter 9) of 2013 ASHRAE *Fundamentals Handbook* shows the relationship between PMV and PPD as symmetrical around the neutral value (0) where the lowest number of dissatisfied occupants is approximately 5% based on the PMV translated into PPD and at thermal comfort votes of +3 and -3 the PPD is shown as 100% (ASHRAE, 2013a). In Figure 1 (after Humphreys and Nicol, 2003) the PPD is clearly asymmetrical around the zero value (thermal neutrality) possibly reflecting physiological differences (discussed above) and psychological tolerances for the human responses to warmth and coolth.

A comparison of results obtained with the model and results obtained through various other research methods show a disturbing lack of correspondence between the PPD values and other expressions of thermal sensation or satisfaction with the thermal environment. (Humphreys, 2002, Charles, 2003, Humphreys and Hancock, 2007, van Hoof, 2008; Kim et al, 2013;).

In spite of a very large body of literature illustrating substantial deviations between model predictions and actual results from field studies (Charles, 2003), the model continues to dominate the design of buildings through its incorporation in standards that become requirements through regulation. Even if such requirements were not enforced by law and regulation, it is likely that designers would use the model to assist in their design process.

3.6 Activity Levels and Metabolic Rates

The metabolic rates at various activity levels referenced in ASHRAE's Standard 55-2013, in the Normative Appendix Activity Levels. (ASHRAE 2013), are based on research performed in the 1960s (Buskirk, 1960; Passmore, and Durnin. 1967; Webb, 1964) referenced in the ASHRAE Fundamentals Handbook (2013a)

3.6.1 Size matters, age matters

Changes in average human body surface area of the American and European populations since the 1960s accompanying the increased individual weight of the general population during the past 45 years results in changes to the metabolic rate at any given activity level. A graph of the U.S. population average body surface area by age and sex is shown in Figure 2. Regional differences within and beyond the U.S. are well-documented. (see Figure 3) Similar changes have been observed in Europe. PMV is strongly determined by metabolic rate used in the calculation. ASHRAE (2013a, b) bases the metabolic rates on a body surface area of 1.8 m^2. Clearly the body size and surface area and associated metabolic rates have changed since the 1960s due to changes in diet and resulting changes in individual size and weight.

Body size and skin surface area also varies by age and sex, as seen in Figure 2. Body surface area and weight are direct determinants of metabolic rate at a given physical activity level.

The default value for body surface area in ASHRAE's Handbook and Standard 55 is 1.8 m^2 although it is acknowledged that there is a difference between males and females. Figure 2 shows that adult male body surface area is higher than 1.8 m^2 and in general, adult female body size is at or below 1.8 m^2. A proportional change in metabolic rate could improve model performance when evaluated in field settings if values for study subjects are more accurate. Also, metabolic rates must reflect the fact that people commonly move about within a space during the time spent in the space and a single assumed activity level related to the main activity-of the space are generally too low.

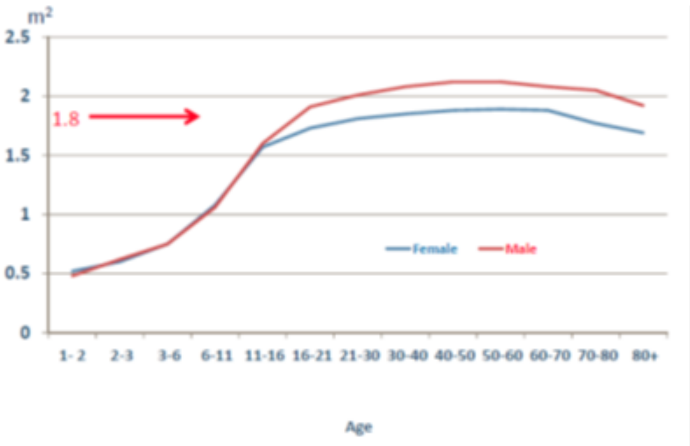

Figure 2. American Male and Female body surface area by age group (based on data in the EPA Exposure Factors Handbook 2011).

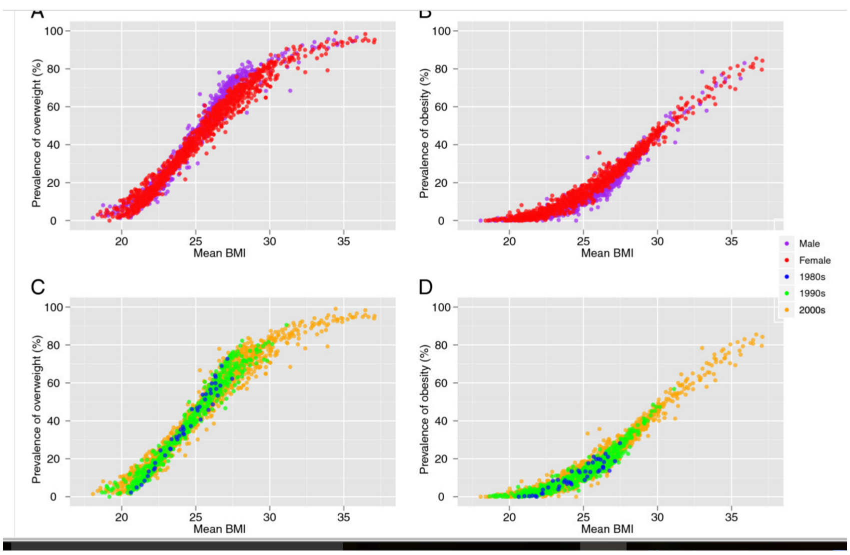

Figure 3. Mean BMI vs. prevalence of overweight (BMI ≥ 25 kg/m 2), (A) by gender and (C) by decade; and mean BMI vs. prevalence of obesity (BMI ≥ 30 kg/m 2), (B) by gender and (D) by decade. Data are from 243 health examination surveys, by age and sex. (Stevens et al, 2012)

Research supported by the U. S. National Institutes of Health produced metabolic rates associated with a very wide range of activities, (Compendium of Physical Activities, 2016). The values for metabolic rates for a given activity in the Compendium are 10 to 25 % higher than those listed in the ASHRAE *Fundamentals Handbook* Chapter 9, and in Mandatory Appendix A of Standard 55-2013 (ASHRAE, 2013a.).

3.7 Naturally-ventilated buildings

Some of the controversy reflected in the research associated with the PMV model is related to the model's poor performance in predicting occupant thermal comfort ratings in buildings without central thermal control systems (free-running or naturally ventilated buildings in warm conditions. The introduction of the adapted thermal comfort model addresses this problem (Brager and deDear,1998; deDear and Brager, 2002).

3.8 Model Imbalance

The thermal comfort model uses a scale that is symmetrical around the so-called neutral thermal state. However, the human physiological response and individual control options are quite different for environments rated as too warm and too cool. Human physiological responses to the thermal environment are not symmetrical above and below the neutral temperature where the body is neither sweating and vasodilating to shed heat to the environment or shivering and reducing blood circulation to the skin and possibly cutting off circulation to the limbs to conserve heat in cold conditions.

In warm environments (or during strenuous exercise), human physiology provides the sweating response and increased blood flow to the skin to maintain thermally neutral core temperatures. "[S]ecretion and evaporation of sweat is the main factor in the dissipation of heat from the skin." The evaporation rate increases as wind speed increases and humidity decreases. As wind speed decreases or humidity increases, sweating increases. Thus the body is in a dynamic relationship with its environment. Evaporative losses are larger than convective losses…." (Brunt, 1945).

In the case of extreme heat and extreme cold, the body's "sensors, "warning systems and response systems are very different Extreme heat and extreme cold a trigger different and not necessarily opposite reactions. Milder heat or cold responses are mediated through changes in blood flow to the skin (vasodilation or vasoconstriction) and sweating.

3.9 Time matters

The ASHRAE Standard includes an equation for calculation of the average activity level during occupancy of a space to account for the distribution of activity levels over time. Typically design is based on assuming an activity level that is characteristic of the use for which the space is intended. It does not account for the fact that people first entering a space are generally at a higher metabolic rate than when at an office workstation, conference room table, or classroom desk. Occupants' previous activities may include walking, exercising, riding a bicycle, eating, etc.

Office workers and students in classrooms do not generally spend the entire time they are present at the lower activity level generally associated with the space. For example, office workers take breaks, to the coffee or refreshment space or to the toilet, walk to communicate with a co-worker or to make copies or retrieve paper mail or supplies, etc. Thus, the actual metabolic rates characteristic of the office population is likely somewhat higher than that associated with the assumed sedentary activity level of the standard. (Goto, 2002). The actual average metabolic for an individual will depend on their activities in the time period preceding their entering the space of interest and during the time spent in the space. The metabolic rate will normally decline after entering an office or classroom, the average value misses the effect of the transitional time and process (Goto, 2002). Clearly someone who has been exercising or eating immediately before entering the space will be at an elevated metabolic level for some period of time after entering the space. The amount of time it takes to shift from the previous met level to the one characteristic of the activity level in the space may be a small (<0.1) or large (>0.4) fraction of the time spent in the space. The larger the ratio of the two met levels, the more important its impact on an individual's average met level while in the space.

3.10 Adjustment and improvement of the model

Research has focused on reducing the uncertainty of some of the model's parameters, particularly the environmental parameters, while the greatest uncertainty tends to be associated with the occupant variables, activity levels and clothing insulation values (van Hoof, 2008). van Hoof found deviations from the expected calculation of PPD based on PMV were large in the ASHRAE database of thermal comfort field studies (2008).One can try to adjust the variables and make other refinements to the model to account for the discrepancies found by many of the researchers reviewed in Charles (2003), and in van Hoof (2008), and Kim and deDear (2013), and summarized in Kim and deDear in their Table 1.

3.11 Interactions with air quality

The combination of indoor air quality (IAQ) and thermal conditions strongly affect the perceptions of occupants, according to Humphreys and Nicol (2003). They reported that "The physical variables that seemed likely directly to affect the perception of air quality were air temperature, relative humidity, and air movement." Thus, three of the four physical environmental factors in the PMV equation are important to the perception of IAQ. Since ASHRAE Standard 62.1-2013, Ventilation for Acceptable Indoor Air Quality (2013c), defines thermal conditions as being out of the scope of the standard, and Standard 55-2013 (2013b) defines indoor air quality as being out of the scope of the thermal comfort standard, these two standards intentionally ignore an important interaction that affects overall satisfaction of building occupants.

Zhang et al found perceived air quality closely correlated with thermal comfort in the range of temperatures from 18 to 30 °C. (Zhang et al, 2013)

4 Discussion of the construct of (thermal) comfort

A focus on the construct itself is rare within the vast literature on thermal comfort. But the choice between two definitions makes a large difference for energy and environmental policy: . "[O]ne that comfort is a universally definable state of affairs, the other that it is a socio-cultural achievement." (Chappells and Shove, 2005).

Cain (2002) discussed the construct of Comfort in his Plenary Lecture at Indoor Air 2002 and suggested how the conversation about thermal comfort could be improved with a more thoughtful construct. Cain made a case for reconsideration of the construct "comfort" and provides some criteria for the development of a more robust guideline or standard for use by building designers.

According to Cain, we must consider the following with respect to the thermal comfort construct:

"1) Comfort is a construct that exists in our thinking and cannot be measured directly.
2) Assessment of a construct requires more than one expression (outcome variable) for valid measurement.

3) A model of a phenomenon, such as comfort, may productively view and assess interaction between constructs.
4) Thinking about the interaction and manifestation of constructs encourages development of hypotheses, the engines of scientific progress.
5) There exists statistical methodology to test models of relations between constructs.
6) The new models can move research beyond the intuitive model of comfort." (Cain, 2002).

"Thermal comfort" drives design, construction and operation of modern buildings in industrialized economies. Because of the very large fraction of total building energy consumption attributable to thermal conditioning, the standards for thermal comfort are primary drivers of design and, therefore construction. Beyond that, they provide the basis for operations in terms of available options to the occupant and operator/facility manager. The construct depends strongly on subjective responses to the thermal environmental based on human physiology and individual physical, psychological, and perceptual responses to the indoor environment. The focus during building design is on meeting the requirements of codes, standards and guidelines for thermal comfort and energy consumption. An important question is whether there will be continued imposition of the model on more and more geographical regions and an accompanying increase in the use of centrally-controlled mechanical systems with air conditioning. The environmental consequences of such a trend are of substantial concern. (Cain, 2002; Chappells and Shove, 2005).

The construct itself is viewed differently by different groups or stakeholders (Chappells and Shove, 2005).

Human physiology is not oriented toward maintaining thermal comfort but is oriented toward maintaining the core body temperature within a fairly narrow range of the normal temperature at basal metabolic rates. There is an imbalance in the model which is based on the 7-point subjective rating scale that is symmetrical on the high and low sides to represent thermal condition satisfaction on the warm and cool sides of "neutral."

The foundation for the construct is poorly defined (vague?) and badly out-of-date. The construct's underlying implicit and explicit assumptions are not supported by the available data and are not relevant for most of the Earth's population. The standards and technologies used to implement the delivery of thermal comfort in buildings ignore the complexity of the human response (*e,g.,* user control and passive means for control and natural ventilation are not given their appropriate place in the construct or its manifestations as standards and guidelines). The dominant design solutions in buildings in industrialized economies and the standards that constrain them ignore the unsustainability of the relevant standards, codes, and practices .typical designs are not meeting the requirements within the resource limitations of planetary boundaries.

Step by step, the mechanism of human thermal adaptation has been discovered to include psychological adaptation, physiological adaptation, and physical factors. Anticipated control (or perceived control) plays an important role in psychological adaptation. Beyond the outdoor climate, long-term indoor thermal experience is a crucial factor for physiological adaptation as well. (Zhu et al 2016.)

4.1 Standards vs design

Humphreys and Nicol (2003) examined the use of "…ISO 7730 (predicted mean vote) to predict the thermal sensations of people in buildings." They used the ASHRAE database of field studies to examine the accuracy of predictions based on the PMV model used in ISO7730 and ASHRAE Standard 55-2013. They found that there are "…underlying biases in relation to all contributing variables, and a further bias related to outdoor temperature. These biases often combine to produce a substantial bias in PMV. In surveys of individual buildings, PMV often differs markedly and systematically from the actual mean vote, both for naturally ventilated and for air-conditioned (AC) spaces. "

"The direction of the overall bias in PMV is such as to overestimate (by a factor not much short of two) the main subjective warmth of groups of people in warm environments. This has practical consequences for the operation of buildings, and can lead to the provision of unnecessary cooling." (Brager and deDear, 1998) "It also affects design decisions, because thermal simulations at the design stage might indicate, mistakenly, that a building would need cooling to maintain comfortable indoor conditions in summer" (Humphreys and Nicol, 2002, 683)

4.2 The role of stakeholders

Chappells and Shove (2005) pointed out that the construct has been developed by a very limited segment of the stakeholders, and that it should be re-examined by a broader group including architects, developers, building occupants, and regulators as well as representative of the affected industries, researchers, and engineers.

5 Conclusions

Is it time to re-evaluate the construct (with all the stakeholders) which implies that we know what thermal comfort is -- for everyone and everywhere?

What are the alternatives to the Thermal Comfort construct? Consider the following:

- Adoption of a model for thermal comfort control by centralized systems that enables a trade-off between reducing the dissatisfied occupants and keeping GHG emissions within a small percentage (e.g., 5%) of the minimum achievable with the best available thermal conditions control technology.
- Requiring maximum use of passive thermal conditions control prior to the use of energy from combustion or nuclear power. This could involve natural ventilation for cooling, passive solar heating, maximum use of economizer cycle ventilation system design and control, and maximum freedom for occupants to choose their clothing for personal comfort.

Some scholars have built their careers on analysis based on the thermal comfort model. One is led to ask: why does the scholarly community resist challenging the model and accepting that it might be the time to shift from efforts to refine the model and that it may be time to develop a new model?

PMV can be seriously misleading when used to predict the mean comfort votes of groups of people in everyday conditions in buildings, particularly in warm environments. The revision of ISO 7730 should note the limitations of PMV for use in buildings, and give a range of applicability in line with the empirical findings.

The biases in PMV affect PPD which can be very misleading when used to predict the extent of thermal dissatisfaction among people in everyday conditions in buildings. Although PMV is capable of modifications to greatly improve the validity of its predictions…" (Humphreys and Nicol 2002), an engineering approach is unlikely to eliminate all inaccuracies and is not sustainable from a global perspective.

Designers cannot control occupant behavior which produces large uncertainty in the model. Behavior can overwhelm the indoor factor measurements or estimates in their impact on the PMV and PPD. By enabling occupants to make small adjustments in their environment, the unpredictability can be removed as an obstacle to a higher fraction of satisfied occupants. Occupant behavior must be fully incorporated in any revision of the existing model or development of a new thermal comfort model.

Larger societal and environmental concerns suggest that alternatives to the standardization of thermal comfort should be seriously considered. The future of indoor environmental quality and thermal comfort may rely more heavily on the occupant to control the environment to reduce thermal discomfort and to improve occupant satisfaction.

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Proceedings of 9th Windsor Conference: ***Making Comfort Relevant***
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Diversity in Thermal Sensation: drivers of variance and methodological artefacts

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Abstract

In this paper we structure biological, psychological and background/experience drivers of thermal comfort variance and their relationships to develop a conceptual interaction model. The aim is to create a theoretical model containing a broad range of influencing factors that can be used for hypothesis generation. Furthermore, the paper provides a framework for assessing how much of the observed diversity in comfort votes may arise from imprecise instruments through the assessment of various forms of validity.
Current comfort models, both predictive and adaptive, focus on the prediction of conditions comfortable for an average person in order to derive comfort bands suitable for the majority of building occupants. Such models do not explain why we observe such a diversity of comfort votes from occupants of the same building. We argue that understanding diversity is important, both practically and scientifically, and that to do so we need to address the physiological, psychological, social, cultural and built-environmental conditions that give rise to observed diversity in comfort. It is expected that in doing so, the research community will both improve its scientific understanding of comfort, but also develop new ways of providing comfort that can create acceptable environments for more people using less energy.

Keywords: Thermal Comfort, Physiological factors**,** Psychological factors**,** Environmental factors**,** Diversity

1 Introduction

Over the past 30 years, both the nature, and the scale, of thermal comfort research have changed significantly. Fanger's PMV model (Fanger, 1970) has been complemented by the adaptive comfort model (Auliciems, 1981; de Dear et al, 2002; Nicol et al, 2010), with both embedded in standards and in wide use. Over this period, the technologies used to measure the environmental factors associated with thermal comfort have similarly evolved rapidly. Technologies for the measurement of ambient (and to a lesser extent radiant) temperature, relative humidity and air speed have become smaller and cheaper. This has enabled the scale of empirical thermal comfort data collection to increase substantially. This is illustrated in the ASHRAE RP 884 database (de Dear et al, 1998) that underpinned the development of the international standards for adaptive thermal comfort containing tens of thousands of data points across a wide range of countries.

There has, however, been less development in the area of identifying and measuring the personal factors that determine an individual's thermal comfort. Whilst metabolic rate and clothing level have long been understood to be important drivers of thermal comfort, our methods of measuring both these parameters have evolved little over the past 30 years - particularly in the context of field studies. Similarly, while there has been a proliferation of thermal comfort concepts - some well-established such as thermal sensation and thermal preference, and some more recently created/revived such as the importance of control, thermal acceptability and alliesthesia - there has been little emphasis on the development and testing of instruments to measure these comfort concepts.

There has similarly been comparatively little work on theorising thermal comfort post the development of the Adaptive Comfort Model. This is not to say that there haven't been signficant individual contributions (e.g. de Dear, 2011; Schweiker et al., 2012; Hellwig, 2015), more that there has neither been a consistent attempt to integrate new ideas emerging from the physiology and psychology communities into our understanding of comfort, nor to specify additional drivers related to behavioral, physiological, or psychological adaptive processes as suggested by Schweiker and Wagner (2015). Both the fields of physiology and psychology, have seen significant theoretical and methodological developments of direct relevance to comfort research in recent years, and we argue that the integration of best practice in these fields can only serve to improve our understanding of thermal comfort.

In this context, the aim of this paper is to simultaneously seek greater conceptual clarity on what thermal comfort concepts to measure, discuss mechanisms for the development of better instruments for measuring them, and suggest a conceptual model that can explain what factors drive diversity in comfort.

2 Why diversity matters

As Nicol et al (2012, Figure 10.6) note with respect to the plot of comfort votes vs. indoor operative temperature: "...One of the most instructive things about this for those who are unfamiliar with field survey data will be how scattered the data are.” An inspection of such a plot quickly reveals the diversity of temperatures at which people report feeling comfortable. For any given temperature between around 22°C and 28°C; there are simultaneously people who regard that temperature as 'much too warm' and others that regard the same temperature as 'much too cool'. The traditional response to such diversity has been to run linear regressions between comfort votes and environmental parameters (notably indoor operative temperature in the case of the adaptive thermal comfort model) to determine the correlation, then to model thermal comfort as a linear relationship with one or more independent variables. Statistically however, this discards a great deal of useful information, and such diversity of responses within the population naturally invites the development of more complex statistical models able to explain the observed variance. In Figure 1 below (reproduced Figure 10.10 from Nicol et al, 2012), the regression of comfort vote against operative temperature explains around 16% of the observed variance in the data. The 84% of residual diversity remains unexplained but is a valuable resource for future explanation of additional factors driving diversity in comfort perception. It is typical to extend such analyses through the introduction of additional variables using multiple linear regression methods, but to date such analyses seldom extend beyond correlation with running mean external temperature.

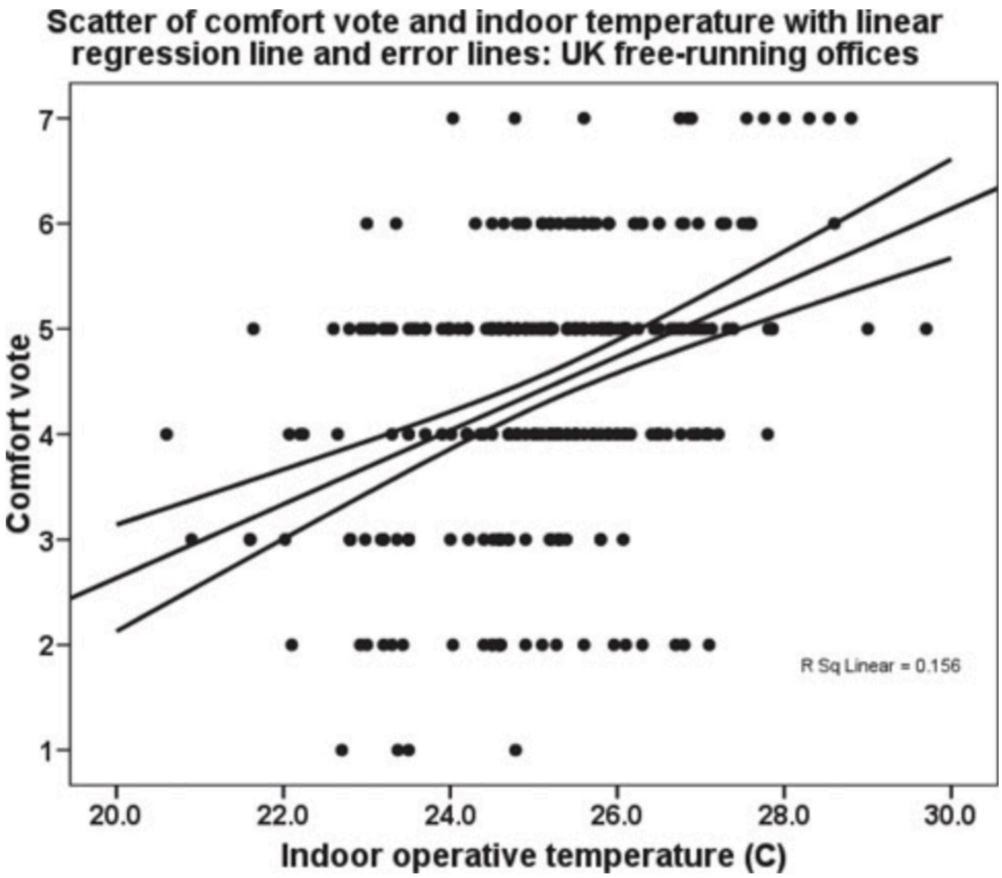

Figure 10.10 The comfort votes measured against temperature from Figure 10.6 with regression line for C on T_o added.

Figure 10.10 from Nicol et al (2012)

2.1 Practical reasons

Models that can better capture the diversity of thermal comfort requirements within the population are important for three reasons. Firstly, models that work on delivering neutral temperatures (the temperature corresponding to the centroid of the comfort votes against operative temperature plot) cannot deliver comfort to those participants that report finding such population-based neutral temperatures thermally uncomfortable. Studies have repeatedly found that the provision of neutral temperatures leaves between 10% and 20% of building occupants in thermally unsatisfactory conditions. Overcoming this requires provision of differentiated comfort conditions between individual offices, and within open plan offices. The design and provision of such systems however requires that we understand the drivers of diversity, and the likely diversity of comfort requirements needed to satisfy occupants in offices of different sizes and in different regions.

Secondly, understanding the diversity of comparable responses creates the opportunity to deliver comfort through different mechanisms than changing ambient temperature. There is considerable work addressing elements of this, for example provision of radiant heating and cooling, however the more we can understand the different mechanisms by which comfortable conditions can be created, the greater variety of ways we have at our disposal to deliver such conditions to occupants. Each mechanism through which we can deliver comfort will have different energy requirements, and will themselves vary in energy requirements depending on the spatial scale at which the technology is deployed. This leads to the requirement for models that can be applied to individuals, and to those parts of individuals more sensitive to heating and cooling.

Thirdly, the primary drivers of, and constraints on, thermal comfort provision are changing. Historically, the primary constraint has been energy demand in buildings, however this is increasingly being matched or surpassed by the requirements for the delivery power demand-side response energy services from buildings to support the deployment of smart grids. One of the primary distinctions between designing comfort systems under constraints on energy, and those under constraints of power, is that power constraints are far more temporally specific. Demand-side response (DSR) usually operates for the periods of hours requiring the capacity for buildings to drift in temperature over the short term. Dynamic thermal comfort models provide the information needed to maintain comfort by adjusting low energy intensity comfort vectors, whilst allowing high energy intensity vectors to drift during the DSR period.

2.2 Scientific reasons

In most scientific fields, model construction is an integral part of the process of knowledge construction. As outlined in Morgan and Morrison (1999), models form an essential element bridging theory and data. They act to support both the construction of new theories, and the testing of hypotheses based on existing theories. This process of theorising, model building, and measuring is at the core of the scientific method of progressively increasing understanding in a given field. The basis of scientific claims to knowledge, the 'scientific epistemic warrant', rests on the process of hypothesis construction and the testing of such hypotheses in unobserved cases. While there is some tradition of this in thermal comfort research, the bulk of the work to date has been descriptive, representing observed relationships in data in models (it is arguable that the adaptive relationship with external temperature is an example of this). Such models tend not to encode theoretically informed relationships expected to drive diversity in responses that can subsequently be evidenced through hypothesis testing.

In many areas, there is an increasing move towards the delivery of comfort through Personal Comfort Systems. This is evident both in the automotive and aviation sectors. Given the potentially considerable energy savings and improvements in occupant satisfaction that such systems can provide (Zhang 2015) it seems likely that such systems will increase within the built environment. As argued above, the design, commissioning, and maintenance of systems providing personal comfort will require models that are able to represent individual's comfort requirements and help identify 'isocomfort'[1] lines and planes (areas of equal comfort) through the multidimensional space of variables that determine comfort for any one individual at any one point in time.

Developing such models will present fundamental challenges to our understanding of the interaction between human physiology and human psychology, and how both of these are

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[1] The term 'isocomfort' is a term used in ergonomics to represent positions of equal comfort in joint movement for people undertaking activities (e.g. Kee and Karwowski 2001). There is an analogous case where occupants report being equally comfortable under different combinations of environmental, physiological and psychological conditions in buildings.

impacted upon by the physical and social environments in which we live. Integrating the effect of such a diverse range of factors into models of thermal comfort is a fundamental scientific challenge that will require a new level of interdisciplinary collaboration across theory development, innovation in methods, and data collection in our field.

3 Conceptualising comfort

One of the most widely cited definitions of thermal comfort is from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE): 'That state of mind which expresses satisfaction with the thermal environment.' (ASHRAE 2013). The concept that is 'thermal comfort' is theorized as being determined by a range of physical, physiological, psychological and social variables in varying ways by the two primary competing theories in the field – Fanger's PMV model (ASHRAE 55; EN15251 (CEN 2007); ISO 7730) and Gagge's SET model (ASHRAE 55; EN15251 (CEN 2007)), as well as the broader academic literature. In both the standards and the literature this broad definition of thermal comfort is broken down into more specific constructs for the purposes of measurement.

A brief note on nomenclature is warranted here. We follow Markus (2008) and distinguish between *concepts*, i.e. the reification of all actual or potential instances of a set of experiences in the real world (in this case experiences relating to thermal comfort) – and *constructs*, which are the the instances of these in a specific population. Within a population, concepts and constructs are the same thing, however the distinction becomes particularly important in international comparative work where concepts transfer between populations and constructs may not. It is worth noting that the ASHRAE definition of comfort cited above neatly meets Mario Bunge's (1974) classical definition of a concept/construct, i.e. "…an ideal object, where the existence of the thing may be said to depend upon a subject's mind".

That said, it is also arguable that its theoretical foundations (Auliciems, 1981; Humphreys et al, 1998; de Dear et al., 1997) are not present in its current applied transformation into an equation with a single predictor (running mean external temperature). While a range of human (metabolic rate, clothing level) and environmental (ambient and radiant temperature, humidity and air speed) are integrated into our models of sensation of comfort, and are understood to be important, these factors remain less well integrated into our understanding of behavioural responses to thermal discomfort. In addition, psychological and broader conceptions of the social sciences are often completely omitted, such as the role of group interactions, social power and comfort practices. This conclusion was also reached by Rupp et al in their recent review article on thermal comfort research (2015 p.195)

> *Through this review of the literature it became evident that there is a gap in thermal comfort studies in relation to interdisciplinary research. The association with other professionals like psychologists, physiologists, sociologists, philosophers and even with other building related ones (architects and engineers that work with visual, aural and olfactory comfort) could be of great value for the development of an integral (systemic/holistic) research approach that may help to a better comprehension about sensation, perception and thermal comfort and its physiological and psychological dimensions.*

The PMV model identifies five concepts relating to thermal comfort that can be constructed and operationalized through scales when assessing the thermal environment. These are:

thermal perception; *thermal evaluation*; *thermal preference*; *personal acceptability* and; *personal tolerance*. (BS EN ISO 10551:2001) Each of these is a separate concept for which the standard provides a method of measurement (a single question with a scale of response choice options).

In addition to the above, there are a range of additional concepts widely discussed in the thermal comfort literature. These include perceived control (Hellwig, 2015); thermal alliesthesia (de Dear, 2011); adaptive opportunity and adaptive response (de Dear, et al 1998; Auliciems, 1981); thermal acceptability (Zhang et al, 2008); occupant satisficing (Leaman et al, 1999); and many others, the subjects of which inform the many review articles in this field.

4 Measuring comfort

Translating concepts and constructs into measurable quantities is an area that receives considerable attention across the social, psychological and physical sciences, but is one of the areas where we feel there has been a lack of methodological focus within the thermal comfort community. Each of the constructs identified in BS EN ISO 10551:2001 above is tested with a single question in which participants are asked to respond on an ordinal scale. It is important to stress in this context that the term 'scale' is used in two quite different ways in the thermal comfort and psychological literature. In thermal comfort literature, the term scale is used to refer to a series of thermal states or preferences (response choice options) offered to participants varying from two (e.g. "is the environment (local climate) acceptable rather than unacceptable"), through to bipolar scales with 11 or more thermal states. In both social and psychological research however, a scale refers to a series of questions each of which is trying to capture an aspect of an underlying construct that is not directly observable (a 'latent variable'). It is very rare for any such latent variables to be accurately measured by a single question scale. In psychology, there is a considerable methodological literature about how such scales (sets of questions) should be developed, and a considerable body of statistical science behind their evaluation. Each of these scales measuring a particular concept will be taken through a great deal of preliminary statistical testing using methods like Confirmatory Factor Analysis to determine which factors (individual questions within the scale) load onto the construct and provide sufficient convergent and discriminant validity to make the measure a good one of the concept (e.g. thermal preference). From the methodological perspective, it is therefore concerning that the five concepts in BS EN ISO 10551:2001 are each measured using a single questions scale. Indeed, the authors have had papers rejected from psychology journals on the basis of the concepts were not operationalised through a scale containing multiple questions per concept.

The lack of robust development and testing of scales (in psychology sense of that term) is a key area in which we feel further research is needed in this area. We feel that methodologically, concepts, constructs, the operationalisation of constructs through instruments, as well as testing aspects of measures' validity, are key to progress in thermal comfort research. This is particularly the case when integrating variables across disciplinary domains of building physics, human physiology and psychology. To do this, a sound intellectual framework for assessing construct validity is needed. One of the most widely used in the social and psychological sciences is the multitrait-multimethod (MTMM) matrix method (Campbell and Fiske 1959, cited and further developed by Brewer and Hunter, 2006). The MTMM method is widely used to test for convergent and discriminant validity of constructs. It also employs multiple methods per construct to distinguish between construct and method-specific variance. In addition, the emphasis within MTMM of applying 'truly different methodologies', is a natural fit to the testing of operationalisation of constructs using variables spanning different disciplines. To our knowledge, this method has yet to be applied to methods development in thermal comfort research.

The issue of quantifying variance arising from methods of measurement is central characterizing diversity in thermal comfort scores. True score theory states that 'X' (the observed score) equals 'T' (the true score) plus 'e' (random error) - i.e. $X = T + e$. The error term in this equation then being decomposed into two elements, random error 'e_r', and systematic error or bias 'e_s' giving: $X = T + e_r + e_s$. This extends in the case of studying variance to: $var(X) = var(T) + var(e_r) + e_s$ (noting that any addition to the variance term is captured in the '$var(e_r)$' and the 'e_s' term simply shifts the mean of the observed values away from the true value of their mean). Any explanatory framework of variance of a concept in a population '$var(T)$' (e.g. variance in thermal sensation) that is assessed through measurement '$var(X)$' must distinguish between the true variance '$var(T)$' and variance related artifacts of the measurement process '$var(e_r)$'. When we consider Figure 10.10 from Nicol et al (2012) reproduced above, measurement theory tells us that some component of the observed scatter will arise from measurement error '$var(e_r)$' however to our knowledge to date there has been no complete systematic evaluation of this component of the variance in thermal comfort studies.

As Trochim (2006) notes: "True score theory is the foundation of reliability theory. A measure that has no random error (i.e., is all true score) is perfectly reliable; a measure that has no true score (i.e., is all random error) has zero reliability." A variety of ways have been developed for the quantitative evaluation of survey instrument reliability. These include test-retest methods; parallel-forms reliability and internal consistency reliability (Trochim 2006). We are only able to find three instances of the quantification of reliability in thermal comfort scales in the literature. Lundgren et al (2014) assessed reliability of their Cold Discomfort Scale (CDS) using test-retest reliability methods. The CDS asks a single question "On a scale from 0 to 10, where 0 means not feeling cold in any way and 10 means feeling unbearably cold: How cold do you feel right now?" The test-retest protocol involved subjecting 13 male and nine female volunteers to -20˚C for one hour with testing every five minutes. The retest was done one week later (for experimental protocol see Lundgren et al 2014). Instrument reliability was assessed using a weighted kappa coefficient (effectively a within-subjects measure of correlation between the test and retest scores) comparing median values for the CDS as well as each five-minute score. The mean weighted kappa coefficient was 0.84 across all tests, with individual (five-minute) test result pairs having kappa's varying between 0.48 and 0.86. This represents is a good degree of instrument reliability, but does still leaves a substantial (~15%) level of unexplained within-subject variation. While this can be represented through a variance error term '$var(e_r)$', it may also be the case that the test subjects' physiological and psychological states varied between the test and the retest. This opportunity for within-subject variance between tests is one of the predominant critiques of the test-retest approach.

Khogare et al (2011) developed a satisfaction scale for measuring thermal comfort in offices in India. They assessed scale reliability using the split-half method. This is a test for internal consistency and is conducted by devising a scale (in the psychological sense of a series of questions), randomly dividing the questions into two halves, applying the whole instrument to a sample, then calculating the correlation between the answers provided by the questions in the two halves. The correlation between the halves was 0.8. They then applied the Spearman-Brown prophecy formula to derive an estimate of the full test reliability of 0.88. This creates an implicit error variance term of 0.23 on the internal consistency measure ($1-0.88^2$).

The most extensive methodological evaluation of a thermal comfort scale found was that by Dehghan et al (2015) of their 'Heat Strain Score Index' (HSSI) - a measure of heat strain in the workplace. In addition to assessing scale reliability, they evaluated content validity, structure validity, concurrent validity and construct validity. They assessed scale reliability through a generalized version of the split-half method called Cronbach's alpha. This was applied as a measure of the reliability of each item (each question) relative to all the others and was used to determine which questions were to be included in final index. They developed a 40 item scale that was reduced to 21 items through reliability analysis. Overall the final 21-item scale had a reliability of 0.91. The index performed well against a range of physiological heat strain parameters such as aural temperature, heart rate and the physiological strain index with Pearson correlations ranging between 0.56 and 0.76. Whilst not directly comparable to established thermal comfort models in the buildings field, this suggests that exhaustive development and testing of thermal comfort indices can construct scales capable of explaining substantially more of the observed variance than is accounted for in existing models in our field.

5 Explaining diversity

5.1 Biological drivers

Biological drivers for thermal comfort relate to how individual biological characteristics such as body composition and age influence individual thermal requirements. In principle, these include both healthy and pathologic states. It is important to consider that the body is an adapting system, which adjusts its regulatory and controlling mechanisms for optimal homeostasis according to the environmental conditions. It has been hypothesized that thermal comfort, or thermal pleasure, serves homeostasis (Cabanac, 1971). This implies that conditions that cause the body to actively engage homeostatic regulatory mechanisms (e.g. shivering) may be perceived as uncomfortable, but because the body adapts, these conditions may become less uncomfortable over time (for acclimatization examples, see also van Marken Lichtenbelt et al. in these proceedings).

Body composition directly affects body tissue insulation and metabolic rate (Rennie, 1988; Cunningham et al., 1978). Both are major components that determine body heat distribution. For instance, matched for metabolic rate/surface area, the obese are likely to have warmer hands and colder abdomen skin than their leaner counterparts (Claessens-van Ooijen et al., 2006; Savastano et al., 2009). This spatial temperature difference is explained by the abdominal body fat, which acts as a thermal insulator for heat conducted from body organs to the skin. In the obese, this abdominal heat is instead dispersed to the hands (hence the warmer hands). In combination with clothing, the spatial distribution of skin temperature greatly influences the efficiency of heat lost to the environment, and also how the body perceives its own thermal state (Romanovsky, 2014).

In tandem with tissue insulation, resting metabolic rate (RMR) is largely determined by lean body mass, and body composition explains, for the major part, the RMR difference observed in subpopulations (e.g. males vs. females; or young adults vs. seniors) (Cunningham, 1980).

That is, with increasing age RMR decreases because of decreasing lean mass (e.g. skeletal muscle) and increasing fat mass. Other predictive models for metabolic rate, that do not use body composition directly, explicitly include those parameters that are influenced by body composition (i.e. body size, age and gender) (Harris et al, 1918; Roza et al, 1984). For thermal balance, these individual differences in metabolic heat production should be balanced by equal differences in heat loss, and therefore may contribute to variance in inter-individual thermal comfort.

5.2 Experiences or background

Our (thermal) experiences and variations in our background are additional drivers of variance. Just as we have varying physiological characteristics, we all have different experiences and backgrounds. Potential aspects leading to inter-individual differences include our climatic and cultural background. At the same time, and again in a similar way as our body is an adapting system, our experiences are constantly modifying our personal background.

5.2.1 Climatic

There is strong evidence that our evaluation of thermal conditions depends on our climatic background – both short term and long term (de Dear et al., 1997; Schweiker et al, 2009; Luo et al, 2016). However, the challenge remains to distinguish between physiological adaptation and acclimatization processes (see above) and non-physiological ones. Examples for the latter might be interlinked with psychological drivers such as emotions. A sunny day in a climatic context with a majority of days being rainy might lead to different emotions of happiness or joy and a distinctive acceptance of an overheated room, compared to a sunny day in a hot and dry climate.

5.2.2 Cultural

Our cultural background affects among others our perception of pain (Callister, 2003) and visual experiences (Segall et al., 1966). With respect to thermal sensation, as early as the 1980s, Auliciems (1981) had assigned differences in thermal sensation of people from England and North America to cultural differences. Auliciems postulated that these differences can be assigned to cultural differences in the way warmth or coolness is supplied to a given space.

5.2.3 Personal

On an individual level, our climatic, cultural, and personal experiences are part of our personality and our preferences. Beyond the field of thermal comfort, studies have shown a relationship between personality traits and well-being (Costa et al, 1980). Therefore, these factors might impact on thermal comfort as well. In the first study to relate personality traits to thermal sensation, Hawighorst et al. (2015) presented results from a field study showing a difference in thermal perception due to differences in the thermo-specific self-efficacy and climate sensitiveness. Schweiker et al (2012) found differences in the interaction with the thermal indoor environment based in thermal preferences. Nevertheless, these drivers are amongst the least investigated ones in relation to thermal comfort.

5.3 Psychological drivers

Psychological drivers might help explain inter-individual differences where different individuals experience the same thermal environment differently according to their specific cognitive or emotional state. They might also foster our general understanding of thermal comfort, such as that in certain settings comfort might be experienced differently by the majority of people because of a certain psychological state they are in (e.g. being very focused on a task as opposed to being at leisure).

Very few potential psychological impact factors on thermal comfort have been tested. However, based on findings in other fields, one can speculate that the followings concepts play a role. Note that the distinction between cognitive and emotional drivers is a loose one; it would need thorough testing to see whether an impact factor is mediated via a cognitive or emotional process. Historically, in psychology, these factors have been treated as largely separate entities, however, in recent years their interdependence has been recognized more. In general, cognitive processes encompass attention, memory, planning, language and problem solving. Emotional processes are harder to define and there is no consensus on a definition. The distinction is not crucial for this paper; and indeed, for the factors listed below, some could either operate via a cognitive or emotional process.

Pain research is in generally a field from which many important insights can be gained, due to the abundance of research, and also because one can argue that thermal stimuli and pain stimuli are to some extent related, or rather a thermal stimulus can turn into a pain stimulus when conditions are too hot / too cold.

5.3.1 Cognitive

Attention is loosely defined as 'the behavioral and cognitive process of selectively concentrating on a discrete aspect of information' (Anderson 2004), and has been extensively studied in psychology. The perceptual load theory as developed by Nilli Lavie (1995) postulates that in tasks involving a large amount of information (= high perceptual load), brain capacity is fully exhausted by the processing of the attended information, resulting in no perception of unattended information. On the other hand, in tasks of low perceptual load, spare capacity from processing the information in the attended task will inevitably spill over, resulting in the perception of task-irrelevant information. For thermal comfort that could mean that if individuals are highly concentrated on a demanding task, they will be less aware of the environmental conditions and would hence judge their thermal comfort differently than when experiencing the same environmental conditions when engaged in an undemanding task. The authors are currently testing this hypothesis, and are not aware of studies having tested it. However, some evidence that attention might play a role can be derived from an early study by Berry (1961). Whereas many other studies found that illumination impacts on thermal comfort (Candas et al, 2005; Huebner et al, 2014; Winzen et al, 2014; Fanger et al, 1977), he did not find such an effect. One reason might be that in his study participants were engaged in a highly demanding, unrelated task which might mean that they were less aware of their (thermal) environment. This speculation is corroborated by the fact that temperature conditions at point of expressed discomfort were of such values that virtually every person would be expected to feel uncomfortable, i.e. a very high value, whereas one would expect half the people to feel uncomfortable already at a much lower level.[2] Hence, different levels of being focused on a task might explain why people exposed to the same environmental conditions judge them rather differently.

[2] For details on the Temperature Humidity Indicator that was used in this study, refer to https://www.google.com/patents/US3124002. Accessed 17.06.2015

Control has been identified as a concept of interest. It has been shown previously that having control over aspects of the local thermal environment can increase satisfaction with a wider range of temperatures (Paciuk, 1990; Brager et al., 2004; Schweiker et al., 2013; Schweiker et al, 2015) and allowing occupants to create a micro-climate is associated with greater worker productivity and significant energy savings (Zhang et al., 2010). Whilst one might argue that having control is inherently a physical property of the environment, it is likely to exert its influence via a psychological process such as increased self-efficacy. Even though there is initial evidence showing an influence of self-efficacy on thermal comfort (Hawighorst et al., 2015), its role is not yet fully understood.

5.3.2 Emotional

A recent study (Taufik et al, 2015) found that participants who were feeling positive about themselves after having received (manipulated) feedback about their environmental footprint judged the temperature in a temperature-controlled room to be higher than those who did not have a positive feeling induced. Hence, depending on how we feel, we might judge the same thermal conditions rather differently. Given that this study employed temperature estimates as opposed to comfort reports, it remains to be tested if participants also actually felt warmer, but it opens up an important avenue for further research.

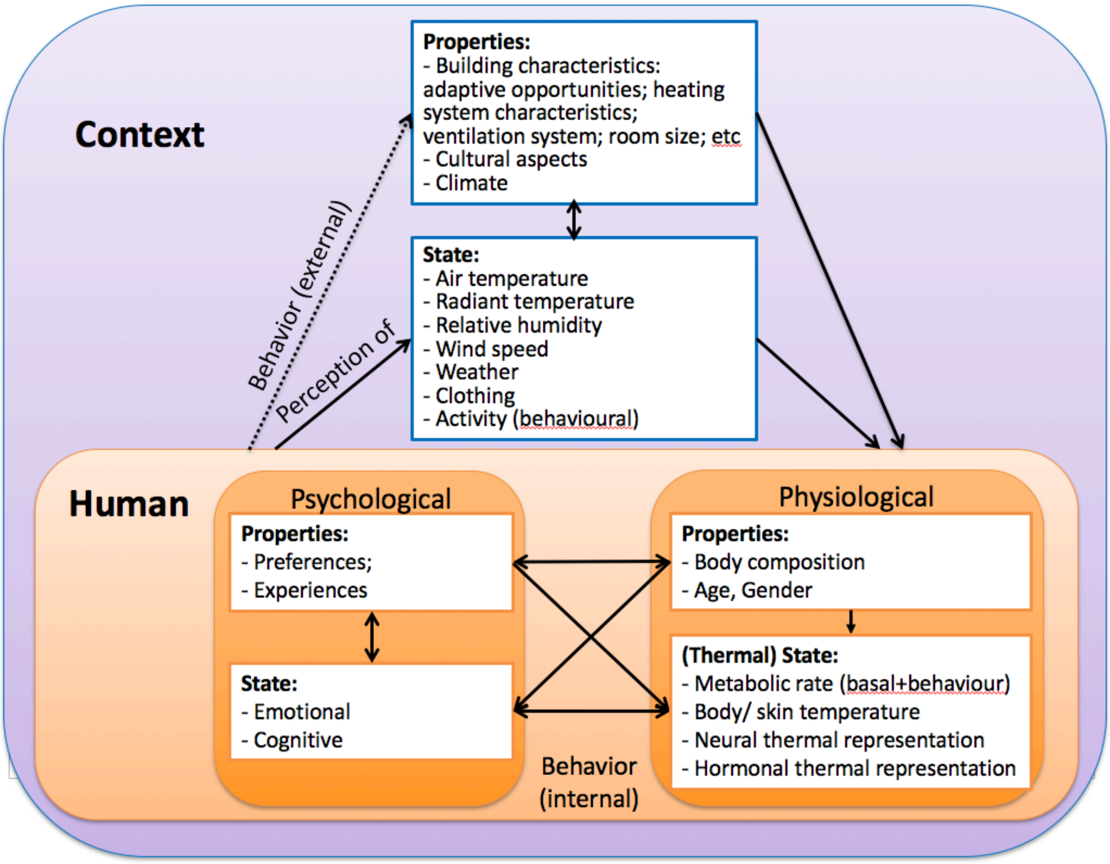
Research mainly from the area of social psychology has shown that being in a group alters behavior. One of the oldest and most striking examples is the conformity experiment from Solomon Ash (1951) which showed that social pressure from a majority group could affect a person to conform to what the majority said - even if the correct answer was clearly a different one. How exactly a social norm effect could play-out in thermal comfort perception remains to be tested – it could be that an individual picks up cues about the thermal environment from others to guide his or her behaviour. It is still debated whether the social norms effect acts through a cognitive or emotional process, with one opinion being that it has both components (eg Heywood, 2002) – a cognitive one, i.e. the memory of that is ‘right’, and an emotional one.

A recent study showed that tolerance of pain increases when engaging in a group activity, in this case singing (Cox, 2015). In a thermal context, obviously being in a group changes the physical thermal characteristics of the environment; however, it might be that there is an additional effect such as tolerance of a wider range of conditions when in a group. On the other hand, feeling socially excluded can also increase tolerance of both physical and emotional pain (DeWall et al, 2006).

This discussion of possible impact factors is far from exhaustive and it remains to be seen which factors do impact on thermal comfort, and if they do, whether they have a similar effect for all people or if not, what in turn determines inter-individual differences.

6 A conceptual model

The conceptual model is based on the description of drivers of variance above. A main distinction is made between the context and the human. Within the human, a further distinction is made between psychological and physiological aspects. Each of the three main elements is divided into *properties* and *states*. Here we define *properties* as those characteristics being (comparatively) stable over a certain period of time, and *states* as more transitory. This period might vary (e.g. building properties vs. body composition), but is significantly longer (months or years) than the time frame for changes in the state (seconds, minutes or hours).



The arrows denote hypothesized pathways and interdependencies. E.g. the human's state of skin temperature is influenced by the physical states and properties of the context. At the same time, the human can change the corresponding states and properties through adjustments to the built environment states (e.g. by opening a window), and properties (e.g. by replacing a single glazing window with a triple glazing one or a fixed window with an operable one).

6.1 Contextual factors

The influence of contextual factors on human thermal comfort are widely studied and will only be touched upon here. Properties of buildings, from the adaptive opportunities provided to occupants, through control of mechanical and natural ventilation, to the properties of heating systems ranging from ambient and task heating and cooling to system responsiveness, all impact both physiologically and psychologically on building occupants. Design decisions relating to spatial configuration, occupant density and emissivity of surfaces are likewise known or postulated to impact on comfort. States of buildings' thermal environments lie at the core of Fanger's PMV model and are the most studied class of comfort variables. While much is known with respect to these, there remain substantial areas in which our understanding of the drivers of individual occupant's different responses to these requires further work. There are clearly substantial interactions between states such as ambient and radiant temperature that underlie the psychological response to alliesthesia that require further research.

6.2 Human factors

Psychological states are temporary behaviors or feelings that depend on a person's situation and motives at a particular time – hence, they can vary across situations. Psychological traits are characteristic behaviours and feelings that persist across situations and time. Whilst both might impact on thermal comfort, the focus here is on the prior, i.e. states.

As discussed above, certain **emotions** might impact on our thermal perception, such as feeling positive about oneself, feeling socially excluded, and being part of a group. Similarly, **cognitive functions** might impact on our thermal comfort, such as attention.

These specific psychological factors might exert their influence on thermal comfort via our **perception of the environment**, such as that we might play less attention to the thermal characteristics of the environment when being in a certain psychological state. They in turn interact with our **preferences and experiences**. They also influence and are influenced by our **bodily state**. Emotions impact on physiological parameters such as heart rate and blood flow. On the other hand, physiological parameters and behaviours can impact on psychological states as well. For example, when the face is being forced into a smile by holding a pen between the teeth, people report a better mood than when maintaining a neutral facial expression (Strack et al, 1988).

Our physiological and psychological states and properties will impact on our judged thermal comfort and potentially on our **comfort related behaviour**.

6.2.1 Physiological factors

As described above, **body composition** (varying with **age** and **gender**) plays a major role in thermal state and temperature distribution over core and skin tissues. The body assesses its own **thermal state** from these tissue temperatures. With respect to appreciation of that thermal state, the dominant view is that the body compares its assessed thermal state relative to a set of fixed set-points to calculate a load-error (for a detailed overview see (Parkinson et al, 2015)). The underlying neurophysiology includes temperature sensitive neurons with distinct nerve types for warm and cold sensing (Benzinger, 1969; Hensel, 1981). These neurons have a non-linear activation pattern over tissue temperature, and transmit their information via distinct neural pathways to the insular cortex for perception and localization of thermal stimuli (Kingma et al., 2012). Note that this is a different brain area than the hypothalamus, which controls autonomous thermoregulation (e.g. shivering, sweating and skin blood flow). The thermo-sensory information is integrated through the neural pathway, and this is often described as being analogous to a set-point controller (Hammel et al., 1963, Cabanac, 2006). The neurophysiological basis for the reference signal (i.e. setpoint itself) is assumed to be non-dependent on temperature, but may scale with other factors (e.g. blood pressure, pathogens, melatonine, etc.), and therefore explain an adjustable set-point (e.g. higher core body temperature in fever, shifted set-point after acclimatization, no circadian effect in thermal sensation despite changes in temperature distribution) (Cabanac, 2006, Krauchi 2007). Therefore, the variation in internal mapping of the thermal state, due is likely to induce noise in observed in thermal comfort on individual basis, and between individuals.

7 Conclusion

Moving from a focus on mean responses to centrally managed environments, to understanding individuated drives of thermal comfort in increasingly comfort-differentiated environments, represents a considerable scientific challenge. We have sought to explore explanatory factors of observed diversity in thermal comfort data from field studies as a first step in elucidating the range of factors worthy of further exploration. The distinction was drawn between artefactual variance arising from poor instrument design and development, and the real (sometimes called 'aleatory') variability that can arise from environmental contextual drives, and drivers of individuation both physiologically and psychologically. This has led to development of a theoretical model that distinguishes between these realms and seeks to represent their interdependencies. The model further distinguishes between short-term 'states', and longer term 'properties' of the environment, mind and body that shape individual's perception of thermal comfort. It is hoped that the model proves useful in expanding the range of hypotheses that can be tested, and that such tests can help add evidential weight to, or call into doubt, relationships in the model.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Extending the Universal Thermal Climate Index UTCI towards varying activity levels and exposure times

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Abstract

The Universal Thermal Climate Index UTCI assesses the outdoor thermal environment based on the multi-node UTCI-Fiala-model of thermoregulation, which was coupled with a clothing model considering the clothing behaviour of an urban population. The applicability of UTCI to exercising, resting or occupational settings is currently limited by the assumed moderate activity level (2.3 MET) and the maximum exposure time of two hours. However, the high level of detail devoted to the modelling of the physiological and clothing system will allow for expanding UTCI to varying exposure times and activity levels, as will be demonstrated by this paper. We calculated UTCI adjustment terms for activity varying from a resting to a high (5 MET) level and for exposure duration covering an 8-hour shift length in 30-min steps. Simulations with the UTCI-Fiala model were performed using the adaptive UTCI-clothing model with air temperatures from -50°C to +50°C for UTCI reference climatic conditions. The adjustment terms indicated that thermal stress decreased with shorter exposure and increased with longer times, and that high activity increased heat stress, whereas low activity increased cold stress. Effect size was moderated by stress category with greater effects of activity and exposure time in the cold compared to moderate or warm climates. These results demonstrate UTCI's capabilities for a comprehensive assessment of dynamic thermal stress in occupational and other relevant outdoor settings. However, extensive simulations are still necessary to include the effects of special leisure and work clothes.

Keywords: thermal comfort, outdoors, model, clothing, metabolic rate

1 Introduction

The Universal Thermal Climate Index (UTCI) was developed by an international group of researchers to assess the outdoor thermal environment in the application fields of human biometeorology (Jendritzky et al., 2012). It is based on the dynamic physiological human response to cold, heat and moderate climatic conditions as simulated by the advanced multi-node UTCI-Fiala-model of thermoregulation (Fiala et al., 2012), which was coupled with an adaptive clothing model (Havenith et al., 2012) considering the clothing behaviour of an urban population. As shown by Figure 1, UTCI summarises the interaction of ambient temperature, wind, humidity and radiation fluxes as an equivalent temperature. The operational procedure (Bröde et al., 2012) was completed using an assessment scale categorising the index values in terms of thermal stress, and by simplified algorithms for calculating UTCI values without the need to run the complex simulation models.

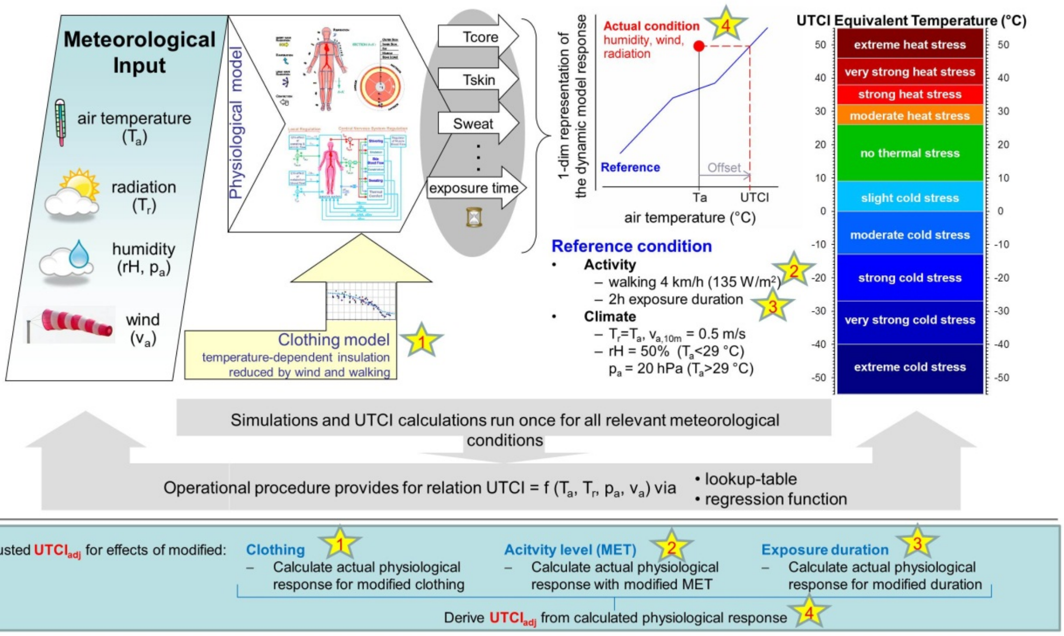

Figure 1. Concept and elements of UTCI and its operational procedure, modified from Bröde et al. (2012). The derivation of UTCI-values adjusted for non-reference clothing, activity and exposure duration ($UTCI_{adj}$) is described in the light blue box below the separating line.

The assessment of cold and heat stress by UTCI was shown to agree well with experimental data (Kampmann et al., 2012; Psikuta et al., 2012) and with international standards concerned with the ergonomics of the thermal environment (Bröde et al., 2013; Kampmann et al., 2012). But in its current stage, UTCI does not consider the characteristics of special protective clothing, and its applicability to occupational thermal stress is limited by the moderate activity level (metabolic rate of 135 W/m^2) and the maximum exposure time of two hours, which were assumed for the simulation runs.

The influence of varying clothing insulations, activity levels (metabolic rates) or exposure durations may not only impact the application of UTCI to occupational settings (Bröde et al., 2013), but also to other scenarios, like thermal comfort assessment of beach tourists (Rutty & Scott, 2015), of persons exercising in urban areas (Vanos et al., 2010), or of occupants inside buildings (Walikewitz et al., 2015).

However, the high level of detail devoted to the modelling of the physiological and clothing systems allows for expanding UTCI to a wider range of activity levels, duration and clothing, which need to be taken into account when assessing these additional settings. This paper aims at demonstrating this with respect to varying exposure times and activity levels for the UTCI reference climatic conditions, as defined in Figure 1.

2 Methods

We calculated additive adjustment terms for UTCI considering activity ranging from a resting level with metabolic rate of heat production of 1.1 MET (1 MET = 58.15 W/m2), to a very high level (ISO 8996, 2004, Table A.2) of 4.9 MET, and exposure duration covering an 8-hour shift length in 30-min steps. Simulations were performed with the UTCI-Fiala model (Fiala et al., 2012) using the adaptive UTCI-clothing model (Havenith et al., 2012).

Air temperatures varied from -50°C to +50°C in 1 K steps for UTCI reference climatic conditions as shown in Figure 1, which were defined by calm air (0.5 m/s air velocity 10 m above ground level), mean radiant temperature equalling air temperature, and 50% relative humidity (but vapour pressure not exceeding 20 hPa).

For the 9,696 combinations of air temperature, activity level and exposure time, UTCI computations were performed with the model output obtained after the actually simulated exposure times replacing the 2-hour values in the original calculations (Bröde et al., 2012). By subtracting UTCI for the reference conditions, which are equal to air temperature by definition (Bröde et al., 2012), from these calculated values, we obtained additive adjustment terms depending on UTCI, activity level and exposure time.

In order to assess the influence of clothing and walking speed (v_w), we additionally calculated adjusted UTCI values for semi-nude (0.1 clo) conditions with v_w=0 m/s simulating sitting or lying in a beach environment for 2h (Rutty & Scott, 2015), as well as for an office scenario with 8h occupancy using the "KSU-uniform" (cotton long-sleeved shirt, long trousers, underpants, socks) plus shoes with an estimated insulation of 0.6 clo (Fiala, 1998), also using v_w=0 m/s additional to the UTCI reference walking speed v_w=1.1 m/s.

3 Results and Discussion

Figures 2&3 illustrate the adjusted values of UTCI ($UTCI_{adj}$) obtained for different exposure durations and metabolic rates; Figure 4 depicts the error of using adjusted UTCI values from reference climatic conditions also for non-reference conditions; and Figure 5 shows the influence of clothing and walking speed for both an office and beach scenario, respectively.

3.1 Effects of metabolic rate and exposure duration

Figure 2 illustrates the adjusted values of UTCI ($UTCI_{adj}$) for 2h exposure with different metabolic rates. As could be expected, lower activity levels increased the limits for the UTCI stress categories, i.e. cold stress occurred at higher UTCI temperatures, as did heat stress. Contrary, with increased metabolic rate, heat stress occurred at lower UTCI values.

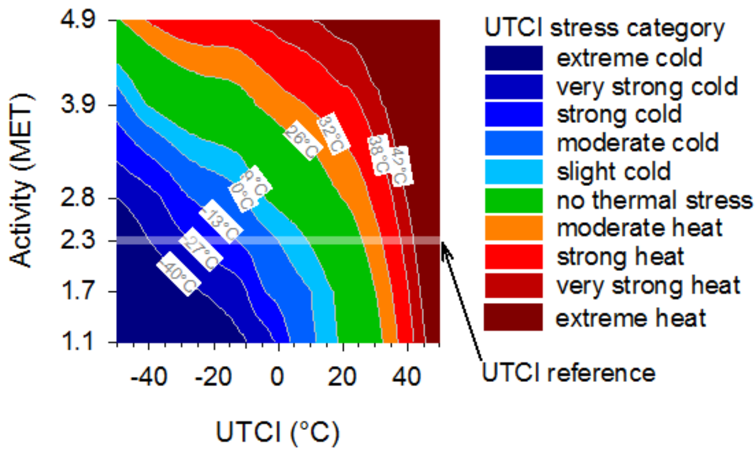

Figure 2. Contours of the $UTCI_{adj}$ adjusted to different metabolic rates (MET) for UTCI reference climatic conditions with 2h exposure duration. Labels mark the limits of the stress categories from the UTCI assessment scale (cf. Fig. 1). The arrow indicates the UTCI reference activity of 2.3 MET with UTCI=$UTCI_{adj}$.

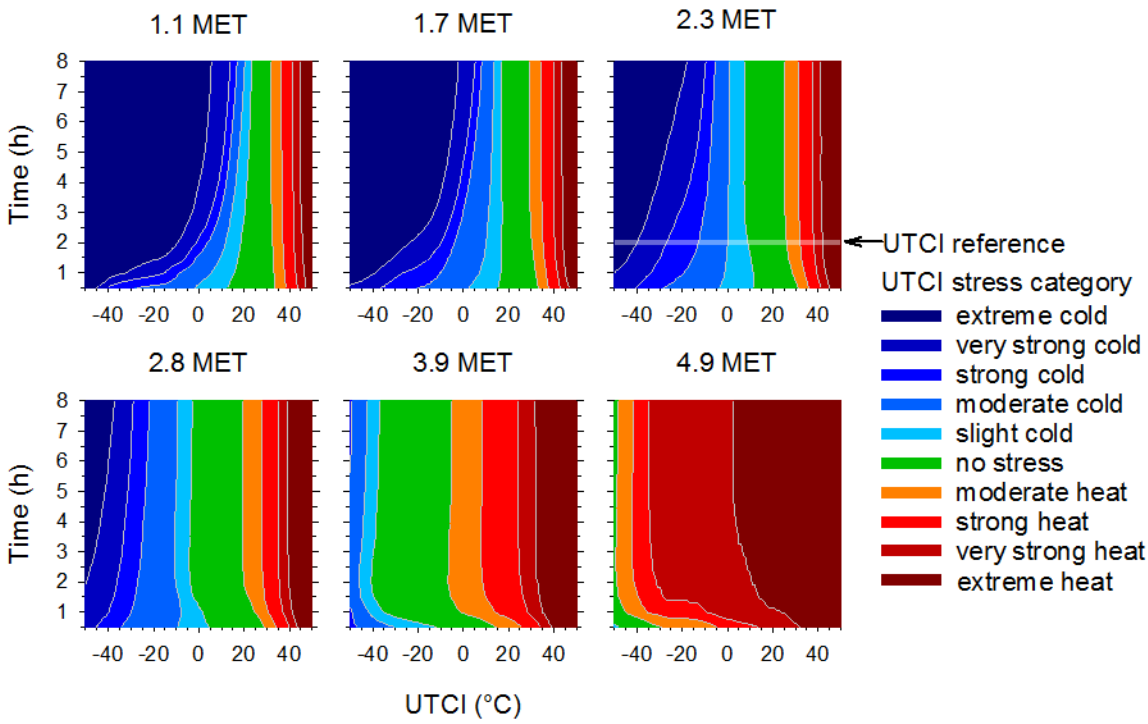

Figure 3. Contours of $UTCI_{adj}$ related to metabolic rates (MET) and exposure duration (Time) over a range of UTCI reference conditions with UTCI stress categories as in Fig. 1. The arrow indicates the UTCI reference activity and duration of 2.3 MET and 2h, respectively, with UTCI=$UTCI_{adj}$.

Looking at the additional effect of exposure duration in Figure 3 indicated that compared to UTCI reference conditions, thermal stress decreased with shorter exposure times and increased with longer times. Again (cf. Figure 2), high activity increased heat stress, whereas low activity increased cold stress. In accordance with previous research (Höppe, 2002), the magnitude of the effect was moderated by the stress category, with greater effects of activity and exposure time in the cold compared to moderate or warm climates.

Simulating high activity levels with highly-insulating clothing at low temperatures turned cold stress to heat stress conditions, as shown in Figures 2 & 3. This phenomenon agrees with field observations and laboratory studies (Rintamäki & Rissanen, 2006), but is not covered by current ergonomic standards for the assessment of cold and heat stress.

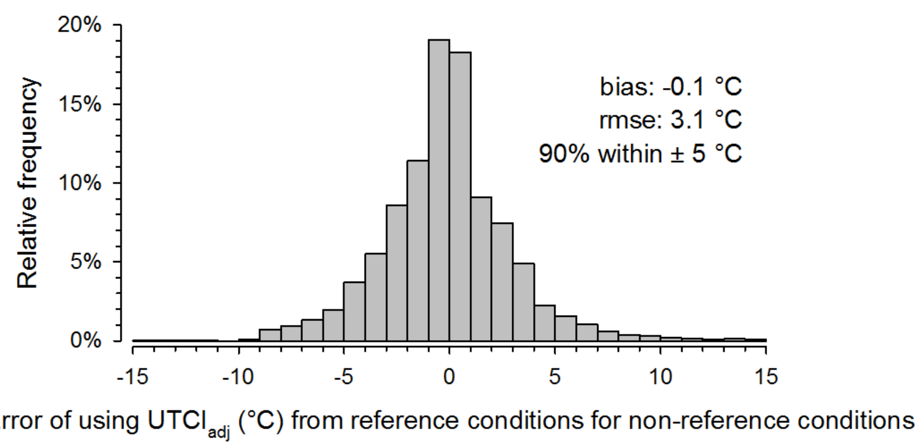

Figure 4. Error distribution of using UTCI adjustments for activity and exposure duration from UTCI reference climatic conditions to non-reference climatic conditions from ECHAM4 (Stendel & Roeckner, 1998).

3.2 Adjusted UTCI for non-reference climatic conditions

Although the UTCI reference climatic conditions considered here cover only a small portion of all relevant thermal environments (Bröde et al., 2012), the adjustment terms obtained in this study might be representative for other climates with UTCI values between -50°C and +50°C as well, because identical index values should represent equal thermal strain (Jendritzky et al., 2012). This assumption was verified for 100 randomly chosen climatic conditions from the ECHAM4 control run (Stendel & Roeckner, 1998) covering a broad range of air temperature (-36 to +40 °C), relative humidity (5 to 100%), wind speed (1 to 15 m/s), difference between mean radiant and air temperature (ΔT_{mrt} -13 to +38 °C), and UTCI values from -40 to +39 °C. Adjusted UTCI ($UTCI_{adj}$) was calculated as before for the same exposure times and metabolic rates for the UTCI reference climatic conditions. Figure 4 compares the resulting $UTCI_{adj}$ between reference and non-reference climatic conditions showing that bias was negligible. However, the root-mean squared error rmse=3.1 °C advocates for future supplemental simulation studies to investigate the effects of modified metabolic rates and exposure durations for non-reference climatic conditions.

3.3 Influence of clothing and walking speed in resting activities

Figure 5 compares the adjusted UTCI ($UTCI_{adj}$) values for scenarios with low activity (1.1 MET) experienced at office and beach, respectively, to reference UTCI (black solid lines), to UTCI adjusted for metabolic rate and exposure duration calculated for a walking person as shown in Figure 3 (open blue symbols), and to values considering the lying or sitting activity (v_w=0 m/s, filled symbols) and typical clothing of office occupants or beach tourists (red symbols for KSU-clothing and green symbols for semi-nude conditions).

For both scenarios, adjusted UTCI ($UTCI_{adj}$) was below reference UTCI, and the values for walking conditions were lower than those with zero walking speed, due to the increased convective cooling caused by the higher relative air velocity.

Given that zero walking with semi-nude clothing (filled green symbols) might represent the typical condition for beach tourists, it could be noted that the adjusted values for 1.1 MET with UTCI-clothing as shown in Figure 3 and represented in Figure 5 by open blue symbols, provided a good approximation to these 'typical' conditions for beach tourists. This might be explainable because the higher insulation of UTCI-clothing was compensated by the higher relative air velocity due to walking. It is also obvious, that 'moderate heat stress' calculated by the reference UTCI will reduce to 'no thermal stress' with $UTCI_{adj}$, similarly the higher stress categories will also be reduced to one category lower when using adjusted UTCI. This will put the findings of a corresponding survey (Rutty & Scott, 2015) reporting a preference for even 'strong heat stress' conditions as assessed by UTCI to a different perspective.

For the office scenario, UTCI-clothing and KSU-clothing gave very similar results with differences occurring only below 23 °C UTCI. If one considers the KSU-clothing with zero walking (filled red symbols) as 'typical' for office occupancy, the adjusted UTCI from Figure 3 (open blue symbols) did not provide a good approximation to those typical conditions, which was contrary to the beach scenario. For 'strong heat stress' (UTCI above 32 °C) the reference UTCI (solid black line) with 2.3 MET and walking 1.1 m/s was close to this typical condition. This happened probably because the relative air movement by walking compensated for the increased metabolic rate in this setting for heat stress conditions. For moderate heat to neutral ('no thermal stress') conditions, reference UTCI values overestimated heat stress while the values adjusted to low activity, but assuming non-zero walking speed showed underestimation, even indicating slight cold stress.

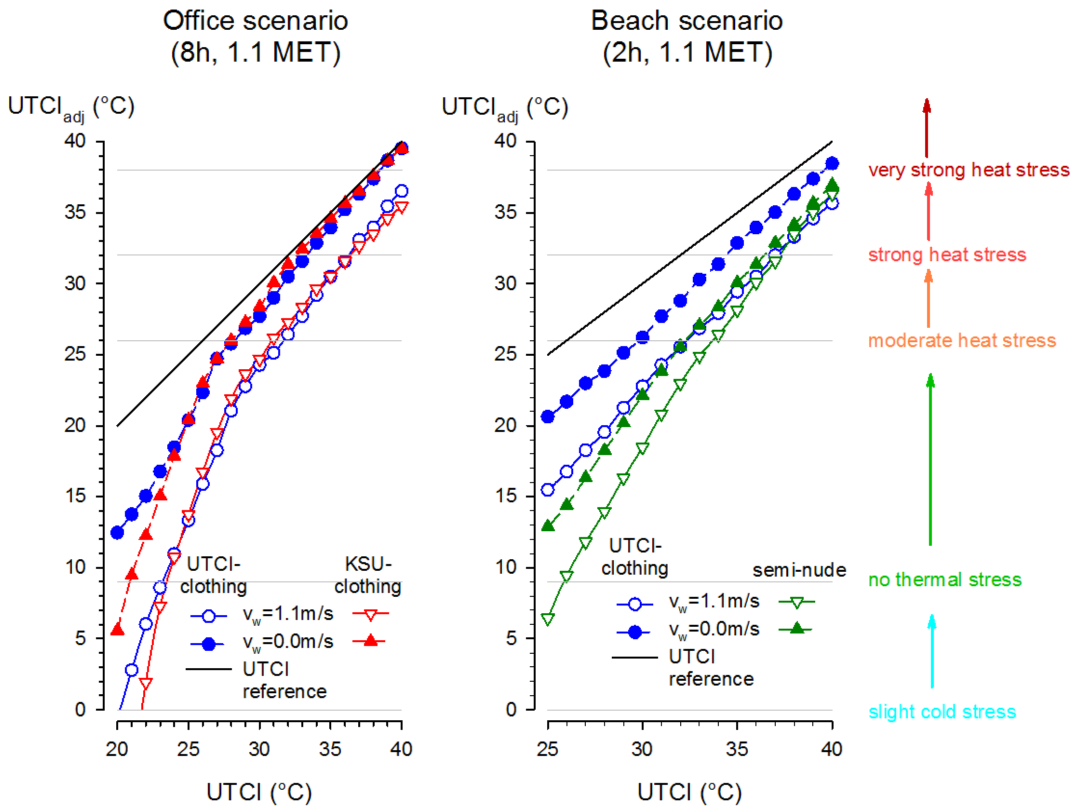

Figure 5. UTCI$_{adj}$ vs. reference UTCI for different clothing ensembles and walking speeds (v_w) simulating an office scenario with 8h occupancy and low metabolic rate (left panel), and a beach scenario (right panel), resting for 2h exposure time. The black line indicates UTCI=UTCI$_{adj}$. Horizontal reference lines correspond to UTCI stress categories (cf. Figure 1).

4 Conclusion

These results open the perspective to a comprehensive assessment of occupational thermal stress and other relevant outdoor settings using UTCI by taking into account different activity and clothing levels. As exemplified for beach tourists' thermal comfort, the use of UTCI adjusted for the lower activity level would provide a better discrimination between the roles of reduced metabolic rate and altered expectations (Rutty & Scott, 2015).

Our results also indicate a warning to be issued for the application of UTCI to indoor conditions (e.g. Walikewitz et al., 2015). Though the UTCI-Fiala-model might well be capable of simulating those conditions, as shown in Figure 5, the boundary conditions for the development of UTCI were chosen targeting outdoor environments. Thus, adjustments towards lower activity levels as presented in Figures 2 and 3 might not work well indoors.

For application purposes, the adjustment terms will be used in a two-step approach to calculate UTCI not only related to parameters of the thermal environment, but also to activity level and exposure time. First, as shown in Figure 1, UTCI values are calculated by the usual operational procedure from air temperature, humidity, wind and radiation (Bröde et al., 2012). Then, the adjustment terms depending on activity level, exposure time and UTCI are determined, e.g. by a look-up table or regression approach as for UTCI calculation, and are added to the UTCI values computed for reference activity and reference exposure time in the first step.

However, as the climatic conditions in this study comprised less than 0.1% of the relevant combinations of temperature, wind, humidity and radiation (Bröde et al., 2012), and because the effects of varying clothes were not yet systematically analysed, further extensive simulation studies are still needed.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Exploring the potential of a biophysical model to understand thermal sensation

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Abstract
This paper explores a biological perspective to understand thermal sensation. The main premise is that thermal sensation serves an organism for homeostasis of body temperature. A biological concept related to this premise is the thermoneutral zone (TNZ), which is defined as the range of operative temperatures where the body can maintain body core temperature without any regulatory changes to the metabolic rate or sweating. The centre of the TNZ can be regarded as the safest state for an animal from energetic and hydration perspective, as it provides most internal flexibility to cope with future thermal challenges. Therefore, we hypothesise that humans express neutral thermal sensation near the centre of their thermoneutral zone. To test this hypothesis, we define $dTNZ_{op}$ as the distance between measured operative temperature and the centre of the TNZ. The TNZ centre was calculated with a biophysical model using measured data from a climate chamber study with 16 female subjects. Regression between observed thermal sensation votes (TSV) and $dTNZ_{op}$ revealed that the intercept corresponds with a slightly higher than neutral TSV (0.14±0.07,p<0.001) and a strong linear relationship between TSV and $dTNZ_{op}$ (R^2=0.98). In conclusion, the approach shows great potential to improve our understanding of human thermal sensation.

Keywords: Indoor environment, biology, homeostasis, heat balance model

1 Introduction

The aim of this paper is to propose a biophysical model to understand and predict thermal sensation in the built environment. The main premise is that thermal sensation serves an organism for homeostasis and allostasis of body temperature. Homeostasis concerns maintenance of a constant milieu intérieur of the body and allostasis is the process of achieving internal balance through physiological or behavioural change (Ramsay and Woods, 2014). In biological sciences thermal sensation is considered to drive thermoregulatory behaviour for energy conservation in mammals (Schlader et al., 2011). From the food and water mammals can obtain they need to grow and reproduce. To maximize these, it is advantageous to spend as little energy and water as possible on maintenance of body core temperature (Porter, 2001, Scholander et al., 1950, Speakman and Krol, 2010). Mammals can do this by maximizing the time spent in the thermoneutral zone (TNZ). The TNZ is defined as the range of operative temperatures where the body can maintain body core temperature without any regulatory changes to metabolic heat production or sweating (IUPS, 2001), see Figure 1.

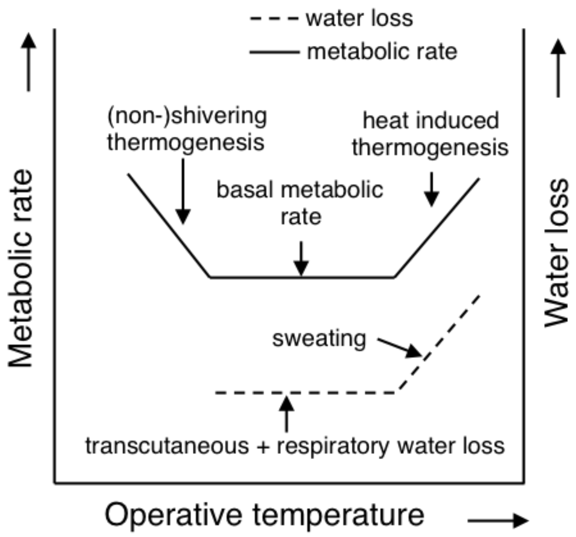

Figure 1: The thermoneutral zone is the range of operative temperatures associated with basal metabolic rate required to support life functions, and minimal water loss. Below the lower critical temperature metabolic rate increases to maintain body core temperature. Above the upper critical temperature water loss increases due to regulatory sweating and may coincide with heat-induced thermogenesis (e.g. Q_{10}-effect).

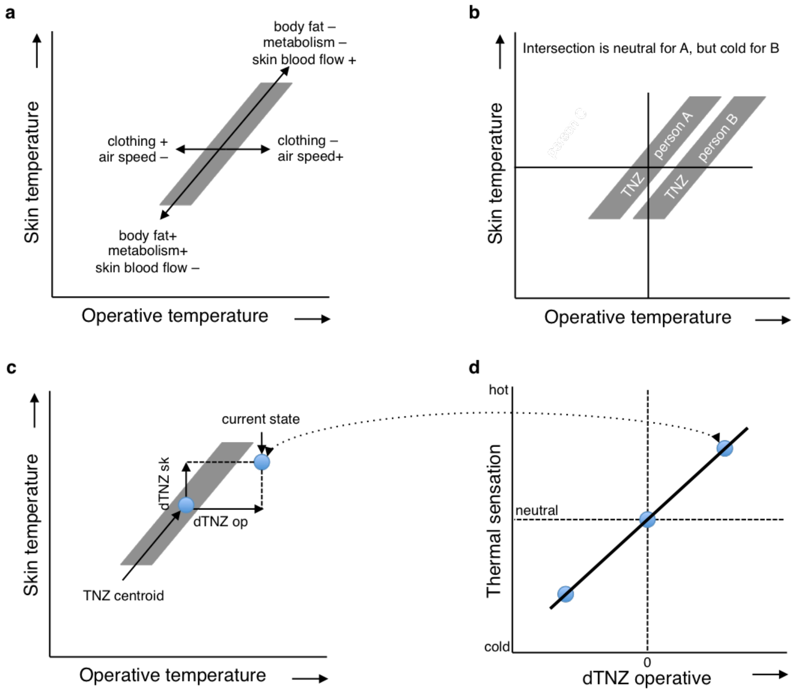

Figure 2: The thermoneutral zone is depicted with the gray area and represents the combinations of skin temperature and operative temperature for which heat loss equals basal metabolic rate and core temperature is in a normal range (e.g. 36.5°C -37.5°C). a) Dependence of thermoneutral zone (TNZ) position on clothing, metabolism, tissue insulation (i.e. body fat, muscle and skin blood flow), air speed and relative humidity. Figure 1a adapted from (Kingma and van Marken Lichtenbelt, 2015). b) TNZ of two individuals, the operative temperature is in the centre of the TNZ for person A, which corresponds to a neutral thermal sensation. The operative temperature is at lower operative temperature than the TNZ centre for person B, which corresponds

to a cold thermal sensation for person B. c) The current state of an individual relative to the TNZ centre expressed as operative temperature distance to TNZ centroid ($dTNZ_{op}$, see link to Figure 1d). d) Hypothesis of this paper: thermal sensation vs. $dTNZ_{op}$: neutral thermal sensation occurs when the distance to the TNZ centroid is zero, a positive distance relates to a warm sensation (see link to Figure 1b)

Within the TNZ the body adjusts heat loss via regulation of skin blood flow. This is also a thermoregulatory measure, but is not associated with increased metabolic rate or water loss. The cooler end of the TNZ corresponds to decreased skin blood flow and colder skin temperatures; vice versa for the warmer end of the TNZ (see gray area in Figure 2a). Outside the TNZ, the body core temperature can be maintained e.g. by shivering on the cold side or sweating on the warm side. However, this increases energy expenditure as described below.

Staying within the TNZ reduces the chemical energy required to maintain body temperature because in cold environments energy expenditure is increased by (non-)shivering thermogenesis, and in hot environments energy expenditure increases because the body needs to work harder to transport excess heat away from core tissues, and because warmer tissues have a higher metabolic rate (i.e. Q_{10}-effect: metabolic rate scales with tissue temperature). Furthermore in a hot environment water loss increases due to sweating. Thus, the centre of the TNZ is the safest state for an animal from energetic and hydration perspective, as it provides most internal flexibility to cope with future thermal challenges at minimal cost of nutrients. Therefore, we hypothesise that humans, as mammals, express neutral thermal sensation near the centre of their thermoneutral zone.

It should be noted, that the exact positioning of the TNZ depends on air velocity, clothing, metabolism and tissue insulation (e.g. body fat, muscle tissue, and skin blood flow) (Kingma and van Marken Lichtenbelt, 2015, deGroot et al., 2006, Rennie, 1988). As shown in Figure 2b, individual differences in aforementioned parameters can therefore explain why a specific operative temperature is perceived as neutral for one individual (person A in Figure 2b), and cold or warm for another (person B in Figure 2b).

Temperature sensitive neurons populate the body skin and core tissues (Benzinger, 1969). The body may use the information provided by these neurons as a heuristic to assess its thermal state. We hypothesize, that this is done by evaluating the distance between the actual mean skin temperature and the skin temperature corresponding to the centre of the TNZ or the TNZ centroid (see dTNZsk in Figure 2c). Parallel to the body, we can use temperature sensitive devices to measure the skin temperature of individuals and derive the distance to their TNZ. However, in the built environment it may be more practical to measure physical values (such as operative temperature) which can be assessed easier than the skin temperatures. As can be seen in Figure 2a, the skin and operative temperatures are closely related within the TNZ. Therefore it is also possible to derive the operative temperature distance between that corresponding to the TNZ centroid of a person and the actual operative temperature of the room ($dTNZ_{op}$) (see Figure 2c).

Concertedly, in this paper we test the hypotheses that 1) neutral thermal sensation corresponds to zero distance from the TNZ centroid, expressed as $dTNZ_{op}$. 2) thermal sensation and the distance from the TNZ centroid, expressed as $dTNZ_{op}$, are linearly correlated (see Figure 2d).

2 Methods

The analysis in this study is performed by reusing data from a study on thermal sensation in young adult females (Jacquot et al., 2014, Kingma and van Marken Lichtenbelt, 2015). The participant characteristics and study procedure are shortly summarised, for details see aforementioned papers.

2.1 Participants and protocol

Participants consisted of 16 healthy young adult females (age: 23±4 yr, height: 1.69±0.06 m, weight: 66±8 kg) who were lightly clothed (underwear, cotton/polyester sweatpants, sport socks and cotton t-shirt) while performing light office work (mainly studying). All participants were exposed to two temperature drifts in random order: the cooling and the warming protocol. Each protocol starts with 45min baseline 24°C, followed by 120min 4K/h cooling or warming.

Thermal sensation was assessed every 15 minutes on a continuous seven-sections ASHRAE thermal sensation visual analogue scale, which ranged from -3 cold, to +3 hot.

Operative temperature and relative humidity were measured using wireless sensors (iButton, DS1923, Maxim Integrated Products). Skin temperature was also measured with iButtons (DS1922L) at the 14 positions as described by ISO 9886 standard (Jacquot et al., 2014).

Energy expenditure was measured by indirect calorimetry (Maastricht Instruments), and recordings of baseline CO_2 production and O_2 uptake were converted into their heat equivalent using the Weir equation (Weir, 1949).

2.2 Biophysical model

The theoretical centre of the TNZ is calculated with the biophysical model developed by ((Kingma et al., 2014), see Figure 1c for a graphic example of TNZ centre). To calculate body core temperature, the model assumes a steady state heat balance within the body and between the body and its environment (see Figure 2). Model variables are given in Table 1.

Table 1: Model variables and values used in the biophysical model for this paper

Description	Symbol	Value or Range	Unit
Metabolic rate	M	46-50 *	W/m^2
Respiratory heat loss fraction	a_{rsp}	0.08	fraction
Tissue insulation	I_{body}	0.032-0.112	m^{2}W/K
Body surface area	A	1.88 *	m^2
Body core temperature	T_c	36.5-37.5	°C
Clothing insulation	I_{cl}	0.1054	m^{2}W/K = (0.68 clo)
Air velocity	V_{air}	0.09*	m/s
Relative humidity	Rh	0.5*	fraction
Lewis relation	λ	2.2	°C/mmHg
Skin wettedness	w	0.06	fraction

* based on measurements during the experimental study.

The mathematical procedure is as follows:

1. Define variables as given in Table 1.
2. Correct metabolic rate for respiratory heat loss, such that only heat transport from body core to skin tissues is considered.
   $M_{min} = (1 - a_{rsp}) \times M_{min}$
   $M_{max} = (1 - a_{rsp}) \times M_{max}$
3. Calculate minimal and maximal skin temperature (Ts_{min}, Ts_{max}) that support internal heat balance.
   $Ts_{min} = Tc_{min} - M_{max} \times I_{body,max}$
   $Ts_{max} = Tc_{max} - M_{min} \times I_{body,min}$
4. Define a 200x200 matrix for mean skin temperature (T_{sk}) and operative temperature (T_{op})
   T_{sk} between 28°C and 38°C
   T_{op} between 14°C and 32°C
5. Calculate T_c for each combination of T_{sk} and T_{op} in above defined matrix according to (Kingma and van Marken Lichtenbelt, 2015).
   $T_c = (I_{body} / (1 - a_{rsp})) \times ((T_{sk} - T_{op}) / (I_{cl} + I_{op}) + Q_e) + T_{sk}$,
   here Q_e is evaporative heat loss, I_{op} is operative insulation (inverse of operative heat transfer coefficient), for more details see above mentioned paper.
6. Calculate heat loss (Q_{out}) for each combination of T_{sk} and T_{op} in the matrix according to (Kingma and van Marken Lichtenbelt, 2015).
   $Q_{out} = A \times ((T_{sk} - T_{op})/(I_{cl} + I_{op}) + Q_e)$
7. The thermoneutral zone is obtained by filtering out those points of the resulting two matrices with values of T_c and Q_{out} for which T_c is within core temperature bounds, and Q_{out} is within metabolic rate bounds (corrected for respiratory heat loss as defined in Table 1).
8. The operative temperature centre of the thermoneutral zone ($TNZcenter_{op}$) is defined as the average T_{op} of the thermoneutral zone.
9. $dTNZ_{op}$ is defined as the difference between the observed operative temperature at the time of vote and the calculated $TNZcenter_{op}$ and thus calculated by.
   $dTNZ_{op} = T_{op} - TNZcenter_{op}$

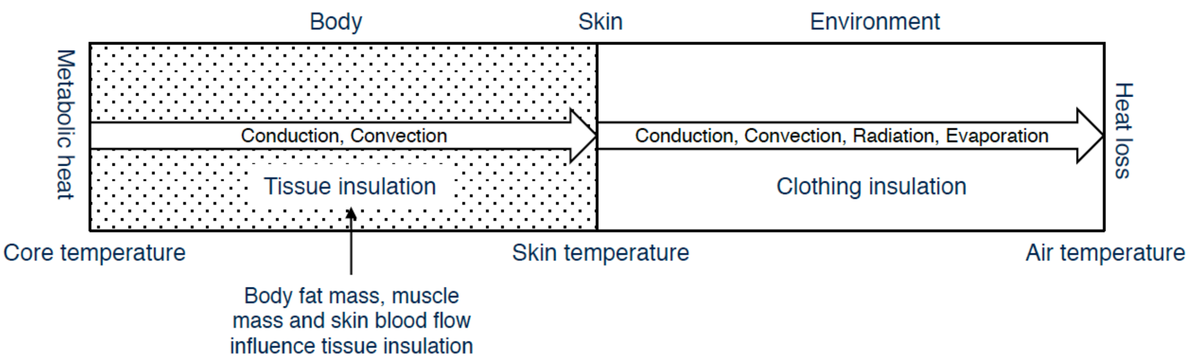

Figure 3: Schematic representation of biophysical heat balance model. From left to right, heat balance is satisfied when metabolic heat production equals heat loss. The temperature gradient between core and skin temperature is determined by metabolic rate and tissue insulation. Likewise the temperature gradient

between skin and air temperature is determined by heat loss and clothing insulation. Figure from (Kingma and van Marken Lichtenbelt, 2015)

2.3 Statistics

For each measurement sample (i) the independent variable ($dTNZ_{op}$) is calculated following the procedure described above. Measured thermal sensation and $dTNZ_{op}$ are represented as the mean per voting timepoint ± 95% confidence interval, starting from the end of baseline period.

The hypotheses are tested by linear regression analysis using the following model

$Y_{sensation} = a_0 + a_1 X_{dTNZop}$

Recapitulating the introduction, in this paper we test the hypotheses that

1) Neutral thermal sensation corresponds to zero distance from the TNZ centroid.

2) Thermal sensation is linearly correlated to the distance from the TNZ centroid.

The first hypothesis is falsified when the model constant (a_0) significantly differs from 0. The second hypothesis is falsified when the slope (a_1) does not significantly differ from 0. The statistics are considered significant when alpha <0.05. The goodness-of-fit, or explained variance, is expressed by the R^2-value.

3 Results

Mean thermal sensation per voting timepoint vs. mean distance from thermoneutral centroid ($dTNZ_{op}$) per voting timepoint are presented in Figure 3 for the cooling and warming protocol.

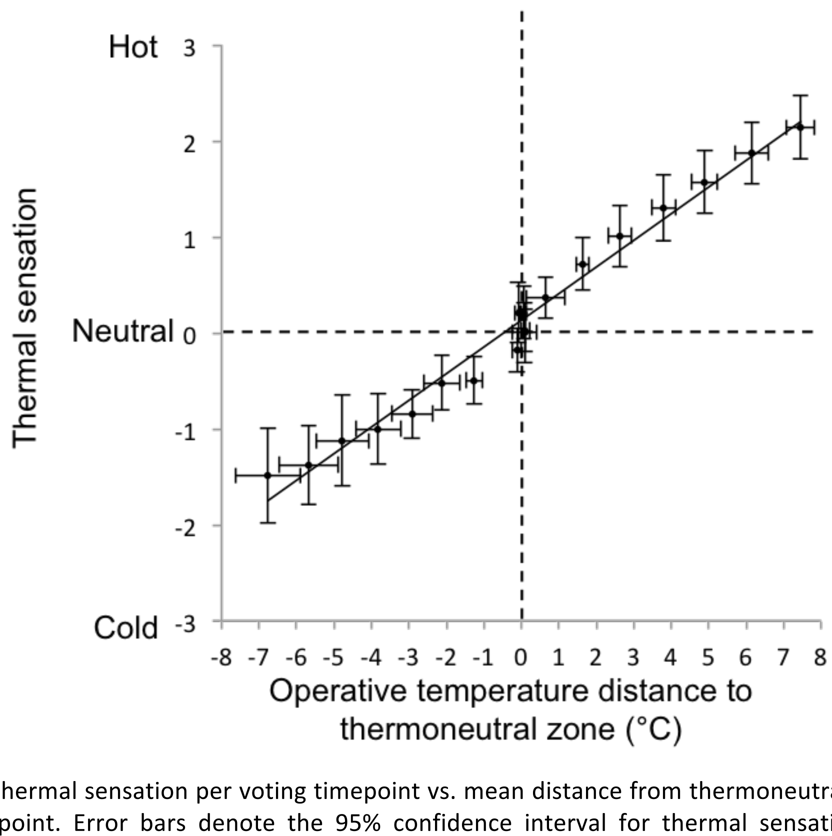

Figure 4: Mean thermal sensation per voting timepoint vs. mean distance from thermoneutral centre ($dTNZ_{op}$) per voting timepoint. Error bars denote the 95% confidence interval for thermal sensation (vertical) and $dTNZ_{op}$ (horizontal). Linear regression is significant ($p<0.001$, $R^2=0.98$; when non-averaged data are used per time point $p<0.001, R^2=0.7$)

Linear regression shows a significant linear relation between observed thermal sensation votes and calculated $dTNZ_{op}$ ($p<0.001$, $r^2=0.98$). Furthermore the intercept is significantly greater than zero ($a_0 = 0.14\pm0.07$) and the slope significantly differs from zero ($a_1= 0.28\pm0.02$). Consequently, the calculated centroid of the thermoneutral zone corresponds to a slightly warmer than neutral sensation. Furthermore, thermal sensation is associated with the distance to the calculated thermoneutral centroid.

4 Discussion

This study shows that the thermoneutral centre is associated with a slightly warmer than neutral thermal sensation vote and that thermal sensation is strongly related to the operative temperature distance to the thermoneutral centre ($dTNZ_{op}$).

The R^2-values presented above signify an extreme good linear relationship between thermal sensation and $dTNZ_{op}$. However, the results shown here must be regarded as preliminary and with great care for the following reasons.

Firstly, the high linearity between dTNZop and thermal sensation may be caused by the dynamic protocol where operative temperature gradually decreases or increases. Basically, the continuous thermal input for the body, could be associated with a high signal-to-noise ratio of thermal status vs. other inputs, and thus makes it easier for the body to assess its own thermal state. Noteworthy, this is then indicative that a dynamic temperature protocol reduces individual variation in thermal sensation. As thermal sensation is related to thermal comfort, this might make it easier to control an environment.

Secondly, this analysis is based on only 16 young adult females observed under controlled conditions in a climate chamber. This means that the number of subjects is low, the expected variance due to age and gender differences is limited, and there are hardly any context related factors increasing the variance (see also Shipworth et al. in conference proceedings). In addition, the averaging per voting time point reduced individual differences. However when non-averaged data are used per time point the explained variance drops to $R^2=0.7$, which is still high compared to other measures.

Despite these limitations, the approach presented here looks promising for understanding human thermal sensation. Therefore, we suggest it to be explored through a broader sample. Furthermore, the influence of dynamical vs. steady state protocols on the model prediction accuracy should be tested. In this context, future analyses need to address issues related to within-subject and between subject differences as well as context related aspects.

4.1 Biophysical model compared to PMV model

The biophysical model presented here is a steady state heat balance model. Therefore, and given its intended context of use, it can be regarded as a physiological extension of the PMV model. Two crucial differences are 1) the biophysical model requires the actual metabolic rate for accurate representation of the TNZ position, in contrast to the PMV model which performs with a consensus value for metabolic rate. 2) The biophysical model incorporates tissue insulation, which is a function of body composition (i.e. fat and muscle tissue) and the ability of the body to adjust skin blood flow.

For a given metabolic rate tissue insulation determines the temperature difference between body core and skin temperature. Given that body core temperature does not deviate much from 37°C during normal conditions, tissue insulation indirectly influences the bodies ability for sensitive heat loss (i.e. through conduction, convection and radiation), and modulates the requirement of latent heat loss (i.e. through transcutaneous water-loss and active sweating). That is, for equal metabolic rate and body surface area, internal heat balance dictates that a lean person will have a higher skin temperature and therefore requires less evaporative heat loss than an obese person.

In case no measurements of metabolic rate are available it can be estimated based on individual/subpopulation characteristics (i.e. height, weight, age and gender) using for instance (Harris and Benedict, 1918) for basal metabolic rate (please note basal metabolic rate is associated with 0.8 MET). Furthermore body surface area can be estimated from height and weight with (Mosteller, 1987). For tissue insulation the range presented in this paper is based on lean young adults during extreme thermal exposures (Veicsteinas et al., 1982, Burton and Edholm, 1955, Hayward and Keatinge, 1981). Literature values are corrected for respiratory heat loss where required. To our knowledge no such data are published for other subpopulations yet.

4.2 Comfort, the neutral zone, further hypotheses and potential applications

Current models of thermal sensation and comfort assume that thermal sensation and thermal comfort are dependent on body core and skin tissues ((Zhang et al., 2010, Fiala, 1998)). The popular consensus is that actual temperatures are compared to one or more set points or reference levels (Schweiker and Shukuya, 2009). The difference between the actual and reference value is an error signal, which conceptually can be interpreted as the drive for a thermoregulatory action (either autonomous or behaviourally).

The concept of TNZ and dTNZ assumes a range of conditions, which do not require further thermoregulatory adjustments except adjustments of the skin blood flow. Based on the results presented above, the closer such conditions are to the centroid of TNZ, the more likely they will be regarded as thermally neutral.

However, the position of the TNZ centroid may change with changes in environmental conditions (e.g. air speed and relative humidity), clothing or physiological conditions (e.g. metabolic rate or skin blood flow). Following current models of thermal sensation and thermal comfort this means that the reference temperature is a function of these parameters as well. This hypothesis is in line with the discussion on the variability of the reference level based on findings from biology, psychology, and neuro science (Schweiker M and Shukuya, 2009), and supports that the body is able to learn which constellations of exposures and thermal state (combining conscious and unconscious information) correspond to optimal homeostasis (Keramati and Gutkin, 2014). If such thermal experiences are not repeated, the body may forget whether a thermal state is favourable or not. A hypothesis to be tested could be that the lack of such thermal experiences due to uniform thermal indoor environments may be one reason for the differences in the range of conditions perceived as comfortable between air-conditioned buildings and naturally ventilated buildings (de Dear and Brager, 1998).

The biophysical model leaves room for individual variation not only in thermal sensation but also in thermal preference due to long-term adaptation (e.g. geographical adaptation) and short-term adaptation or acclimatization (e.g seasonal or shorter adaptive processes (Hori, 1995). This means that through adaptation and acclimatization the body learns a new optimal position relative to its thermoneutral centroid. Quantifying the drivers and their effects related to people's individual parameters is a challenge still to be faced.

Nevertheless, we believe that the basis for analysing and understanding such research needs to be a biophysical approach.

Beyond the interpretation with respect to thermal sensation, preference and comfort, the approach presented here can be linked to the concept of alliesthesia (de Dear, 2011). Leaving conditions outside the TNZ towards its centre should be related to a perception of relaxation: the actions performed (thermoregulatory or non-thermoregulatory) reached the goal to get back to the safest state for an animal from energetic and hydration perspective, the TNZ. The result of such a change might lead to pleasure, as it “occurs whenever sensation indicates the presence of a stimulus which helps to correct an internal trouble” (Cabanac, 1971).

In addition, the biophysical model could be extended by the framework for an adaptive heat balance model, which includes effects of behavioural (non-thermoregulatory) and psychological adaptation and acclimatisation processes (Schweiker and Wagner, 2015). At the same time, physiological adaptation could be included in the biophysical model directly and not solely through an alteration of metabolic rate as input variable to a heat balance model.

In conclusion, the biophysical approach presented does not only look promising with respect to understanding and predicting thermal sensation, but also to be a promising base for future research related to thermal comfort, alliesthesia, and non-thermoregulatory and psychological behavioural adaptive processes.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Adaptive thermal comfort in domestic buildings

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Abstract
Accepted sources tend to assume that buildings with active mechanical heating/cooling systems will have a narrower indoor temperature range than those without. The assumption is that the indoor temperature will be adjusted to reflect the comfort needs of occupants, which are assumed to be approximately the same for all. Using records of indoor temperatures and comfort in buildings in Japan, England and Saudi Arabia, with less complete data from Russia, China, Australia, Belgium and New Zealand the paper looks critically at this assumption. We show that evidence from a number of surveys in domestic buildings suggests that differences between the preferences and circumstances of different occupants can lead to a wide range of indoor conditions. The reasons for this discrepancy from normal assumptions are discussed.

Keywords: Domestic Buildings, indoor temperatures, adaptive thermal comfort

1 Introduction

1.1 Visualising the relationship between indoor and outdoor temperature in buildings

The relationship between indoor and outdoor temperatures can be visualised by plotting one against the other. A 'cloud' of such points can be formed by plotting the indoor temperatures against their concurrent outdoor temperatures. Such a plot will show how the indoor temperature in a particular building responds to the physics and construction of the building, the behaviours of the building occupants and their use of mechanical services and passive systems. Such a cloud could be described as a 'temperature cloud'. Indoor temperature may be a response, not to the concurrent instantaneous outdoor temperature, but rather to a wider measure of the outdoor conditions in the recent past that influence the actual 'core' temperatures of the building that take time to react to outdoor temperature changes.

In thermal comfort work another kind of plot is commonly used where the neutral or comfort temperature has been calculated using the comfort votes of one or more building occupants. This comfort temperature can also be plotted against the outdoor mean temperature to give a relationship like that shown in Figure 1 where the possible values of comfort temperature can be estimated from the outdoor temperature. Such a cloud of points could be referred to as a 'comfort cloud'. Such a response relationship is acknowledged and familiarly represented in the adaptive comfort method by the use of the running mean or other measures of outdoor temperature such as daily or monthly mean. (Humphreys et al 2013).

1.2 Temperature clouds in free-running buildings

In free-running (FR) buildings (whose heating or cooling systems are not in use) the relationship between indoor and outdoor temperatures will primarily be a measure of how the performance of the physical form, the structure of the building and its passive features such as windows and sun shading modifyies the indoor temperature without the use of mechanical energy to control internal conditions. If we assume that the indoor temperature can be, and is, to some extent controlled by the building occupants using the passive controls then the difference between the indoor and outdoor temperatures will also reflect the effectiveness of the efforts of the building occupants both to adapt themselves to be comfortable at the prevailing outdoor temperature and to adapt the indoor temperature to provide their preferred environment.

In a paper which investigates the adaptive relationship between indoor neutral temperatures and the outdoor environment in free running buildings Humphreys et al. (2013)[1], used a database of indoor and outdoor temperatures from some 700 comfort surveys known as the Database of Thermal Comfort Summary Statistics (DTCSS). They showed that a zone of slope about 0.5 between indoor neutral temperature and prevailing mean outdoor temperature is most representative of that relationship in FR buildings (Figure 1). Note that in this figure each point is a not an instantaneous temperature but the neutral temperature calculated from a whole field survey. This is therefore better described as a 'comfort cloud' rather than a temperature cloud. The width of the 95% zone of inclusion is ~7K.

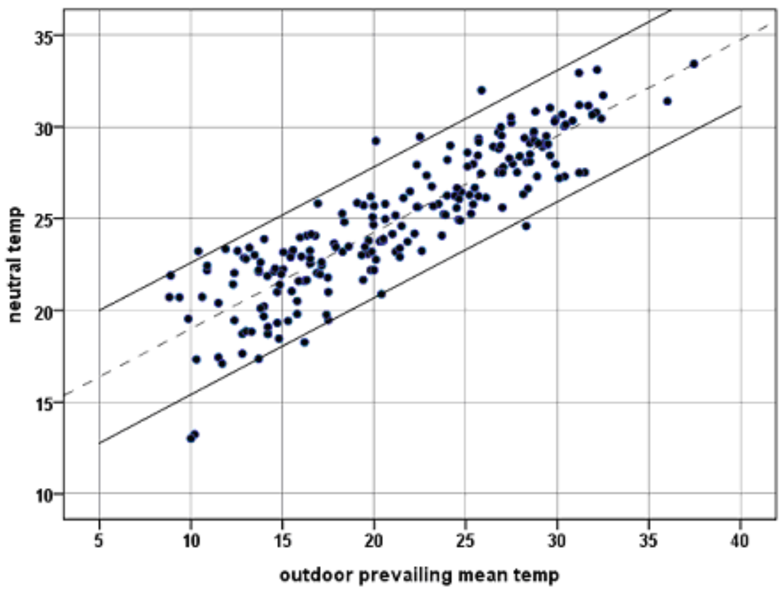

Figure 1. The neutral temperature (C) for buildings in the free-running (FR) mode as a function of outdoor prevailing mean temperature (C) in FR Buildings. Lines show the regression line for the database and the 95% confidence limits around it. (From Humphreys et al 2013).

The equation of the central comfort line in figure 1 is

$$T_n = 13.8 + 0.53(\pm 0.02)T_o \quad (1)$$

Where T_n in the best estimate of the neutral temperature at an outdoor prevailing mean temperature T_o.

If avoiding thermal discomfort is assumed to be a major motive driving occupant behaviour then the indoor temperature will respond to the outdoor temperature in a way to which, to an extent, reflects the desires of the occupants to be comfortable. The temperature cloud will be less precise that the comfort cloud because in the comfort cloud each point includes the statistical process of determining the comfort temperature for a group of subjects from the temperature data and the comfort votes.

1.3 Temperatures in mechanically controlled environments.

The relationship between indoor and outdoor temperatures in buildings which are being mechanically heated or cooled is comonly assumed to be well controlled, with some or all of the building occupants regulating indoor conditions to achieve a selected neutral temperature. This assumption seems well-attested by the comfort cloud from Humphreys et al. (2013) shown in Figure 2 showing comfort temperatures in mechanically controlled environments. The data used to compile this graph was largely from comfort surveys in offices and other well-controlled environments.

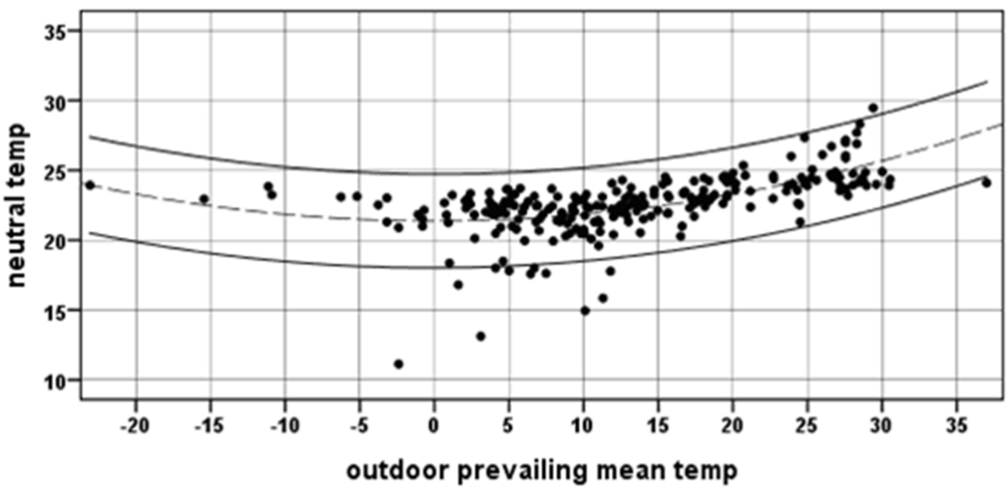

Figure 2. Indoor neutral temperatures plotted against outdoor temperature. This is a comfort cloud for buildings which were heated or cooled at the time of the survey. The majority are within the accepted range of temperatures for comfort (say 20-25^{o}C) though there are a number of exceptions (from Humphreys et al 2013)

Figure 2 suggests that the temperatures in conditioned spaces are relatively closely controlled. The dependent variable is the comfort temperature, not the temperature which is actually achieved in the recorded buildings. The data in figure 3 shows an example of the kind of temperature cloud from which the comfort cloud in figure 2 is derived. The data in the figure are bounded by the extreme values of the outdoor and the indoor temperatures. The cloud in figure 3 is formed from temperature measurements taken in a mechanically controlled indoor environment which is reasonably successful in maintaining a chosen, constant indoor temperature. In figure 3 a typical relationship between the two emerges with a resulting change of indoor temperature of 0.08K per degree centigrade outdoor temperature.

$$T_i = 0.08T_o + 23.0 \text{ (K)} \quad (2)$$

Where T_i is the indoor operative temperature and T_o in the outdoor air temperature. The width of the 95% interval of Ti is 4.7K

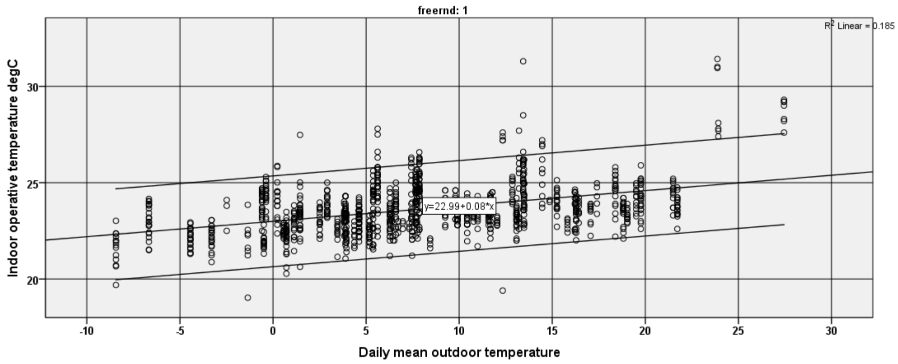

Figure 3. A plot of indoor measured temperature in heated or cooled buildings against outdoor daily mean temperature. Data from SCATs project in European buildings.

1.4 The case of free-running domestic buildings

The DTCSS surveys (Humphreys et al. 2015) are overwhelmingly in workplaces – offices, colleges etc. where most surveys are made during the day. It does also include results from about 100 surveys in homes, 40 of these are NV and were FR at the time of the survey. To check whether there are differences between homes and other buildings the results from these homes were compared to the 95% limits for the entire database (shown in Figure 1).

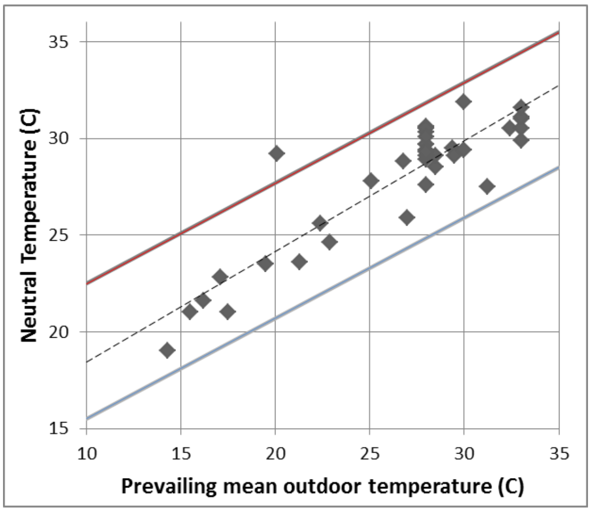

Figure 4. Overlay of results from free-running homes on to the 95% confidence intervals from the whole DTCSS (figure 1). The dashed line is the regression line for homes (eq 2). (Author)

Figure 4 shows the results of this analysis: almost all of the points in this comfort cloud for homes fall within the 95% limits for the whole database shown in figure 1 and the regression line for homes:

$$T_n = 12.7 + 0.58T_o \tag{3}$$

is almost congruent with that for the whole database. This finding gives some evidence that comfort in FR domestic buildings relates to outdoor conditions in much the same way as it does in non-domestic buildings.

2 Review of results from different climates

2.1 Japanese dwellings

2.1.1 Results from free-running dwellings in Japan

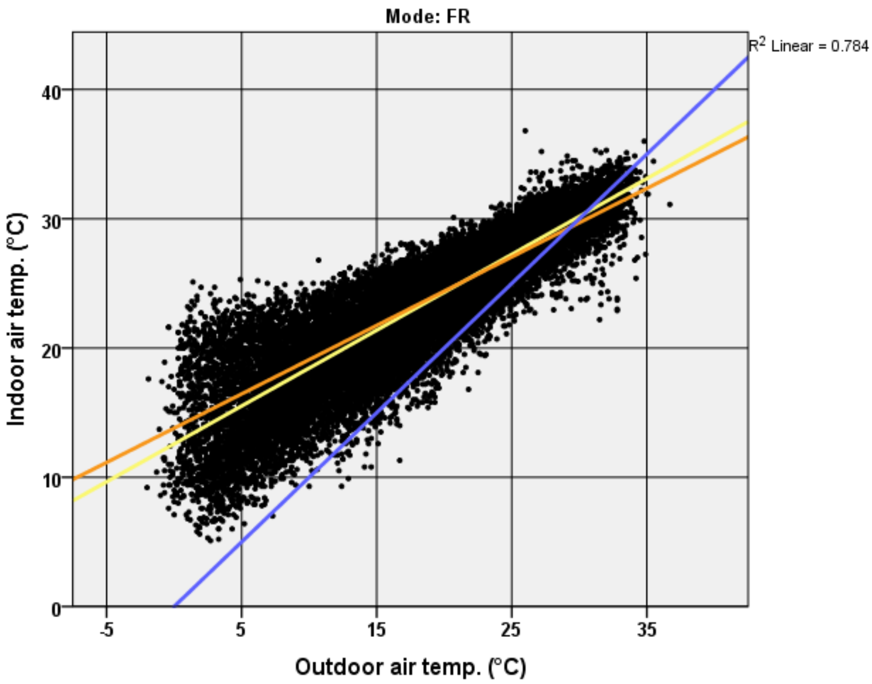

Figure 5. Temperature cloud for Free-running domestic buildings in Japan. A large proportion of the 25,520 datasets were collected in the morning and evening as part of a study. The yellow line is the regression line for indoor temperature on outdoor air temperature. The thicker orange line is the Humphreys comfort estimate (equation (1)). The blue line shows where the indoor and outdoor temperatures are equal suggesting the relationship between indoor and outdoor conditions.

Figure 5 shows data for Free-running dwellings from a large survey in Japan (Rijal et al 2016). It illustrates some results from Tokyo that suggest that the Humphreys relationship (equation 1) holds well for people in free-running (FR) buildings, including those in cooler or warmer conditions. Although the indoor air temperatures shown are not necessarily experienced as comfortable, comfort votes collected at the times shown by the markers on the cloud in figure 5 were 89.4% for the central three values in the seven-point comfort scale which are generally assumed to signify comfort (see section 2.1.3). The regression equation for neutral temperature on outdoor temperature from the Japanese data is

$$T_i = 0.59T_o + 12.6 \qquad (4)$$

The spread of indoor temperatures is greater than the Humphreys comfort zone but it should be remembered that the process of calculating the comfort temperature reduces the variance compared to the original data as explained in secton 2.1. The slope of the regression line between the outdoor temperature and comfortable temperatures indoors is an expression of the role of the building in modifying the external environment.

2.1.2 Heated and cooled Japanese domestic buildings

The assumption that heated or cooled buildings maintain a constant indoor temperature is not borne out generally by measurements made in domestic dwellings. Houses differ from each other to a greater or lesser degree because they are occupied by different people.

Temperatures in domestic buildings vary from room to room, each room expressing the use to which it is put and the person who occupies it. Of course not all temperatures, nor variations in temperature are entirely voluntary. Some may be caused by faulty domestic heating or cooling systems, or by the cost of fuel.

Rijal's set of Japanese data whose free-running temperature cloud is shown in figure 4 also includes data from dwellings which are heated (HT) or cooled (CL) at the time of the survey. The clouds for these two groups are shown in figure 6. They are characterised by a 'horizontal' surface suggesting that there is a limiting upper temperature in heated buildings and a limiting lower temperature in the cooled buildings. These limiting temperatures are similar in both clouds at between 20 and 25°C. This is also true of the point at which mechanical conditioning starts to be used at an outdoor temperature of 15-20C. As the outdoor temperature increases (CL) or decreases (HT) away from this cross-over the range of indoor temperatures also increases to reach 10-15K in both cases.

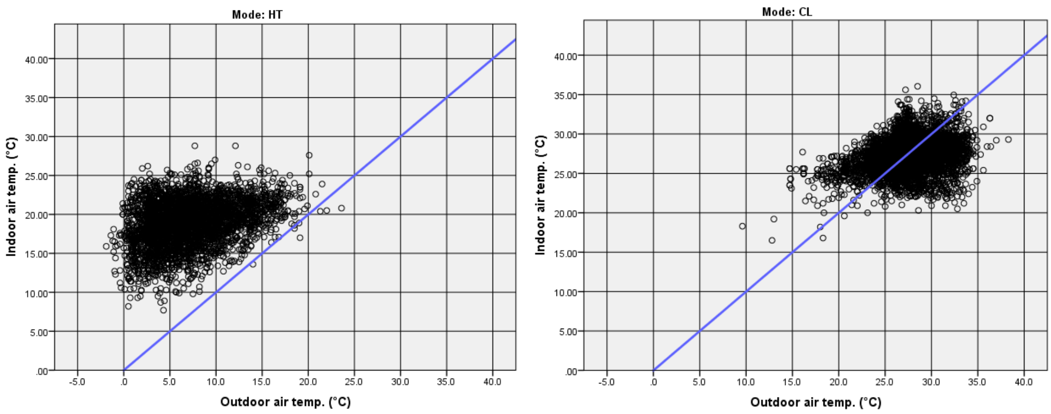

Figure 6. Temperature clouds for rooms being heated (HT) or cooled (CL) at the time of the survey from the database of temperatures in Japanese houses (Rijal et al 2015).

Figure 7 shows the result of superimposing the three separate clouds (figures 5 and 6) in a single diagram. Seen as a divergence between indoor and outdoor temperatures (equality is indicated by the blue line) it is clear that as the difference increases the use of mechanical conditioning becomes more essential. At 0-5°C about half of all rooms are mechanically heated and at 25-30°C about half are mechanically cooled. The mean indoor temperature in rooms with heating running was 19.6°C (SD 2.8K) and in those with cooling was 27.6°C (SD 1.7K).

The temperature clouds shown in Figure 7 suggest a different model for the range of indoor temperatures to that assumed by many users of building standards: the indoor temperature range is as great or greater in those parts of the combined graph where mechanical conditioning is used to heat or cool the building. Indeed the shape of the cloud suggests that the range of indoor temperatures may actually be smaller where the building is free-running (FR). In Free-running mode the building itself, along with any passive controls, creates a less diverse indoor temperature than when it is combined with mechanical controls. This finding is explained further below.

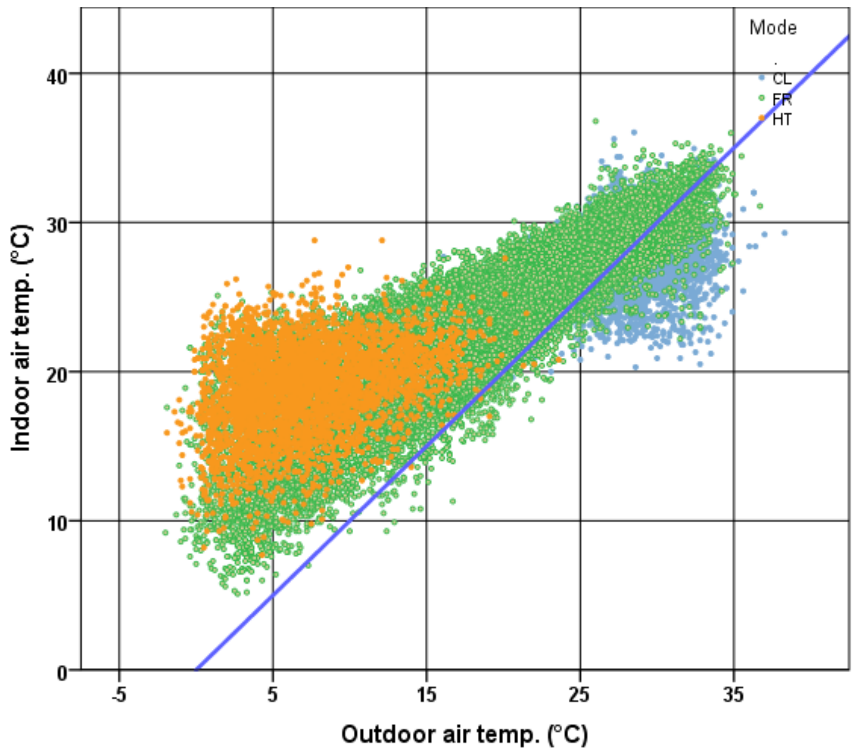

Figure 7. Temperature clouds for different modes of operation in the Japanese buildings. Blue line: indoor and outdoor temperatures are equal

2.1.3 Comfort in Japanese homes

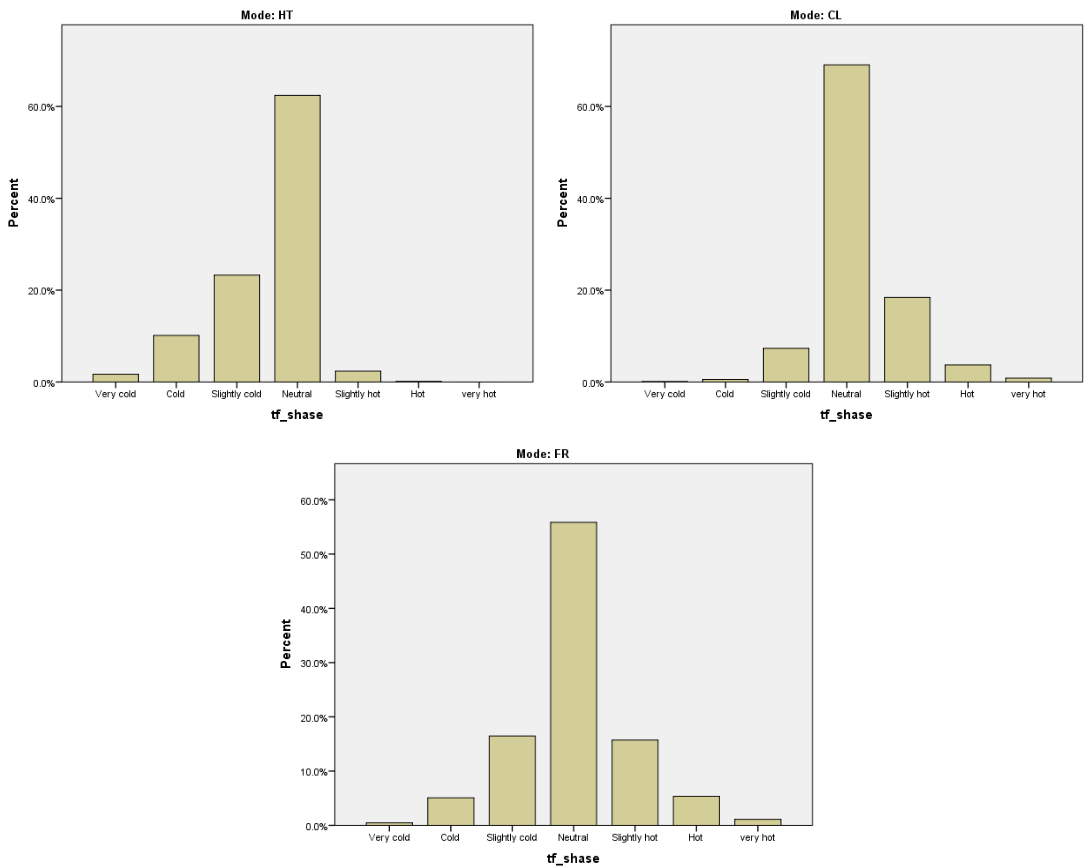

Figure 8. Showing the distribution of comfort votes on the 7-point SHASE scale in buildings which are cooled (CL) heated (HT) or free-running (FR) at the time the comfort votes were taken.

The distribution of comfort votes on the ASHRAE scale in each mode of operation is illustrated in Figure 8. Note that when the building is being heated the number feeling cold as greater than those feeling hot suggesting that the heating is turned on to combat the cold, likewise the cooling is run to overcome the heat. In the free-running building the comfort votes are symmetrically divided. In all modes close to 60% of all comfort votes are neutral. In the FR mode most of the discomfort occurs at the extreme values of indoor temperature.

2.2 English houses

2.2.1 Temperatures in English homes

Indoor temperatures in a balanced cross section of 427 English houses were measured at 45 minute intervals between August 2007 and January 2008 and plotted against outdoor temperature (Kelly et al 2013). The results are shown in the temperature cloud(s) in Figure 9.

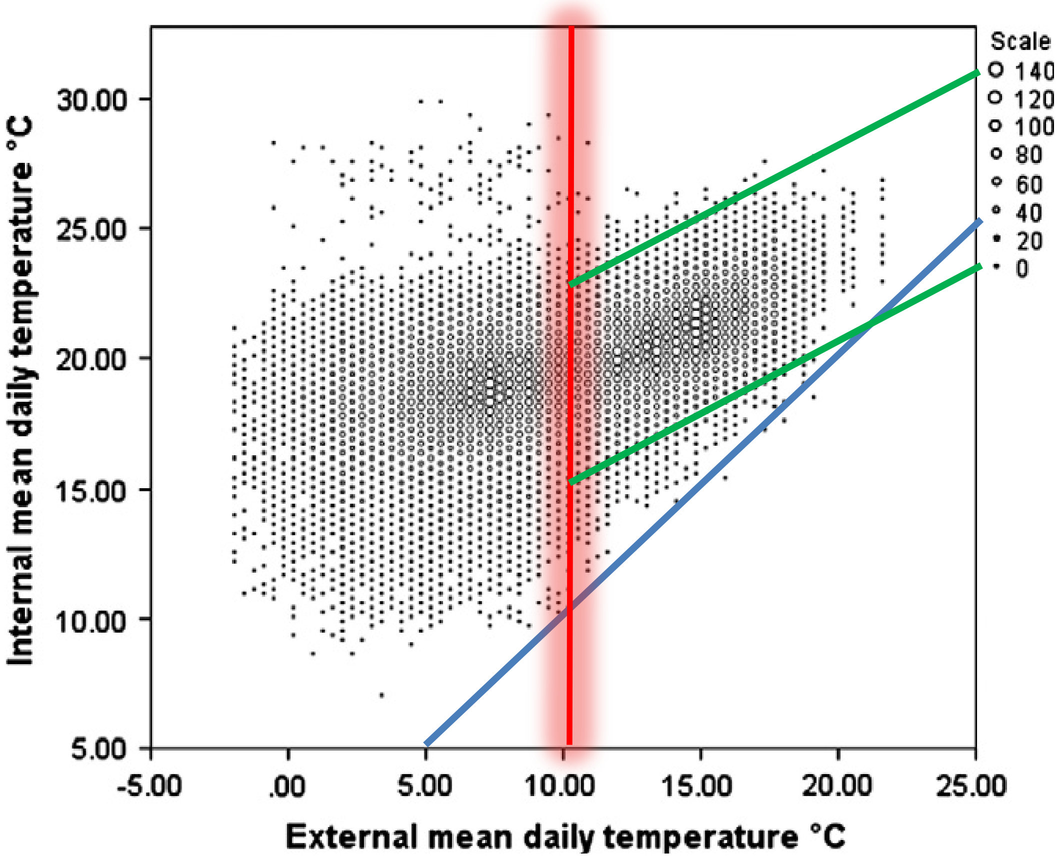

Figure 9. Indoor temperatures in English houses. They are most likely to be heated when outdoor temperatures fall below 10^{o}C. Above 10^{o}C they are likely to be free-running. Green lines show the limits of comfortable indoor temperatures in free-running buildings according Humphreys et al 2013. Blue line: indoor and outdoor temperatures equal. Temperature records from Kelly et al, 2013

The use of heating in winter (or cooling in summer) were not recorded nor were to comfort feelings of the occupants. In common with many European countries (Nicol 2001), a majority of English buildings are heated when mean outdoor temperatures fall lower than roughly 10^{o}C. In figure 9 we have assumed that indoor temperatures where the outdoor temperature is less than 10^{o}C will be for heated interiors, and above 10^{0}C the buildings will be free running. Though an increasing proportion of offices and other commercial buildings now have mechanical cooling in summer is still rare in English homes. Interestingly the two temperature clouds above and below 10°C outdoor temperature are fairly distinct suggesting that there are 'shoulder months' where outdoor temperatures change relatively quickly.

Note that the temperatures in houses which can be assumed to be free-running (To >10°C) the indoor temperatures rise as the outdoor temperature rises and that the data points fall roughly within the Humphreys 95% limits shown in figure 9. When the outdoor temperature is such that we would expect the heating to be running (To <10°C) the range of indoor temperatures is greater but the mean indoor temperature changes more slowly. Heubner et al (2014) estimate the standard deviation among the wintertime indoor temperatures to be around 2.5K in the heated homes suggesting a 95% temperature range in the region 10K – at least as great as that in the buildings which are free running.

2.2.2 Within-day temperature variations in English houses in the heating season

The overall spread of indoor temperatures can also mask an internal daily order. Thus in English data (figure 10) there are changes of indoor temperature with a diurnal repeat. Huebner et al (2015) report on the changes of temperature which occur in UK houses within a given day and report that there are four distinct daily temperature clusters in UK homes in the winter season: 1) Steady Rise, 2) Flat Line, 3) Two peak and 4) Steep Rise. These are illustrated in figure 11. But the mean changes from one dwelling to another. The particular shapes of the clusters reflect the common use of time-controlled heating systems in UK homes which are often turned off over night in order to save fuel. In addition in many UK homes the heating is switched on early in the day and then off during the middle of the day and again in the evening creating a double peak as is seen in cluster 3.

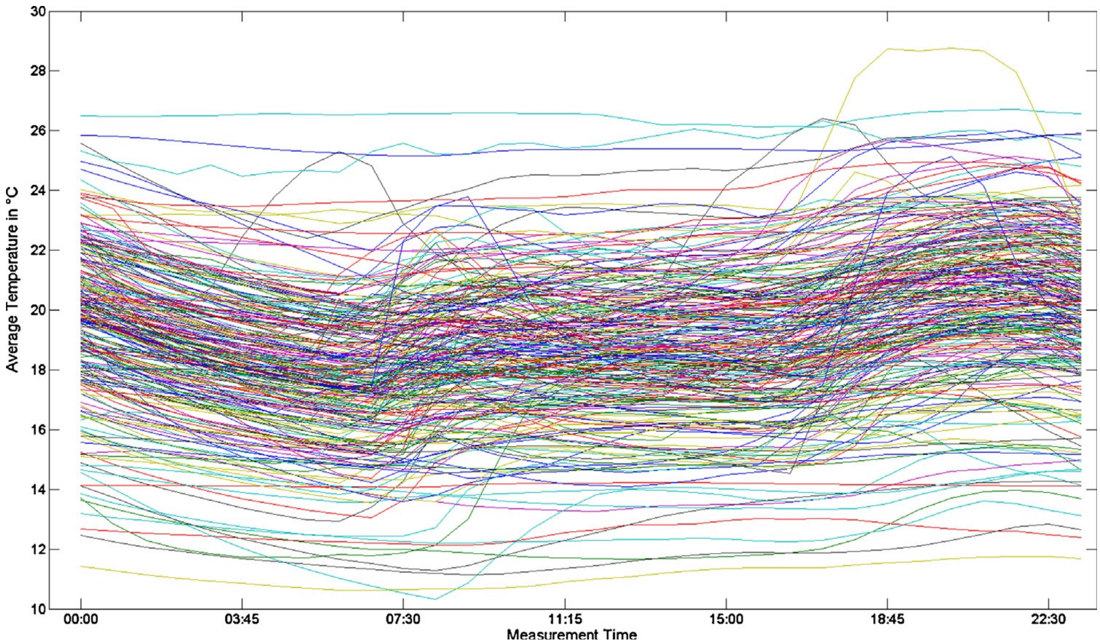

Figure 10. Scatter diagram of within-day temperature traces in 257 buildings. Each trace is the mean of the traces recorded for a particular room over the period November to February (Heubner et al 2015)

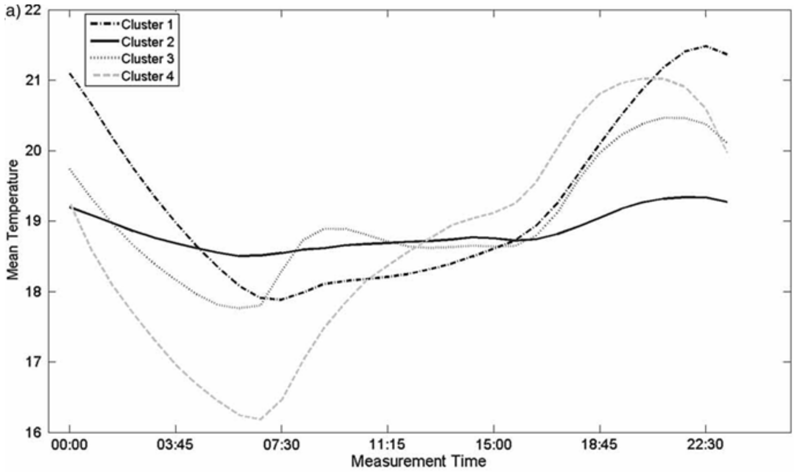

Figure 11. Showing characteristic clusters of temperature profiles in English houses (Heubner et al 2015)

2.3 Saudi Arabia

2.3.1 Mechanically cooled buildings in Dammam, Saudi Arabia

Alshaikh (2016) collected temperature and comfort data from 17 dwellings in Dammam, Saudi Arabia. The temperature cloud for these mechanically cooled buildings in summer is shown in figure 12. There is a small positive correlation between indoor and outdoor temperature and the regression equation for indoor temperature against outdoor temperature is

$$Ti = 0.09To + 23.7 \qquad (5)$$

The width of the 95% temperature limits (shown in figure 12) is about 13K. Overall the range of indoor temperatures is from 20 – 35^{o}C and of outdoor temperature from 29-48^{o}C.

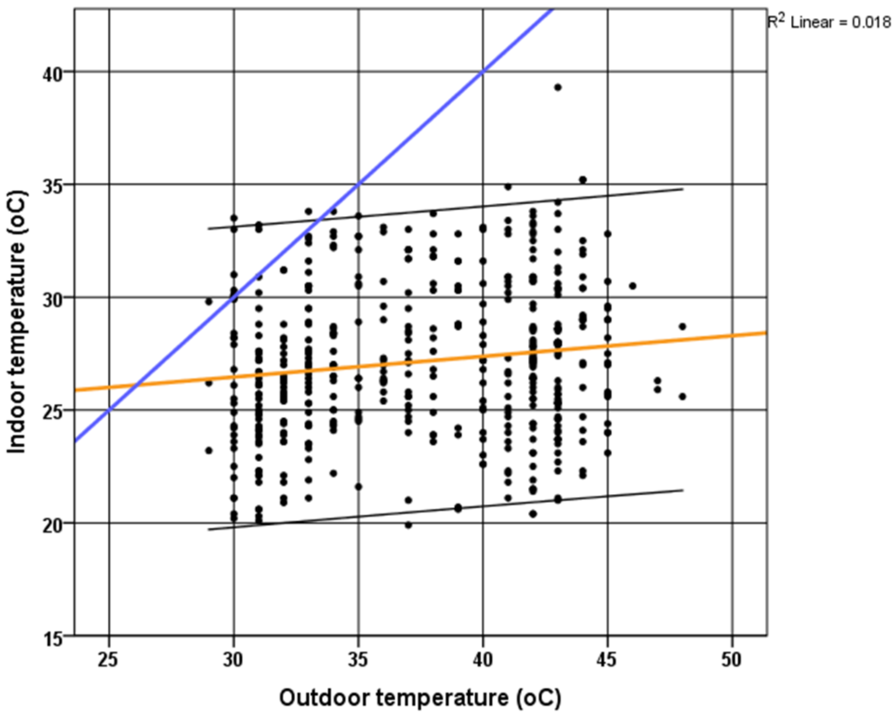

Figure 12. Temperature cloud for dwellings in Dammam showing regression and 95% temperature limits (from data of Alshaikh, A. 2016)

A pattern is found in the Dammam data where there is a tendency for a dwelling-specific mean characteristic temperature which changes from one dwelling to another. The range of mean indoor temperatures is from 22.4 to 31.5°C but can remain relatively constant for any particular dwelling. This suggests an element of adaptive control exerted ovr the building by the occupants.

2.3.2 Comfort in mechanically cooled buildings in Dammam

Figure 13 shows a histogram of the comfort votes cast by subjects in the Dammam dwellings (1 = cold, 7 = hot). It is clear that there is more discomfort from heat than from cold in the dwellings in Dammam but some 70% of votes indicated comfort, and a closer analysis of the votes shows that a large proportion of the votes of ‘warm’ (5) are from just two dwellings (cf figure 14).

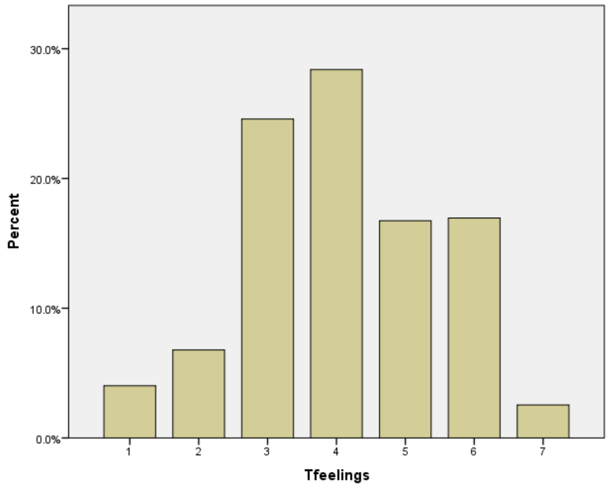

Figure 13. Histogram of comfort votes in the Dammam dwellings (from data of Alshaikh, A. 2016)

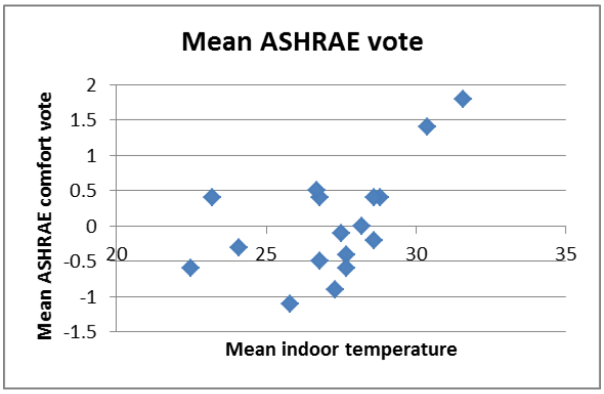

Figure 14. Mean comfort vote at different indoor temperature (from data of Alshaikh, A. 2016)

2.4 Combining the evidence from Japan, England and Saudi Arabia

Figure 15 overlays the temperatures clouds from Japan (figure 7) England (Figure 9) and Saudi Arabla (figure 12). The results show three temperature ‘regions’ associated with buildings which are heated (Japan and England), cooled (japan and Saudi Arabia) and free-running (England and Japan). Nptably the heated and cooled regions have a greater range of indoor temperature (about 15K) than does the free-running region about 8-10K. This shape contradicts the shape expected in most standards and guidelines which assume that conditioned buildings will have the narrower temperature range.

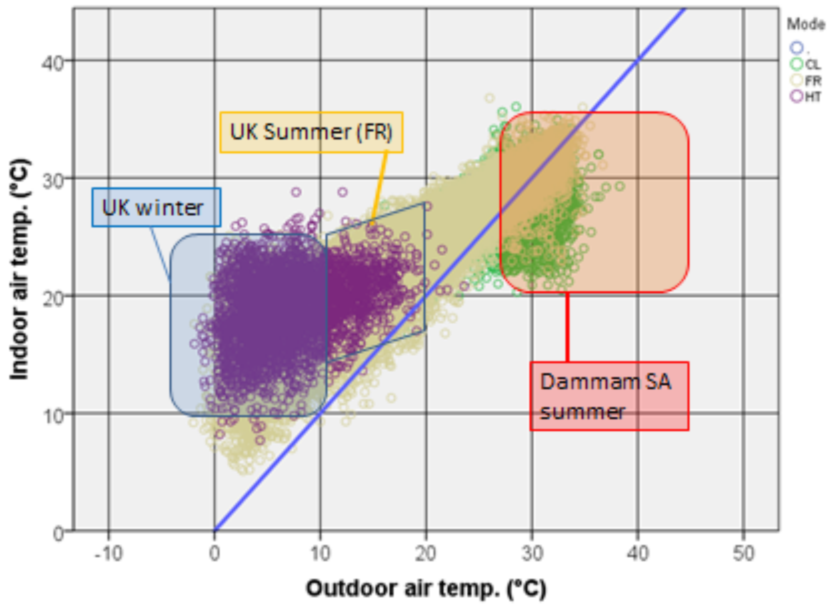

Figure 15. Adding the English heated temperature cloud, the English FR temperature cloud and the Dammam cooled temperature cloud to the combined clouds of the Japanese data (figure 7) extends the overall range of indoor temperatures and emphasises the shape of the combined clouds. (see section on guidelines)

3 Temperature variations in buildings in other climates

3.1 Russia

560 comfort datasets collected over the internet in buildings in Khabarovsk, Eastern Russia by Galina Borovikova 2013 show a substantial range of indoor temperatures at a mean outdoor temperatures of –19.5°C. Mean indoor temperature was +22.6°C with a standard deviation of 3.2 K suggesting a 95% temperature range of about 12K. Comfort temperature for the group was 23.4°C. The winter data were mostly collected within a single day so a regression slope of indoor temperature with outdoor temperature is not possible to estimate with any precision (Figure 16). The data were a mixture of workplace and home locations but the timing of the comfort votes suggests that the majority were from home. A similar estimate of indoor temperatures in the summer months when the outdoor temperature was 22.4°C for buildings are free running give a mean indoor temperature of 24.0°C with a standard deviation of 2.3K. 75% of the votes cast were in the comfortable range.

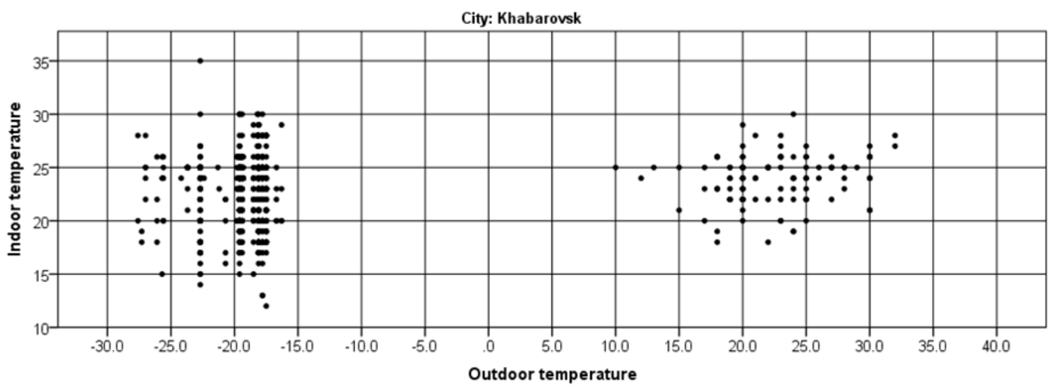

Figure 16. Temperature clouds in Khabarovk, Russia for winter (Left) and Summer (right) (G Borovikova)

3.2 China

Wang et al (2006) found that in Harbin, China when the outdoor temperature averages about -10^{o}C the mean indoor temperature is 20.1^{o}C with a standard deviation of 2.4K and an indoor temperature range of almost 14K. Note that the mean temperature in Harbin offices is lower at 17.5^{o}C but the temperature range is only 10K.

Cao et al (2016) show a trend in teaching buildings in the colder climates of Northern China that indoor temperatures tend to be higher as the outdoor temperature drops. Thus in a survey of three cities in China, Harbin, Beijing and Shanghai the outdoor mean temperatures were respectively -8.9, +3.6 and +7.9 ^{o}C the indoor operative temperatures were respectively 24.3, 20.7 and 16.5 ^{o}C, though the range of indoor temperatures was relatively small as might be expected in non-residential buildings.

3.3 Australia

Daniel et al. report on the case of the Australian 'Mavericks' (see figure 17). The buildings they inhabit are in two very different climatic regions of Australia (Darwin and Melbourne) and of two different types, the homes in Darwin being naturally ventilated all year and those in Melbourne typically being higher mass mud brick homes that are often heated in winter. The reported comfort temperatures are described as atypical. But the range of adaptive opportunities they use are not unique. The subjects here are persons committed to a green agenda who pride themselves on minimising their use of energy to make themselves comfortable. The authors of the paper report that the aggregated slope of the case study data trend line including subjects from both climatic regions is 0.52 which is close to that reported by Humphreys et al (2013) and shown in Figure 1 and eq (1).

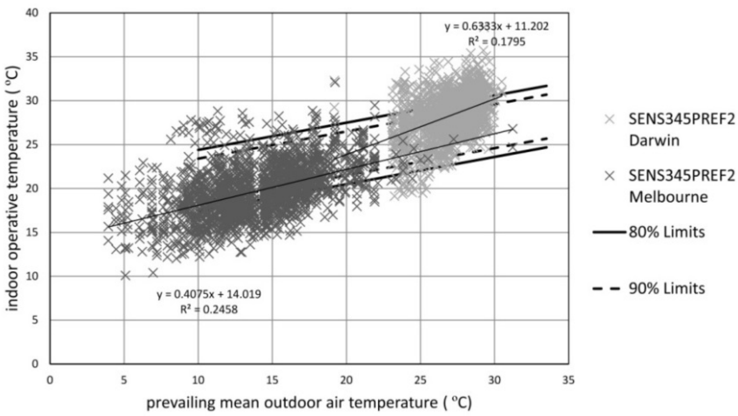

Figure 17. Temperature clouds recorded in Darwin (light grey) and Melbourne (dark grey) in Australia by subjects described as thermal mavericks, i.e. they try to make themselves comfortable in temperatures beyond the normally accepted range in order to reduce their energy use for mechanical heating or cooling. The data points shown were collected when the subjects voted 'neutral' (Fifure from Daniel et al 2015)

3.4 Belgium

Reporting on a survey of indoor temperatures in Belgian dwellings Peeters et al (2008) reports a wide range of indoor temperature particularly in bedrooms when the outdoor temperature was below 11^{o}C. The authors point out that bedrooms can be used for a wide variety of activities (e.g. watching TV, homework etc) and the wide range of temperatures will need to reflect this if discomfort is to be avoided (Figure 18).

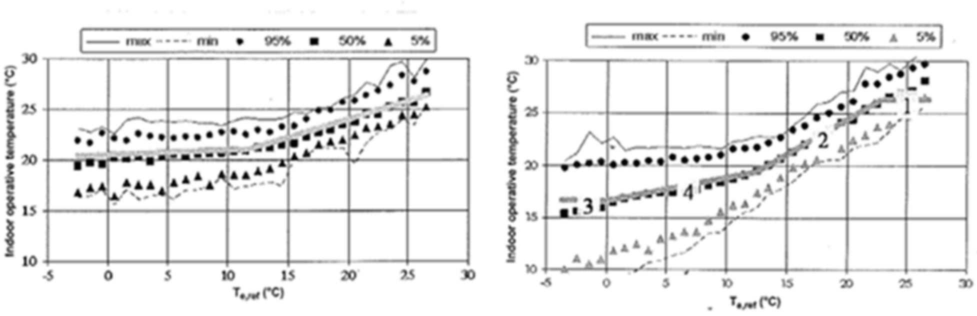

Figure 18. Indoor temperatures in Belgian living rooms and Bedrooms (Peeters et al 2008)

3.5 New Zealand

Nigel Isaacs and his co-workers in the Household Energy End-use Project (HEEP) carried out a survey of 397 dwellings in all parts of New Zealand. They found them to have evening (1700-2300) living room temperature in winter (Jun-Aug) between 10^{o}C and 23.8^{o}C with a mean of 17.9^{o}C (French et al 2006a). In the summer (Dec-Feb) the daytime (0900-1700) eighty-five percent of the houses were found to have a mean living daytime temperature between 20°C and 25°C, while less than 1% are over 25°C and just over 14% are under 20°C (French et al 2006b). The authors report that the average mean daytime living room summer temperature is 21.8°C, the maximum mean temperature is 25.9°C and the lowest mean temperature is 16.3°C. The distributions of temperature are shown in Figure 19. Whilst there is some room for dispute with the difference in time of day, there is evidence that the summer temperature range is smaller than that in winter when the heating system is on.

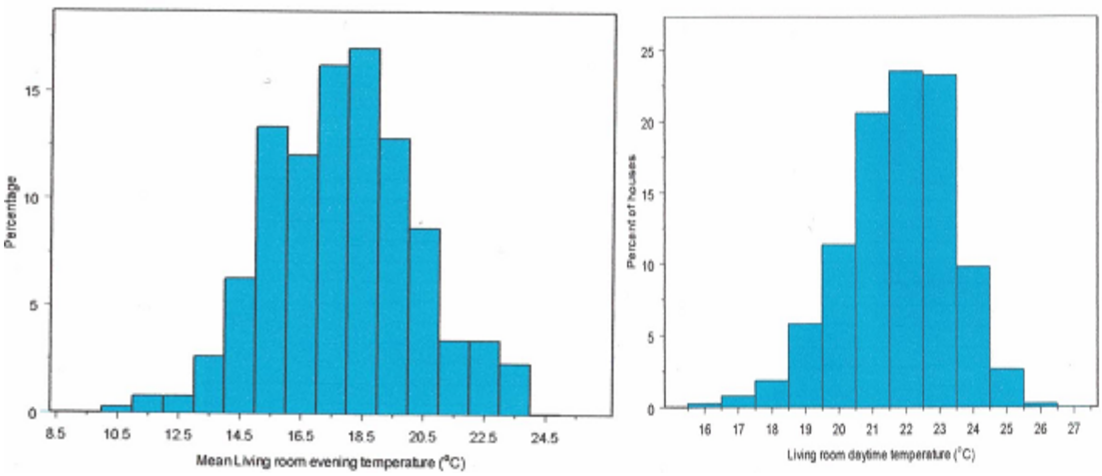

Figure 19. Temperatures in New Zealand living rooms in winter (left) and summer (right), From French et al (2006a and 2006b)

4 Discussion

This paper has gathered together information from dwellings in a range of climates and buildings. It is a collection of surveys each of which was different to the others both in design and scientific intent. As a result each survey tells a rather different story but together they give some interesting insights into the role of mechanical systems in domestic buildings.

4.1 Adaptive comfort and indoor temperature in mechanically conditioned buildings

Adaptive thermal comfort is often presented as applying only to buildings which are free-running. In fact the theory of adaptive thermal comfort does not make any such stipulation. Adaptation to the prevailing thermal conditions will always occur according to the adaptive principle:

If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort

Such changes can occur on conditioned spaces as well as those which are free running. The adaptive actions can take two principal forms:

1. The person can change themselves to suit the environment (e.g. by changes of clothing or activity)
2. The person can change the environment to suit their own needs (e.g. turn up the heating)

The first form of adaption suits the occupant of a free-running building as well as the person in a conditioned environment; the second is the obvious choice where the environment can be controlled directly by the person in question through a mechanical conditioning system. In a conditioned environment where the heating (cooling) system is remotely controlled (as it might be in an office) the first form of control is likely to continue to predominate and if necessary the occupant will find ways to remain comfortable (such as bringing in extra clothing).

In their own home people have more direct control over the conditioning system and the conditions for changing the environment are more likely to be at hand. This is one explanation for the wide range of environment found in domestic buildings with mechanical heating or cooling systems. Another difference between domestic and non-domestic buildings is that in the former the occupants are financially responsible for the energy used and therefore have an interest in reducing energy use within their personal means. They may therefore be more motivated to wear more clothes in cold weather to reduce their energy bills, and at the same time to reduce the indoor temperature to suit their clothing. The use of control system in English heating homes mentioned in section 2.2.2 is an instance of this behaviour. Other possible behaviours such as putting up with short-term discomfort to avoid energy use could also affect the thermal record.

4.2 Evidence about temperature and comfort clouds from these surveys

4.2.1 Dwellings in the free-running mode

The rate of change of indoor temperature with outdoor temperature was calculated in the free running Japanese (figure 5 and equation 4) and Australian (section 3.3) data and estimated visually in the UK (figure 9) and found to be roughly comparable with the estimate of comfort zone from the DTCSS in figure 1 and equation 1 as well as for free running dwellings equation 3. A regression slope of between 0.5 and 0.6 between outdoor air temperature and indoor operative temperature. A range of indoor temperature ±4 and ±5K at any given outdoor temperature.

4.2.2 Dwellings in mechanical cooling or heating mode

In mechanically heated buildings in Europe (figure 3 and equation 2) and cooled buildings in Saudi Arabia the (figure 13 and equation 5) indoor temperature rises less than one degree for every 10K rise in outside temperature. Indoor temperatures in buildings in cold climates in China and Russia seem to average about 23^{o}C suggesting a change in the slope of the line around 0^{o}C.

A characteristic of mechanically heated or cooled residences is to have a considerable indoor temperature range. This is shown in practically every study quoted. In Japan (10-15K figure 6), England (13K figure 9) and Saudi Arabia (13K, Figure13) and Russia (15K figure 16). In New Zealand the summer range of indoor temperatures is 10K whereas in winter it is 14K.

4.2.3 Temperature range is smaller in free-running buildings

The evidence gathered in this paper suggests that buildings display a greater range of indoor temperatures in heating or cooling mode than they do when they are free-running at any given outdoor temperature. The indoor temperature may vary considerably from one season to another in any one building but only when the outdoor temperature changes. This is suggested by the data from Japan, England, and New Zealand

4.3 Regular daily variations can be found in the indoor temperature

The English data in particular exhibits regular daily changes in the temperature in buildings. To an extent these reflect the control regime of the heating system. Similar changes were also observed in the cooling regime in the Dammam residences (Alshaikh 2016) the changes in use at different times of day. These within-building changes will account for some of the observed temperature ranges.

Looking separately at the four clusters which were identified in the English data (section 2.2.2 and figure 12) Huebner et al 2014 found that the mean temperature was similar for all four clusters but that the standard deviation of the temperature was greatest for the 'flat-line' cluster (which has the smallest within-day SD) suggesting that a significant part of the temperature range is a difference between buildings.

4.4 Guidelines for indoor temperatures

International Standard ISO 7730 (BSI, 2005) sets out the accepted method for calculating indoor temperatures in heated or cooled buildings according to the PMV method. In addition other standards show a range of acceptable indoor temperature in free-running buildings related to a measure of mean outdoor temperature. When the indoor environment is mechanically heated or cooled the comfort temperature for occupants is assumed to be defined as one in which the value of the Predicted Mean Vote (PMV) is close to zero, and the Predicted Percentage (of occupants) Dissatisfied (PPD) is a minimum. The quality of the environment is assumed to be most satisfactory when both PMV and PPD are close to their minimum values.

Guidelines for the setting of indoor temperatures in mechanically controlled indoor environments such as those shown in Table 1.5 of the CIBSE Guide A (CIBSE 2016) are based on the PMV calculation method. For dwellings CIBSE Guide A Table 1.5 quotes a number of temperature ranges with a minimum of 17^{o}C and a maximum of 24^{o}C, but for any given room the range is generally within 2K (e.g. living rooms 22-23^{o}C bedrooms 17-19^{o}C).

5 Conclusions

The evidence presented in this paper suggests the dwellings show a wide range of indoor temperatures, especially when they are mechanically cooled or heated.

The paper identifies this as an adaptive response to the presence of a mechanical system which allows a considerable degree of control over indoor temperatures. The resulting temperature variability reflects the different preferences of building occupants reflecting their range of activities, clothing, expectation, financial circumstances and so on.

The temperatures found in free-running buildings are largely determined by the form and character of the building and the response of the inhabitants to environment.

Regular diurnal temperature variations were identified particularly in the English winter data and are probably the result of the way in which indoor temperature is controlled.

The results shown in the paper suggest that guidelines for setting temperatures in mechanically conditioned dwellings may need to consider whether the advice given about temperatures in domestic buildings needs to be revised.

The implications of temperature variability in heated or cooled home for energy use in domestic buildings needs to be better understood. This is particularly important in light of the fact that domestic buildings are the biggest users of energy.

Acknowledgements
Thanks are due to all the researchers whose work has contributed to the insights in this paper, in particular to the group at the UCL energy institute. Thanks are particularly due to those who allowed me to use and interpret their valuable data in the paper, Dr Hom Rijal of the Tokyo City University for the Japanese data, Abdulrahman Alshaikh of Heriot Watt University for the data from Dammam and Galina Boroskowa for her remarkable data from Khabarovsk Russia.

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Exploring potentials and limitations of the adaptive thermal heat balance framework

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Abstract
Recently, a framework for an adaptive thermal heat balance (ATHB) model was presented with the objective to combine the adaptive comfort approach with existing heat balance models. This was done by setting up equations for each of the three adaptive processes (behavioural, physiological, and psychological) individually to modify the input values for the clothing level and metabolic rate of the PMV calculation. This paper explores the application of this framework to the SET model together with further potentials related to the implementation of psychological factors. Thereby, the predictive power of the implemented framework is tested against the performance of the PMV-model, modified PMV-models such as aPMV or ePMV, and modified SET-models using data from unpublished field studies in 2 naturally ventilated and 4 mixed mode office buildings. The results show, that the indices related to the ATHB approach outperform the other indices in terms of predicting thermal sensation. In addition, coefficients for psychological adaption showed a linear relationship with building characteristics and perceived control. The implementation of adjusted psychological coefficients further improved the performance. In conclusion, the results support the applicability of the adaptive thermal heat balance model to a broad context given additional studies supporting these findings.

Keywords: thermal sensation, field study, psychological adaptation, adaptive comfort

1 Introduction

Searching for methods to obtain a better prediction of thermal sensation, recent studies introduced variations and combinations of predicted mean vote (PMV) model (Fanger, 1970), standard effective temperature (SET) model (Gagge et al., 1986) and adaptive comfort model (de Dear et al., 1997, Humphreys and Nicol, 1998). The intention was to benefit from advantages of specific aspects of these three models in order to decrease the gap between predicted and observed sensation votes.

The first approach to be mentioned is the PMV model adjusted for the cooling effect of elevated air speeds using the SET-model as described in ASHRAE 55-2013. This index will be referred to in this paper as PMV_{adj}. The second approach is that of Yao et al. (2009) with the intention to combine PMV and adaptive comfort model through an adaptive coefficient, λ, leading to the aPMV index. The third approach is that of Fanger and Toftum (2002), who introduced the expectancy factor, e, which aims at accounting for differences between actual/observed sensation votes (ASV) and predicted sensation votes (PSV) by the PMV-model leading to ePMV. The fourth approach is that of Gao et al. (2015) who introduced the ePTS and aPTS indices, which are developed similar to aPMV and ePMV indices, but applied to the SET model. PTS thereby stands for predicted thermal sensation derived from SET. The fifth and last one is the framework for an adaptive thermal heat balance model (ATHB) introduced by Schweiker and Wagner (2015a). The ATHB was originally applied to the PMV model, so that this index will be referred to in this paper as $ATHB_{PMV}$. The ATHB approach aims at the combination of the adaptive approach with traditional comfort models. Therefore, a set of coefficients were defined with respect to the three adaptive principles, behavioural, physiological, and psychological. As a consequence, the ATHB allows the prediction of thermal sensation votes varying with the six classical indoor environmental and personal factors as well as the outdoor running mean temperature.

Despite their introduction and application to a limited number of samples, there is no comparison of the predictive performance of these indices with respect to thermal sensation votes of individual persons.

Therefore, this paper aims at

- evaluating the predictive power of each index based on field measurement data,
- assessing the impact of false assumptions of missing variables in the data sets from field studies, and
- evaluating the relationship between estimates for the coefficient related to psychological adaptation and building characteristics.

In addition, the ATHB framework will be applied to the SET model by Gagge et al. (1986), to form an additional index denoted as $ATHB_{PTS}$.

2 Methods

In the following, the methods used for this paper are described according to the background of the field studies forming the database used for this paper, the calculation procedure of thermal sensation indices, the evaluation criteria used to assess the performance of the indices, and the steps for the analysis of estimates for the coefficient for psychological adaptation.

2.1 Summary of field studies

Two datasets from different field study campaigns were combined for this paper.

The first and unpublished dataset originates from a field study conducted during summer 2011 in three office buildings situated within the centre of Karlsruhe, Germany. Two of the buildings were mixed mode buildings, where occupants could tilt or open the window at any time, while the supply air provided through the centralized ventilation system was cooled during summertime. The third building had no active cooling; occupants could control the indoor environment during summertime by tilting or opening the windows or closing blinds.

HOBO data loggers for air temperature and relative humidity were placed in each office two times for two weeks. In addition outdoor air temperature and relative humidity were measured with another HOBO data logger on the roof of each building.

Subjects were visited up to 4 times during each two week period. The number of votes obtained by each subject differs due to absence periods of subjects. During each visit, subjects were asked about their thermal sensation (7-point categorical scale) together with a set of additional questions not relevant for this paper. While the subjects answered the paper-pencil based questionnaire the investigator noted down the clothing level of each subject together with the state of windows, blinds, fans, and internal doors.

The second dataset originates from a field study conducted during summer 2012 in three office buildings situated in the Stuttgart area, Germany. The outline of this study was presented in detail by Hawighorst et al. (2015). Two of the buildings had no active cooling, but occupants could tilt or open the windows. The third building had thermal activated building components set to 20°C together with a ventilation system. Occupants could not control the set point temperatures for cooling, but open the windows up to an angle of 20°. Subjects were asked up to three times during a period of two weeks. The measuring equipment was the same as used in the 2011 campaign.

Written informed consent was obtained from the subjects in both studies.

In total, the combined data base consisted of 620 valid votes from 214 subjects. In total 32 votes had to be excluded due to missing data points or unrealistic values (e.g. an actual thermal sensation vote (ASV) of 6). The number of subjects and number of votes for each building are given in Table 1. Subjects were in average 41 years of age (range = 19 years to 64 years, standard deviation = 11.6), 172cm of height (range = 156 cm to 195 cm, standard deviation = 8.7), and 75 kg of weight (range = 48 kg to 140 kg, standard deviation = 16.8).

Table 1. Number of subjects and votes for each building.

Building	N (Subjects)	N (votes)
1	32	51
2	19	59
3	59	155
4	32	175
5	22	130
6	50	50
Total	214	620

2.2 Calculation of thermal sensation indices

In total 8 thermal sensation indices were calculated based on the data obtained through the field studies as shown in Table 2 and described in detail as follows. The calculation was performed using statistical software R (R Development Core Team, 2012).

In case, the resulting value of the predicted sensation votes had to be binned for the following steps, this was done by cutting the continuous data into 7 bins with values ≤ -2.5 binned as -3, values > -2.5 and ≤ -1.5 binned as -2, and so on.

Table 2. Acronyms, descriptions, sources and required parameters for calculated thermal sensation indices

Indices acronym	Indices description	Source(s)	Required parameters*
PMV	Predicted mean vote	Fanger (1970), ASHRAE (2013)	Tair, Trad, Rh, Av, MET, CLO
PMV_{adj}	PMV adjusted for cooling effect of elevated air speed using SET	ASHRAE (2013)	Tair, Trad, Rh, Av, MET, CLO
aPMV	PMV extended with adaptive factor	Yao et al. (2009)	Tair, Trad, Rh, Av, MET, CLO, λ_{PMV}, ASV
ePMV	PMV extended with expectancy factor	Fanger and Toftum (2002)	Tair, Trad, Rh, Av, MET, CLO, e_{PMV}, ASV
$ATHB_{PMV}$	Adaptive thermal heat balance indices applied to PMV	Schweiker and Wagner (2015a)	Tair, Trad, Rh, Av, MET, Trm, PSYCH
aPTS	Predicted thermal sensation calculated based on SET model extended by adaptive factor	Gao et al. (2015)	Tair, Trad, Rh, Av, MET, CLO, λ_{PTS}, ASV
ePTS	Predicted thermal sensation calculated based on SET model extended by expectancy factor	Gao et al. (2015)	Tair, Trad, Rh, Av, MET, CLO, e_{PTS}, ASV
$ATHB_{PTS}$	Adaptive thermal heat balance indices applied to SET model	This paper	Tair, Trad, Rh, Av, MET, Trm, PSYCH

* Tair = indoor air temperature, Trad = indorr radiant temperature, Rh = indoor relative humidity, Av = indoor air velocity, MET = metabolic rate of person, CLO, clothing insulation level of person, TRM = running mean outdoor temperature, λ_{PMV}/e_{PMV}/λ_{PTS}/e_{PTS}/PSYCH = coefficients for specific models (see description below), ASV = actual sensation vote.

PMV and PMVadj were calculated according to the code given in the appendices of ASHRAE 55-2013.

For the calculation of aPMV, λ_{PMV} had to be derived based on the existing data. Therefore, first the standard PMV was calculated based on the physical and personal data related to each obtained ASV. Then λ_{PMV} was calculated using ASV and PMV according to the formula given in Yao et al. (2009) and Gao et al. (2015). It should be noted here, that a) one needs to discard all votes either having an ASV or a PMV of 0, as the required calculation of 1/AMV or 1/PMV would lead to 1/0, which is not valid, and b) at least for this dataset with categorical ASV, only reasonable values for λ_{PMV} (and for the resulting aPMV) were obtained, when the PMV values were binned prior to the calculation of λ_{PMV}. With respect to a) this lead to the omission of 243 out of 620 votes for the calculation of λ_{PMV}. Once λ_{PMV} was obtained, aPMV = PMV / (1 + λ_{PMV} * PMV).

Before ePMV can be calculated, the expectancy factor e_{PMV} had to be obtained first. According to the information given by Fanger and Toftum (2002) in combination to that given by Gao et al. (2015), this is done by calculating the standard PMV based on physical and personal data related to each ASV with an adjusted metabolic rate depending on the ASV (if ASV>0, then MET = MET * (1 - .67 * ASV)). The resulting PMV-values are then used to calculate the value of e_{PMV} for the particular dataset according to Gao et al. (2015) and finally calculating ePMV = e_{PMV} * PMV. It should be noted here, that both binned and non-binned PMV values lead to reasonable values of e_{PMV} and the resulting ePMV. For consistency and due to the evaluation results being better, the binned PMV-values were used for this study to obtain e_{PMV}.

$ATHB_{PMV}$ was calculated according to Schweiker and Wagner (2015a). This means, that standard PMV-values were calculated with the input parameters of Tair, Trad, Rh, Av as in the database or assumed (see 2.3), but modified input values for MET and CLO. The assumed value of MET was adjusted according to physiological and psychological adaptation. The adjustment due to physiological adaption is based on the running mean outdoor temperature. The adjustment due to psychological adaptation is based on a) a variable part depending on the indoor operative temperature and b) a fixed part depending e.g. on properties of the building affecting the perceived control of the occupants. For the first part of the analysis, the fixed part of the psychological adaptation was assumed to be 0. The value for CLO was calculated based on the running mean outdoor temperature as given in Schweiker and Wagner (2015a). It should be highlighted here, that a) the coefficients used to calculate the adjusted values for MET and CLO were taken from Schweiker and Wagner (2015a) and neither adjusted nor calibrated to this dataset, and b) the CLO values used as input values for the PMV calculation were not the actual CLO values included in the database (obtained by the researcher), but calculated based on the running mean outdoor temperature as described in Schweiker and Wagner (2015a).

aPTS and ePTS were calculated according to the procedure described for aPMV and ePMV except that instead of using the PMV model, the SET model was considered for calculation of λ_{PTS} and e_{PTS}. The same notes as above apply also here. The values of PTS were obtained through .25*SET - 6.03 as given in McIntyre (1980) and also presented in Gao et al. (2015).

Finally $ATHB_{PTS}$ was calculated according to the procedure described for $ATHB_{PMV}$. Instead of applying the modified input parameters for MET and CLO to the calculation of PMV, they were applied to the calculation of SET/ PTS as described in Gagge et al. (1986).

2.3 Assumptions for missing data points

According to the classification given in de Dear et al. (1997), both field studies would be classified between Class III and Class II. In line with the requirements for Class II, measurements were obtained at the same time and place as the questionnaires were given to the subjects and on one height. However, not all variables were obtained: the metabolic rate and air velocity were missing and only the air temperature was collected. Therefore, the following three assumptions were made:

1) The radiant temperature was assumed to be equal to the air temperature obtained by the HOBO data loggers, because there were no radiant cooling devices, at least double glazed windows and the knowledge that the temperature value given by the HOBO data loggers is already affected by the radiant environment.
2) Metabolic rate was assumed to be 1.1 MET, which is in line with the value given in ASHRAE 55-2013) for typing. It differs slightly from the values given in DIN EN 15251 (2012) and DIN EN ISO 7730 (2006) for general office work (1.2 MET), and the values for reading/ writing (1.0 MET) and filing (1.2 MET) in ASHRAE 55-2013.
3) Air velocity was assumed based on the state of windows, internal doors, and pedestal fans according to Table 3.

Table 3. Assumptions of air velocity related to window, door, and fan states

Window	Door	Fan	Assumed value for air velocity
Closed	Closed	Off	.05
Opened	Closed	Off	.15
Opened	Opened	Off	.2
-*	-*	On	.3

* in case a fan was switched on, window and door states were neglected

2.4 Calculation of evaluation parameters

Two different evaluation parameters were calculated in order to compare the predicted sensation vote (PSV) by each of the 8 indices to the actual sensation votes (ASV).

The first one, the mean bias, is based on the analysis by Humphreys and Nicol (2002). This is calculated according to

$$meanBIAS_j = mean(PSV_{j,i} - ASV_i) \quad (1),$$

with j denoting the thermal sensation indices and i the individual vote.

The second one, the true positive rate (TPR), is based on Schweiker and Wagner (2015a) and presents the proportion of the true predicted cases, where the ASV vote is equal to the binned PSV and calculated according to

$$TPR_j = \frac{\sum_{i=1}^{k} TP_k}{n} \quad (2),$$

with j denoting the thermal sensation indices, k the category of the sensation scale (e.g. cold), n the total number of votes, and TP those cases, where the binned PSV is equal to the ASV.

2.5 Evaluation of the effect of false assumptions on outcome

In order to evaluate how assumptions 2 and 3 described in section 2.3 affect the results, the values for meanBIAS and TPR were calculated for all thermal sensation indices and all combinations of air velocity being a) 0.01 at each vote, b) 0.1 at each vote, c) 0.2 at each vote, or d) as assumed above, and metabolic rate being A) 1.0 MET, B) 1.1 MET (as assumed above), or C) 1.2 MET. I.e. the values of all 8 thermal sensation indices were calculated for all votes in total 12 times.

2.6 Analysis of the adaptive coefficient related to psychological adaption for each building

According to Schweiker and Wagner (2015a) the fixed part of psychological adaptation can be calculated according to

$$MET_{\text{constant psychological adaptation}} = g = PSYCH * (-.55) * .092 \quad (3).$$

In their example, they related PSYCH to the mean of obtained perceived control votes of a group of occupants. For this study a different approach was chosen. In order to obtain a specific value of PSYCH for each building under investigation, first, $ATHB_{PMV}$ and $ATHB_{PTS}$ were calculated for each vote using for PSYCH all integers between -3 and +3. Then, for each building (1-6) and each index ($ATHB_{PMV}$ and $ATHB_{PTS}$), the value of PSYCH was chosen, which lead to the lowest meanBIAS and highest TPR, i.e. the best fit between predicted and actual sensation vote. In case the lowest meanBIAS and highest TPR were associated with different values for PSYCH, the value of PSYCH leading to the highest TPR was chosen.

The values of PSYCH for each building were then applied to the calculation of $ATHB_{PMV}$ and $ATHB_{PTS}$ in order to derive meanBIAS and TPR for the whole dataset.

3 Results and discussion

3.1 Evaluation of thermal sensation indices based on initial assumptions

Mean and standard error of the bias between PSV and ASV are shown in Figure 1. Among those thermal sensation indices based on the PMV-model, ePMV had the smallest mean bias. Among those based on the SET-model and among all indices, $ATHB_{PTS}$ had the smallest absolute mean bias. This showed that the $ATHB_{PTS}$ predicted the thermal sensation of occupants under real office conditions in a German setting with the smallest difference. In this context, it is noteworthy, that ePMV, aPMV, ePTS, and aPTS were calibrated to the existing dataset while neither of the two ATHB indices was adjusted to the existing dataset. In addition, for all indices but the ATHB indices, the observed clothing values were used as input to the calculation. For the ATHB indices, estimated clothing levels were based on the running mean outdoor temperature. This signifies that using the ATHB models a prediction of individual thermal sensation is possible without the necessity of obtaining actual CLO-values.

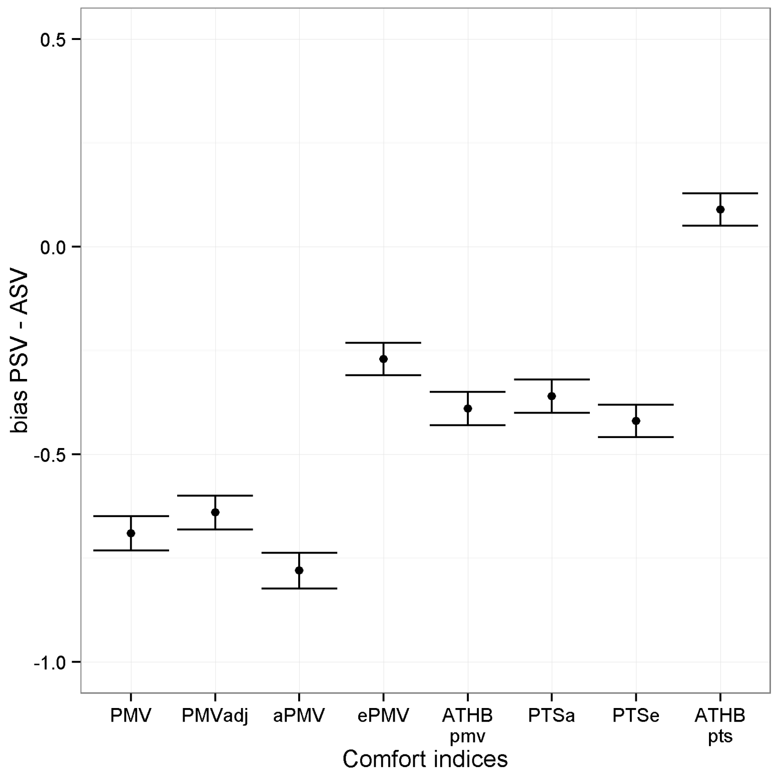

Figure 1. Mean and standard error of the bias between ASV and PSV over all data points using initial assumption for the metabolic rate and air velocity described in section 2.3.

Figure 2 is presenting the TPR for all indices. In this case, the $ATHB_{PMV}$ had the highest TPR among the PMV-based indices, while the $ATHB_{PTS}$ had the overall highest TPR with a value of 48%. This means that nearly half of the actual sensation votes were predicted correct. In comparison, the original PMV model predicted less than a third (30%) of actual sensation votes correct.

Even though, the $ATHB_{PTS}$ had the best performance in terms of mean bias and TPR, especially the TPR showed that there is still a need for further improvements. A TPR of 48% tells us that still more than half of the votes were not predicted correct. On the one hand, this could be related to the quality of the PMV/SET model on which the ATHB approach is based so far. In the next step, the combination of the ATHB approach with the biophysiological approach presented in Kigma et al. (these conference proceedings) should be tested with respect to this question. On the other hand, additional factors must play a role leading to such differences in individual votes. The search for these factors is still to be faced in future studies (see also Shipworth et al. in conference proceedings).

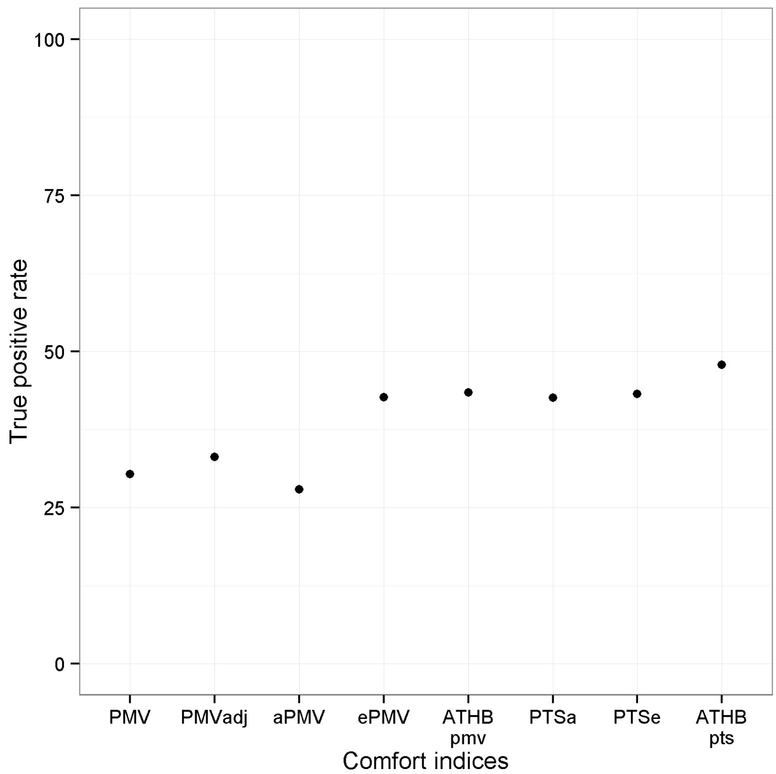

Figure 2. True positive rates over all data points using 1.1 MET as assumption for the metabolic rate and the assumptions for air velocity based on window, door, and fan state (see Table 3).

3.2 Evaluation of false assumptions

The results presented in section 3.1 were based on the assumptions for air velocity and metabolic rate described in section 2.3. However, these assumptions could be inaccurate and results different when using other assumptions.

Table 4 shows the minimum absolute value of the mean bias (together with its sign) and the maximum TPR obtained through one of the 12 combinations of assumptions tested. In this case, the $ATHB_{PMV}$ had the best evaluation values in both categories among all thermal sensation indices with a minimum mean bias of -.011 and a maximum TPR of 48.9.

Figures 3 and 4 show the mean bias and TPR for each thermal sensation indices and each combination of assumptions related to metabolic rate and air velocity. The comparison of both figures showed, that e.g. for $ATHB_{PMV}$ (as for most others) the minimum mean bias and the maximum TPR were not obtained by the same combination of assumptions. Additional findings among others were:

- The mean bias got smaller with increasing assumed metabolic rates for most thermal sensation indices. However, for $ATHB_{PTS}$, the minimum values were related to a metabolic rate of 1.1 MET.
- The mean bias was higher with increased assumptions for air velocities, except for the ePMV index.
- TPR increased with increasing assumed metabolic rates for all indices but ePMV and $ATHB_{PTS}$.
- TPR decreased with higher assumed air velocities for all but ePMV and $ATHB_{PTS}$.

Summing up, the assumptions made do have a significant effect on the performance of the indices. However, the ranking between the indices was less affected. Overall, the best performing indices related to the mean bias were $ATHB_{PMV}$, PTSa and $ATHB_{PTS}$ and related to TPR these were $ATHB_{PMV}$ and $ATHB_{PTS}$. Within each combination of assumption, the best ranking indices related to the mean bias were 2 times the ePMV and 10 times the $ATHB_{PTS}$. With respect to the TPR, these were six times the $ATHB_{PMV}$ and the other 6 times the $ATHB_{PTS}$.

Table 4. Minimum absolute value of mean bias and maximum TPR among 12 combinations of assumptions for metabolic rate and air velocity for each thermal sensation indices

Thermal sensation indices	Minimum absolute value of mean bias	Maximum TPR
PMV	-.19	44.5
PMV_{adj}	-.23	44.2
aPMV	-.17	44.2
ePMV	-.12	44.0
$ATHB_{PMV}$	-.011	48.9
PTSa	.032	45.5
PTSe	-.25	44.0
$ATHB_{PTS}$	-.072	48.1

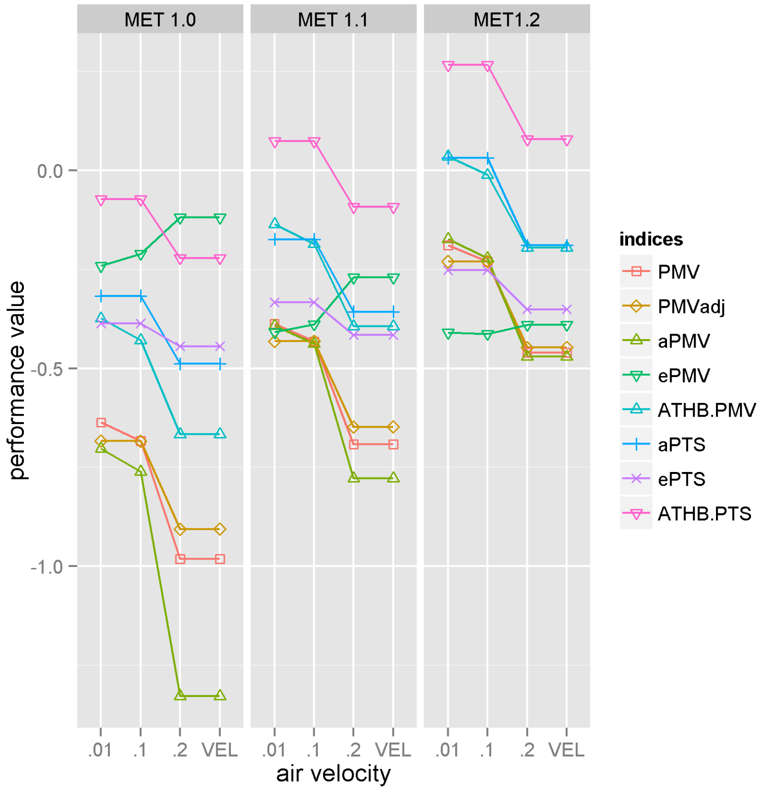

Figure 3. Mean bias for each thermal sensation indices and each combination of assumption for metabolic rate and air velocity. VEL is the assumption for air velocity as presented in Table 3.

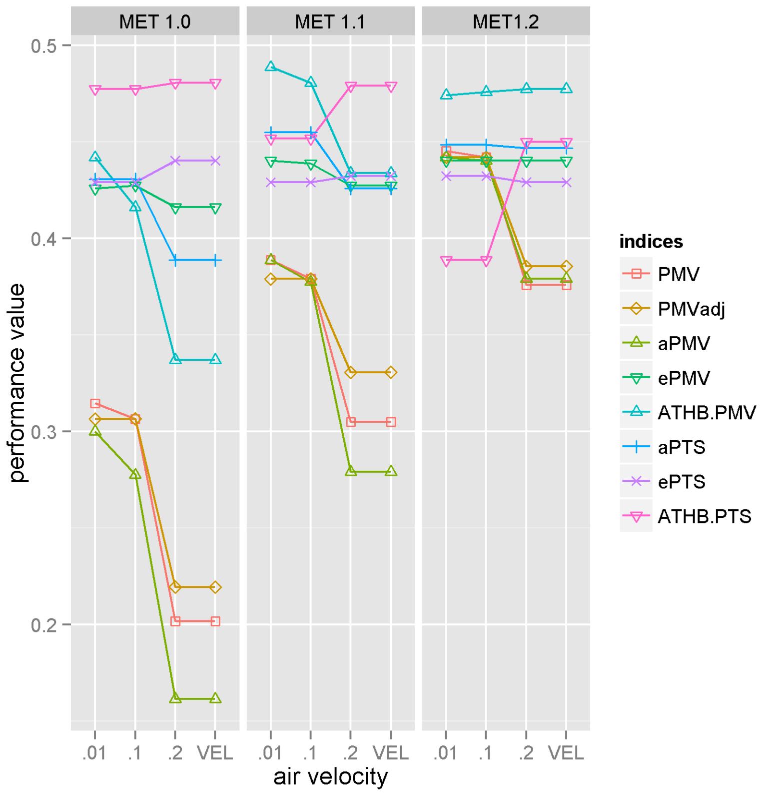

Figure 4. TPR for each thermal sensation indices and each combination of assumption for metabolic rate and air velocity. VEL is the assumption for air velocity as described in Table 3.

3.3 Relationship between the coefficient of psychological adaption and building characteristics

Within the framework of the adaptive thermal heat balance model, the coefficient related to psychological adaption, PSYCH, introduced by Schweiker and Wagner (2015a) can be used as a mean to adjust predicted thermal sensation votes according to specific characteristics of a building. Table 5 presents the values for PSYCH between -3 and +3 leading to the highest TPR for $ATHB_{PMV}$ and $ATHB_{PTS}$. Thereby, a lower value of PSYCH signifies that warmer conditions are still evaluated as cooler (i.e. closer to neutral on the sensation scale) compared to a higher value of PSYCH.

Even though general conclusions need to be made with great care due to the small sample size of six buildings, the following observations were made:

- All three naturally ventilated buildings (NV) had negative values for PSYCH, while the mixed mode and air-conditioned buildings had positive values. This confirmed findings related to the adaptive comfort model by de Dear et al. (1997) signifying that people in naturally ventilated buildings accept higher indoor temperatures compared to those in conditioned buildings.
- Among the three NV buildings, and related to $ATHB_{PMV}$, the value for PSYCH decreased with a smaller office size (number of persons per office). This supports the findings e.g. of Schweiker and Wagner (2015b) made under experimental conditions, that a higher number of persons in the office decreases thermal satisfaction. However, no such distinction was found with respect to $ATHB_{PTS}$.
- There were strong and medium linear relationships between PSYCH and the actual mean perceived control for the three buildings this question was included in the questionnaire. The correlation coefficient (Pearson-r) between PSYCH and mean perceived control was - .91 for $ATHB_{PMV}$ and -.73 for $ATHB_{PTS}$. This supports the observed relationship between perceived control and subjective evaluation of the thermal indoor environment presented by Brager et al. (2004) as well as Schweiker and Wagner (2015a).

Table 5. HVAC type, office size, PSYCH leading to highest TPR, and observed mean perceived control for each building

Geb	HVAC type	Office size [people]	PSYCH for ATHB.pmv	PSYCH for ATHB.pts	Mean perceived control
1	NV	2-4	-3	-1	3.56
2	NV	2-5	-2	-1	Not assessed
3	NV	2-10	-1	-1	2.68
4	Mixed mode	2-4	0	2	Not assessed
5	Mixed mode	2-4	0	3	Not assessed
6	AC + windows 20°	2-4	3	3	2.30

When applying the values for PSYCH presented in Table 5 to the calculation of $ATHB_{PMV}$ and $ATHB_{SET}$, the values for the evaluation criteria as presented in Table 4, Figures 3 and 4 further improved except for the minimum mean bias of $ATHB_{PMV}$ as shown in Table 6. This signifies that the consideration of differences in the psychological adaptation between building types further improved the predictive accuracy of individual thermal sensation votes.

Table 6. Minimum absolute value of mean bias and maximum TPR among 12 combinations of assumptions for metabolic rate and air velocity for the two ATHB indices considering building specific coefficients for PSYCH

Thermal sensation indices	Minimum absolute value of mean bias	Maximum TPR
$ATHB_{PMV}$	.059	50.4
$ATHB_{PTS}$	-.0014	50.3

3.4 General discussion

The results presented above signify that the ATHB-indices, especially the $ATHB_{PTS}$ index, enable a better prediction of thermal sensation votes compared to other previously published indices. Nevertheless, this statement needs to be limited to the dataset used for this paper, which is rather small e.g. compared to the huge amount of data points on which the PMV-model was evaluated in the past. At the same time, compared to ePMV, aPMV, PTSe, and PTSa, the ATHB indices were not calibrated to the dataset, but still derived within the same cultural and climatic context. Still, the potential of such holistic approach is visible. The ATHB-indices perform better on the existing dataset without the need to be calibrated to it, which is an advantage over e.g. ePMV and aPMV.

The framework of the ATHB model offers several elements through which it could be further calibrated to the context. These are the coefficients related to the adaptive processes as presented by Schweiker and Wagner (2015a). The potential of one of those coefficients, the one for the fixed part of psychological adaptation, PSYCH, was demonstrated in this paper. Two aspects related to these adaptive coefficients require further discussion.

On the one hand, it is reasonable to assume, that also the other coefficients, namely the ones related to the variable part of psychological adaptation, behavioural adaptation, and physiological adaptation, would need to be adjusted for a given cultural and building characteristics related context. Such analyses are beyond the scope of this paper and need to be done in future studies.

On the other hand is the question about the applicability to everyday building design practice. So far, there are only two examples for variations in the adaptive coefficients given. With an increased number of studies repeating the approach presented here and analysing those values for these coefficients leading to the best predictive performance, we assume, that it will be possible in the future to define a set of coefficients applicable to specific building related and cultural related contexts. In the design phase of a construction or restauration project, these coefficients could be used when evaluating results obtained by simulations of building indoor environmental quality and energy performance. Despite evaluating each design alternative using the same boundaries for thermal acceptable conditions, designers would be enabled to use e.g. one value for PSYCH for the alternative being a mixed mode building and another value for the naturally ventilated alternative. This way, the predicted energy use will depend even more on the chosen design alternative. The selection of a suitable value for the coefficients could be implemented directly into the source code of a given building energy performance software together with a set of rules and/or left to the decision of the engineer.

4 Conclusions

In order to evaluate the predictive performance of 8 thermal sensation indices, their values for a dataset of 620 sensation votes from 6 office buildings in Germany were calculated. These predicted sensation votes (PTS) were than compared to the actual sensation votes (ASV) through the mean bias and true positive rate. Among the 8 indices, the ATHB indices either based on Fanger's PMV ($ATHB_{PMV}$) or Gagge's SET ($ATHB_{PTS}$) performed best.

This result was valid for 10 out of the 12 tested combinations with respect to assumed air velocity and metabolic rate. In the other two cases, the ePMV index performed better.

Through the estimation of individual psychological adaptation coefficients included in the ATHB approach, there was a strong relationship between the type of building, the mean perceived control and the value of the corresponding coefficient. Using these coefficients to calculate $ATHB_{PMV}$ and $ATHB_{PTS,}$ the mean bias decreased and the true positive rate increased.

The results show that the ATHB approach is performing better than other indices. However, the increase in predicted performance is not a quantum jump, as the TPR is still around 50%, i.e. rather low. Nevertheless, compared to the other indices, the ATHB approach already includes the potential to implement further individual and/ or building related differences in behavioural, physiological, and/ or psychological adaptive processes. As for the individual differences, further understanding is required e.g. to which extend individual perceived control affects thermal sensation.

In conclusion, the first application and evaluation of the ATHB approach to field data showed its advantage compared to other sensation indices. Future analyses are necessary in order to support or reject these findings and to determine reliable values for the adaptive coefficients related to distinctive contexts with respect to building characteristics and cultural aspects. A set of coefficients for specific cultural, climatic, or building related context would enable a designer to evaluate design alternatives more realistically in terms of how a specific characteristic, e.g. an operable window, would influence the requirements for thermal indoor environmental conditions together with the resulting predicted energy use.

Acknowledgements

This work was conducted within the framework of the WIN-Kolleg (Junior Academy for Young Scholars and Scientists) project "Thermal comfort and pain" of the Heidelberg Academy of Sciences and Humanities. The data collection was partly funded by the German Federal Ministry of Economics and Technology (BMWi) with the project ID: 0327241D and partly financed within the Eliteprogramme for Postdocs of the Baden-Württemberg Stiftung.

Special thanks go to Jie Gao for the valuable feedback with respect to calculation methods for the adaptive coefficient, λ, and the expectancy factor, e. Special thanks go to Maren Hawighorst for the permission to use the data collected during the second field campaign.

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SESSION 2

People, Behaviours and Ageing

Invited Chairs: Edward Ng and Fionn Stevenson

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Putting thermal comfort in its place

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Abstract
Much research into thermal comfort has treated the subject in relative isolation – as a single outcome for individual persons. This paper seeks to extend the way in which research is now moving on, by considering comfort not simply as the thermal state of individuals but in terms of the actions of groups of individuals, in the context of conflicting needs. It begins from the perspective of why and how people use energy for heating their homes. It explores the various needs and household-level dynamics that drive such energy use. These factors were investigated through qualitative research and a quantitative social survey of 2,313 British households. The needs are not simply about individual thermal comfort but relate to five factors, here labelled *Hygiene*, *Ease, Resource, Other people* and *Comfort* (not only thermal comfort),. These factors discriminate among population groups in a way that can be used to inform the design and implementation of heating arrangements for homes.

Keywords: comfort, heating, energy, residential buildings, user needs

1 Introduction
Future home heating will deploy new technologies and business models and will potentially feature different consumer involvement in the provision and management of energy-based services. It is therefore important to develop a clear understanding of consumer requirements and preferences, and build these into the design of home heating and energy supply services. One key consideration is the thermal comfort of the occupants of buildings. However, contrary to much of the relevant research, thermal comfort should not be considered in isolation. In the extreme, research has entailed detailed laboratory analysis of non-interacting human subjects, studying the impact of hygrothermal parameters, clothing insulation and metabolic rate, with a single subjective comfort rating as the dependent variable. Even field studies exploring the adaptive approach have often seen comfort as a single outcome for individual persons. Together, these approaches have predicted comfort sufficiently for the design and management of buildings, even if practice has not always achieved the theoretically possible levels of comfort.

This paper seeks to extend the way in which research is now moving on, by considering comfort not simply as the thermal state of individuals but in terms of the actions of groups of individuals, in the context of conflicting needs. The assumption is that what people do in relation to heating the home is related to a set of needs that underlie their use of the home – not just their use of heating. The research therefore begins from the perspective of why and how households use energy for heating. It explores the needs that drive such energy use and the household-level dynamics that determine how needs are prioritised and actions taken.

This distinguishes the work from much other research that aims to inform the design of heating-related technology and practice – research that takes the physical characteristics of the property as its starting point. The rationale for this is understandable: the characteristics of a property (e.g. age, size, heating system and insulation) set the boundaries of what is possible for people to do when trying to heat their home and keep warm. However, it is essential to understand not only what constrains and enables heat energy behaviour, but the underlying goals and motivations that drive and structure their behaviour – including both conscious decisions and the routines and habits that form much of domestic heating behaviour. To design sustainable heating solutions it will be crucial to understand the basic and more complex human needs for heat energy, not just how we currently interact with it. Without this understanding of consumer requirements, future heating solutions could be technically sound but not meet the needs of different types of household.

The new research adopts a broad definition of "needs" (based on Raw *et al*, 2010) to capture the full range and diversity of people's goals when using energy: anything that people are aiming to achieve through, or what they achieve as a consequence of, using energy. This definition encompasses a wide range of needs, from those objectively essential for life, to preferences based on individual perceived requirements or values. The analysis presented here takes this forward by seeking to understand the different types and roles of needs, and how individual needs may be characterised in terms of underlying dimensions that can inform the design and implementation of home heating.

2 Method

2.1 Survey sample

The study comprised a quantitative social survey of 2313 households, which took place in January-February 2014, using quota sampling to generate a nationally representative sample of British households. Quota sampling involves issuing interviewers with a set of quota characteristics (tenure, property type and the presence of children in this case) and a corresponding number of interviews to be achieved in each category of each characteristic. Its aim is to achieve a representative sample by reflecting the demographic make-up of the areas where interviews are sought. Because quota sampling does not use only random sampling, it is not possible to determine the exact representativeness of a sample, in particular due to the risk of sampling bias during respondent selection.

A total of 250 sample points (COAs – Census Output Areas – containing an average of 300 addresses and derived from the 2011 Census) were randomly selected, covering England, Scotland and Wales. COAs were stratified by Government Office Region (GOR) and a household-level socio-economic indicator – the social grade of household reference person (% Grade A or B). Sampling units were selected proportionate to the numbers of households within each GOR.

Interviewers were issued quotas of 10 interviews in binary categories: owner vs renter, house/bungalow vs flat/maisonette, children (aged under 18) vs no children. These quotas were selected because a literature review (extending earlier reviews, principally Raw & Ross, 2011) and qualitative research (reported in summary by Lipson, 2015) showed them to be closely linked to heat energy needs and behaviours. The quotas numerically reflected sampling unit characteristics (for instance, if, in a given sampling unit, 40% of addresses are owner-occupied, we issued a tenure-based quota of 4 owner-occupied and 6 rented addresses). The achieved sample (see Table 1) closely represented the population on the three issued quotas and patterns of other characteristics (such as age of property and size of household).

Table 1. Quota characteristics

Quota criterion	*Quota group*	*Achieved interviews (%)*
Tenure	Owns home	65
	Rents home	35
Dwelling type	House/bungalow	78
	Flat/maisonette	21
Presence of children (under 18)	Yes	32
	No	68

The sample was based upon household, rather than individual, characteristics because the primary aim was to collect data from individual respondents but relating to their household. For this reason, and to avoid selection bias with regard to knowledge of heat energy in the household, there was no systematic respondent selection within households with regard to, for example, who pays the energy bills, who makes more of the energy decisions or who spends most time at home. Interviewers were asked to interview anyone aged over 18 living at the address without selecting (or encouraging self-selection) on the basis of how householders saw their role in relation to energy (although this role was recorded during the interview).

2.2 Data collection

The questionnaire design process was iterative and involved extensive collaboration across the research consortium. The earlier qualitative research provided considerable learning about the terminology used by the public to discuss heat energy needs and behaviours, which informed the design of survey questions. The full questionnaire was field piloted and certain elements (including measurement of heat energy needs) were subject to cognitive testing and redesign.

Respondents in the survey completed a face-to-face computer-assisted personal interview (CAPI) that lasted around 60 minutes, in which they were asked questions relating to household and dwelling demographics, facilities and household behaviour in relation to heating, cooling and hot water, and paying for heat energy. Where respondents consented (89% of cases), interviewers conducted observations of heating and hot water systems. Respondents were given a paper self-completion questionnaire (covering mainly their recent and desired renovation activities); this was returned by 78% of respondents.

Respondents were also asked to complete card-sort exercises in which they organised a range of pre-defined heat energy needs according to the degree of influence on their heat energy behaviour, first in relation to (space) heating and keeping warm, then heating water and using hot water, and – if mechanical cooling or ventilation was in use – cooling the home and keeping cool. The items on the cards were informed heavily by the literature review and qualitative research. This paper focuses on the card-sort relating to heating and keeping warm; the 21 card headings and examples are shown in Table 2. The same headings, with different examples, were used in the other two card-sorts.

The shuffled cards were given to the respondent, who was asked to sort them into three piles according to whether each was a 'Big Factor', 'Smaller Factor' or 'Not a Factor' in relation to heating and keeping warm. These factors were explained to respondents thus: big factors are *very important in influencing what you do*; smaller factors are *less important but still influence what you do to some extent*; "not a factor" means that *something that does not influence what you do or something that is not relevant to you or your current situation*. The task overall was explained as follows (the wording was adapted for single-person households).

> *You told me earlier some of the things you and your household do to heat the home and keep yourselves warm – including {examples based on responses to earlier questions}.*
>
> *Different people and households take into account different kinds of need as they decide how to heat the home and keep warm. I would like you to tell me what is important to you and your household, using these cards. Each card has on it a factor that might influence how a household decides to heat the home and keep warm. Some of the factors will probably not seem relevant to you or your household in your current home, in which case you can just tell me that.*
>
> *The cards show the basic factor or need that you could be thinking about – in the bold headings – and have some examples of how each factor could influence how you and your household decide how to heat the home and keep warm. These examples are included to explain some particular ways in which the factors might influence what you do. If you feel that the need could influence what you do, it doesn't matter if some or all of the examples are not relevant to you – just think about things that are relevant and focus on the basic need that you are trying to meet.*

We wanted households to consider all their relevant behaviours when they were asked about which needs they were trying to meet. For this reason, the three card-sorts were all conducted after first asking detailed questions about behaviours in the three domains: heating the home and keeping warm; cooling the home and keeping cool; and heating water and using hot water (always in this same order). The intention was that their full range of behaviours should be "top of mind" while sorting needs, increasing the likelihood of respondents taking all relevant issues into account.

There are potential risks to keeping the questionnaire sequence the same for all respondents, in that the first card-sort may influence respondents' choices in subsequent sorts. However, the focus of our analysis here is on the card-sort relating to heating the home, which was completed first. Had we randomised the order of the sorts, the effects of this on the heating the home exercise would have been unpredictable, weakening the analysis of this set of data. The sequence eliminates risk of the card-sorts progressively influencing responses to other questions; it is also quicker and easier for respondents and interviewers; and makes it clearer to respondents how the three sorts differ from each other.

A further set of questions addressed household dynamics more directly. Heating is not necessarily decided by a single individual – it could depend to a greater or lesser extent on any or all members of the household, depending (for example) on the overall household dynamics and who is at home at any given time. The qualitative research suggested the existence of three types of household dynamics:

- "YOU" – heating is operated according to the needs of one or more individuals, such as a young child or elderly person;
- "ME" – individuals decide independently to operate the heating according to their own needs;
- "US" – there is some degree of consensus or cooperation around heating decisions.

In the interviews, a series of questions sought to assign households to one of these types (single-person households were automatically placed in a fourth "JUST ME" group). The first question asked how the household (if more than one person) decides about heating. Answer options were classified as follows.

- *It's largely down to one person* (ME).
- *It's mainly to care for someone who needs to keep warm or cool, for example because of a health condition or age* (YOU).
- *It varies – depending on whose needs are greatest at the time* / *It depends more-or-less equally on the needs of everyone who is at home at the time* (US).

Any respondent who answered *It depends on the needs of the person deciding at the time how to heat the home* or *Everyone has a say but one or more people's needs have a greater influence than others* was asked how much influence s/he personally has over decisions about heating. Responses were classified as follows.

- *I tend to have the most influence* / *Someone else tends to have the most influence* / *Nobody – we all make decisions about it separately* (ME);
- *It varies – different people influence decisions about the heating at different times* / *We decide together* (US).

2.3 Data preparation and analysis

Because the achieved sample closely matched the population on a range of characteristics, the findings presented here are based on unweighted data. "Don't know" and "Refusal" responses are included in bases because they can be relevant responses when measuring behaviour, perceptions and needs (e.g. to identify respondents who are unclear about what their needs or usual behaviour are). Some secondary variables were derived by aggregating levels of a variable (e.g. to assign to income quartiles) and/or by combining more than one variable. These derived variables were defined by examination of frequency distributions (e.g. to merge small groups) and the logic of combining particular groups.

Analysis has so far focused on descriptive and bivariate analysis (using the statistical package SPSS), which is a logical starting point for understanding the data and the most relevant variables, but multivariate analysis will be required to gain a more complete understanding of the findings and implications. Principal components analysis (PCA) was also undertaken, to identify whether the 21 needs related to heating the home and keeping warm could be reduced to a smaller number of dimensions. PCA is designed to identify, where they exist, underlying unobservable dimensions based upon the associations between variables measured using an identical scale. While interpretation of results is partly subjective, and cannot identify causality, it can be a powerful way of identifying fundamental drivers of behaviour.

The PCA used a set of 21 binary variables: whether or not a respondent categorised each need as a “big factor” in the card-sort for heating the home and keeping warm. A correlation matrix of the 21 variables was examined to check for (a) sufficient correlation that the existence of a smaller number of underlying dimensions incorporating all variables would be a valid possibility and (b) multi co-linearity (two or more variables being very highly or entirely correlated) which would suggest they were measuring the same variable, invalidating the assumptions of PCA. The variables were found to be suitable for PCA.

3 Results

3.1 Heat energy needs

The card-sort was completed by 2,287 respondents, who identified a mean of 9.4 big factors, a mean of 5.5 as small factors and a mean of 5.3 as not a factor. Therefore, British households report that they are trying to meet a large number of needs when heating the home; this needs to be understood when proposing alternative ways of heating the home and keeping warm. Further analysis focuses on the binary variable of whether or not a need is categorised as a big factor; this was because:

- having more than two groups in further analysis would sometimes require arbitrary assignment of numerical values to big factors, small factors and not a factor;
- the number of big factors typically selected suggests that the small factors were genuinely small;
- the frequency distribution of big factors is close to normal and indicates that this measure is closest to providing an even split of the sample;
- follow-up questions, seeking to divide the big factors into two groups, reduced the potential for including all needs in further analysis.

Using big factors as the principal outcome allows further analysis to account for diversity in numbers of heat energy needs reported by different households. It also ensures that any underlying dimensions identified do not over-simplify a complex picture. All the needs were identified as big factors by a proportion of respondents. If far fewer needs had been identified as big factors, it might have been necessary to include needs identified as small factors. However, the statistics indicate that the big factors are sufficient for the task and we therefore concentrate on these.

The number of needs categorised as big factors ranged from zero (1.4% of households) to 21 (0.2%) with 6% or more selecting each number of needs from 5 to 12. The mode was 10 needs, selected by 10.3% of respondents. The prevalence of the particular 21 heat energy needs selected as big factors varies substantially – see Table 2.

More than two-thirds of households identified five particular heat energy needs as big factors: being comfortable, energy costs, avoiding wasting energy, being able to rest and relax, and wanting to feel clean. This supports the findings of the earlier qualitative research, which argued that comfort and energy costs were primary needs when heating the home for all types of households and that other needs were not considered substantially until these needs had been met. The qualitative research also identified health as a primary need; the survey findings confirm that it is important although in sixth place behind the needs mentioned above (most likely because it is a met need in most cases).

Table 2. Prevalence (%) of needs (big factors for heating the home and keeping warm)

Heading	*Examples*	*%*
Being comfortable		85
Energy costs	Not spending more than is necessary. Keeping the cost of heating under control.	76
Avoiding wasting energy	Not leaving the heating on when it is not needed.	70
Being able to rest and relax		69
Wanting to feel clean	Having a warm room where people can wash and dry themselves. Having a warm place or radiator to dry laundry.	67
Keeping healthy	Using heat to sooth aches and pains. Keeping warm to avoid or treat health problems.	61
Feeling in control	Knowing the heating will come on when you want, at the temperature you want.	60
Caring for other members of the household	Making sure the home is warm enough for people (adults or children) with particular needs.	53
Wanting to keep the home clean	Using the heating to avoid damp/mould. Not using open fires that leave ash or soot.	51
Keeping the home looking, feeling or smelling nice	Avoiding feeling dry or having mould or ugly equipment. Using fires or heaters to make the home appear cosy.	47
Wanting to feel safe and secure	Not using heating that you worry might be unsafe. Switching heating systems off when no-one is at home because of safety concerns.	47
The value or cost of your home	Preventing damage to your property that might cost you money. Installing heating that could increase the value of the home.	41
Concern for the environment	Concern about air pollution, climate change, or the effect of heating on the country's energy resources.	34
Doing what is easiest	Letting the heating controls do the work.	34
Wanting to be productive	Being warm enough to do work at home.	33
The needs of visitors	Ensuring the home is warm enough for visitors.	33
Keeping to your everyday routines	Always having the heating come on at the same time.	28
Doing what you have traditionally done	Doing what you did in previous homes.	16
How you and your home appear to other people	How the temperature of your home appears to other people. Avoiding appearing either mean or extravagant in your use of heating.	13
Wanting to avoid arguments / disagreements within the home	Avoiding arguments about how warm it is or when the heating is on.	13
Doing what you think most people do	Heating your home in the way you think most people with similar homes would do.	8

Some of the 21 needs are relatively rarely prioritised – particularly those classified in qualitative work as sitting in categories of need defined as "Agency" (the capacity of a person to act independently, and make choices) or "Relational dynamics". Less than 30% of households indicated that big factors, when deciding how to heat the home, included keeping to everyday routines, doing what has traditionally been done, how they and their home appeared to other people, wanting to avoid arguments within the home or doing what they thought most people do. This may, however, reflect a general tendency for people to believe they are not influenced by what others think or do; in the qualitative research, these needs were not necessarily "top of mind", but arose from in-depth discussions with respondents. The qualitative research also characterised these needs as more peripheral than the "core" needs more frequently identified as big factors in the survey.

3.2 Dimensions of need

The PCA suggested that five underlying factors (dimensions) of need exist for heating the home; in combination, these dimensions explain 44% of the variance in the data. This indicates that more than half of the variance in the data cannot be explained by the five underlying dimensions and, in effect, does not fit into a neat pattern or series of patterns across the population as a whole. This reflects both random variance and the sheer diversity of the range and balance of heat energy needs across different households. Nevertheless, such levels of unexplained variance are fairly common for models of this type and a review of relevant statistics suggested that this factor solution gave a very effective summary of the underlying variables.[1] Each factor has an Eigenvalue of at least 1.1 whereas subsequent possible factors had Eigenvalues of less than 1.0. The five dimensions and the individual heat energy needs that they encapsulate are presented in Table 3.

The range of needs that contribute to each of the five dimensions suggested that these dimensions can be labelled as *Hygiene*, *Ease*, *Resource*, *Other people* and *Comfort*.[2] These five "HEROC" dimensions respectively account for 10.95%, 8.94%, 8.41%, 7.93% and 7.35% of the variance and they can be characterised as follows.

- *Hygiene* is defined by five needs: wanting to feel clean, wanting to keep the home clean, keeping the home looking/feeling/smelling nice, keeping healthy, and wanting to feel safe & secure. It represents hygiene in both the specific modern sense of cleanliness and the broader (original) sense of healthiness[3]. It also relates to Herzberg's two-factor theory of occupational psychology, in which "hygiene factors" (including work conditions) do not positively create satisfaction or motivation, whereas their absence causes dissatisfaction. In our context, this dimension denotes basic needs that tend to be regarded as fundamental but may be taken for granted if they are currently met.
- *Ease* is defined by four needs: doing what's easiest, keeping to everyday routines, doing what you have traditionally done, and doing what you think most people do. It

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[1] The KMO statistic (measure of sampling adequacy) is 0.829 – with the literature defining between 0.7 and 0.8 as "good" and any higher figure as very good. Bartlett's test of sphericity – which tests whether there is some relationship between the variables we want to include in the analysis – produced a significance level of 0.000, indicating that we can be confident that this is the case.

[2] These labels aim to capture the essence of the dimension but they are more useful as a shorthand to refer to the dimensions rather than as a definitive description.

[3] As used by the British Occupational Hygiene Society (http://www.bohs.org/aboutus/) and the American equivalent (https://www.aiha.org/Pages/default.aspx).

represents convenience and simplicity, adopting (perceived) norms and other familiar behaviours which make life easier because we do not have to think about what we are doing every time we do it.

- *Resource* is defined by four needs: energy costs, avoiding wasting energy, the value or cost of the home, and concern for the environment. This dimension has a clear financial focus although "waste" can also be seen from a non-financial perspective as something that is inherently wrong. It is interesting that concern for the environment fits in this dimension, perhaps indicating that protecting the environment is seen as a consequence of the same actions that save money and avoid waste, rather than being a strong motivator in its own right.
- *Other people* is defined by five needs: caring for other members of the household, wanting to avoid arguments within home, the needs of visitors, how you and your home appear to other people, and wanting to be productive. This dimension represents a concern for other people, within or outside the household. The inclusion of productivity is intriguing, suggesting that this need may be interpreted in relation to being able to get on with work within the home, facilitated by cordial relationships and mutual support.
- Whereas the specific need, "being comfortable" relates primarily to thermal comfort, the *Comfort* dimension has broader connotations, being defined by three needs: being comfortable, feeling in control, and being able to rest and relax.

Table 3. Underlying dimensions in relation to heating the home and their link to specific needs

	Dimension of need				
Specific needs	*Hygiene*	*Ease*	*Resource*	*Other people*	*Comfort*
Wanting to feel clean	++				
Keeping healthy	+				
Wanting to keep home clean	++				
Wanting to feel safe & secure	+				
Keeping the home looking/feeling/smelling nice	++				
Doing what's easiest		++			
Keeping to everyday routines		++			
Doing what have traditionally done		++			
Doing what you think most people do		++			
Energy costs			+++		
Avoiding wasting energy			+++		
Concern for environment			++		
Value or cost of home			+		
Caring for other members of household				+++	
Wanting to be productive				+	
Needs of visitors				+++	
How you & your home appear to other people				+	
Wanting to avoid arguments within home				++	
Being comfortable					+++
Feeling in control					+
Being able to rest and relax					+++

Note: + denotes a positive relationship between the specific heat energy need and the underlying dimension of need, interpreted by a component score greater than ±0.2 (++ denotes a score greater than ±0.3 and +++ greater than ±0.4).

These five dimensions and their linkages with the 21 needs are similar to the initial categorisation developed from the qualitative research. That research suggested four broad categories of need (health and well-being, relational dynamics, agency, and resources) of which eight sub-needs were found to have the most influence on daily, routine behaviour (health and comfort, cost and waste, control and convenience, harmony and hospitality). The PCA of survey data identifies five dimensions of need within the population as a whole. In essence, the "health and well-being" category identified in the qualitative research was found to divide into two different dimensions – *Hygiene* and *Comfort*.

The qualitative research also found that households' needs shift over time – sometimes within a day. This might suggest that the needs dimensions of the population will shift. While this cannot be tested directly by using the survey data, there are three reasons that it is unlikely.

- The survey asked for a general response rather than a response at a particular point in time.
- Respondents could choose any number of needs and so could identify any that were sufficiently important to them – they were not restricted to needs that are relevant at a particular time or in a particular context.
- While individual households might change over time, the survey provides data at population (or sub-population) level rather than individual level. Changes in individual households should therefore "cancel out" so long as a sufficiently large number of households are included in the population or sub-population.

Reflecting on the third point, the needs should vary over a lifetime and that is part of their analytical value: it is possible to observe what is important to households that are at different stages. This is observable and interpretable variation, rather than instability. The factors remain, while individuals may move in or out of them over a period of years.

3.3 Characterising households

The five dimensions of need offer a powerful and flexible means to characterise particular population groups, as a guide for design and implementation of heating technology and strategies. In general we found that household characteristics and the heating system, rather than characteristics relating to the property, tended to produce different profiles of heat energy needs. We found no marked differences between the needs profiles of those with different tenures, dwelling types or property ages. However, households identified by the presence of children, household size, education levels and household income varied quite markedly. Some examples are shown here, demonstrating some logical relationships between group characteristics and needs profiles – relationships that promote greater confidence in the needs dimensions themselves.

Combining the needs dimensions with household dynamics reveals a consistency in survey responses and, in consequence, a challenging approach to thermal comfort. Figure 1 shows the needs profiles for the four household dynamics types. This shows, first, that the two categories of ME household are rather different. Multi-person ME households are most distinct – primarily in the extent to which they prioritise *Ease* at the expense of *Other people*. This is not the case for JUST ME households who are rather more similar to the population average in their pattern of needs.

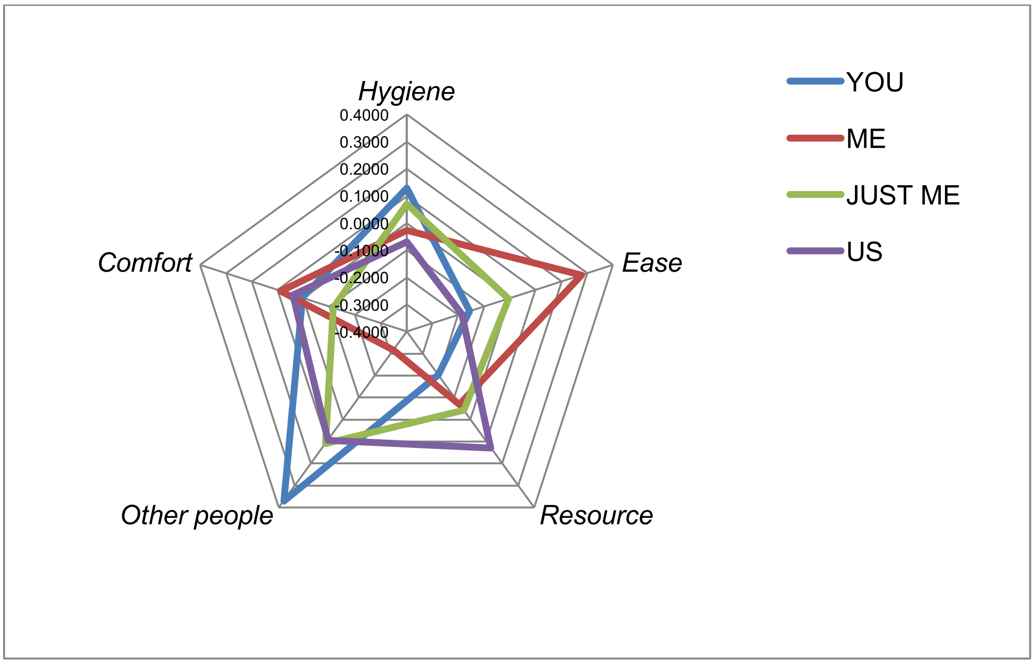

Figure 1. Needs profiles based on relative factor scores for four household dynamics types[4]

Key differences in the scores of the types of households exist on all of the five dimensions of need, with the exception of *Comfort*. The qualitative research suggests that comfort is the most fundamental need addressed by heating, so it is not surprising that it varies least across households that adopt different approaches to achieving comfort. YOU households are most distinct in the degree to which they prioritise *Other people* and, to a lesser extent, *Hygiene*, at the expense of *Ease* and *Resource*. The main difference with US households is that the latter are slightly less likely than average to prioritise *Hygiene* and more likely to prioritise *Resource*.

Figure 2 shows that relationships also exist between household composition and the five dimensions of need. Households with children under school age stand out as having the greatest variation: this group prioritises *Other people* and, to a lesser extent, *Hygiene*, at the expense of *Ease*, *Resource* and *Comfort*. Once children have reached school age, *Hygiene* becomes less important and *Resource* more important, although both dimensions are close to average. Households containing all adults over 60 are rather different, prioritising *Ease* and *Comfort* at the expense of *Other people*. Households without children but with at least one adult under 60 are most similar to the population as a whole in their profile of needs.

[4] Scores on the dimensions have been standardised to emphasise variation among groups. A score of zero represents the average for the population of British households as a whole.

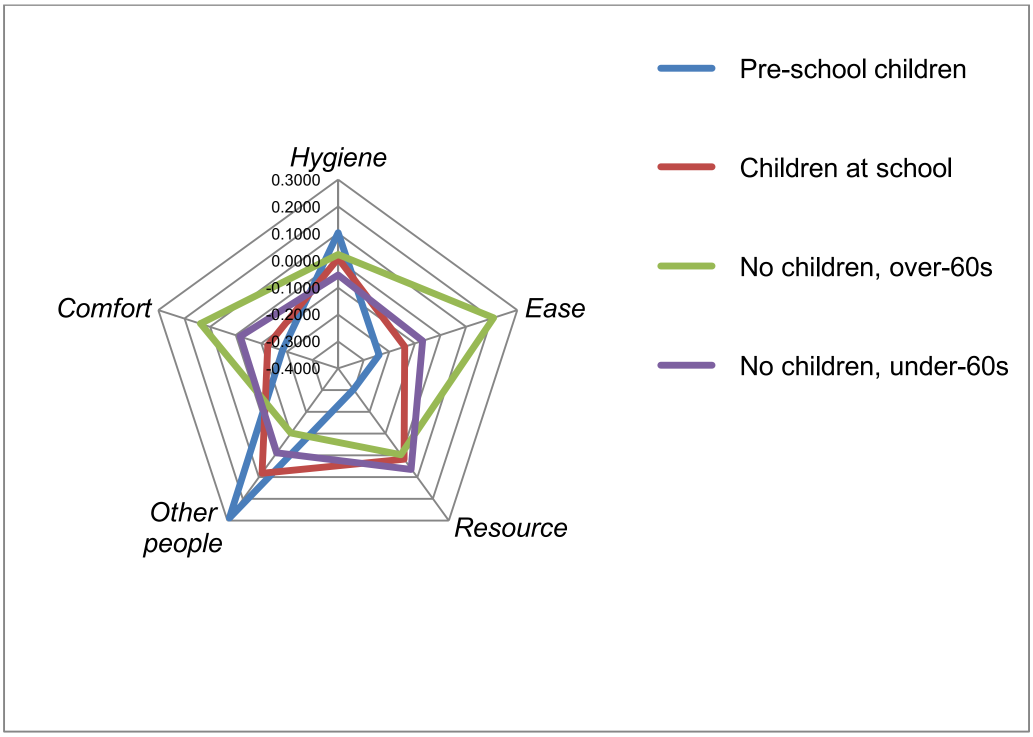

Figure 2. Needs profiles based on relative factor scores for four household compositions

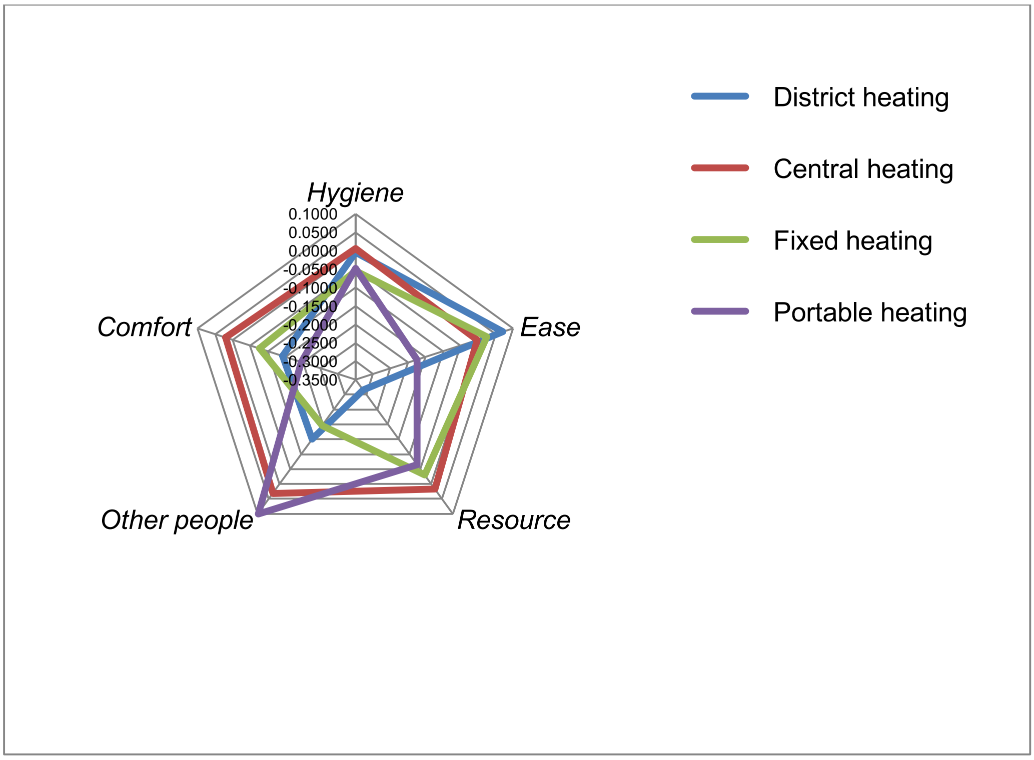

Figure 3. Needs profiles based on relative factor scores for four heating arrangements

Figure 3 presents scores across the five dimensions for four heating arrangements. As might be expected, households with central heating being in the majority, their profile of needs is similar to the average. Respondents with district heating placed the least emphasis on *Resource*, and low emphasis on both *Other people* and *Comfort*, perhaps reflecting that heat tends to be available all the time through a system that they have little control over. Households with portable heating also place little emphasis on *Comfort*, despite being the group that appears to have greatest difficulty keeping warm (44% of respondents with portable heating said they always keep warm enough by what they normally do on a typical winter day, compared with an average of 72%). This can be explained logically if (a) people who prioritise comfort do not use portable heating and/or (b) people with portable heating have learned to limit comfort. Those using fixed heating place little emphasis on *Other people*, whereas the opposite is true of those using portable heating.

4 Conclusions

Thermal comfort has to be seen in the context of other influences on heating strategies. This is perhaps obvious but there is now a greater degree of quantification about what such an assertion means. The need to be comfortable is the need that respondents most often identified as a big factor in determining how they use heating and keep warm. However, it was not the only consideration: concerns about energy cost or wastage are also major influences and all 21 needs influenced at least 8% of respondents. The "*Comfort*" dimension is the fifth of five dimensions. Furthermore, whereas the specific need "being comfortable" relates primarily to thermal comfort, the *Comfort* dimension has broader connotations of being at ease, in control and free of concerns.

The "needs profiles" show that different groups emphasise different needs; one implication is that they may have different expectations or requirements for their means of keeping warm. This insight can support action at national or local level. The fact that household – rather than dwelling – characteristics have most influence on needs profiles suggests that appropriate actions should be based more on the household than the dwelling, once the constraints of the dwelling have been taken into account. If surveys are conducted to determine the actual needs profiles of a household or defined population, this should be yet more effective than relying on household characteristics as a proxy.

It is also important to understand the household dynamics that underlie decisions about heating and keeping warm: heating is not a purely individual activity. The "YOU-ME-US" typology is a simple way to characterise households, which can be overlaid on the dimensions of need. However, the dynamics have the potential to shift (over short and long timescales) depending on circumstances such as the weather and who is at home.

In summary, comfort should be seen not simply as the thermal state of individuals but in terms of the actions of groups of individuals, in the context of conflicting needs and priorities.

Acknowledgements

This research was commissioned and funded by the Energy Technologies Institute as a part of its Smart Systems and Heat Programme, Work Area 5: Consumer Response and Behaviour. The project as a whole was a partnership of PRP Architects and University College London, with NatCen Social Research as subcontractors. Under the guidance of the authors, the fieldwork was conducted by NatCen, with assistance from Seb Junemann of PRP Architects. Analysis was assisted by Matt Barnes of NatCen.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
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Healthy excursions outside the comfort zone

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Summary

Comfort and health may be related but are no synonyms. In the last years, we enhanced our knowledge regarding health effects of temperature exposure outside the human thermal comfort zone. Mild cold and warm environments increase metabolism, thereby targeting obesity by counterbalancing excess energy intake. Furthermore, we recently showed that mild cold influences glucose metabolism. Ten days of intermittent mild cold exposure in type 2 diabetes patients significantly increased insulin sensitivity, and thereby glucose handling capacity with more than 40%. This is comparable to the best currently available pharmaceutical therapies. A new study in obese subjects confirms these findings. Does this mean that we have to suffer from discomfort in order to become healthy? Probably not. Firstly, prolonged temporal excursions outside the thermal comfort zone result in acclimatization and we show that both cold and heat acclimation go hand in hand with increased comfort ratings. Secondly, low or high temperatures in a dynamic thermal environment may be perceived as acceptable or pleasant and evoke alliesthesia. We advocate studying dynamic thermal conditions, link this to the adaptive comfort model, and monitor these conditions in actual living conditions. This information is needed to design both healthy, comfortable and energy-friendly indoor environments.

Keywords: Health, thermal comfort, indoor climate, obesity, diabetes, acclimation

1 Environmental temperature and health

The effects of environmental temperature on our health are difficult to study, since changes in health status are slow and may also have indirect causality with temperature. Important diseases or syndromes that may link to environmental temperature are obesity, diabetes, cardiovascular diseases, and eventually even cancer (Keith et al., 2006, Prospective Studies, 2009). When we started about ten years ago, we focused on the effects of mild cold on human energy metabolism, because of its mechanistic relation to obesity and the metabolic syndrome. In the next sections, we will elaborate on the recent findings on the relations between environmental temperature and some important diseases.

2 Obesity

The metabolic syndrome is one of the most widespread diseases worldwide and is characterized by obesity, accompanied by a high risk of developing type 2 diabetes and cardio vascular diseases (Singh et al., 2013). A positive human energy balance typifies obesity. Treatment is generally directed at weight loss or weight maintenance by affecting the energy balance. This can be achieved by dieting, by increasing physical activity or a combination of the two. Dieting affects the energy intake and physical activity may affect the energy expenditure. However, long-term effects of such life style interventions are disappointing. An alternative way to affect the energy balance could be environmental temperature.

We hypothesise that environmental temperature relates to our body (energy) metabolism and thereby may affect our health status. Ideas were formulated earlier (van Marken Lichtenbelt and Kingma, 2013), but in the mean time, new data has been collected and insights have been deepened. Clearly, classical thermoregulation shows that both cold and warm environments can increase our energy expenditure. The latter has been described in the so-called Scholander model, which uses the concept of the thermoneutral zone ((Kingma and van Marken Lichtenbelt, 2015), and Kingma 2016 for an update on this model in these proceedings). In the past, the field of thermoregulation mainly focused on extreme temperatures, which may not be relevant to our daily circumstances. Despite some older studies (Dauncey, 1981, Kräuchi et al., 1999), investigations on mild temperature variations that may be encountered in daily practice originate from the last 10-15 years (van Marken Lichtenbelt et al., 2002, van Marken Lichtenbelt et al., 2001, Celi et al., 2010, Yoneshiro et al., 2013). Mild cold (i.e. cold conditions that do not evoke shivering) leads to non-shivering thermogenesis (NST), and brown fat (the 'healthy' fat) is activated (van Marken Lichtenbelt et al., 2009). Brown fat is different from white fat. White fat stores energy, while brown fat burns fatty acids and glucose when needed, for instance, during cold exposure. NST accounts for up to 30% of our resting metabolism (van Ooijen et al., 2004). However, NST is lower in obese persons and in elderly. Our research group showed that regular exposure to mild cold conditions may lead to an increased capacity of NST and brown fat in lean healthy young adults (Figure 1) (van der Lans et al., 2013), but also in obese subjects and elderly (Hanssen et al., 2016). Moreover, cold acclimation leads to a decrease of thermal discomfort in cold conditions (14-15 °C) (van der Lans et al., 2013, Hanssen et al., 2016).

A warm environment can also increase energy expenditure. Currently, we are studying the effect of mild heat acclimation on energy expenditure and other health related parameters. Preliminary results show that mild heat can affect human energy expenditure and that heat acclimation affects thermoregulatory behavior (Pallubinsky et al. 2016, these proceedings). The results indicate that higher indoor temperatures may be more easily accepted.

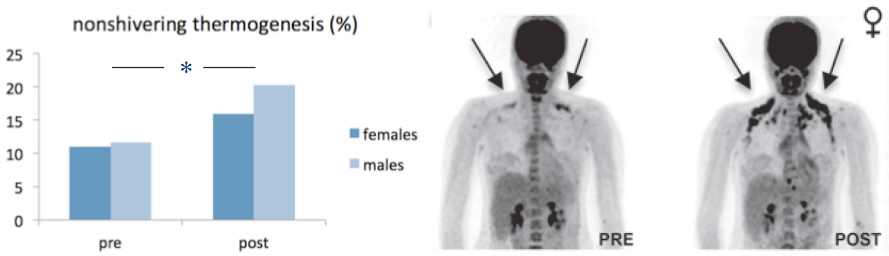

Figure 1. Nonshivering thermogenesis and brown fat (arrows) activity before (PRE) and after cold acclimation (POST) (van der Lans et al., 2013).

3 Diabetes

The effect of environmental temperatures on our energy metabolism is relatively straightforward. Studies on the effect of temperature on diabetes and insulin sensitivity are more complicated. Since we showed highly significant effects on energy metabolism even achieved by mild cold intervention, and because some studies hint towards an affect of low environmental temperature on insulin sensitivity (Lee et al., 2014), we recently performed an experiment in patients with type 2 diabetes and cold acclimation. One of the primary outcome variables was insulin sensitivity. Insulin is one of the main regulators of blood glucose levels. High insulin sensitivity means that relatively small amounts of insulin are needed to metabolize glucose. Low insulin sensitivity or insulin resistance can ultimately turn into type 2 diabetes and can cause related health problems.

Results derived from our first experiment clearly showed that, in line with former studies in healthy volunteers, energy expenditure was affected by 10 days of cold acclimation (15°C, 6h per day). The most striking result, however, was that cold significantly, and to a high extent, affected insulin sensitivity (Hanssen et al., 2015). On average, insulin sensitivity increased by 43%, which is comparable to the best treatments strategies we know of, such as intense exercise programs. Interestingly, we showed that cold acclimation affected metabolic pathways in skeletal muscle (Figure 2). This tissue is known to be the main tissue with respect to the uptake of glucose. Parallel to the study in type 2 diabetic patients, we studied cold acclimation in healthy obese subjects and showed that cold acclimation lead to a cold-induced increase in energy expenditure too, affecting the same skeletal muscle metabolic pathways (Hanssen et al., 2016).

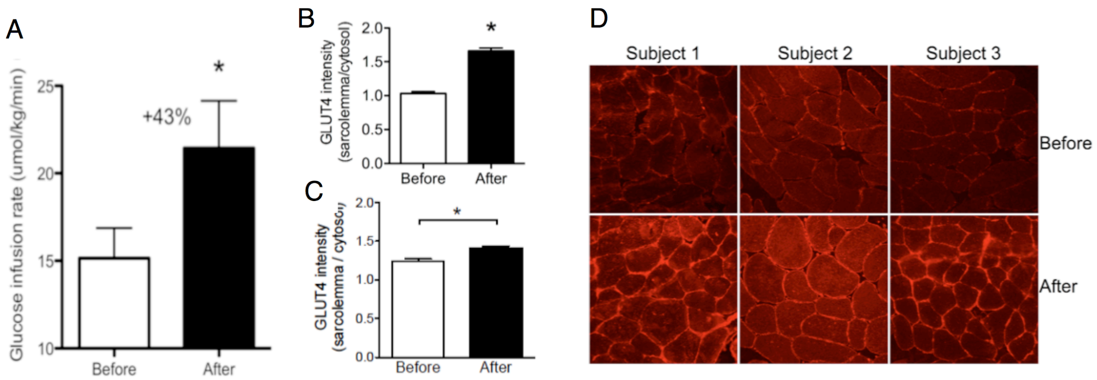

Figure 2. Insulin sensitivity and skeletal muscle GLUT4 localization before and after cold acclimation. A: group mean ± _s.e.m. (right) for glucose infusion rate (GIR), which is the measurement for insulin sensitivity. B and C: GLUT4 translocation in skeletal muscle before and after acclimation in diabetic (B) and obese (C) subjects, as made visible in D: Representative images of GLUT4 immuno-staining of skeletal muscle tissue sections from three individuals in the study. GLUT4 is the insulin-regulated glucose transporter in skeletal muscle fibers. The pictures show that there is more GLUT 4 on the membranes of the cells after cold acclimation.

4 Cardiovascular and other diseases

Both obesity and diabetes are known to increase the risk of developing cardiovascular diseases. Therefore, thermal conditions may indirectly affect this risk, but it may also work more directly. Repeated exposure to hot or cold climates may elicit cardiovascular adaptations (Corbett et al., 2014). Clearly, changes in environmental temperature affect the heat strain on the body and a significant redistribution of the blood pool is accomplished, thereby affecting cardiac output and cardiac and vascular strain. Our hypothesis is, that through variation in environmental temperatures, the cardiovascular system is exercised, which may affect the resistance to heat and cold, but also the human immune system and resistance to flew or pneumonia. The latter, however, needs to be investigated in the near future. A first indication of the effect of mild cold acclimation on the immune system derives from our study inducing 10 days of intermittent cold exposure, that evoked considerable changes of immune cell markers expression in skeletal muscle of healthy lean subjects (example see Figure 3) (van der Lans et al., 2015). The physiological consequences and therapeutic relevance of these changes remain to be determined.

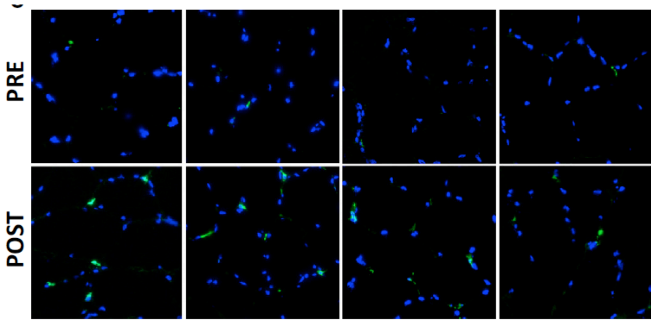

Figure 3. Expression of adaptive and innate immune markers in muscle biopsies before (PRE) and after (POST) 10 days of cold acclimation in healthy subjects. Immunofluorescence staining of CD68 in skeletal muscle cross sections. CD68 positive macrophages are stained in green, nuclei are stained in blue. Note the increase of green (CD68 macrophages, markers of the immune system) post acclimation.

5 Environmental temperatures, health and the built environment

The above made clear that, apart from healthy lifestyle factors as diet and physical exercise, *temperature training* might also be linked to health. Certainly, more studies are needed to confirm the results in different populations and to better determine time and intensity effects, as well as to study additional health related parameters. Moreover, we need to address long-term effects on health. Nevertheless, in the recent years, we have identified several important health-related parameters that are now known to be affected by temperature and can be studied in greater depth, such as the above mentioned parameters: energy expenditure, brown fat activity, insulin sensitivity, blood pressure and cardiac output.

We feel that enough physiological information on the effects of indoor temperature on health has been gathered to start putting this knowledge into practice. Therefore, the question rises: how can this knowledge be translated into the built environment?

Several aspects need to be taken into account. First of all, the proposed interventions must be acceptable. Secondly, an important aspect that should be taken into consideration is compliance with the intervention. Lifestyle intervention studies identified many reasons for the lack of compliance that may in part also affect temperature interventions: habits, discomfort, social conformation, and lack of tailored information. With respect to thermal (dis)comfort, the adaptive comfort model shows that variation in daily and seasonal temperatures can be offered without discomfort (Nicol and Humphreys, 1973, de Dear and Brager, 1998); ASHRAE's adaptive comfort model; Annex 69). Moreover, we showed that independent of season, even elderly accept a daily variation of 7˚C in a *dynamic* situation (Schellen et al., 2010). The temperatures used include those of which we now know that they do affect the body's energy metabolism, glucose metabolism and potentially the cardiovascular system (see above). Secondly, low or high temperatures in a dynamic thermal environment may be perceived as acceptable or pleasant and support alliesthesia (de Dear, 2011). Another important facet is the building energy saving which could be achieved by implementing a dynamic temperature profile rather than a steady-state temperature.

We think dynamic (drifting) and locally varying temperatures can be implemented in practice. In fact, there already are quite a few modern buildings that make use of dynamic temperatures and different local indoor climate zones. In future, we need to set up monitoring studies under actual daily living conditions, preferably comparing different thermal strategy interventions. This can be accomplished by using living lab environments and even by studying effects in neighbourhoods. The latter can ideally be used for research involving long-term effects on health and wellbeing in combination with other lifestyle interventions.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Too hot, too cold? An analysis of factors associated with thermal comfort in English homes

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This paper focuses on factors associated with feeling too hot / too cold in English homes and compares internal temperatures for homes where occupants report either and those where not.
The data analysed for this paper are part of the Energy Follow-Up Survey (EFUS), commissioned by the Department of Energy and Climate Change (2013).
Across the sample (N = 2616), 6.7% of households reported that during cold winter weather, they cannot keep comfortably warm in the living room. 9.2% reported that during summer, they have difficulties to keep the living room and 11.3% to keep the bedroom cool.
In winter occupants in homes with uninsulated cavity walls and with less double glazing are more likely to indicate that they cannot keep comfortably warm. In summer, households with presence of a sick / disabled person were more likely to report that they cannot keep living rooms cool. Energy consumption and internal temperatures did not differ between those reporting discomfort and those who did not.
One important finding is the high degree of variability in internal temperatures. This variation of temperatures that householders apparently experience as comfortable is reassuring in that acceptable temperatures are not limited to a narrow range.

Keywords: thermal discomfort, internal temperatures, energy consumption, logistic regression, homes

1 Introduction

This paper focuses on factors and temperatures related to feeling too hot or too cold in one's home. Data were collected from a sample of homes in England. Thermal comfort is often looked at a momentarily state linked to certain environmental parameters and personal factors. For example, in the heat-balance models the following six factors predict the occupants' overall satisfaction with the thermal environment as expressed by the Predicted Mean Vote (PMV): (1) ambient air temperature (Ta), (2) mean radiant temperature (Tr), (3) relative humidity (RH), (4) air velocity (Va), (5) metabolic rate (met), and (6) clothing level (clo) (EN ISO 7730:2005, Annex D; Fanger, 1970). In adaptive models of thermal comfort additional factors are of importance, such as previous and current climatic experiences (Nicol et al, 1973). Also, a range of other factors have been discussed as impacting on thermal comfort such as gender (e.g. Karjalainen, 2012; Schellen et al, 2013), age (e.g. Olgyay, 1963; Schellen et al, 2010), and in general, weight and height are related to physiological parameters that in turn impact on thermal comfort (for an overview, see Huizenga et al, 2001).

This paper is not focused on momentarily determinants of thermal comfort, but rather looks at factors that are associated with feeling thermally uncomfortable in one's home, and analyses accompanying temperatures. It has been shown that internal temperatures vary widely in homes (Huebner et al, 2013), show distinct temporal patterns (Huebner et al, 2015b), and do not map on temperatures expected at certain times in building stock models (Huebner et al, 2013). However, these temperatures have not been mapped onto thermal comfort experiences.

In particular, this paper aims at answering the following questions.

1. How many households in the UK experience thermal discomfort in the home? (Section 3.1 'Prevalence of thermal discomfort')

2. What household and dwelling characteristics are associated with experiencing thermal discomfort? (Section 3.2

3. Does energy consumption vary between homes experiencing and not experiencing thermal discomfort? (Section 3.3

4. Do average, minimum, and maximum internal temperatures vary between homes where occupants experience thermal discomfort and where not? (Section 3.4 Internal temperatures for comfort / discomfort)

Note that the expression "thermal discomfort" is used for brevity to indicate when someone stated to not be able to keep comfortably warm in winter and having difficulties in keeping rooms cool in summer. The data analysed for this paper were collected as part of the Energy Follow-Up Survey (EFUS), commissioned by the Department of Energy and Climate Change (DECC, 2013), and consist of survey responses, estimated annualized energy consumption, building information, and internal spot temperature measurements.

This paper is organized as follows. First, some further information about the underlying data is provided, and then in turn the four research questions are addressed and as necessary further methods information given.

2 General methods

The 2011 EFUS consisted of a follow-up interview survey of a sub-set of households first visited as part of the 2010/2011 English Housing Survey (DECC, 2013). The English housing survey (EHS) is a continuous national survey commissioned by the Department for Communities and Local Government (DCLG). It collects information about people's housing circumstances and the condition and energy efficiency of housing in England.

The EFUS 2011 face-to-face interview survey was undertaken by interviewers from GfK NOP between December 2010 and April 2011. A total of 2616 interviews were completed, drawn from a sample of addresses provided from the first three quarters of the 2010/11 English Housing Survey (EHS). These data were then weighted to account for survey non-response and to allow estimates at the national level to be produced. Temperature monitoring was done in a subsample of N = 823 homes. Spot temperature measurements were taken every 20 minutes, i.e. from midnight to 23.40h, resulting in 72 measurements per day. The temperature loggers used were modified TinyTag Transit 2 data loggers, produced by Gemini Data loggers. Householders were instructed on how to place them in the house (e.g. away from direct sunlight); for details see (DECC, 2013b). Temperature measurements were taken in the living room, the main bedroom, and the hallway.

Finally, meter readings were obtained in a sub-sample of 1345 homes and annual gas and electricity consumption calculated.

The exact items to elicit judgements on thermal comfort / discomfort were:

- During the cold winter weather, can you normally keep comfortably warm in your living room? (response options: yes, no)
- During a typical summer (June to August), do you find it difficult to keep this room

cool – [Living room / main bedroom / other bedrooms / other - specify]?

3 Research questions: Results

3.1 Prevalence of thermal discomfort

Across the total sample of the EFUS (N = 2616), 174 householders (6.7%) reported that during cold winter weather, they normally cannot keep comfortably warm in the living room. The main reasons for this were that it was not possible to heat the room to a comfortable standard (N = 92) and that the costs of keeping the heating on were too high (N = 48).

N = 240 householders (9.2%) reported that during a typical summer, they find it difficult to keep the living room cool, and N = 295 (11.3%) of householders reported difficulties in keeping the main bedroom cool. Householders were also asked about other rooms; the individual cases are too small for meaningful analysis as 12 different rooms were mentioned; however, across the sample, N = 539 households reported that at least one room would get uncomfortably hot, i.e. 20.6% of all households. Hence, not being able to keep rooms cool in summer was more prevalent than not being able to keep comfortably warm in winter.

3.2 Household and dwelling characteristics associated with thermal discomfort

For analysis of factors associated with thermal discomfort, only homes that had reported no change in dwelling or household characteristics since the last EHS were considered (as these changes were not carefully documented) and for which energy consumption data was available. This left N = 1000 homes. N = 58 of those reported that they were unable to keep their living rooms comfortable warm in winter. N = 78 and N = 108 respectively, reported not being able to keep the living room or bedroom cool in summer. Whilst these case numbers are relatively small, they allow quantitative statistical analysis. Three multivariate logistic regression analyses were used to characterize homes that experience thermal discomfort (not being able to keep living room comfortably warm in winter, not being able to keep living room cool in summer, not being able to keep bedroom cool in summer) as opposed to those that did not report any issue. Binary logistic regression has a categorical outcome variable (in this case, reporting discomfort or not), and the aim is to predict the probability of belonging to either one category given certain values on the predictor variables. The logistic regression coefficients give the change in the log odds of the outcome for a one unit increase in the predictor variable. Table 1 summarizes the variables used as predictors in the logistic regression (for more details, see Huebner et al, 2015a). Reference category is indicated in bold. HRP stands for 'Household Reference Person' which refers either to the sole owner or the tenant of a property, or, if there is more than one occupant, the person with the highest income, and in the case of equal incomes, the oldest of those (ONS 2012).

Table 1. Frequency / summary statistics of the predictor variables.

Variable (abbreviation)	Categories (N)
Floor area (FloorArea)	n/a (continuous: M = 90.8m^2, SD = 43.05)
Dwelling type (DwType)	Converted & purpose built flat (157), **detached** (234), end terrace (120), mid- terrace (183), semi-detached (306)
Number of storeys (NoStorey)	n/a (continuous: M = 2.14; SD = 0.95)
Government Office Region (GOR)	**East (110),** East Midlands (68), London (108), North East (74), North-West (178)), South East (135), South-West (96), West Midlands (98), Yorkshire and the Humber (133)
Dwelling age (DwAge)	**pre 1919** (142), 1919-44 (171), 1945-64 (230), 1965-80 (236), 1981-90 (79), post 1990 (142)
Wall type (WallType)	9-inch solid wall (139), cavity uninsulated (302), **cavity with insulation** (489), other (70)
Double glazing (DblgGlaz)	**entire house** (795), more than half (117), less than half (38), no double glazing (50)
Attic (Attic)	Yes (106), **no** (894)
Conservatory (Conservatory)	Yes (195), **no** (805)
Main heating fuel (Fuel)	electrical system (50), **gas system** (950)
SAP rating (SAP)	**B& C** (138), D (557), E (256), *F*&G (49)
Number of occupants (HHSize)	n/a (continuous: M = 2.37, SD = 1.26)
Age of youngest dependent children (DepChild)	**No dependent children** (687), 0-4 years (131), 5-10 years (88), 11-15 (64), older than 16 (30)
AHC (After-Housing-Costs) equivalised income quintiles (Income)	1st quintile – lowest (149), 2nd quintile (220), 3rd quintile (210), 4th quintile (211), **5th quintile- highest** (210)
Tenure (Tenure)	Local authority (120), **owner occupied** (635), private rented (102), Registered Social Landlord RSL (143)
Sex of HRP (SexHRP)	**Female** (394), male (606)
Age of HRP (AgeHRP)	16 - 29 yrs (52), 30 - 44 (239), 45 - 64 (407), **65 or ove**r (302)
Employment status of household (EmployHH)	1 or more work full time (485), 1 or more work part time (86), none working and none retired (101), none working, one or more retired (328)
Someone in household sick or disabled? (Sick/disabled)	**No** (649), yes (351)
Someone in household over 75 years? (over75)	**No** (876), yes (124)
Length residency (LengthRes)	**2 yrs or less** (171), 3-4yrs (117), 5-9years (198), 10-19 (218), 20-29 (134), 30+years (162)

Income was coded as equivalized income, meaning that household incomes were adjusted for household composition and size such that those incomes can reasonably be directly compared with each other. This implies increasing the incomes of small households and decreasing the incomes of large households and the extent of these increases and decreases is determined by an internationally agreed set of scales. Equivalized income was chosen as it is considered to provide a better indication of household disposable income

3.2.1 Predicting winter discomfort living room

The outcome variable was whether householders reported that they could keep comfortably warm in the living room in winter ('no' coded as 1) or not (coded as zero). Table 2 summarizes the results; for brevity, only significant predictors are listed

Table 2. Winter discomfort – results of logistic regression.

Predictor	*B*	*SE*	*p*	*Odds ratio*
Walltype cavity uninsulated (Ref = Cavity insulated)	0.88	0.411	.031*	2.418
Dbglz: less than half (Ref = whole house)	2.18	0.671	0.001**	8.799
Equivalized income: 5th quintile (Ref = lowest)	-1.73	0.798	0.030*	0.177
none working and none retired (Ref = 1 or more full time)	1.19	0.477	0.012	3.295

Pseudo R^2: Hosmer and Lemeshow R^2=0.228; Cox and Snell R^2= 0.096; Nagelkerke R^2 = 0.269. Significance levels: $p < .05$ indicated with *; $p < .01$ indicated with **

Note that odds-ratios are always positive values. The distinction regarding a positive or negative relationship in the odds ratios is given by which side of 1 they fall on. 1 indicates no relationship. Less than one indicates a negative relationship and greater than one indicates a positive relationship. Also note that for categorical predictors, the estimates refer to the comparison of the respective category and the reference category. The odds of experiencing thermal discomfort in winter in the living room are 2.418 higher when living in a dwelling with an uninsulated cavity wall as opposed to an insulated cavity wall. Having less than half of double-glazing as opposed to full double-glazing is associated with increased odds of 8.799. Being in the highest income class as opposed to the lowest decreases the odds of experiencing thermal discomfort. 'None working and none retired' is associated with an increased risk of experiencing thermal discomfort (as opposed to at least one working full time).

3.2.2 Predicting summer discomfort living room

Here, the outcome variable was whether householders complained about not being able to keep the living room cool in summer.

Table 3. Summer discomfort living room – results of logistic regression.

Predictor	*B*	*SE*	*p*	*Odds ratio*
GorEHSEast Midlands(Ref= East)	1.46	0.701	.036*	4.319
GorEHSYorkshire and the Humber (Ref=East)	1.45	0.622	.020*	4.272
1 or more work part time (Ref = 1 or more full-time work)	0.86	0.434	.030*	2.357
Sick / disabled (Ref = No)	0.70	0.297	.018*	2.020
Length residency 20-29 years(Ref = 2yrs or less)	1.69	0.579	.003**	5.425
Length residency > 30 years (Ref = 2yrs or less)	1.65	0.606	.007**	5.188

Pseudo R^2: Hosmer and Lemeshow R^2=0.186; Cox and Snell R^2= 0.097; Nagelkerke R^2 = 0.229. Significance levels: $p < .05$ indicated with *; $p < .01$ indicated with **.

The significant effects point towards some characteristics of vulnerability of householders who do experience thermal discomfort in summer; i.e. those saying that there is someone sick or disabled in the household have higher odds of reporting thermal discomfort, as do those who have lived somewhere for a long time which is likely to be older residents.

3.2.3 Predicting summer discomfort bedroom

Finally, experiencing thermal discomfort in the summer in the bedroom was the dependent variable.

Table 4. Summer discomfort main bedroom – results of logistic regression.

Predictor	*B*	*SE*	*p*	*Odds ratio*
Dwelling age post 1990 (Ref= Pre 1919)	1.42	0.616	.021*	4.129
Household size	0.27	0.128	.033*	1.311
Dependent children 5-10 years (Ref = none)	-1.02	0.516	.049*	0.3619
Age HRP 16-29 (Ref = over 65)	1.97	0.728	.007**	7.152
Age HRP 30-44 (Ref = over 65)	1.40	.628	.026*	4.053
Length residency 20-29 (Ref = 2 years or less)	1.04	0.496	.036*	2.835

Pseudo R^2: Hosmer and Lemeshow R^2=0.139; Cox and Snell R^2= 0.091; Nagelkerke R^2 = 0.183. Significance levels: $p < .05$ indicated with *; $p < .01$ indicated with **.

Results are somewhat harder to interpret. In terms of building characteristics, the finding that the most modern buildings have a greater chance of overheating than old dwellings makes intuitive sense given that modern buildings have higher levels of insulation and such buildings are prone to overheating unless care is taken in the design to prevent this. However, why younger people should be more affected than older is unclear clear.

3.3 Differences in energy consumption depending on comfort reporting

Ordinary least squares regression (OLS) was used to see if thermal comfort vs. discomfort would have an impact on annual energy consumption. The dependent variable was annualized total energy consumption (winter discomfort) or annual electricity consumption (summer discomfort); all predictors were used as in 3.2 with the added predictor of thermal comfort / discomfort which was dummy-coded, with the reference category being thermal comfort (i.e. thermal discomfort was coded as 1). One might speculate that those not being able to keep comfortably warm in winter will heat more and hence have higher energy consumption, and those who experience thermal discomfort in summer (i.e. not being able to keep cool in summer), will use air-conditioning and hence have higher electricity consumption. Note that for brevity only the overall result of the regression is reported together with more detailed information for the comfort predictor. For general findings on what predicts energy consumption, see e.g. Huebner et al (2015b).

In the first OLS, annualized energy consumption was the dependent variable, and reported thermal discomfort in winter in the living room the crucial predictor of interest. Whilst the overall model was highly significant [$F(58, 941) = 9.51$, $p < .001$] and explained $R^2 = 36.96$ of the variability in energy consumption, the predictor “thermal discomfort” was not significant, $t = 0.758$, $p = .449$.

In the second OLS, annualized electricity consumption was the dependent variable, and reported thermal discomfort in the living room in summer the predictor of interest. The overall model was significant, $F(58, 941) = 3.04$, $p < .001$, $R^2= 15.77$; however, the predictor of thermal comfort was not significant, $t= -1.03$, $p = .304$. The final OLS looked at summer discomfort in the bedroom; again, the predictor of thermal discomfort was not significant, $t=-0.21$, $p = .831$; with the overall model being significant, $F(58, 941) = 3.02$, $p < .001$, $R^2= 15.68$.

Hence, there is no indication of differences in energy or electricity consumption, respectively, for householders experiencing winter or summer discomfort, and those who do not. This analysis is controlling for other predictors (as detailed in 3.2).

3.4 Analysis of temperature data

The exact time period when temperature measurements were taken during EFUS varied slightly from home to home depending on sensor instalment; however, as the EFUS report itself used measurements in the time period from February 2011 until January 2012 for analysis the same was done here (even though that meant that some homes were excluded).

The question about not being able to keep warm in the living room was phrased as “during the cold winter weather”; here, the months February 2011, December 2011, and January 2012 were taken as winter months. For summer overheating, the months June, July, August were specified as the period under consideration, all from the year 2011.

3.4.1 Winter discomfort

For N = 53 households that reported feeling too cold in the living room in winter (initially, 55, but two exhibited faulty sensor readings), and for N = 735 who were comfortable in winter in their living room, temperature data were available.

For each household, we first calculated the average daily temperature over the winter period in the living room. We then used boxplot analysis to identify outliers in the average daily temperatures. This was done to capture and remove those days where the house was likely to be unoccupied. An outlier is defined as a data point that is located outside the whiskers of the boxplot (i.e.: outside 1.5 times the interquartile range above the upper quartile and below the lower quartile).

3.4.1.1 Variability within and between homes

Temperatures varied greatly between homes, and to a significant extent also within homes.

Figure 1 shows the daily temperature profile for the living room in one house [i=54, T228.txt] where each line represents one day.

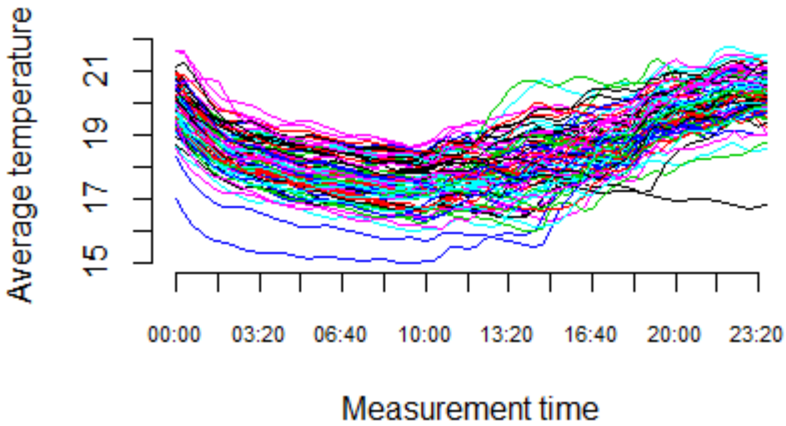

Figure 1. Day to day variability of internal temperature in one home.

Figure 2 shows average winter temperature profiles for those experiencing cold thermal discomfort with each line representing one house.

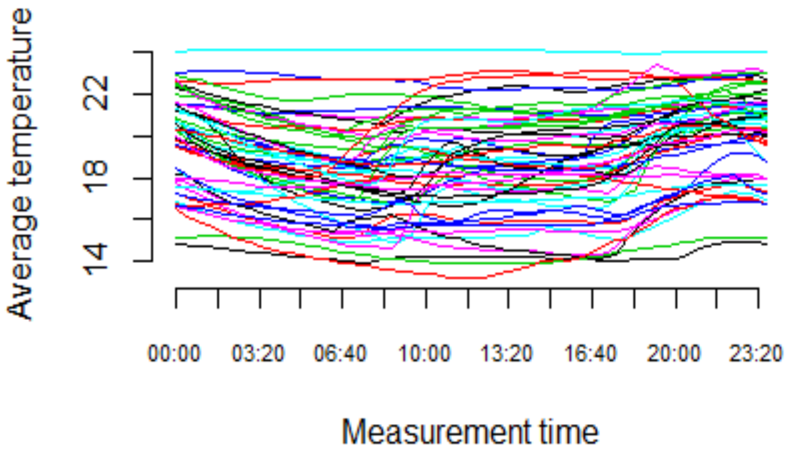

Figure 2. Average winter temperatures for homes not being able to keep comfortably warm in winter.

For homes not experiencing thermal discomfort, similar variability is observed (however, a plot would be illegible because of the number of properties).

As a way of quantifying the variability, we calculated the standard deviation of temperature measurements for each day. We then averaged these values across all days for each home. One might expect that a household in which thermal discomfort is experienced, sees greater variability in daily averages as the house presumably will vary to a greater extent with varying external conditions, including days where the heating system will not cope in bringing the room temperature up to desired levels.

For those experiencing thermal discomfort, the average standard deviation across homes was $M_{discomfort}$ = 1.16. For those not experiencing thermal discomfort, the average standard deviation across homes was $M_{comfort}$ = 1.28. This difference was not significant as shown by an Welch 2-sample t-test, $t(63.34) = 1.64$, $p = .105$) but if anything the trend goes towards larger standard deviations in the sample not experiencing thermal discomfort.

3.4.1.2 Average winter temperatures

First, we calculated the average winter temperature in each house, i.e. we averaged temperatures across each day, and then averaged these 90 values to arrive at one single estimate of the internal temperature at the sensor. Averaged across all homes experiencing discomfort, the mean temperature was $M_{discomfort}$ = 19.03 (SD = 2.26). Averaged across all homes not experiencing thermal discomfort, the mean temperature was $M_{comfort}$ = 19.00 (SD = 2.46).

An independent samples t-test showed that this difference was not significant, $t\ (62.59) = -0.09$, $p = 0.927$. Hence, those reporting thermal discomfort did on average not have lower indoor temperatures in the living room.

We then looked at average day-time temperatures, with day being defined as 7 am to 22 pm. The average temperature across homes and days was $M_{discomfort}$ = 18.95 (SD = 2.35), and $M_{comfort}$ = 18.93 (SD = 2.51), the difference again was not significant.

Note that whilst it might be surprising that day time temperatures are not higher than whole day averages, this is explained when looking at the temperature profile (Figure 3). Temperatures rise almost continuously until about 23.00; and then take some time to fall off, reaching a low point in the morning, i.e. average day time temperatures will not be higher than during the rest of the period.

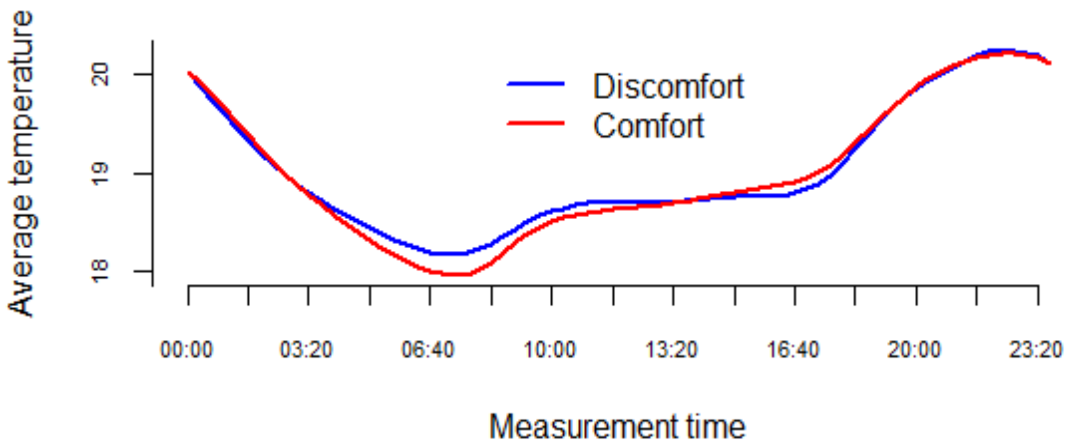

Figure 3. Average temperature profile for households experiencing thermal discomfort (blue line) and those not (red line).

Figure 3 also reinforces the point that average temperatures do not differ for homes experiencing thermal discomfort and those that do not.

3.4.1.3 Ten coldest days

For each home, we calculated the average internal daily temperature across the 72 measurements per day. We then selected those ten days with the lowest average internal temperature. Figure 4 shows the histogram of those for homes that complained about not being able to keep their living room warm in winter (blue), and those who did not (red).

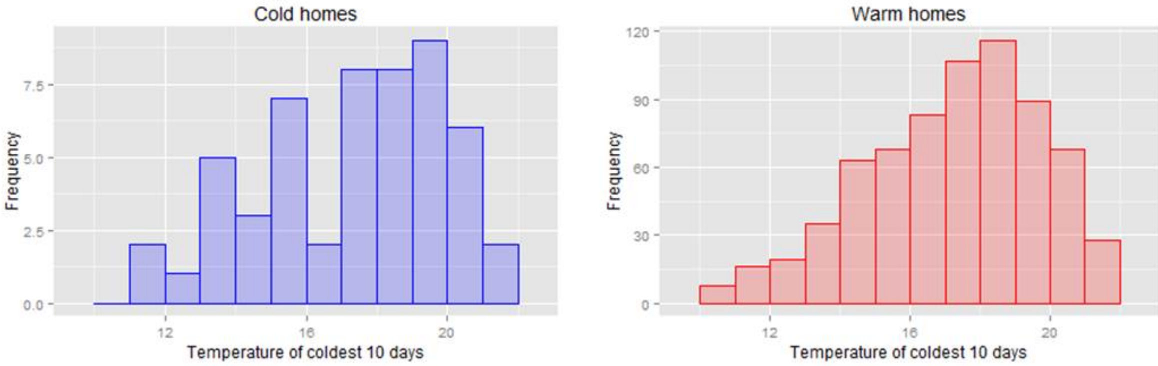

Figure 4. Histogram of average temperature of coldest 10 days.

Across all 53 ‘discomfort homes’, the average of the 10 coldest days was $M_{discomfort}$ = 17.46 (SD = 2.72). For those homes not experiencing thermal discomfort, the average of the coldest 10 days was $M_{comfort}$ = 17.28 (SD = 2.86); again, this difference was not significant (independent samples t-test, $t(61.97) = -0.49$, $p = 0.627$). Hence, it was not the case that those experiencing thermal discomfort experienced lower temperatures on the ten coldest days inside.

3.4.2 Summer discomfort

N = 68 reported finding it difficult to keep their living room cool in summer, and for those, temperature data was available for 67 homes and temperature data was available for N = 718 did not have such an issue. Note that no outlier detection was performed in summer, as it was assumed that high temperatures in summer were genuine (i.e. whereas in winter outliers at the lower end would indicate a house not being occupied and hence the temperatures not experienced by occupants). This assumption might not always hold given that a house might heat up even more than usually when occupants are away, leaving all windows closed. However, the data do not allow testing for this (whereas in winter, temperature differences are very pronounced between presumably unoccupied and occupied days).

3.4.2.1 Average summer temperatures

The average temperature across homes who experienced difficulties in keeping the living room cool was $M_{discomfort}$ = 20.95 (SD = 1.46), and for those who do not, $M_{comfort}$ = 21.22 (SD = 1.54); difference n.s. This value includes night time temperatures; indicating that day time temperatures might indeed be much higher. We then identified the highest temperature for each day in each house, and averaged this across days for each house. Across homes, this value was $M_{discomfort}$ = 22.47 (SD = 0.14) for homes experiencing discomfort. For those who can keep the living room cool, the average was $M_{comfort}$ = 22.69 (SD = 0.14). This difference was significant, t(80.17) = 12.82, p < .001; those not reporting discomfort experiencing higher maximum average temperatures (by numerically 0.2 degrees).

3.4.2.2 Ten hottest days and hottest temperatures

For those stating they find it difficult to keep the living room cool, the average of the ten hottest days was $M_{discomfort}$ = 22.55 (SD = 1.51), i.e. this estimation was based on the average daily temperature of which the 10 days with highest average values were chosen. For homes not reporting comfort issues the mean temperature was $M_{comfort}$ = 22.88 (SD = 1.69). This difference was significant, t(833.35) = 5.29, p < .001. Those not reporting comfort issues actually have warmer internal temperatures when looking at the ten warmest days.

We then identified the ten highest maximum temperatures experienced (i.e. the maximum temperatures of 10 distinct days; which were not necessarily the days with the highest average temperature). Here, the mean value was $M_{discomfort}$ = 23.88 (SD = 1.65) for those saying they cannot keep their living room cool. For those who did not report problems with keeping the room cool, $M_{comfort}$ = 24.40 (SD = 1.97). This difference was significant, t(84.54) = 2.43, p = .0173, i.e. those not reporting comfort issues experiencing higher maximum temperatures (Figure 5).

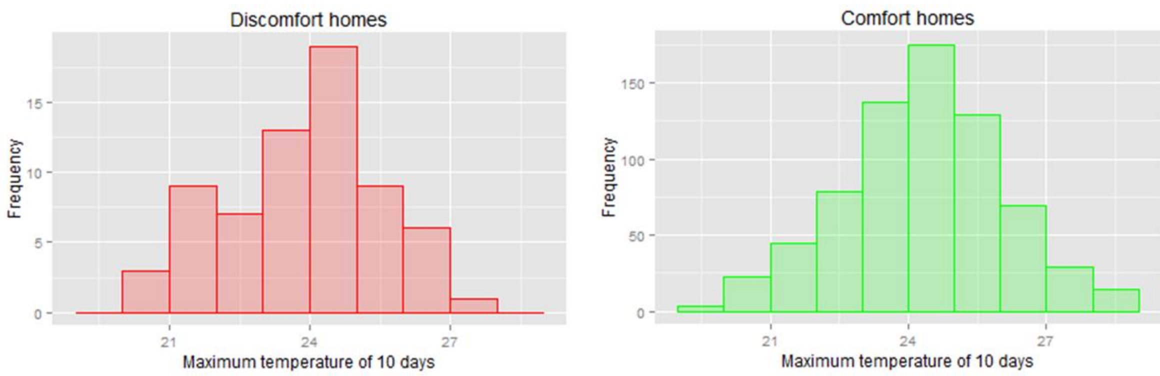

Figure 5. Histogram of maximum temperatures for homes experiencing summer comfort issue (red) and not (green).

It is noteworthy, that some householders stated that they cannot keep their living room cool in summer, yet the maximum temperature experienced was only around 20 – 21 degrees.

4 Discussion

The analysis carried out for this paper showed that a significant proportion of English homes experiences issues with thermal comfort. About 20% in total report not being able to keep cool in summer in at least one room in the home; with about 10% reporting that they cannot keep the living room comfortably warm in winter.

No difference was found in energy consumption for homes that experienced thermal discomfort in winter and those that did not, and in electricity consumption for discomfort in summer. None of the temperature analyses showed that winter discomfort was associated with lower internal and summer discomfort with higher internal temperatures; hence, one might not expect differences in energy consumption.

The finding that statistically similar temperatures were both reported as comfortable and uncomfortable by different participants, could arise from at least three possible causes. It could either indicate that experience of thermal discomfort is strongly dependent on individuals, their characteristics and preferences (as opposed to specific temperatures), or that environmental conditions not directly monitored in the study (such as radiant temperature, exposure to sunlight, experience of draughts, etc.) played an important role. Additional studies assessing such variables would be required to make more definite statements on the extent to which the experienced environments differ for those experiencing thermal discomfort and those that do not. Finally, it might be that the survey instrument was not suitable for best differentiating between those experiencing discomfort and those that do not. For example, the winter question asked whether people can keep comfortably warm in their living room. Given that it was not specified how people kept warm, it might well be that one household reported being able to keep warm and another one that not at the same ambient temperatures if one household used other means to keep warm such as jumpers, blankets, and hot drinks. Hence, specifying the question differently might have led to different findings. Also, the questions for winter and summer differed substantially, i.e. a different construct might have been measured for the two seasons.

Analysis of the temperature data indicated a large amount of variability within and between homes, irrespective of whether thermal discomfort was experienced. This wide variation of temperatures that householders apparently experience as comfortable is reassuring in so far as that acceptable temperatures are not limited to a narrow range. In terms of factors associated with winter discomfort, some variables associated with poorer building quality (non-insulated cavity wall, and not full double-glazing) indicate that building factors do contribute to thermal discomfort and hence buildings ought to be improved. Somewhat worrying is that those in the lowest income quintile are more likely to experience winter discomfort than those in the highest income band. For summer discomfort, effect of predictors varied drastically depending on which room was considered. For living room discomfort, it was more variables that might characterize the occupant as more vulnerable (more likely to be in the house, more likely for those sick / disabled); however, this was not the case for bedroom discomfort. One potential issue with the logistic regressions was the presence of some multicollinearity between predictors which can lead to instable regression coefficients, i.e. it is not clear which variable really had an effect. For brevity, this could not be dealt with in this paper, but see e.g. Huebner et al. (2015a). It might be that when some regression coefficients would change if controlling for multicollinearity.

Acknowledgements
Funding for this research was provided by the Research Councils UK (RCUK) Centre for Energy Epidemiology, grant reference EP/K011839/1.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Cold Comfort: Thermal sensation in people over 65 and the consequences for an ageing population

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Abstract

In Australia the preference of most of the ageing population is to age in place. It is therefore necessary that the thermal environment in homes provides comfort for its occupants to promote healthy ageing. Houses that are too hot or too cold are not only unpleasant to live in but may pose a health risk, especially amongst a vulnerable population.

The study reported in this paper is part of larger research into the thermal practices of people over 65 in Adelaide, South Australia. The aim of this study was to examine the thermal comfort of people over the age of 65 during the coldest winter month as well as during a record breaking hot summer month in 2015. A longitudinal comfort study of both living areas and bedrooms was conducted in 10 South Australian households during these periods. The comfort vote survey included the ASHRAE 7-point sensation scale and the McIntyre 3-point preference scale.

Preliminary data indicate these occupants find thermal conditions comfortable at cooler temperatures than predicted by the ASHRAE thermal comfort standard, with significant numbers of neutral votes occurring at lower temperatures than expected. During the warmer conditions however, the majority of neutral votes were in the region predicted by the model.

This research presents a unique perspective of household thermal comfort in older people during two extremes in temperature conditions in Adelaide. This may have implications for healthy housing design for an ageing population.

Keywords: ageing, health, thermal comfort, heat wave, Australia

1 Introduction

Like much of the world, Australia has a rapidly ageing population. By the year 2061, over 20% of the nation's population will be aged 65 or over (Australian Bureau of Statistics 2013). Currently the preference for older Australians is to 'age in place', to remain living independently in either their existing family home or in a smaller private residence. Aged care and other government agencies are then able to provide various levels of care through Home Care Packages (Department of Social Services, 2015).

Ideally the home is a place that is comfortable and healthy. Many housing factors can contribute to the heath of the occupants; temperature, drafts, air quality, damp and associated mould have all been shown to negatively affect occupant health (Howden-Chapman 2004; Martin et al. 1987; Williamson et al. 1997). Conversely, programs which improve insulation and heating in cold climates have shown positive influences on health (Critchley et al. 2007; Howden-Chapman et al. 2008). In this study, the focus is on the thermal environment, and the thermal comfort of older people. Research indicates a higher degree of health problems and deaths during extremes in both heat and cold, especially amongst older people (Nitschke et al. 2007; Wilkinson et al. 2004). These health problems include respiratory and cardiovascular illnesses in the colder temperatures (Analitis et al. 2008) and kidney diseases in extreme heat (Bi et al. 2011).

When examining thermal comfort, it is important to examine not only the environmental conditions themselves, but more importantly the occupant's sensations in those conditions. This is especially true of the older population. Research has shown that as the human body ages, the body's thermoregulatory response is altered and it loses some of its ability to sense heat and cold. Measurements of patterns of sweating, shivering and vasoconstriction in older people have shown quantifiable differences than in younger people (Anderson et al. 1996; Drinkwater et al. 1978; Wagner et al. 1972), with these reactions being slower and/or decreased. A slower response to changes in the external conditions has the potential to cause accidental hypo- or hyperthermia. By studying the self-reported thermal comfort of older people, this study aimed to determine whether older people experience a sensation of comfort in their homes despite the fact the conditions may be considered uncomfortable or indeed unsafe and unhealthy.

2 Context

Adelaide is located at 34.9^{o} South Latitude and 138.6 ^{o} East Longitude, and has a hot Mediterranean climate (Sturman et al. 1996) with hot dry summers and mild winters. Summer extends from December through to February and winter from June to August. The average maximum temperatures in Adelaide during December and February are 27.2^{o} C and 29.5 ^{o} C respectively; however, the city experiences frequent heat waves, during which temperatures often exceed 40^{o} C. These heat waves can occur anywhere from November to March. In July, the average daily minimum and maximum are 7.5^{o} C and 15.3^{o} C respectively (BOM 2016a)

In 2015, conditions in both July and December were markedly different from typical years. July is typically the coldest month of the year; however, whilst the average minimum in July was 6.7 ^{o} C, the temperatures dropped as low as 1.8 ^{o} C, and both maximum and minimum temperatures across the city were close to 1 degree colder than average across the city (BOM 2015). Typically February is the hottest month in Adelaide; however, December 2015 recorded averages equal to that of February and was the hottest December on record for the Adelaide region. Maximum temperatures were 5.4 degrees higher than average, and minimum temperatures more than 2.5 degrees above average (BOM 2016b). Heat wave conditions occurred in the third week of December, with six consecutive days over 36 degrees, four of which exceeded 40 degrees. In the month of December there were 7 days with temperatures over 40 degrees, the highest number of days above 40 degrees in a single month on record. For this reason, this study focuses on the experiences of older people during these two months, to compare and contrast their thermal comfort experiences during these extremes in conditions.

Due to the aforesaid hot Mediterranean climate, much of the focus of public health messages is on extreme heat conditions. Indeed, as there are frequent heat waves this seems to be the prudent approach. However, recently attention has turned to the dangers of cold, even in mild winters (Cheng 2015; Gasparrini et al. 2015). Unfortunately houses in Adelaide are typically not designed for colder conditions, with few houses having central heating and many having fixed heating only in the living area, and relying on portable heating appliances for other rooms. Similarly few houses, especially older ones, have whole house cooling, but may have individual reverse cycle appliances (or similar) in living rooms and bedrooms.

3 Methods

3.1 Participants

Participants were recruited from an earlier survey of housing and health in which they could volunteer for the longitudinal study (Bills and Soebarto 2015). For the earlier survey, the participants were recruited through invitations distributed by local councils and church groups. Some participants were also recruited through the University of the Third Age, “a worldwide organisation for 'over 50s' who wish to expand their interest in the world, increase their knowledge by learning and to pass on the experiences of life to others” (University of the Third Age, n.d). In total, 18 households participated in this longitudinal study; however, this paper only focuses on results of the study from 10 households (4 men and 7 women), as the collection of data from the other participants is still ongoing. These 11 participants completed comfort vote surveys during the study period. One participant did not complete the study due to ill health.

3.2 Protocol

Unobtrusive data loggers were installed in the bedrooms and living rooms of the participants’ houses. These recorded air temperature, humidity and globe temperature every 15 minutes. Participants were asked to regularly complete short comfort vote surveys which included the ASHRAE 7-point thermal sensation scale (ASHRAE 2013) and the McIntyre 3-point preference scale (McIntyre 1973). They were asked to rank their clothing pictorially out of 6 and their activity level pictorially out of 4 (see Figure 1). They were also asked to indicate whether other environmental factors such as ventilation and the operation of any heating, cooling or fans were employed. Times and dates in July and December when surveys were completed were recorded and responses matched with data from the loggers.

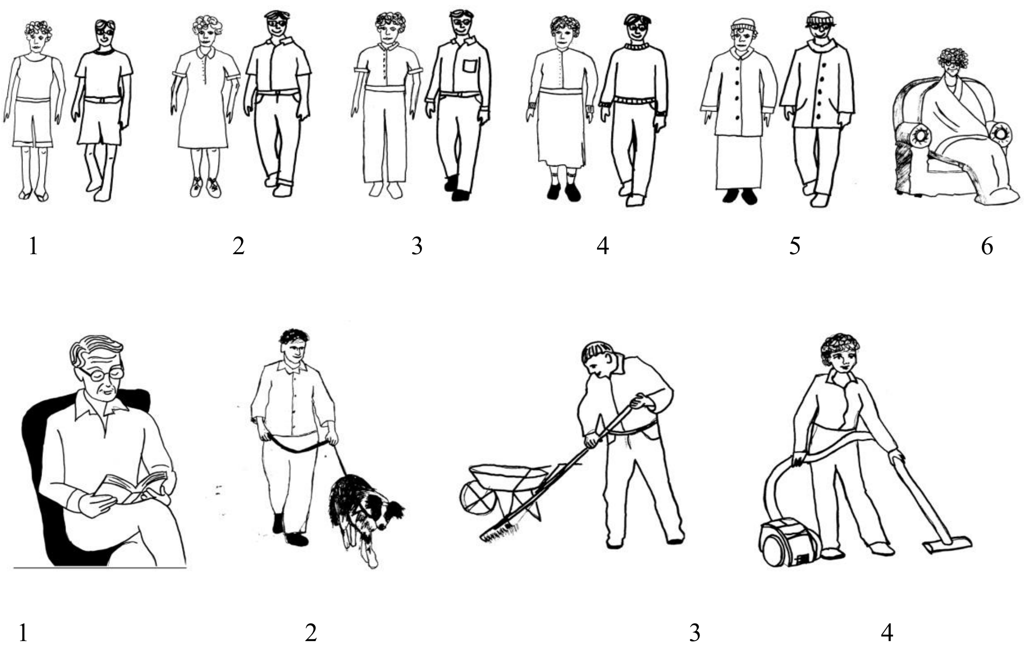


Figure 1 – Pictures used to represent clothing and activity levels in the comfort vote survey

The air temperature and humidity data at the times of the neutral sensation votes (3, 4 or 5 on the ASHRAE 7-point sensation scale) were analysed using the Graphic Comfort Zone Method of ASHRAE 55 (ASHRAE 2013). This model was chosen over the Adaptive thermal comfort model due to the high percentage of votes filled out when heating or cooling was in use. The votes were filtered to remove responses made when very high levels of clothing were being worn, or when very high levels of activity had been completed in the last 15 minutes before completing the survey.

4 Results

4.1 Outdoor and Indoor Conditions

Average outdoor maximum and minimum temperatures were sourced from the Australian Bureau of Meteorology and were taken from the weather stations closest to the participating houses. Table 1 shows the comparison between the average outdoor conditions during the study and the average conditions inside the 10 houses studied.

In July, the average, minimum temperatures in the living rooms and bedrooms were close to the outdoor maximum. Maximum temperatures in the living rooms were slightly warmer than in the bedrooms. Many respondents reported not using or not having heating in the bedrooms, which would account for this slightly cooler temperature. All had some form of heating in the main living areas, and movement of this warmer air upward and outward could potentially pull warm air from other areas, like the bedrooms, into these living spaces. However, solar gains from windows and thermal mass from the brick walls, would act to keep the bedrooms warmer than the outside conditions during the day in July.

Table 1: Average outdoor and indoor maximum and minimum temperatures

	Average Outdoor Maximum (°C)	Average Outdoor Minimum (°C)	Average Living Room Maximum (°C)	Average Living Room Minimum (°C)	Average Bedroom Maximum (°C)	Average Bedroom Minimum (°C)
July	14.1	6.7	20.8	14.8	18.0	14.8
December	32.5	18.1	26.7	22.9	26.7	23.0

In December, the average indoor maximum in the living rooms and bedrooms was approximately 6 degrees cooler than the average outdoor maximum. In general the living rooms and bedrooms were very similar in temperature, despite fewer participants reporting using air conditioning in their bedrooms than in their living rooms. The movement of cooler air from the living areas into the bedrooms as well as the effect of shading and insulation may explain these temperatures.

4.2 Thermal sensation votes and preference

In total, 183 thermal comfort votes were completed by participants in July, and 147 in December. Overall, more neutral thermal sensation votes (TSVs) of slightly cool, just right, slightly warm were recorded during December (78.4% neutral votes) than July (47.7% neutral votes). There were subsequently more votes at the extreme ends (cold and hot) during July than December (29.3% vs 6.3%) (Figure 2). This is despite the fact that during the cold July period, participants recorded having heating on 54% of the time in the living area and 41% of the time in the bedrooms. In contrast, participants only recorded using cooling 40% of the time in the living room and 31% of the time in the bedroom in December.

Despite the higher number of 'cold' votes during the winter, participants were less likely to express a desire to be warmer when it was 'cold' (66.7% of the time) than they were to express a desire to be cooler when voting at the 'hot' end of the scale (100% of the time) (see Figure 3). When they reported being 'cool' or 'warm', they were still slightly less likely to report desiring change in July (46% of the time) than in December (58.8 % of the time).

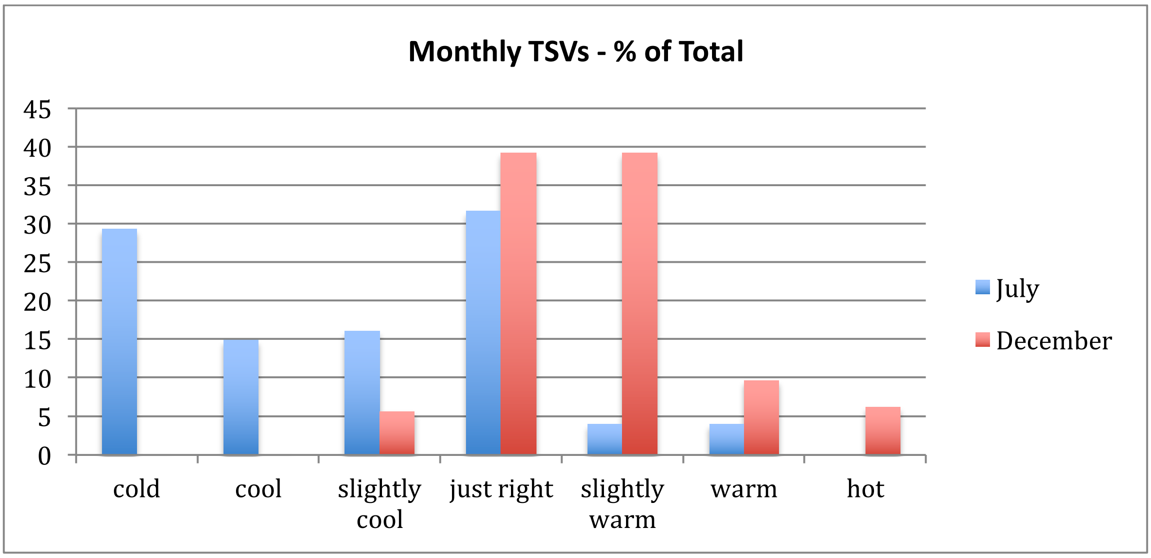


Figure 2: Percentage of total of each TSV separated by month.
Votes in July are in blue. Votes for December are in Red

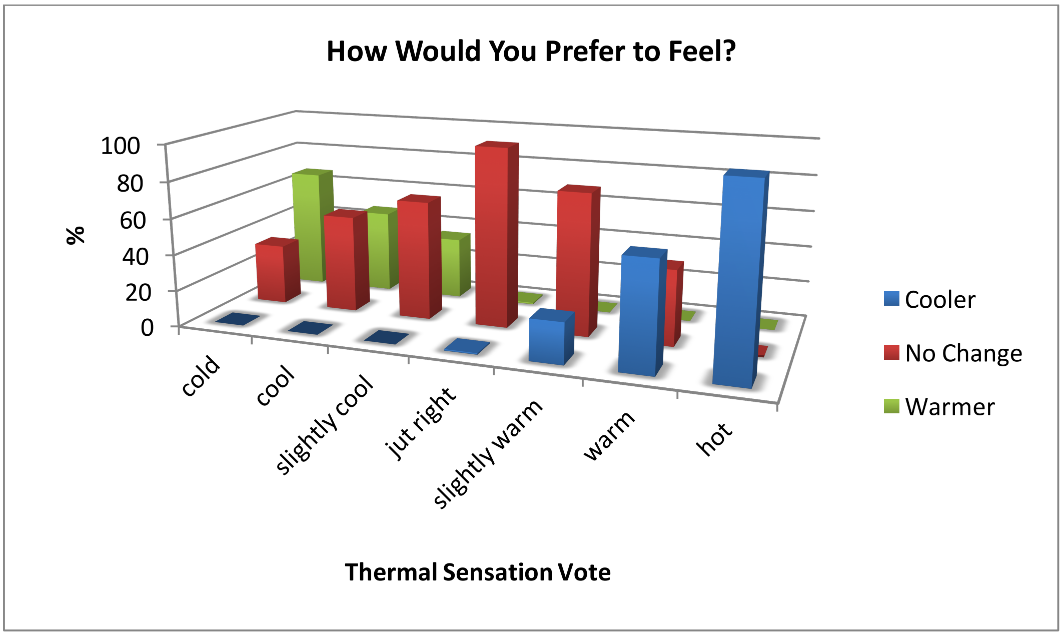
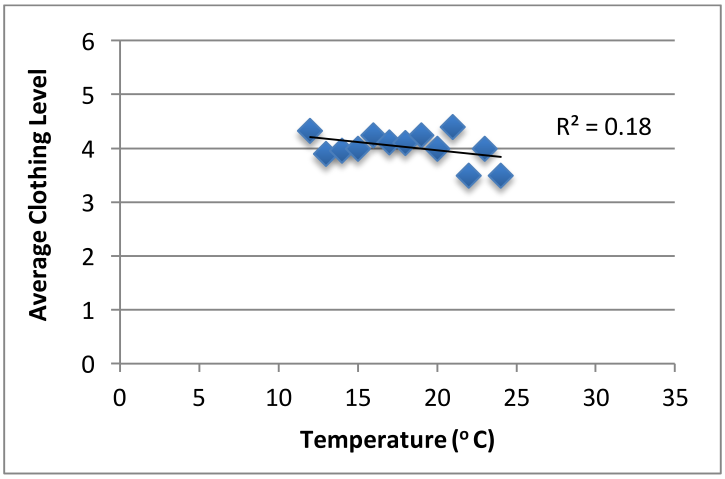


Figure 3: Participants preferences for change by thermal sensation vote

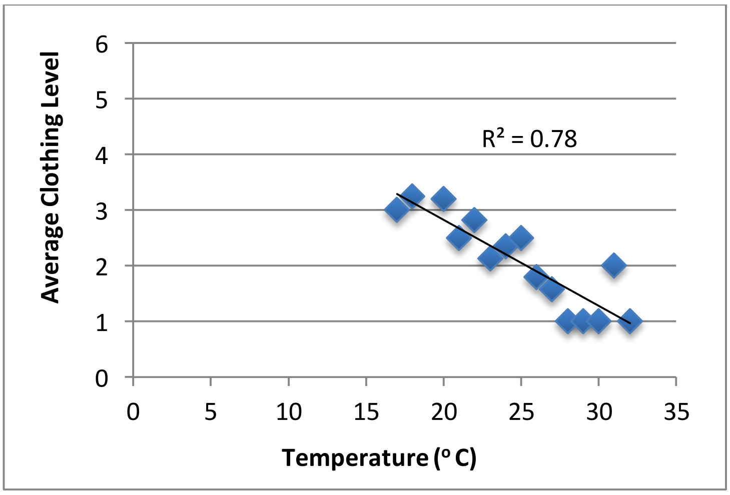
4.3 Clothing

The average clothing level was obtained by binning the clothing scores per degree of indoor operative temperature and calculating the mean.

During July, the results showed that there was no correlation between the clothing worn and the indoor air temperature (Figure 4a). The clothing worn remained very similar regardless of the temperature, around a level 4 (refer to Figure 1). In December there was a clear negative correlation between air temperature and clothing worn. Participants reported much lower levels of clothing as temperatures increased (Figure 4b).



(a)



(b)

Figure 4: Binned average clothing levels for each degree of temperature in (a) July and (b) December.

4.4 Comparison with ASHRAE 55 acceptable range of temperature and humidity

When comparing the air temperature and humidity at the times neutral votes were recorded (figure 5) with ASHRAE 55 acceptable range of temperature, there is a difference to experiences of comfort in July when compared to December. In July, participants were more likely to express feelings of comfort at colder temperatures than suggested, whilst in December participants expressed comfort in conditions more aligned with the operative temperature zone outlined in solid lines (see Figure 5). This was observed not only when the neutral votes were considered, but also when participants indicated no preference for a change in thermal conditions, and when participants indicated that conditions were thermally acceptable, as shown earlier in Figure 3. In contrast, most of the neutral votes collected during the December period fell within the comfort zone, with far fewer falling outside.

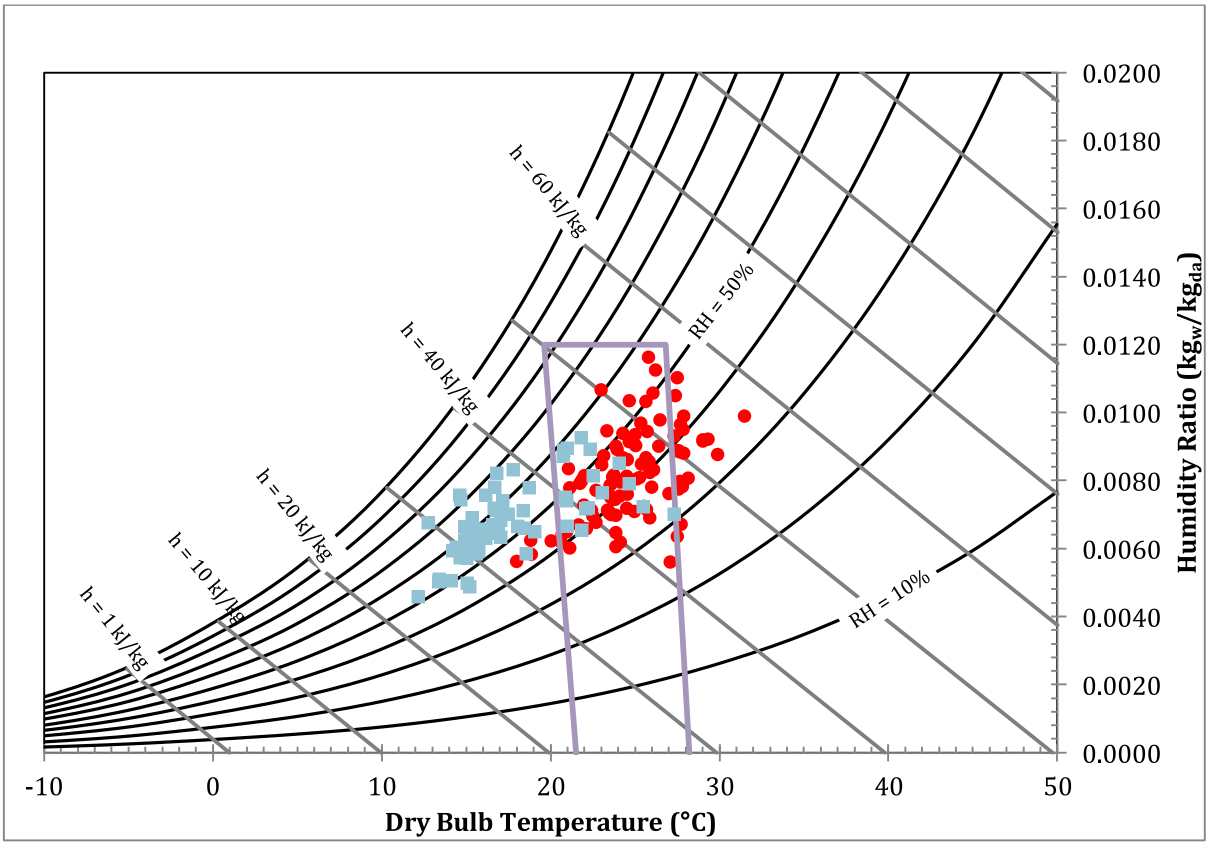


Figure 5 – ASHRAE-55 Acceptable Comfort (1 clo Zone) - Temperature and humidity ratio at times when neutral Thermal Sensation Votes (3,4, or 5 on the ASHRAE thermal sensation scale) were recorded by participants. Votes recorded in July are labeled blue whilst those recorded during December are labeled red
Note: The Comfort Zone assumes clothing 0.5 ≤ clo ≤ 1.0 and metabolic rate 1.0 ≤ met ≤ 1.3
Source: Adapted from ASHRAE 55-2013, Figure 5.3.1

5 Discussion

Overall, the older people in this study expressed sensations of thermal comfort at colder temperatures than predicted by the ASHRAE standards most of the time, but rarely reported feelings of comfort at warmer temperatures than predicted. Their neutral thermal sensations during the hot month of December were largely within ASHRAE's acceptable operative temperature and humidity, despite very hot weather throughout the month. In the cold months however they expressed feelings of neutral thermal sensations at temperatures as low as 12 degrees inside, even when only wearing moderate levels of clothing and at times when they were largely at rest.

There are a number of reasons that older people might describe feelings of thermal comfort in conditions that are otherwise considered uncomfortably cold. First, the results indicated that the participants wore heavier clothing in July, with majority wearing long pants, long sleeve jumpers or sweaters, socks and shoes. The results also showed that there was very little correlation in July between the level of clothing and thermal sensation in winter (R^2 = 0.18) compared to those in December (R^2 = 0.78, Figure 4b), indicating that they wore similar clothing throughout July regardless of the indoor temperatures. Wearing heavier clothing seems to be the personal strategy that older people in the study employed to keep themselves comfortable, rather than, for example, turning on the heater. However, it is also worth noting that upon closer examination, the clothing level at lower temperatures (i.e. 13 to 14 degrees) was slightly less than at temperatures above 14 degrees (Figure 4a) even at times when they were largely at rest. Physiological changes associated with age, behavioural factors and adaptations to conditions over the life course are all possibilities as suggested by Hitchings et al. (2011) and Horvath et al. (1955) respectively, but the exact reason for this unexpected clothing value at lower temperatures is still unknown. Also, despite the exclusion of votes where high levels of clothing were reported, and despite of every effort taken to tailor the survey to the clothing typically worn by older people, the actual clothing worn by the respondents in cooler conditions may still be heavier than assumed by the ASHRAE standard for winter (i.e. 1.0 clo). Nevertheless, further research is needed to investigate these peculiar results.

Ageing brings with it inevitable physical changes. The metabolism slows, and general frailty increases which can lead to a decrease in physical activity, all of which changes the body's response to thermal conditions. Ageing has also been shown to reduce the body's ability to feel changes in temperature. When examining the data from the cold month of July, any of these could be contributing factors. For instance, a person's activity level can influence their perception of thermal comfort. In general, participants were more active during July than in December, with 50% reporting being at rest at the time of the survey, whereas in December participants reported being at rest 66% of the time. There was a range of frailty in the participants, with some being very sedentary and some being quite active. However, when the data were analysed by participant, respondents were equally represented across the whole range of votes. In contrast, during the warmer weather, participants' votes were largely in the expected range, suggesting that at least in warm conditions they are sensing temperature as expected. Further biomedical testing of metabolic rate and other physiological changes may help in understanding the changing thermal perceptions of older people, and why these changes seem to be limited to colder conditions.

Regardless of the reason for the acceptance and tolerance of colder temperatures, there are concerns about various health conditions that may occur when older people are chronically exposed to cold temperatures. During the study period between the months of May and October, 2 of the female participants reported having fallen, and 2 male participants also reported that their wives (who were not completing comfort vote surveys) had fallen. Falls are of a particular health concern amongst the older population, and their occurrence has been linked to colder temperatures in women(Lindemann et al. 2014) Fractured bones, especially hips are a common result of a fall. Aside from injuries sustained in a fall, other problems can arise. Around half of those who fall are unable to get up unassisted (Tinetti et al. 1993). If left on the floor for a prolonged period, there are risks of hypothermia, pneumonia, pressure sores, dehydration and in some cases death (Tinetti et al. 1993). For those who fall and fracture a hip, there is significantly increased mortality; reports of between 12 and 37% mortality within 12 months exist in the literature (Foster 2015). Half will not be able to continue to live independently following the fracture (Wolinsky et al. 1997). Whilst there are other contributing factors, provision of a healthy thermal environment may thus be important in preventing falls amongst the aged and the subsequent morbidity and mortality.

Along with the changes in sensation amongst older people, there are certain behaviours and attitudes which may also be at play. Older people may have a tendency to be reluctant to identify as an 'old person' and therefore distance themselves from the problems and vulnerabilities of ageing (Day et al. 2011; Hitchings et al. 2011). Some may not regard themselves as being vulnerable due to age and may therefore ignore public health warnings from government and other agencies regarding health and wellbeing during extremes in weather which may be aimed specifically at older people (Day et al. 2011). Having always coped in the past they see no reason to change their behaviours now. This makes a certain amount of sense when potential loss of sensation to cold is taken into consideration. However dissociation from vulnerability could in fact make an older person less likely to take steps to adapt to a cold environment, and therefore increase the risk of health complications from the cold.

Assuming the operative temperature zone assumed by the ASHRAE Standard is appropriate to the Australian context, it would appear that the participants in this study are largely able to keep their houses at an appropriate temperature during hot conditions. In colder temperatures, it seems they keep their houses cooler than would be expected and recommended. Despite this, these participants expressed satisfaction with these cooler conditions. It is possible that this is a cultural acceptance of the cold, due to the fact that the winters in Australia are generally considered to be mild. It is also possible that extensive public health campaigns in recent years have made participants more aware of the dangers of the heat, and therefore more likely to keep their houses cooler during the extreme heat. These public health campaigns are founded in research that has examined mortality during the summer months ((Hansen et al. 2011; Hansen et al. 2008; Nitschke et al. 2011), but as yet few studies of morbidity and mortality during winter have been conducted in Adelaide. Studies during colder weather are complicated by the chronic nature of conditions associated with the cold, such as respiratory infections, as opposed to the more acute nature of health conditions which arise during extreme heat, such as heat stroke and dehydration.

One of the difficulties when conducting residential thermal comfort studies in Australia is the lack of understanding of how the public at large experience thermal comfort to compare possibly outlier groups against. It is reasonable to assume that the climate and culture of Australia means the operative temperature zone used by the ASHRAE standard is not the zone in which Australian people will feel most comfortable, despite the predictions of the thermal comfort model. Such a study has yet to be undertaken in Australia, so any conclusions that may be drawn from residential studies of particular groups are cautious at best. In terms of creating policies and building standards that may improve conditions for older people, the preferences of the general population must also be understood in order to fully understand any changes that are occurring.

6 Conclusion

Some older South Australians appear to experience sensations of acceptable thermal sensations in a wider range of conditions that would otherwise be predicted by the ASHRAE Standard. This study of thermal comfort during the winter months shows experiences of neutral thermal sensation at colder temperatures than expected. It is still unclear what is causing this, and a number of factors including physical and physiological changes, behavioural changes and adaptations over time may be at play. Further research into the reasons for these observed results is required to make definitive statements about the cause. It is important to understand the mechanisms and any health consequences so that interventions can be recommended to ensure older people can remain healthy and comfortable in their own homes.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

The psychological factors that affect the mapping of thermal sensation to thermal evaluation

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Abstract

The physical environment leads to a thermal sensation, which is then evaluated by building occupants. The present study focusses on the relationship between sensation and evaluation. We asked 166 people to recall a thermal event from their recent past. They were then asked how they evaluated this experience in terms of ten different emotions (frustrated, resigned, dislike, indifferent, angry, anxious, liking, joyful, regretful, proud). We tested whether four psychological factors (appraisal dimensions) could be used to predict the ensuing emotions, comfort, acceptability and sensation. The four dimensions were: conduciveness of the event, who was responsible for the event, who had control and whether the event was expected. These dimensions, except for expectation, were good predictors of the reported emotions. Expectation was also useful for predicting thermal sensation, acceptability and comfort: the more expected an event was the more uncomfortable a person felt, and the less likely they reported a neutral thermal sensation. These results suggest a new way of conceptualising expectation and supports an embodied view of how subjective appraisals affect experience. Overall we show that appraisal dimensions mediate occupants' evaluation of their thermal sensation, this suggests an additional method for understanding psychological adaption.

Keywords: Emotion, appraisal dimensions, psychological adaption, thermal comfort

1 Introduction

1.1 Thermal environment, thermal sensation, and evaluative response

Treating thermal comfort as a problem of energy balances lends itself to a physiological approach, which has been very successful. However, adaptive comfort theory provides scope for a range of psychological factors to be considered. It indeed seems intuitive that there is some part of thermal comfort for which thinking and conceptualising is important and constitute of the overall experience (Clements-Croome, 2013). The aim of the present study is to reveal a mechanism whereby the thermal environment is conceptualised and this conceptualisation shapes thermal experience.

For the purpose of this investigation, thermal experience can be broken down into three components. Firstly, physical environments, of temperature and air movement constitute the medium within which occupants operate. Secondly, thermal sensation is the interface between the occupant and the environment, which is predominately described using the ASHRAE thermal sensation scale that runs from cold, through cool, neutral, warm to hot.

Thirdly, an occupant's evaluation of their thermal environment, conventionally satisfaction, comfort and acceptability are used for evaluation (ASHRAE, 2010).

This study looks at the psychological factors that shape how thermal sensations are evaluated. To do this we look at how four appraisal dimensions (the psychological factors) shape acceptability, comfort, thermal sensation and emotions (the evaluations) resulting from the thermal environment. By doing this we show that the way people think about (appraise) their environment is important for their thermal experience.

1.2 Appraisal theory: factors that affect the evaluation of sensations

A fundamental question of emotion psychology is how can two people experience the same situation and have different subjective experiences. Fifty years of work on the topic suggests that there is an appraisal step between sensation and evaluative response (Figure 1) (Arnold, 1960; Scherer *et al.*, 2001). It is this subjective appraisal process that quite literally shapes the unique emotional response to a particular stimulus, giving rise to any one of a number of emotions from pride or joy to anger or frustration. In this light, two people can feel the same cold stimulus, but appraise the situation differently depending on whether it is conducive or obstructive to their respective need. For instance, two people could enter a cold office, and one feel happy because they are able to wear a favourite jumper, whereas the other could feel regret because they do not have appropriate clothing.

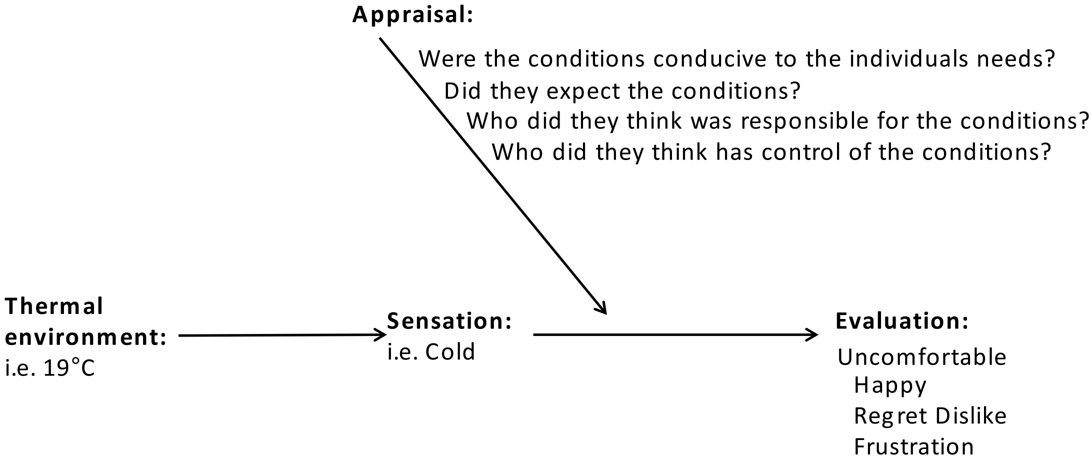

Figure 1: Appraisals mediate how sensations are evaluated.

The example above exposes the relationship between appraisals and the subjective experience that ensues. In this example, a single appraisal dimension of conduciveness is used to evaluate the thermal situation. One person appraises the situation as conducive to their goal (wearing their favourite jumper) and experiences positive emotions, while the other appraises the same environment as not conducive (it is unavoidably unpleasant) and so experiences negative emotions. These appraisal processes occur on a subconscious level; it is the role of theory to expose what they are and the experiences they lead to.

We propose to use appraisals as proxies for understanding how participants' life history will affect their conceptualisation of a given environmental stimulus or scenario. This life history gets reduced to a limited number of fixed appraisals. Appraisal theories of emotions attempt to define the finite set of appraisals that are relevant to a given situation (Scherer *et al.*, 2001). One of the simplest appraisals is whether a stimulus is consistent with a person's motives and desires or not, if it is then the resultant emotion is likely to be positive, if not then the emotion is likely to be negative.

Further appraisal dimensions can be used to predict which positive or negative emotions will be experienced. For example, another common appraisal is what or who is responsible for the cause of the experience. If a person appraises themselves as responsible (for a negative outcome) then regret will be felt. If someone else is appraised as responsible anger or dislike would be experienced. Finally, if circumstance was appraised as causing the event then frustration or resignation would be experienced. When several appraisal dimensions are used in conjunction they can predict specific emotions (Scherer, 2001).

The value of appraisal theory is that it provides a framework to understand how peoples' conceptualisation of a situation affects their experience. This sheds light on the mapping between sensation and evaluation. Four commonly used appraisals are goal conduciveness, responsibility for the situation, control, and expectation (Roseman, 1996; Scherer, 2001; Smith & Ellsworth, 1985). Used together they predict a range of positive and negative emotions (Table 1). We suggest that these four appraisals are similar to concepts that have been found to be important to the adaptive theory of thermal comfort. Therefore we aim to use them to understand the psychological causes of thermal experiences.

Table 1: Emotions mapped to different appraisal combinations (derived from Roseman, 1996; Scherer, 1999).

<table>
<tr><th rowspan="2">Responsibility</th><th rowspan="2">Control</th><th colspan="2">Goal conducive</th><th colspan="2">Unconducive</th></tr>
<tr><th>Expected</th><th>Unexpected</th><th>Expected</th><th>Unexpected</th></tr>
<tr><td rowspan="3">Circumstance</td><td>C</td><td colspan="2" rowspan="3">Joyful</td><td>Resigned</td><td>Frustrated</td></tr>
<tr><td>O</td><td>Anxious</td><td>Anxious</td></tr>
<tr><td>S</td><td>Indifferent</td><td>Indifferent</td></tr>
<tr><td rowspan="3">Other</td><td>C</td><td colspan="2" rowspan="3">Liking</td><td>Dislike</td><td>Dislike</td></tr>
<tr><td>O</td><td>Anger</td><td>Anger</td></tr>
<tr><td>S</td><td>Dislike</td><td>Dislike</td></tr>
<tr><td rowspan="3">Self</td><td>C</td><td colspan="2" rowspan="3">Proud</td><td colspan="2" rowspan="3">Regret</td></tr>
<tr><td>O</td></tr>
<tr><td>S</td></tr>
</table>

1.3 Models of thermal comfort

Both the heat balance and adaptive comfort approaches relate the indoor thermal environment to the evaluation of satisfaction and comfort (ASHRAE, 2010; de Dear & Brager, 2001; Fanger, 1970). The universal thermal climate index (UTCI) relates outdoor thermal environment to thermal sensation (Fiala *et al.*, 2012). These theories focus on the relationship between thermal environment and either thermal sensation or thermal evaluation. In their basic usage, they overlook processes that map a person's thermal sensation to their thermal evaluation (Figure 2).

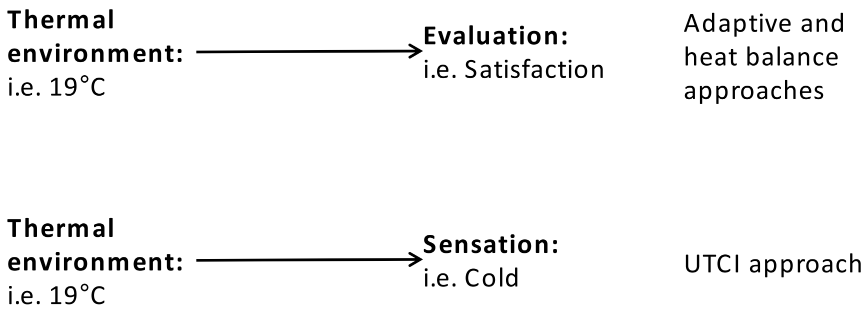

Figure 2: Thermal models tend to focus on the thermal environment and either sensation or evaluation. They tend to overlook the relationship between sensation and evaluation.

Physiological models of thermal experience aim to understand the energy flows within the body. They split the body into several layered sections, each with different thermal properties, which are used to predict the energy balance and temperature throughout the body (Fiala *et al.*, 2012; Schellen *et al.*, 2013). Then by understanding these body temperatures and their rates of change, thermal sensation can be predicted (Fiala *et al.*, 2012; Kingma *et al.*, 2012). This still leaves the problem of relating a given thermophysiological state to an evaluation of the thermal environment. Most often it is assumed that thermal neutrality is desired and equates to maximum comfort (Fanger, 1970).

Alliesthesia predicts why a neutral thermal sensation, or any other single thermal sensation, will not always lead to the same evaluation. As such it provides a theoretical approach to understanding the relationship between sensation and evaluation. It suggests that when a person is overheated they will find a cold sensation pleasant, while if a person is overcooled they will find a hot sensation pleasant (Cabanac, 2006; Parkinson & de Dear, 2015). However Alliesthesia relies on a physiological approach to explain the mapping between sensation and evaluation. In contrast, we aim to demonstrate psychological reasons that the same thermal sensation can lead to different evaluations.

Theories of psychological adaption suggest that expectation and perceived control shift or broaden the comfort band. Previous thermal experience shapes habituation and expectation, these shift the mapping between physical conditions and evaluation (Brager & de Dear, 1998; Ole Fanger & Toftum, 2002). This leads us to hypothesise that the greater the level of expectation the more likely someone is to be comfortable or accept the thermal conditions (H4TC).

In contrast, occupants' level of control broadens their comfort band (rather than shifts it) (Brager & de Dear, 1998). This leads us to hypothesise that the greater the level of perceived control the more likely someone is to be comfortable or accept the thermal conditions (H3TC).

There is little in the thermal comfort literature about the appraisal of responsibility for an event. However, Leaman and Bordass (2007) do talk about naturally ventilated buildings having a forgiveness factor. This leads us to tentatively hypothesise that when an event is appraised as caused by circumstance it will be more acceptable and comfortable than when it is appraised as caused by another person (H2TC).

There has also been work that is not so much concerned with psychological adaption but how certain environments can engender specific psychological states (Farshchi & Fisher, 2006); this is known as embodied cognition (i.e. the similarity and interrelation of physical and psychological experience). Firstly, parallels have been drawn between the feeling of physical and social warmth. It has been shown that experiencing physical warmth can promote interpersonal relations (Williams & Bargh, 2008) and experiencing social inclusion can affect the judgement of temperature and desire for hot and cold experiences (Zhong & Leonardelli, 2008). These findings suggest psychological factors can affect bodily sensations directly rather than by changing the nature of evaluations. This leads us to hypothesise that the effects on comfort and acceptance will be accompanied with an effect on sensation (H1E to H4E).

In this study we focus solely on thermal sensation and thermal evaluation. We test the utility of psychological factors (appraisal dimensions) for predicting thermal evaluations (comfort, acceptability and emotion). We also test whether the psychological factors have a systematic effect on thermal sensations. This provides a methodology for understanding multiple psychological factors at one time. It also elucidates whether psychological adaption changes the mapping from sensation to evaluation or changes sensation itself.

1.4 Hypotheses

We related the above four appraisals of interest to thermal comfort theory. This provides us with a set of hypotheses that use the appraisals to explore psychological adaption.

> H1TC: People who consider the event to be conducive to their needs are more likely to feel: comfortable and find their thermal sensation acceptable.
>
> H2TC: People who consider circumstances, rather than another person, responsible for the event are more likely to feel: comfortable and find their thermal sensation acceptable.
>
> H3TC: People who have high perceived control of their office environment are more likely to feel: comfortable and find their thermal sensation acceptable.
>
> H4TC: People who expected the event are more likely to feel: comfortable and find their thermal sensation acceptable.

We further propose that appraisals affect the mapping of sensation to evaluation and are not embodied in the thermal sensation that people experience. To test this we reframe the first set of hypothesis in terms of thermal sensation. Given a lack of embodiment we expect only H1E to hold.

> H1E: People who consider the event to be conducive to their needs are more likely to feel: neutral rather than hot or cold.
>
> H2E: People who consider circumstances, rather than another person, responsible for the event are more likely to feel: neutral rather than hot or cold.
>
> H3E: People who have high perceived control of their office environment are more likely to feel: neutral rather than hot or cold.
>
> H4E: People who expected the event are more likely to feel: neutral rather than hot or cold.

The four appraisals of interest can also be related to common emotions (

Table 1). This provides us with a set of hypotheses that test appraisal theory.

> H1A: People who consider the event to be conducive to their needs are more likely to feel: joyful, liking or proud.

H2A: People who consider circumstances, rather than another person, responsible for the event are more likely to feel: resigned, anxious, frustrated or indifferent rather than dislike or anger.

H3A: People who consider circumstances, rather than another person, to control the environment are more likely to feel: resigned, frustrated or dislike rather than anger or anxiety.

H4A: People who expected the event are more likely to feel: resigned rather than frustrated.

2 Methods

2.1 Participants and buildings

As part of a wider field study focusing on evaluating the relationship between environmental factors and psychological experience, occupants of seven office buildings responded to our survey (N=166). The sample size is similar to other appraisal studies (Folkman & Lazarus, 1985, N=136-189; Roseman, 1996, N=182; Scherer & Ceschi, 1997, N=112). Respondents were a range of ages and genders (Table 2) and from seven different buildings (Table 3). Participants were rewarded with a snack of their choice.

Table 2: Summary of participants.

N	Female	Male	Undisclosed	18-34yrs	35+ yrs	Undisclosed
166	105	57	4	84	77	5

Table 3: Overview of buildings. NV= naturally ventilated, MM= Mixed mode, AC =fully air conditioned.

Building	N (resp.)	Occupier	Typology	Plan	HVAC
A	9 (18%)	Design	Open plan	Shallow	MM
B	9 (69%)	Academic	Open / cell	Shallow	NV
C	46 (17%)	Academic	Open / cell	Shallow	NV
D	29 (15%)	Academic	Open / cell	Shallow	MM
E	9 (18%)	Design	Open plan	Shallow	NV
F	25 (2%)	Charity	Open plan	Deep	AC
G	39 (26%)	Design	Open plan	Shallow	NV

2.2 Questionnaire development

Tapping into the subjective experience of an individual is a major challenge, the mere attempt to ask a question is likely to disrupt the unfolding experience altogether. To eliminate this disruption we chose to use a recall survey. This also allows us to access a much greater range of experiences than if it was necessary to be present, measuring the thermal environment as the experience unfolded. The reliance solely on user reported data, with little or no measurement of the physical nature of the stimuli, is common in psychology (Fontaine *et al.*, 2007) and is appropriate here because of this study's focus on the relationship between participants' sensation and their evaluation.

The recall survey started with a prompt for the participants to recall an event in detail. To do this they were asked to:

> *"Imagine a specific time when you have been aware of the temperature in your office and it has given rise to strong feelings. Describe what happened leading up to the event and how you felt."*

After this, a number of questions were asked about each of the four appraisal dimensions. Details of the questions and how they were combined can be found in the appendix. These were used to understand:

- Whether the participant felt the event was conducive to them (appraisal 1);
- Who or what they thought caused the event (appraisal 2);
- Who or what they thought controlled conditions in their office (appraisal 3);
- How much they had expected the event to happen (appraisal 4).

To finish the survey, there was an open response to describe feelings and a closed list of emotions to choose from: frustrated, resigned, dislike, indifferent, angry, anxious, liking, joyful, regretful, proud, or, none of these. Then three questions were asked about the participant's thermal experience, using a thermal sensation scale, a comfort scale and an acceptability scale.

2.3 Analysis technique

To test this theory, we examine whether appraisals have an effect upon emotions, acceptability, comfort and sensation. The model used compares the likelihood of a particular evaluation, dependent upon the score on an appraisal dimension. The most appropriate statistical model for this is a logistic regression model. This predicts the presence or absence of a factor (a set of emotions or acceptance) dependent upon an ordered factor (the appraisal dimension). An extension to this model is the ordinal logistic model, which predicts the likelihood of achieving a given level of comfort or sensation depending on an appraisal dimension.

Equation 1 shows the logistical regression model. The model comprises a linear function and a link function. Just as in a standard linear model the coefficients are derived so as to maximise the fit of the model. The link function $m()$ transforms the linear model to a probability of success, π_i bounded between one and zero. There are several functions that fit this criteria, the most commonly used are the "logit", "probit", "cauchit", "log", and the "complementary log log"(McCullagh & Nelder, 1989). In this study we compare all possible link functions and selected the best fitting model.

$$\pi_i = \mathrm{m}(\beta_0 + \beta_1 x_i + \beta_2 x_i + \dots) \qquad \text{Equation 1}$$

To compare the logistic models we used a chi square test of the deviance accounted for by the regression model. For both the logistic and ordinal logistic model we also characterised the model by the likelihood that the regression coefficients (β_i) are non-zero.

3 Results

3.1 The experiences reported

3.1.1 Sensation, comfort and acceptability

Participant were asked to report their thermal experience during the period that they recalled. Generally, they recalled times when they were at the extreme of thermal sensations, either hot or cold (Table 4). Most participants found this to be uncomfortable rather than very uncomfortable (Table 5). Overwhelmingly these conditions were found to be unacceptable (Table 6).

Table 4: Thermal sensation counts.

Thermal sensation	Count
Cold	30
Cool	6
Slightly cool	1
Neutral	8
Slightly warm	6
Warm	30
Hot	84
Undisclosed	1

Table 5: Comfort counts.

Comfort rating	Count
Very uncomfortable	42
Uncomfortable	84
Slightly uncomfortable	38
Comfortable	1
Undisclosed	1

Table 6: Acceptability counts.

Acceptability rating	Count
Not acceptable	129
Acceptable	33
Undisclosed	4

3.1.2 Emotions recalled

Participants were asked to choose an emotion that best matched their feelings from a closed list. No one reported a positive emotion or an emotion associated with personal responsibility, i.e. regret (Table 7). Mostly participants reported feeling frustrated, resigned or dislike. A smaller number of participants felt indifferent, angry or anxious. There were also sixteen who felt that none of the ten emotions fitted well with how they felt. Across buildings the trend was generally the same, except Building A and B where people were more likely to feel dislike and building F were they were more likely to feel angry (Figure 3).

Table 7: The emotions reported across all buildings.

Emotion	Count
Frustrated	74
Resigned	30
Dislike	20
None of these	16
Indifferent	10
Angry	8
Anxious	8
Liking	0
Joyful	0
Regretful	0
Proud	0

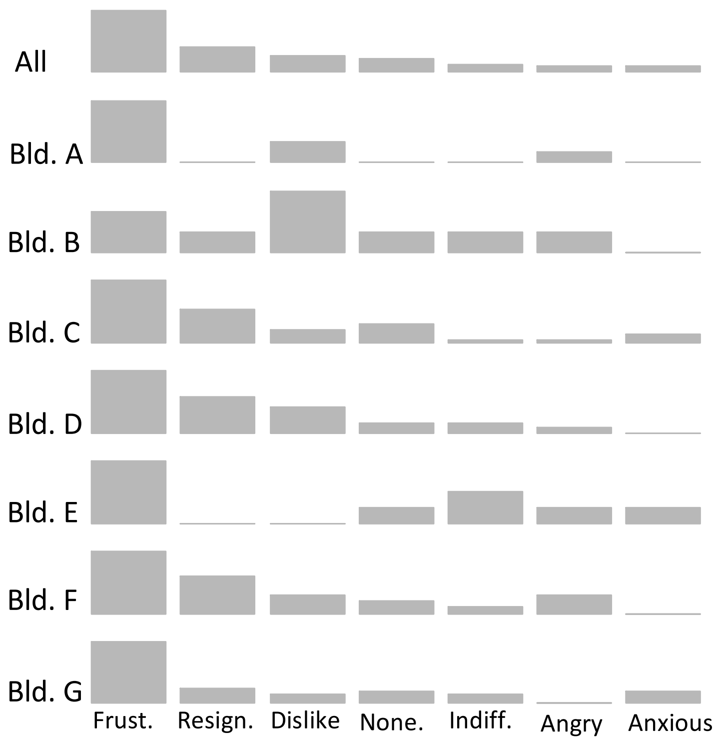

Figure 3: The emotions reported across all buildings.

3.2 The appraisals

Generally, participants reported that the event was unpleasant and worsened their ability to work. We also asked who they thought was responsible for the events leading up to their emotional experience (Figure 4). They rarely thought they themselves were responsible. We asked the participants who they thought was generally in control of the temperature in their office (Figure 5). Occupants of building F felt they had especially little control. Occupants of building C and D thought no person was in control. Across most buildings circumstances was thought to control conditions. Overall, there was a mixture of whether people thought the event they reported could have been expected. However, there is a lot of difference between buildings (Figure 6). Occupants from building E and F tended to report events that were unexpected. Elsewhere events reported had been expected.

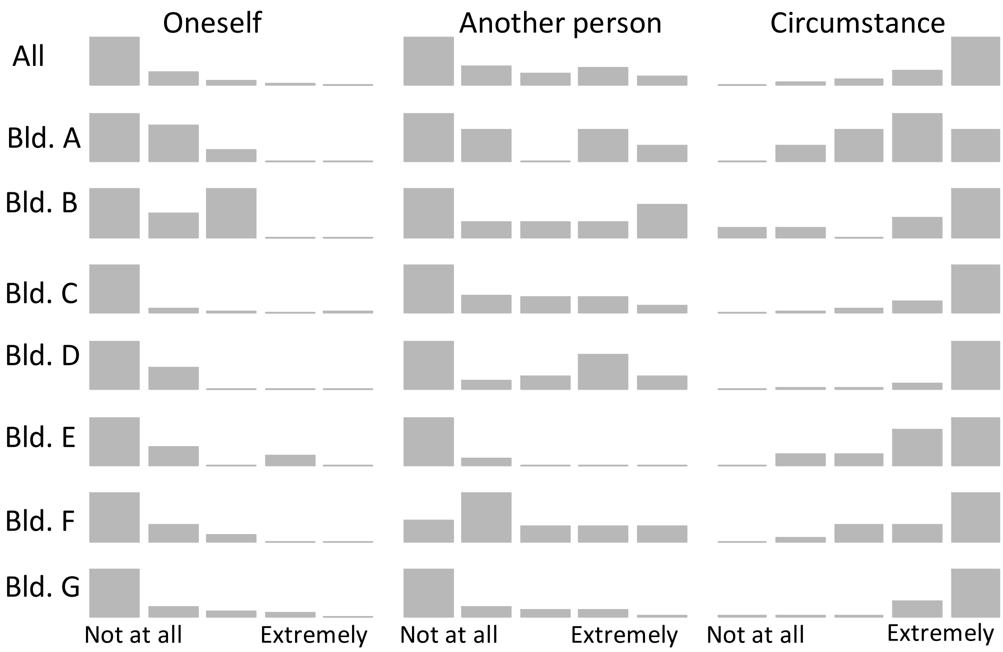

Figure 4: Who is appraised as responsible for the event, across the different buildings.

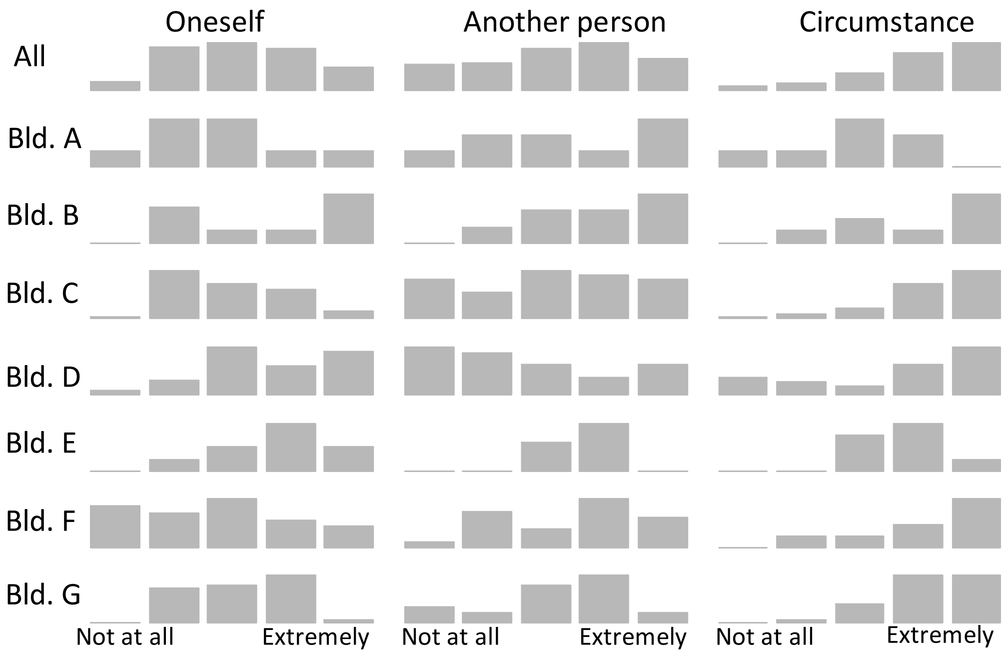

Figure 5: Who is appraised as in control in general, across the different buildings.

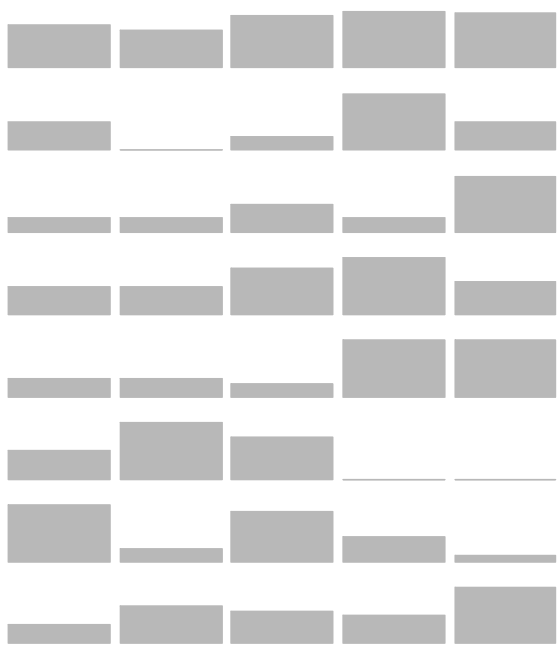

Figure 6: Appraisal of expectedness of the event, across different buildings.

3.3 Using appraisals to predict emotions

The absence of positive emotions and the absence of positive appraisals of conduciveness is in accordance with appraisal theory. However, the lack of positive emotions also means it is difficult to build a statistical model for validation. This partially support H1A.

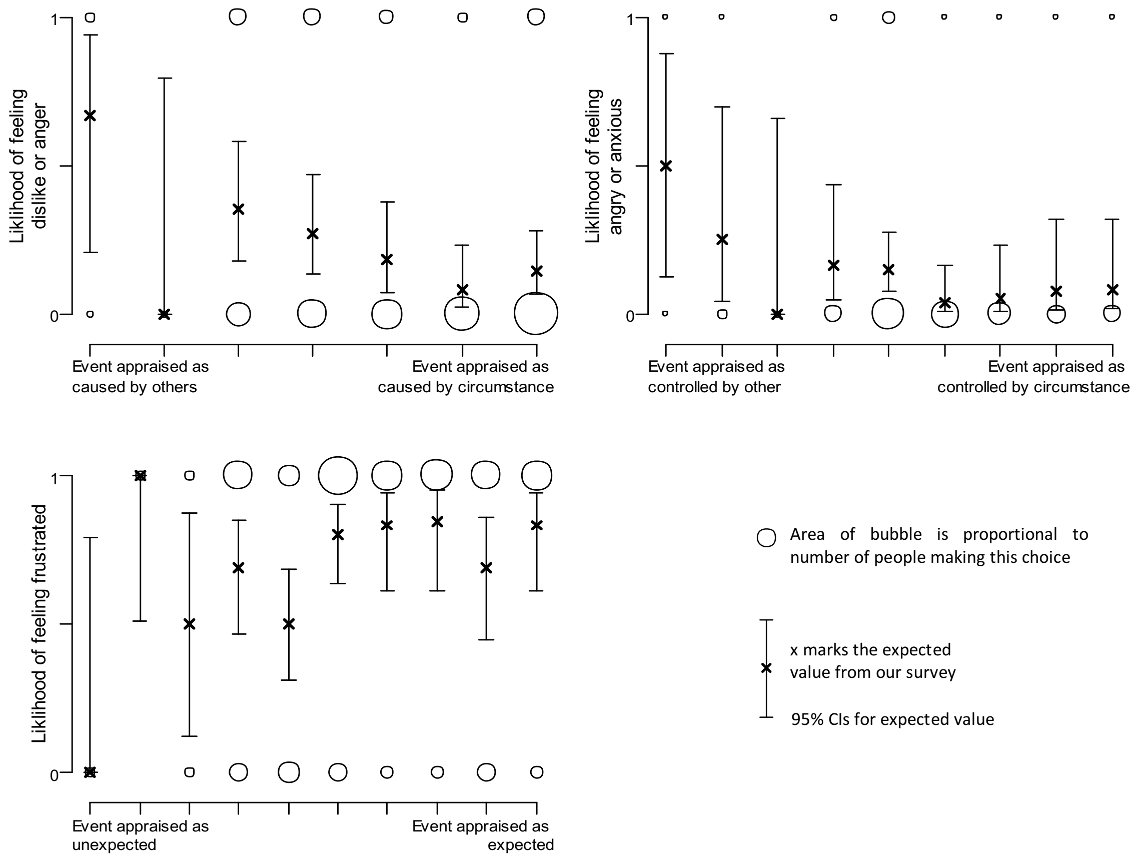

Figure 7: Appraisals of responsibility and control have an effect on the emotion reported.

For each appraisal the emotions reported were partitioned in two groups according to the relevant hypothesis, i.e. for responsibility, one group was aligned with the appraisal of caused by another (dislike and angry) and the other with appraisal of caused by circumstance (frustrated, resigned, indifferent, anxious). Where emotions were not relevant to the hypothesis they were discarded from the analysis (i.e. for H3A indifference is discarded). Figure 7 shows how the likelihood of feeling one set of emotions rather than another varies with participants' appraisal.

Table 8: Characteristics for emotions models.

Appraisal	Best link function	χ^2 goodness of fit		Model coefficients	
		χ^2	Single tailed	β_0	β_1
Responsibility	Poisson	7.1 (df=1)	***P***=0.01	-1.1 (***p***<0.001)	-0.28 (***p***=0.003)
Control	Cauchit	3.8 (df=1)	***P***=0.05	-2.7 (***p***<0.001)	-0.65 (***p***=0.03)
Expectation	Cauchit	2.70 (df=1)	***P***=0.10	-0.15 (***p***=0.81)	0.21 (***p***=0.11)

Several different link functions were tested to model the data, statistical tests of the best model are reported in Table 8. These suggest that there is a tendency to feel angry or dislike when another person is deemed responsible for the thermal experience, this supports H2A. The results also show a tendency to feel angry or anxious when another person is appraised as in control of the thermal experience, this support H3A. For the appraisal of expectedness there is not such an obvious pattern as for the other appraisals, this is counter to H4A.

3.4 Using appraisals to predict comfort and acceptability

The absence of positive appraisals of conduciveness means H1TC was not tested. Figure 8 shows how the likelihood of finding a thermal experience acceptable varies with participants' appraisal. Figure 9 shows the effect of the same appraisals on comfort rating.

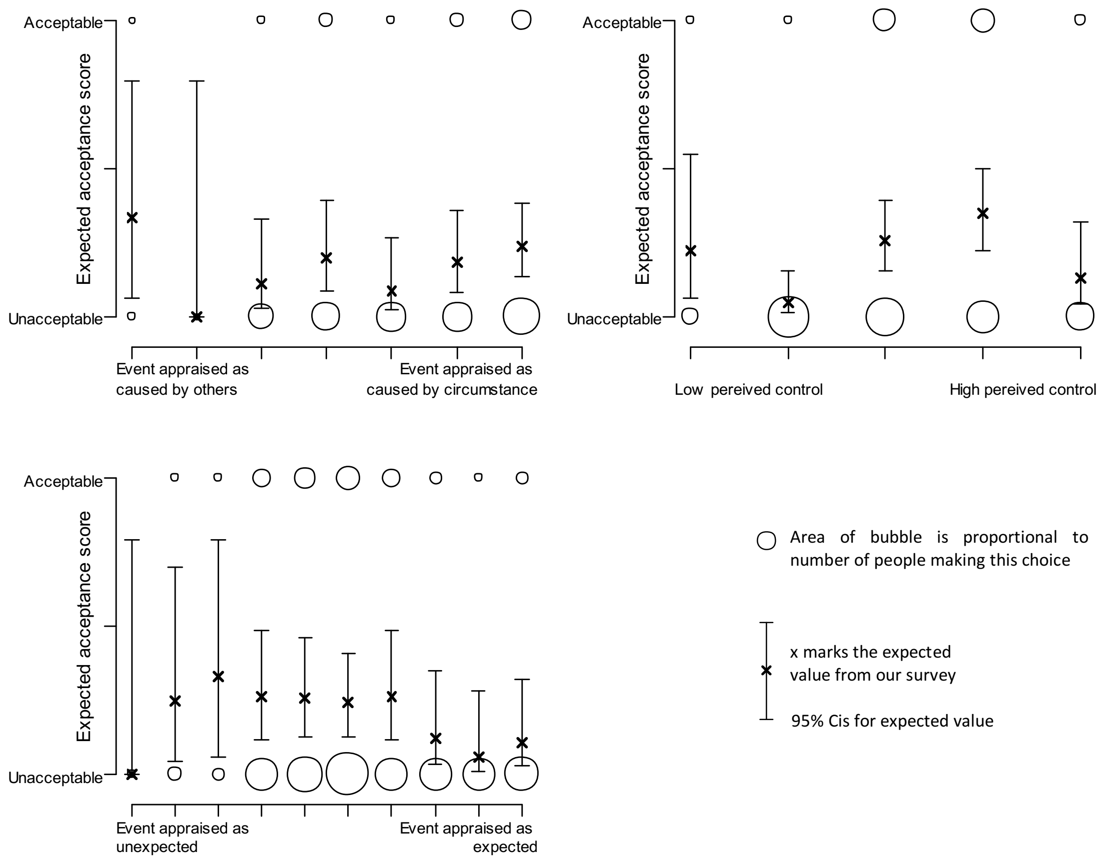

Figure 8: The appraisals of expectation has a small effect on acceptability.

Several different link functions were tested to model the data, statistical tests of the best models are reported in Table 9. These suggest that the appraisals have little effect on the acceptability of the experience (counter to H2TC and H3TC). There is a weak link that suggests that the more a situation is expected the less acceptable it is (opposite of H4TC). Similar results are found for comfort (Table 10).

Table 9: Characteristics for acceptability models.

Appraisal	Best fitting link function	χ^2 goodness of fit		Model coefficients	
		χ^2	Single tailed	β_0	β_1
Responsibility	Cauchit	0.82 (df=1)	***P*=0.37**	-2.2 (***p***<0.01)	0.24 (***p***=0.36)
Perceived control	Probit	2.46 (df=1)	***P*=0.12**	-1.3 (***p***<0.001)	0.16 (***p***=0.11)
Expectation	Probit	3.48 (df=1)	***P*=0.06**	-0.27 (***p***=0.39)	-0.10 (***p***=0.06)

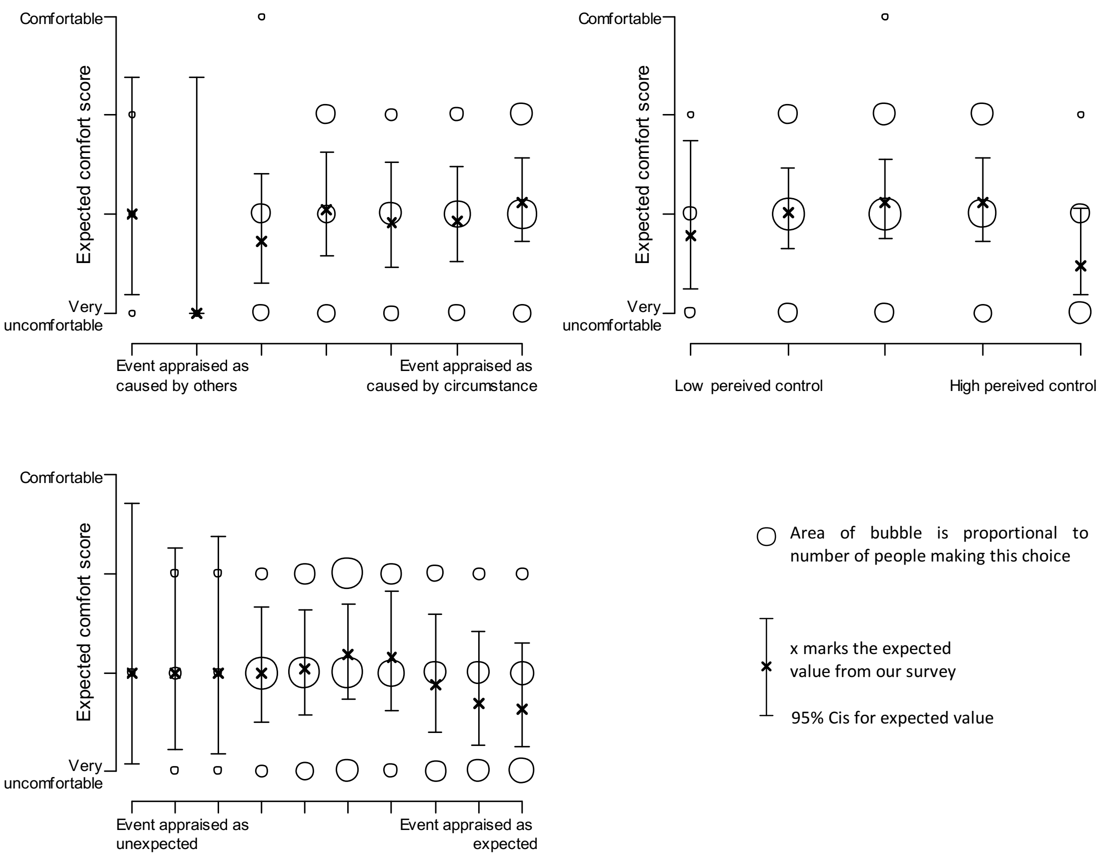

Figure 9: The appraisals of control and expectation have a small effect on comfort.

Table 10: Characteristics for comfort models.

Appraisal	β_1	SE	t-value	p-value
Responsibility	0.18	0.10	1.76	0.08
Perceived control	-0.20	0.13	-1.55	0.12
Expectation	-0.16	0.07	-2.26	0.02

3.5 Using appraisals to predict deviation from neutral sensation

The absence of positive appraisals of conduciveness means H1E was not tested. Figure 10 shows how the likelihood of reporting a neutral thermal sensation changes with participants' appraisal.

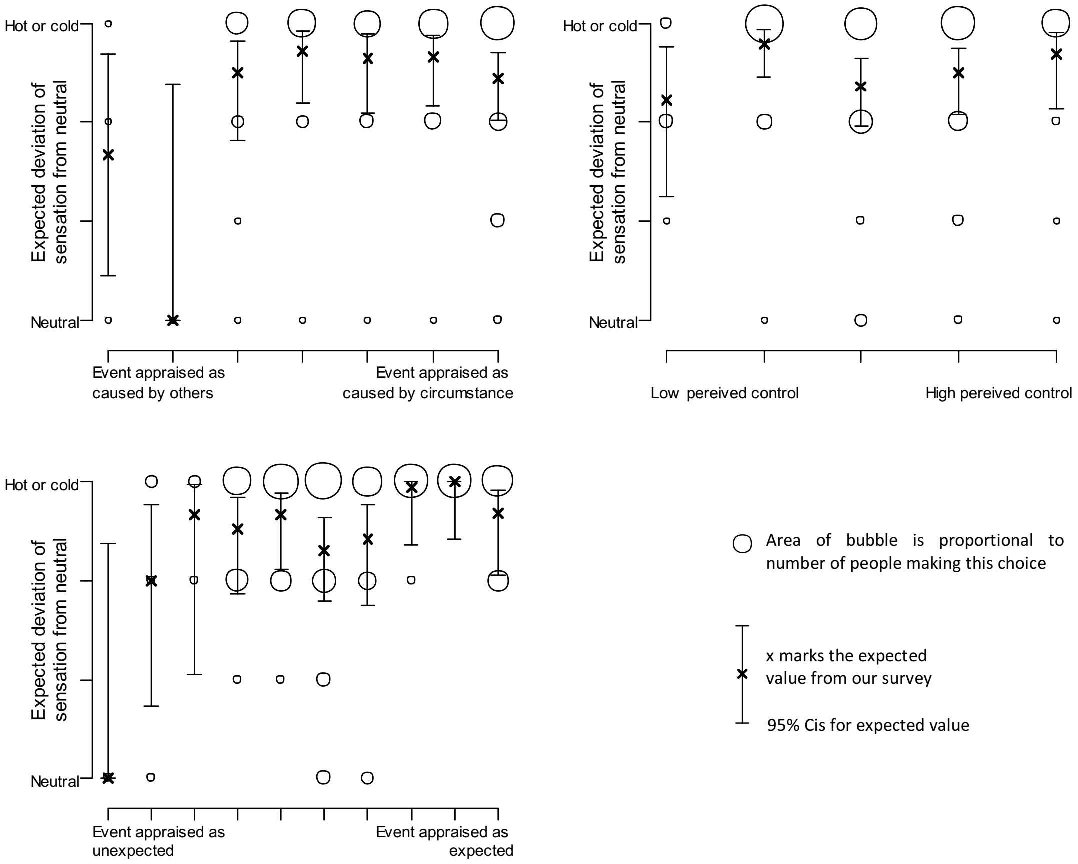

Figure 10: The appraisals of expectation has an effect on thermal sensation.

Table 11 shows the different model characteristics. The results confirm the null hypothesis for H2E and H3E. They run counter to H4E because the more expected an event is the less likely the person is to report being thermally neutral.

Table 11: Characteristics for sensation models.

Appraisal	β_1	SE	t-value	p-value
Responsibility	0.04	0.12	0.30	0.76
Perceived control	0.07	0.15	0.51	0.61
Expectation	0.24	0.87	2.75	0.006

4 Discussion

We have presented evidence that supports hypothesis HA1, HA2 and HA3. These results show that appraisal processes are important for shaping evaluation of the thermal environment. This work supports the notion that thermal experience is rich and complex, and requires understanding of how people conceptualise their thermal environment (Heschong, 1979). It is possible that appraisals, especially conduciveness, could be driven by the thermophysiological state of the participant, though there is no need for this to be the case.

The appraisals of responsibility and control were less useful for predicting the traditional thermal comfort evaluations of acceptability and comfort (H2TC and H3TC). This contradicts the extensive literature on perceived control and thermal comfort (Brager & de Dear, 1998; Hellwig, 2015). This anomalous result could be a side effect of the recall method. The recall method provides access to thermal events that are of high saliency. It is possible that perceived control does not affect the severity of the most extreme bad events.

The appraisal of expectation was successful in predicting comfort evaluation (H4TC). However, the correlation was opposite to that expected. The more an event was predictable or expected the more uncomfortable it was. Thermal comfort theory would predict that occupants acclimatise to events over time (Brager & de Dear, 1998). Our results, however, suggest that events that are novel and fleeting may cause less discomfort than recurring and predictable problems.

When we asked about expectation it seems that we were asking about whether a problematic or eventful situation was recurrent. Whereas the classic expectation of thermal comfort refers to repeated exposure to a ubiquitous climatic experience. Considering this it appears that our results draw attention to a different type of expectation effect. Namely that when problematic conditions are recurrent they becomes less and less acceptable.

The work on psychological adaption and embodied cognition suggest two different mechanisms through which psychological factors could affect thermal experience. The first suggests that psychological factors change the mapping between thermal sensation and thermal evaluation. These theories suggest that the benefit of personal control is that it reduces stress from mildly unfavourable conditions and effective control provides pleasure (Hellwig, 2015). In contrast embodied cognition suggest that the psychological factor would change thermal sensation itself. Interestingly a study carried out in a climate chamber by Zhou *et al.* (2014) suggest that perceived control actually changes both bodily sensation as well as reducing stress.

Our results support theories of embodiment because where appraisals have an effect on comfort they also have an effect on sensation (H2-4TC and H2-4E). However, this can only be taken as weak support for embodiment because we cannot trace our results back to a specific thermal environment. The inclusion of synchronous temperature measurements would provide conclusive evidence that the appraisal caused a sensation change as opposed to thermal sensations causing both comfort and appraisal.

The lack of positive emotions supports work that suggests temperature is a hygiene or basic factor responsible only for dissatisfaction (Herzberg, 1964; Kim & de Dear, 2012). However, it may be that people just chose to focus on negative events from their past. Future investigations could be contrived to test this by asking participants to describe two experiences and stipulate that one had to be positive. This approach would provide a greater range of experiences and hopefully contribute positive emotions to improve the analysis of H1A.

To improve the methods application and repeatability the survey could also be made easier to analyse. First, it should be made easier to obtain scores for each appraisal dimension. The current system of combining many ordinal responses is convoluted and builds in uncertainty to the method. Second, continuous response for variables could be used. This would mean that analysis could be done with genuine ratio scale numbers rather than an ordinal scale that was transformed into a ratio scale.

5 Conclusions

Appraisal theory provides a simplified way to encapsulate peoples' thoughts about their thermal experience. These thoughts not only cover a person's core temperature and peripheral thermal stimulus but also their past experiences and future desires. The theory does not try to predict why people make certain appraisals but it identifies which appraisals are key. Overall, our results show that it is the combination of these appraisals that shape a thermal experience. Multidimensional appraisals require multidimensional evaluations, and in this case we have successfully used ten emotions to describe thermal experience.

Our analysis suggests a new aspect to how expectation affects psychological adaption. We observe that recurrent problems (those that happened often and were predictable) resulted in greatest discomfort. People did not appear to adapt to them. This suggests an alternative way to conceptualise expectation.

With further modifications, the survey developed here could be used as a diagnostic tool where discomfort and dissatisfaction is caused because of psychological factors (as opposed to poor thermal conditions). From this it may be possible to design a programme of measures that tackled those psychological causes. This would be in contrast to current industry approaches that focus on costly technical fixes and chase ever more control over the physical environment.

Interpretation, meaning and other psychological approaches have been shown to play a part in subjective experience across a range of indoor environmental quality indices (Kwon *et al.*, 2011; Lehman, 2011). This leads us to suspect that this method could be used to understand emotions and their appraisals caused by multisensory experiences of buildings, beyond only thermal comfort.

Acknowledgements

This work would not have been possible without the Institute of Technology for a Sustainable Built Environment (TSBE), Reading University, the Engineering and Physical Science Research Centre (EPSRC) Doctoral Training Scheme (grant number EP/G037787/1) and Buro Happold Engineering. Queries regarding underlying research materials related to this study (for example data, samples or models) should be addressed to the corresponding author.

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Appendix I: Survey questions

№	Question	Possible answers	Subject
1	Imagine a specific time when you have been aware of the temperature in your office and it has given rise to strong feelings. Describe what happened leading up to the event and how you felt	Open response	Recall
2	How did the temperature feel leading up to the event?	Cold / Cool / Slightly cool / Neutral / Slightly warm / Warm / Hot	Sensation
3	Thinking about the lead up to the event... - To what extent did the experience improve your ability to work?	Not at all / A little/ Moderately / Quite a bit / Extremely	Appraisal: conducive
4	Thinking about the lead up to the event... - To what extent did the experience worsen your ability to work?		
5	Thinking about the lead up to the event... - Did you find the experience pleasant?		
6	Thinking about the lead up to the event... - Did you find the experience unpleasant?		
7	Who or what did you feel was responsible for the temperature leading to this specific incident? - Yourself		Appraisal: respons-ibility
8	Who or what did you feel was responsible for the temperature leading to this specific incident? - A colleague		
9	Who or what did you feel was responsible for the temperature leading to this specific incident? - Building/ facilities manager		
10	Who or what did you feel was responsible for the temperature leading to this specific incident? - The heating or cooling system		
11	Who or what did you feel was responsible for the temperature leading to this specific incident? - The building design		
12	Who or what did you feel was responsible for the temperature leading to this specific incident? - The activities going on at the time		
13	Who or what did you feel was responsible for the temperature leading to this specific incident? - The weather		
14	Regarding the event... - Did it occur suddenly and abruptly?		Appraisal: expected
15	Regarding the event... - Could it have been predicted in advance?		
16	Regarding the event... - How often does it happen in summer?		
17	Regarding the event... - How often does it happen in winter?		
18	In general who or what controls the temperature in your office? - Yourself		Appraisal: control
19	In general who or what controls the temperature in your office? - Colleagues on an ad hoc basis		
20	In general who or what controls the temperature in your office? - A particular colleague		
21	In general who or what controls the temperature in your office? - Building/ facilities manager		
22	In general who or what controls the temperature in your office? - Automated building system		
23	In general who or what controls the temperature in your office? - It is subject to the weather		
24	In general who or what controls the temperature in your office? - It is subject to the activities going on inside of it		
25	How easy is it to make yourself... - ...warmer in the office		
26	How easy is it to make yourself... - ...cooler in the office		
27	Thinking back to the experience you initially described how would you sum up how you felt in your own words? Please write a word or a short expression describing how you felt in the box provided	Open response	Recall
28	Which of the emotion terms below corresponds best to how you felt because of the experience	Angry / Resigned / Indifferent / Frustrated / Anxious / Liking / Joyful / Regretful / Proud / Dislike / None of these	Evaluation
29	Was the temperature acceptable?	Acceptable / Not acceptable	
30	Please rate on the following scale how YOU felt because of the experience?	Very uncomfortable / Uncomfortable / Slightly comfortable / Comfortable	
31	Please rate on the following scale how YOU felt because of the experience?	Open response	
32	Please enter your age group	<18 / 18-24 / 25-34 / 35-44 / 45-54 / 55-64 / >65	Demo-graphics
33	Please enter your gender	Male / Female	

Appendix II: Combination of independent variables

This section summarises how individual survey questions were combined into scores for each appraisal dimension. This was not done for conduciveness because of the results obtained.

For the appraisal of responsibility the participant's seven relevant answers were grouped in to those that suggested a circumstantial cause (i.e. building or weather) and those that suggest a cause by another person (i.e. colleague or building/facilities manager).Those that suggested a cause by self were discarded. Each of the two groupings were combined into a single score by taking the maximum rating across the group (i.e. extremely equals highest possible score). We took the maximum across the questions instead of an average because the emotional response is contingent on the relative importance of the highest scoring items in each group (i.e. overall did this participant think the event was more caused by a person, regardless of the specific person, or more caused by circumstance, regardless of the specific circumstance). These two groupings were combined into a single score by subtracting the person appraisal from the circumstance appraisal.

$$A_2 = \max(Q10, Q11, Q12, Q13) - \max\,(Q8, Q9)$$

For the appraisal of control the nine relevant answers were combined into three scores (circumstance, self and other) by taking the maximum rating across the relevant answers. The circumstance and self groupings were combined into a single score by subtracting the person appraisal from the circumstance appraisal, this was used to test H3A. Those that suggested a cause by self were separated and used for testing H3TC and H3E.

$$A_3 = \max(Q22, Q23, Q24) - \max\,(Q19, Q20, Q21)$$

$$A_{3perceived\ control} = \max(Q18, Q25, Q26)$$

Producing a combined expectation score, from the four relevant questions, was more complicated than the other appraisal scales. Firstly the two questions "How often does it happen in winter?" and "How often does it happen in summer?" were merged by taking the highest score as per before. This produces a score equivalent to, does it happen often in any season. This was then combined with the levels for the two remaining questions by adding scores that were suggestive of predictability and subtracting scores associated with suddenness. This produced a scale running from -3 (most unexpected) to 13 (most expected).

$$A_4 = \max(Q16, Q17) + Q15 - Q14$$

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Perceptions of thermal environments in dementia friendly dwellings

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Abstract
This study follows on from a research project that developed guidelines for the *Universal Design (UD) of Dementia Friendly Dwellings for People with Dementia*, their *Families and Carers*. Research findings point to the need for thermal environments that support people with dementia and do not provoke stress, agitation or anxiety. Using semi-structured interviews and qualitative analysis of people with dementia this paper aims to provide insight into the questions of appropriate thermal environments. The qualitative analysis is supported by example simulated indoor environment studies that investigate comfort in common thermal environment provision scenarios in the homes of people with dementia. This paper focuses on the thermal environment, its impact on people with dementia, its therapeutic value, and its role in encouraging engagement in every day activity.
Findings from the interviews emphasize that control over their own internal environment is a priority for people with dementia. A strong preference for naturally or passively conditioned environments over mechanical conditioning is evident. Preferences are expressed for naturally ventilated environments enabling occupant instigated air movement. Repeated emphasis is placed on familiar elements including the fire and hot water bottle. Little desire is expressed for information feedback or technological displays.

Keywords: Dementia, Thermal Comfort, Dementia Friendly Dwellings, Care Residence

1 Introduction
It is estimated that 47.5 million people globally live with dementia (WHO, 2012). This number is expected to triple by 2050. In Ireland, there is approximately 48,000 people living with dementia and two-thirds of these live at home in the community. It is reported that up to 87% would prefer to live at home rather than in care facilities (Pierce et al., 2015). This is supported by the Irish National Dementia Strategy which aims to ensure that people with dementia can live at home and in their communities for as long as possible (Department of Health, 2014). However, as it stands the design of housing and the provision of indoor environments presents considerable issue for people with dementia, and in turn challenges for building designers in terms of providing appropriate dwellings.

TrinityHaus Research Centre in collaboration with the Trinity College Dublin's Dementia Services Information and Development Centre undertook a comprehensive participatory research study involving people with dementia and those who work with, and care for, people with dementia. This research resulted in the development of guidelines for the Universal Design (UD) of Dementia Friendly Dwellings for People with Dementia, their Families and Carers (Grey et al., 2015). A key guideline deriving from this research emphasizes the provision of an environment that is easy to interpret and calm, with particular attention given to the reduction of acoustic and visual disturbances. Similarly research points to the need for thermal environments that do not provoke stress or anxiety in people with dementia, but are consistently comfortable.

The objective of current comfort standards is to ensure only a minority of occupants are dissatisfied (Brager et al., 2015). However in the context of dwellings for people with dementia it is important that thermal environments achieve much higher comfort levels since occupants may not request help or express adequate response in the case of discomfort. They may not or be incapable of taking adaptive action via active clothing or metabolic change (Hyde, 1983) and prolonged discomfort may result in significant impacts to health and well-being. It is proposed that the built environment has a fundamental effect on a person with dementia, which is probably much greater than for people without a cognitive impairment (Marshall, 1998). However, specification of thermal environments, and evaluation of thermal comfort, of people with dementia are a significant challenge given the nature of the pathology, which results in reduced thermoregulatory capacity that affects thermal sensation, and damage to brain tissue that also impacts on the perception of environments. In addition, people with dementia may have thermal preferences that change over time due to their progressing pathology (van Hoof et al., 2010a). Also they may find abstract ideas difficult to comprehend. As van Hoof (2010) states the concept of thermal comfort is vague for people with an unknown 'state of mind'. Documented research is anecdotal in the main due to ethical constraints of scenario testing on people with dementia.

As a first objective; through distinction of sensation and perception, this paper aims to investigate the role these two concepts play in the context of comfort for people with dementia. The study is focused on private dwellings, where people with dementia will often spend a significant proportion of their day due to the limiting nature of dementia. Questions initially raised during the guideline development project for Dementia Friendly Dwellings are pursued through semi-structured interviews with a small sample set of people with dementia. This initial work will form the basis for a larger investigation of comfort, priorities and concerns. A second objective aims at assessing the fundamental thinking behind the provision of thermal environments and comfort conditions for people with dementia. Care facilities and housing for older people, or people with dementia often prioritise functional and safe environments (Davis et al. 2009), and thereby risk becoming sterile and monotonous. This paper develops from the basis that older people have a more sophisticated understanding of their thermal environments than is often acknowledged (Tweed et al. 2015). This paper advances this concept for those with and without cognitive dysfunction that is often observed in older people (Brayne, 2007). It proposes that thermal comfort and its means of provision is central to an ecological approach to design, which can enhance quality of life and encourage pleasure, curiosity and engagement.

To date, extensive publication of research focused on thermal environmental intervention, design of homes and care facilities for people with dementia, and review of the relevant medical, nursing and care literature, have been undertaken by the research group of Joost van Hoof (van Hoof et al., 2010b)(van Hoof et al., 2010a). This seminal research work outlines comfort concerns and solutions for designing for people with dementia (van Hoof et al. 2010, 2013). This study builds on this research, and the growing body of recent research, and investigates alternatives to the common thinking on comfort. This is achieved through the evaluation of novel contemporary ideas of thermal comfort provision that propose a move away from the common provision of thermal monotonous environments (Brager et al., 2015) and instead activate pleasant physiological sensations of allesthesia. This contextual evaluation allows for insightful investigation of ethical, therapeutic and operational aspects of thermal environment provision for people with dementia. If people with dementia are to remain living in the home then (as an example question) is it better to define tight control of thermal environments or, recognize that there remains a variety of thermal preferences and expectations and that people should be able to take action to achieve comfort. Such issues may be at the core of occupant satisfaction, and allow for enhanced experience of life with dementia.

2 Background

2.1 The multi-sensory environment of home

The interaction of light, air and sound with the form and materiality of architectural space is of the very essence of the architectural imagination (Hawkes, 2008). The significance of light and sound, in achieving visual and acoustic comfort conditions, are recognised in the design guidelines for dementia friendly dwellings (Grey et al. 2015). Both are key to the orientation, way-finding and cueing for the occupant with dementia, but also can create unwanted disturbances of glare and background noise. Well-considered thermal environments can offer the same potential benefits, and encourage activity. In contrast poorly conditioned environments can result in prolonged discomfort and even hypothermia or heat stress. This paper focused on thermal comfort and hence air; temperature, humidity and movement are essential.

Contemporary sustainable, and low-energy, building typologies aim to define a comfort condition by constraining these parameters in a narrow range. Thermal environments become static, uniform, neutral, even boring and monotonous (Brager et al. 2015). Seminal thinkers on thermal comfort have long advocated for a greater variety of thermal experience within buildings, and have shown through extensive field studies that such dynamism is preferred by occupants (Brager et al. 2015; de Dear 2015). Distinguished architectural theorists agree that “every touching experience of architecture is multi-sensory” (Pallasmaa, 2005) and “the most vivid, most powerful experiences of architecture are those involving all of the senses at once” (Heschong, 1979). However, the pragmatic and mechanical processes of climate modification and comfort engineering create environments far removed from the complex sensory experience advocated by Hawkes (2008) or Pallasmaa (2005).

This reductionist approach to comfort limits the opportunities that might otherwise be presented by a more sensory and contextually flexible architecture (Henshaw and Guy, 2015). Proponents of salutogenic design dismay at how architecture, when considered in the context of care, often lose its considerable manipulative power as it becomes subservient to its parts (Golembiewski, 2012). The priorities of residential care are often ‘the passive provision of a safe, caring environment’ with a focus on designing for the purpose of control, to affect or diminish behavioural difficulties.

Presently, people can typically spend up to 17 hours a day in their homes, increasing to 20 hours a day for older people (Bluyssen, 2009). To compound this, the impairments of dementia will often further restrict activity outside the home, in this way the internal home environment becomes the main setting for many people’s lives and frames the vast majority of their sensory experiences. If this is the case, and if sensory stimulation, including varied thermal experiences, is a key part of the human condition, then there is a greater onus on the home to provide rich and meaningful sensory experiences.

2.2 Dementia and the environment of home

While people will experience dementia in very difference ways, common symptoms will include high levels of anxiety and stress, and increased sensitivity to the social and built environment (Marshall, 1998). This increased sensitivity stems from a reduction in the individual's ability to understand the implications of sensory experiences (Sloane et al. 2002) As many authors put it "problem behaviours may be exacerbated by inappropriate environments" (Van Hoof, 2012).

Marshall (2009) points out that people with dementia are typically older, and therefore may also have to deal with age related impairments such as mobility, visual, and hearing difficulties. These impairments may then be exacerbated by dementia as the person may fail to comprehend, or compensate for these difficulties.

While some authors caution against the effectiveness of design in terms of treating dementia (Van Hoof, 2012, Warner, 2003), other authors pronounce the value of a well-considered environment for people with dementia and its ability to offer therapeutic treatment (Marshall, 1998), enhance the quality of life (Cohen and Weismann, 1991) and positively impact behavior, stress and anxiety. Concepts of salutogenic design have grown out of the hypothesis of salutogensis first introduced in 1979 (Antonovsky, 1979). Antonovsky asked the question, "How can this person be moved toward greater health?" Salutogenic design purports to improve the occupant's health by providing them with a well-designed environment. New ideas in cognitive neuroscience are proposing cognition to be less rational and more associative than has traditionally been assumed (Dickinson, 2012) – of particular importance with a view to the design of the built environment for people with reduced cognitive ability.

When environment is considered in relation to the development of dementia it is commonly accepted that cognitive impairment is not caused by environmental design (Van Hoof, 2012). However, more recent research has challenged the theory that environment is distinct from the development of dementia, and instead proposes that it may be a contributing factor entangled with brain pathology, lifestyle, and socioeconomic status (Lock, 2013). In this context, the thermal environment is not proposed as a primary effector but shares a causal relationship with socio-economic factors including (fuel) poverty, which impacts indoor environments, thermal comfort conditions and occupant physical and mental health (Clinch and Healy, 2004). Lock (2013) outlines how research focused on dementia causing Alzheimer's disease has been overly focused on the localization theory, which proposes that dementia onset is related directly to brain pathology defined by a build-up of amyloids, plaques and tangles. Lock pronounces the lack of consistent causality between observed brain pathology and people exhibiting signs of dementia and calls for a greater focus on environmental factors in the development of dementia.

The quality of home environments is a determinant of human health and well-being, demonstrated by studies from varied disciplines (Webb et al., 2013). The widespread presence of sub-standard, inefficient buildings in much of Europe, particularly housing, represents a significant public health concern. Irish housing has long been considered to be thermally sub-standard where a high proportion of occupants live in fuel poverty (Healy and Clinch, 2004), (Curtin, 2009) and face an increased risk of mortality and morbidity. Respiratory health is particularly affected by sub-standard housing, particularly for the old and vulnerable (Webb et al., 2013), with high levels of condensation, mould and damp reported. People living in cold conditions for prolonged periods are also reported and hence enduring thermal discomfort in their own home for much of their lives.

2.3 Comfort in the home

Many people with dementia continue to live at home, and hence thermal comfort is provided through traditional, commonly passive means, which in many cases may involve non-centralized heating, and without designed ventilation. In such home environments people essentially live abiding by the adaptive comfort model, although as described, often in substandard and unhealthy conditions. However, there is strong rational for maintenance, with improvement, of these modes of environment conditioning. A change to mechanical conditioning or even to constrained conditions including tight temperature set-points or highly reactive space heating systems may overcompensate and create confusion and disorientation. As O'Keeffe states; "our ability to locate ourselves in a space or area, to know if its morning or night, windy or wet, hot or cold, is based on our experiencing changes in our environment consistent with being outside." (O'Keeffe, 2014)

The adaptive comfort hypothesis argues that contextual factors and past thermal history influence building occupant's thermal expectations and preferences (Nicol and Humphreys 2002). Therefore, when designing dementia friendly dwellings, there are strong reasons to maintain familiarity with known means of heating and ventilation, notwithstanding that mechanical and high-tech alternatives may offer more controlled conditions. The adaptive comfort model recognizes three categories of adaptation to achieve thermal satisfaction; physiological, psychological and behavioural adaptation. All these adaptive response methods may be affected by dementia.

The experience of comfort can vary with age and health amongst other parameters, and dementia is entangled with both. These variations are due to changes in our nervous sensitivity (sensation) and/or our cognitive processing of stimuli (perception). Both sensation and perception may be impaired by dementia. Although intimately related, sensation and perception play two complimentary but different roles in how we experience and interpret our thermal environments. Sensation refers to the process of sensing our environment through touch, taste, sight, sound and smell. Raw sensory information is sent to the brain. It is processed and perceived by the mind. This process allows us make sense of the environment around us and interpret, amongst an array of sensations, our comfort levels. The sensation of temperature for example activates sub-cutaneous receptors embedded in the dermis layer of the skin. However, it is our perception of this sensation that enables pleasure or displeasure. The concept of thermal allesthesia presents an interesting interaction of these systems. It proposes temporal and spatial variations of thermal conditions, result in hedonic and pleasurable sensations that are generated by the dynamic response of thermoreceptors. These transient effects may be of great benefit to people with dementia in their experience of environments and enable orientation, promote engagement and activity.

Ageing results in changes in the senses to varying degrees, for instance, thermoregulatory capacity is significantly affected, while physiological changes can also result due to inactivity and reduced metabolism (Havenith. 2001). However, dementia can change how people interpret what they sense. This is highly individual depending on the neuropathological changes and sensory loss an can fluctuate depending on time of day, medication management and the social and physical environment (Bakker 2003).

3 Dementia and the Available Opportunities for Comfort

As discussed, the tendency in residential care architecture is to focus on the safe and functional, to the detriment of variety and familiarity (Davis et al. 2015). Such environments tend toward managed and homogenous thermal environments, resulting in thermal monotony and a dearth of experience of spatial and temporal thermal variations.

At the previous Windsor Conference in 2014, presented five new ways of thinking, or paradigm shifts, for designing or operating buildings to provide enhanced thermal experiences. These include shifts from active to passive design, from centralized to personal control, from still to breezy air movement, from thermal neutrality to delight, and from system disengagement to improved feedback loops. As with the majority of comfort literature, these are proposed as comfort opportunities in the non-domestic environment, but are here evaluated in the context of dementia friendly dwellings.

These proposed alternatives aim to shift toward more thermally dynamic and non-uniform environments that brings pleasure and energizes building inhabitants, while requiring less energy to provide thermally comfortable environments. This moves the focus from the commonly designed thermal monotony (which is energy intensive to achieve) to a more adaptive model of living, breathing architecture that responds to local climate context.

4 Methodology

This study is based on: i) findings from a recent research project which looked at dementia friendly dwellings from a universal design approach (Pierce et al., 2015); ii) a literature review; iii) semi-structured interviews, and finally iv) scenario simulation testing.

Semi-structured interviews were carried out on a one-to-one basis with four female and one male participant, all aged between 79 and 82. All of the interviewees are living with early stage dementia and reside at home in their own houses, either alone or with family members. The interviews were conducted in Rose Cottage, which is a Dublin based Dementia Resource Centre run by the Alzheimer's Society of Ireland.

A questionnaire was used to structure the interview and this contained an initial section to collect general information and overall levels of thermal comfort satisfaction within the home. This was followed by five subsequent sections focused on the following: level of personal control over thermal comfort; preference for still air conditions or air movement; preferences for constant or varied temperatures; natural or mechanical ventilation; and finally preferences for information feedback regarding comfort conditions. The interviews were carried out in conjunction with centre's coordinator and following the interviews a brief group discussion was held with all attendees of the centre, which consisted of a group of 12 individuals.

Common means of thermal environment provision in Irish homes were investigated through simple scenario testing. Simulations were carried out using the DesignBuilder CFD analysis tools based on the EnergyPlus building physics platform.

5 Findings and Discussion

The paradigm shifts proposed by Brager et al. (2015) provide a framework to examine alternative approaches to thermal comfort for people with dementia. These authors are not only suggesting wider temperature parameters, but also connecting thermal conditions to ideas around person control, environmental perception, pleasure and variety, closer alignment with natural climatic conditions, and the provision of increased feedback. If the needs of people with dementia are carefully considered within these strategies, can they contribute to a more enriched dementia friendly environment?

These issues were discussed as part of the interviews outlined in the methodology, and the feedback from the interviewees, which is presented in Tables one to five (names changed for anonymity), is examined in the context of the five strategies as set out by Brager et al. (2015). This investigation draws on the literature and the simulation exercise, to examine the implications for dementia friendly design, bearing in mind the various design issues associated with supportive and sensory enhanced environments for people with dementia as previously discussed.

5.1 General findings from interviews

Before the five strategies are examined in detail, some general findings from the aforementioned interviews are outlined to set the context for specific participant feedback.

All of the participants lived in their own terraced or semi-detached, three or four bedroom dwellings, which had been built in the early 1970s. The participants moved into these houses when they were newly built, and have raised their families and remained there since.

Three of the interviewees live alone; one lives with his wife and two adult sons, while the other has one adult son living with her. Four of them have gas or oil powered central heating, while one has an open fire with a back-boiler that heats radiators throughout the house.

As mentioned in the methodology, there were a number of initial questions in the interview to elicit overall levels of comfort and satisfaction within the home. In general the interviewees reported that they are fairly satisfied with the level of heating and ventilation in their homes but stated that other occupants or visitors to the home often find it either too warm or too cold.

5.2 From Centralized to personal control

A key element here is the use of personal control systems (PCS), such as desktop fans or radiant foot warmers, to allow people control their local thermal environment. Other examples might include hot water bottles, electric blankets, or a specific section within a room such as fireplace or inglenook. It can also refer to the opening of a window for ventilation or cooling. Table 1 presents the responses with regard to questions regarding personal control over their thermal environment.

As mentioned above, all of interviewees stated that other occupants within their home, or visitors, often found the house to be either to warm or too cool. Looking back to the literature, it is reported that older people and in particular people with dementia may experience temperature differently or have alternative comfort requirements compared to other occupants within a space. In the context of a typical dwelling, where other occupants may include younger adults or children, the potential for conflicting thermal requirements is a real possibility. In these circumstances the provision of greater flexibility, such as more localized or person-centred thermal comfort, may be more appropriate.

It also emerged that many of the interviewees liked the flexibility and enjoyed the experience of being able to light fires, or use hot water bottles or electric blankets in colder conditions - "I love to light a fire"…. it's very homely" (Agnes). The importance of the open fire to older occupants is well recognized in the literature (Neven et al., 2015).

Autonomy for people with dementia to "take initiative and make choices for their lives and care" is a key issue for Lawton (2010), and for Calkin (2001), who describes "Personal Control" as a central component to person-centred therapeutic design. In contrast, highly controlled environments, with an emphasis on health and safety, have be shown to have a negative impact of the quality of life of older people (Torrington, 2007). In this regard Innes (2011) refers to research (Chalfont, 2007)(Chalfont and Rodiek, 2005) which proposes "..a move away from design intended for control, surveillance or to diminish behavioural difficulties to considering how environments can encourage curiosity and engagement in everyday activities." (Innes et al., 2011)p.548). With this approach in mind the provision of greater individual control over the thermal environment for people with dementia may not only allow them adapt their thermal environment to their specific needs, but also provide a level of control that reinforces autonomy, personal control and engagement with everyday activities.

Table 1. Survey of personal control over thermal comfort.

	Agnes	Liz	Margaret	Sean	Yvonne
Do you think it's a good idea to let the temperatures with a house vary a little bit and then use more localized heat sources (i.e. hot water bottle) to warm you up.	Yes – "I love to light a fire …. it's very "homely" - she loves the glow, warmth, sound etc	Yes - but not a key concern	Not really	Yes – likes to use electric blanket or hot water bottle- often finds his feet very cold at night / also takes care to dress appropriately for the seasons	Yes-but not a key concern- likes to use a hot water bottle
Do you like being able to easily open a window or door to let in some fresh air or cool the place down?	Yes – definitely – likes the "feeling of freshness"	Yes – but her house is a bit exposed and if it is windy at all it can blow in fairly hard - she also lives near motorway so traffic noise can be an issue	Yes – but sometimes it can be too cold outside to do that	Yes – definitely – "there is nearly always a window open somewhere"	Yes – would open it in winter

During the interviews the issue of personal control was a very important issue for the participants. They valued being able to open a window, light a fire, or fill a hot water bottle as needed - "I'm very happy with the current situation because I'm in control" (Agnes)

Of course, this personal control must be carefully designed to ensure that the actions of any individual do not compromise safety and health as discussed by van Hoof (2010). This is where good design underpinned by knowledge and universal design is required (Maki and Topo, 2009).

5.3 From still to breezy air movement

Most of the interviewees enjoy a gentle breeze coming through the window when external weather conditions permit, and some of them stated a preference for having windows open all year around. While an open window and a gentle breeze was associated with freshness, there were also concerns about noise from passing traffic and drafts in more exposed locations (see Table 2).

Brager et al. (2015) refer to the refreshing effect of breezy air movement and the positive impact on perceived air quality, and while these factors will benefit people with dementia, there may be other potential benefits, which were not articulated during the interviews.

Table 2. Survey of preference for still conditions or little breeze within home.

	Agnes	Liz	Margaret	Sean	Yvonne
Do you like a bit of air movement within the house (not including a draft)?	Yes	Yes - but can be problems with wind and sound (see Table 1)	No real preference	Yes – likes the idea of fresh air coming in	Yes
If so, would you prefer this during warmer weather?	All year if conditions are right	Not really in winter	See above	All year if conditions are right (see note about windows being open all yr above)	All year
Do you like a gentle breeze coming in through a window or door at certain times?	Likes to open windows to let in air - enjoys the "feeling of freshness"	Yes but can be problems with wind and sound (see Table 1)	No real preference	Yes – see above	Yes
Or do you prefer very still conditions where you don't feel any air movement within the house	No	No	See above	No	No

If properly managed, air movement against the skin will produce a pleasant sensory stimulation in line with Calkin's (2001) call for 'Maximal positive stimulation'. If this air movement is perceived as a natural breeze it may also provide a therapeutic connection to nature:

> "Connection to nature can be understood in many forms, from passive stimulation by natural sensations, made possible by simply stepping outside or opening a window (e.g. the wind, sunshine or birdsong)" (Gibson et al., 2007)p57)

Air movement within a dwelling, for instance in the form of a breeze coming through a window, may represent a "familiar, domestic" environment as advocated by Marshall (1998). Such air movement might also be used as part of a building's cueing system. According to Judd (1998) cues provide "encouraging and confirming clues to assist wayfinding" (p.16) and while cues are typically visual, Judd argues that the other senses can also be employed to provide cues for people with dementia. In this regard Hall discusses how people with visual impairments use air movement around windows to navigate and also to "maintain contact with the outdoors." (Hall, 1988) p.59)

5.4 From thermal neutrality to delight

In a similar manner to a breeze or air movement, thermal variations may contribute to positive sensory stimulation or provide way-finding cues within the dwelling. As above, Hall discusses alternative wayfinding strategies, and in terms of thermal perception, he points out how people with visual impairments use the radiant heat from objects to help them navigate. In terms of people with dementia, who will often depend on a variety of senses to compensate for cognitive impairment (Marshall, 2009)(Nygard, 2009), any sensory cue that provides information or helps with orientation or wayfinding will be a benefit.

This issue regarding environmental cues and navigation was not discussed in the interviews, but instead questions were asked about the pleasure derived from different thermal experiences (See Table 3). Generally the interviewees preferred a cooler bedroom and this was typically associated with being wrapped up warm in bed, or the use of an electric blanket, or hot water bottle – "I like a hot water bottle, there's something comforting about it" (Yvonne).

Table 3. Survey of preference for constant and fixed temperatures or greater variety and range.

	Agnes	Liz	Margaret	Sean	Yvonne
Do you like all rooms within the house to be the same temperature?	No real preference - however stated that she probably likes bedroom to be cooler	No real preference but would probably like constant enough temperature throughout house	Usually has bedroom a bit cooler	Likes a cooler bedroom and then uses electric blanket / hot water bottle – complained about feet getting cold in bed	Maybe a cooler bedroom – "I like a hot water bottle, there's something comforting about it"
Or do you like slightly different temperatures, such as a cooler bedroom or kitchen and a warmer sitting room or bathroom?	Likes a slightly cooler room	See above	See above	See above	Yes see above
Do you get any pleasure from experiencing different temperatures within the house?	See note about fire in Table 1	Not really	Not really	Enjoys sitting by a warm fire and to wrapped up warm in a cool bedroom	Enjoys a hot water bottle in bed
Do you get any pleasure from feeling air movements within different parts of the house, such as a breeze in a certain room or location?	See note about windows and freshness in Table 2	Yes but can be problems with wind and sound (see above)	Not really	Yes – see notes above	

5.5 From Active to passive design

Passive design buildings are typically more climate responsive, utilise natural ventilation, and offer greater levels of individual control. Therefore passive design, which offers greater personal control, and more connection with nature and natural cycles, may provide dementia friendly design benefits for the reasons outlined in previous sections.

During the interviews the participants conflated the issue of control and the opening of windows, with the subject of natural ventilation, and therefore the same answers were often given for each. Table 4 outlines some of the key responses and again that the issue of control is important. A perception of freshness was associated with natural ventilation, while one participant explained how they enjoy the sound of birdsong through an open window.

Table 4. Preference for naturally ventilated home or mechanical ventilation using fans or air conditioning.

	Agnes	Liz	Margaret	Sean	Yvonne
Would you like if the house was ventilated naturally using air coming in through open windows or vents?	Yes – see note about windows and freshness in Table 2	Yes but can be problems with wind and sound (see above)	Yes - but might have concerns about security and remembering to close them	Yes – likes to be able to control things and adjust the conditions to his preferences.	Yes – has window open all year
Do you think this approach would give you a better sense of connection with nature, the seasons, or outside weather conditions?	No explicit answer to this but likes the breeze coming in	No real comment	No real comment	Yes – but mostly about fresh air coming in.	Like a breeze and birdsong etc.
Or would you prefer if the house was cooled and ventilated by mechanical fans or air conditioning?	No - quite definitively	No	No	No – and wouldn't like the idea of a fan or mechanical vent making noise, especially at night.	No

Concerns were expressed about traffic noise and other external sounds, while another interviewee spoke about problematic drafts entering the house through open windows. These concerns highlight the challenges presented by passive ventilation in many homes, whether this is through windows, trickle vents, or passive wall vents. In this context, Sinnott (2016) draws attention to the problems associated with passive wall vents, and finds that occupants often perceive the air ingress as uncomfortable and as a result these vents are frequently sealed or taped up. While variations in thermal conditions within a dwelling may be acceptable, or even desirable (i.e. a cooler bedroom) sharp temperature differences within a room or cold air movement perceived as a draft will be considered as a discomfort for many people (Kinnane et al., 2015). As a brief exploration of this issue the following scenario simulations show the ingress of cold air through a passive wall vent during windy conditions and the resulting localized conditions of discomfort as evaluated using Fanger's PMV. Cold air dumping can result in dramatic variation in thermal conditions and create extreme discomfort (Kinnane et al., 2014). For people with dementia this may be difficult to comprehend and create anxiety, stress and possible excessive adaptive actions.

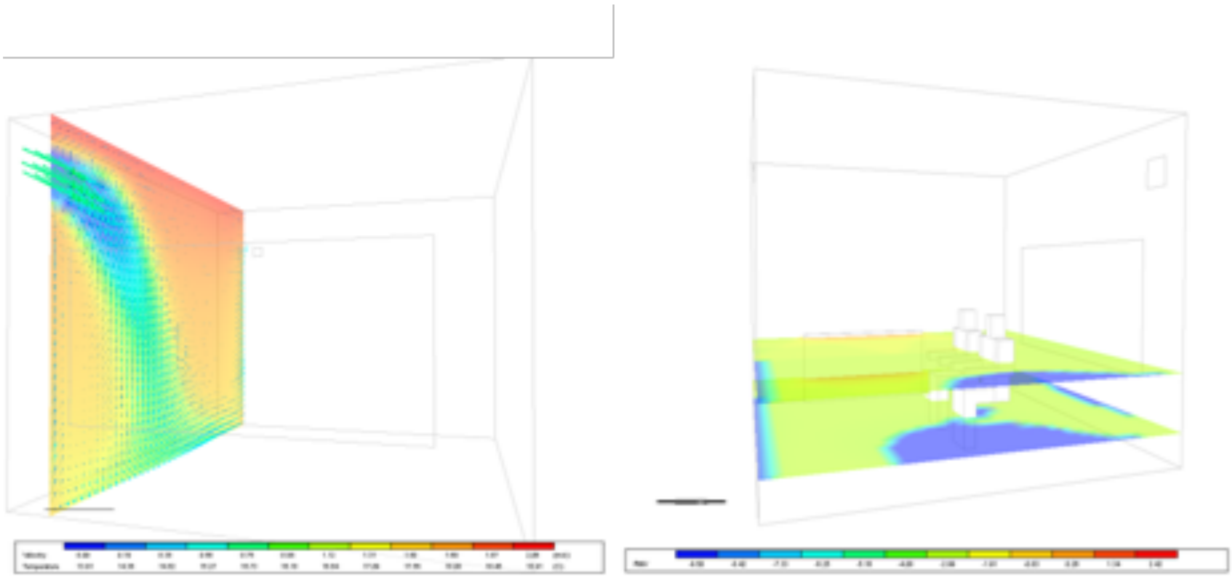

Figure 1: (left) Cold air ingress through passive through-wall vent and (right) resulting thermal localized discomfort due to passive through-wall vent.

As evident from Table 4, the interviewees were not favourably disposed towards mechanical ventilation as an alternative to natural ventilation. While a lack of experience with mechanical ventilation may explain some of this, it was interesting that one participant expressed concerns about the potential for noise generated by fans or mechanical ventilation. Noise has been identified as major problem for people with dementia (Judd 1998) and therefore the design of any mechanical or natural ventilation system must take cognisance of this and ensure a silent running system. This will have added significance for bedrooms as sleep disturbance may be an issue for some people with dementia.

5.6 From system disengagement to improved feedback loops.

The issue of occupant information feedback was difficult to discuss as most of the interviewees had no experience with such systems and therefore saw little advantage (See Table 5 below). One of the participants had a thermostat within their house that gave temperature readings and this appeared to have some influence over her behaviour.

Table 5. Preference for information and feedback of heating and ventilation or less information feedback allowing control to automatic systems

	Maisie	Mary	Rose	Seamus	Sheila
Would you like if there was some easily read and easily understood information about room temperature or other thermal conditions displayed somewhere within the house so you are aware of what is going on?	No real interest	No real comment - but has a thermostat that gives temperature information and finds that useful and will sometimes be an influence in terms of adjusting the heating	No	No real benefit for him	No real interest
Or would you prefer if temperature, ventilation or other information about the thermal conditions was not displayed and the buildings systems just managed things without having to bother you?	See above	See above	No preference	Likes it as it is	No – see above
Would you find such information comforting or helpful in terms of giving you a sense of control?	No – see above Might be useful for others so they can see the room is warm enough	No comment -See above	No comment - See above	No comment -See above	No – see above

Beyond the responses received in this research, the issue of information feedback to people with dementia is a complex one. Nygard (2009) argues that while people with dementia have the same rights as everyone else to access technology, she advises that it may be better to limit the provision of technology within a dwelling to avoid unnecessary confusion. The benefits of feedback through building management systems or in-home displays requires further research. However, research shows that when presented with technology or devices within the home, older people with memory impairments will makes great efforts to understand, and learn about the technology (Nygard 2009).

As a consequence, Nygard argues that such technology should always actively involve the user and provide a sense of autonomy. Technology should provide reassurance while supporting the users remaining abilities and supporting decision making. It should be reminiscent of solutions known to the user and provide legible and accessible information that requires minimum learning and interaction.

Involving a person with dementia in the status of the thermal environment and providing greater levels of occupant feedback has its challenges in terms of design. However, if greater levels of personal control are offered, then information feedback, in line with Nygard's recommendations, will need to be carefully designed to provide relevant, usable, and clearly legible information that avoids information overload and supports the person with dementia.

6 Concluding remarks

This paper argues that the thermal environment within the home is an important issue for people with dementia for a number of reasons. Firstly, given that an older person with dementia will often spend a large proportion of their time inside their home, greater significance is placed on the quality of their thermal environment. Secondly, due to potential thermoregulatory and cognitive issues, a person with dementia may experience their thermal conditions in a very different way to others, and if coupled with communication difficulties, can lead to frustration and anxiety for the person with dementia. Thirdly, if conditions are right for the person with dementia, then thermal factors such as warmth, coolness, or air movement, can have a positive stimulating influence leading to a more familiar setting with an enriched multi-sensory environment. Finally, flexibility, occupant control and adaptive comfort play a crucial role in dementia friendly design where personal control and autonomy are critical to the creation of a supportive and therapeutic environment.

It is also proposed that the alternative thermal comfort strategies presented by Brager et al. (2015) represent a framework to consider the thermal needs of people with dementia. In this regard, findings from the literature review and interviews provide some valuable insights, while also presenting some interesting challenges. Responses emphasize that control over their own environment is a priority for people with dementia. A strong preference for naturally or passively conditioned environments over mechanical conditioning is evident. Unsurprisingly interviewees place significant value on familiar elements including the open fire and hot water bottle, and these are emphasized as preferred adaptive measures. Preferences are expressed for naturally ventilated environments enabling occupant instigated air movement. Little desire is expressed for information feedback or technological displays; although this may be partly attributable a lack of experience or knowledge with such technologies. People with dementia should retain control over their own internal environmental conditions as this is behaviorally advantageous and ethically preferable. Removal of control may result in feelings of anxiety and in extreme situations may lead to a misunderstanding of personal well-being and ultimately to risks of hypo or hyperthermia. Consideration should however be given to the use of a temperature range limiter on heating and cooling controls to ensure extreme conditions are avoided.

All of the investigated strategies offer greater levels of autonomy and control which move away from the risk-averse attitude to people with dementia that according to Marshall further disables people (Marshall 2009). These strategies also engender greater engagement with the world through everyday occurrences and natural rhythms which may have therapeutic benefits for people with dementia. It can be argued that sensory design, including thermal conditions, can help create more embodied and orientating experiences for people with dementia and support Pallasmaa's assertion that:

"Architecture reflects, materialises and eternalises ideas and images of real life. Buildings and towns enable us to structure, understand and remember the shapeless flow of reality and ultimately, to recognise and remember who we are." (Pallasmaa, 2012)

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Acknowledgement

We would like to thank everybody at Rose Cottage for being generous with their time, feedback and food! Special thanks to Mary Hickey of the Alzheimer Society of Ireland and centre coordinator, and to Seamus Cunningham of the Irish National Working Group of People with Dementia, both of whom are doing fantastic work in this area.

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Investigating the impact of thermal history on indoor environmental preferences in a modern halls of residence complex

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Abstract

Numerous field studies conducted in different locations have demonstrated that comfort conditions vary due to adaptation to the local climate. This study aims to investigate how preferences for the indoor environment change when the climate context changes and how thermal history influences comfort conditions in a new thermal environment. A new halls of residence complex in the south of England, housing occupants from various climatic regions, is used as a case study. Two thermal comfort surveys were conducted in October and December 2015 (N=53 residents) within the first three months of the occupants. Air temperature and relative humidity measurements were collected during this period.

Results show a range of comfort temperatures of over 10°C across the study period. The first survey (October) found no significant difference between residents when grouped by previous climate of residence. The second survey (December) found that the mean comfort temperature for residents from the UK had dropped by 1°C, despite an unseasonably warm winter, and mean comfort temperatures for residents from other climates remained the same. This could be an indication of psychological adaptation whereby residents accustomed to the UK climate expect cooler temperatures moving from October to December and thus come to prefer this.

1 Introduction

With increasing focus on reducing carbon emissions to mitigate climate change impacts and meet the UK's 2050 emissions reduction target of 80% of the 1990 level (Crown Copyright 2008), energy efficiency measures are being addressed in a number of sectors. In the UK, domestic space heating alone accounted for 23% of total energy demand in 2011 (DECC 2013). While the technology to build highly efficient, low energy homes already exists, the challenge for designers is to provide functional and comfortable dwellings while maintaining low energy use. The difficulty lies in characterising occupant behaviour in the design stage which has been found to impact significantly on energy performance (Bonte et al. 2014; Gill et al. 2010; Martinaitis et al. 2015) and occupant satisfaction (Grandclément et al. 2014).

At present, occupants are usually assumed to be a homogenous population with similar thermal preferences. The recommended design temperature ranges in regulations and standards are based on studies carried out mainly in temperate climates (ISO 2005; CEN 2007). While this may be appropriate in the situation where all occupants under consideration are long term residents of the region, it becomes questionable when considering occupants from mixed climatic backgrounds. Many field studies have been conducted in various climates across the world which serve to demonstrate that comfort temperature is closely linked to local climate and to indoor temperature variation which is influenced by ventilation strategy (Rupp et al. 2015; Kwong et al. 2014; Taleghani et al. 2013; Brager & de Dear 1998). These studies have demonstrated that occupants of naturally ventilated buildings in hot climates can be comfortable at temperatures far higher than expected by deterministic models of comfort, sometimes exceeding 30^{o}C (Djamila et al. 2013; Dhaka et al. 2013). Similarly, some studies have found the reverse, that occupants in cold climates can adapt to find comfort in low indoor temperatures (Ye et al. 2006; Yu et al. 2013; Luo et al. 2016).

Adaptive thermal comfort theory explains these variations in comfort temperature by asserting that over time, people are able to adapt to their climate through a combination of behavioural, physiological and psychological mechanisms (Nicol et al. 2012; de Dear & Brager 1998). Behavioural adaptation, linked to personal control, has been found to lead to diverse thermal preference (Brager et al. 2004; Luo et al. 2014) and in a number of cases this has been linked to energy performance implications both with respect to heating and cooling (Luo et al. 2015; Zhang et al. 2013; Zhang et al. 2010). Physiological adaptation or acclimatisation refers to changes in thermoregulatory mechanisms, such as sweating and vasodilation, which allow people accustomed to a particular climate to deal with exposure to that climate more effectively. While it is often considered to be less significant in explaining moderate changes in climate than behavioural and psychological adaptation (de Dear & Brager 1998), studies have suggested evidence for this (Lee et al. 2010; Yu et al. 2012). Finally, psychological adaptation is often hard to distinguish as a factor as the process and its impacts are hard to characterise. However, it has been postulated that expectations of how environments should be, based on experience, influences how people experience them (Humphreys & Nicol 1998)

This study aims to investigate how these adaptive processes change when considered in the context of a new climate. That is to say, the impact of individuals moving, with all their existing adaptations and thermal history developed in their ‘home’ climate, to a new climate where indoor environments are designed for residents with a different set of adaptations.

2 Methodology

This study employed a mixed methods approach utilising environmental monitoring, subjective questionnaires and data from a local weather station in a halls of residence complex. The case study is the University of Southampton’s newly constructed Mayflower Halls of Residence located in the city centre of Southampton, UK. First occupied in October 2014, the complex provides 1104 naturally ventilated accommodation rooms most of which are single ensuite rooms arranged in cluster flats with shared kitchen/living room, although some studio and 1-bedroom flats are also available. This is considered a suitable case study as it houses a large number of international students who are likely to be of a similar age.

Figure 1 Mayflower Halls of residence facades. Top left: North-East facade, right: South-East facade, bottom left: courtyard and internal East and North West facades

Figure 3 shows schematic plans of typical accommodation units in Mayflower Halls. Each resident has access to controls enabling them to, in principle, maintain their indoor environment to suit their preferences. These include curtains, top opening tilt windows with trickle vents (Figure 2; left) and individual radiator valves with settings 0 to 5, where is 0 is off and 5 the highest setting (Figure 2;right).

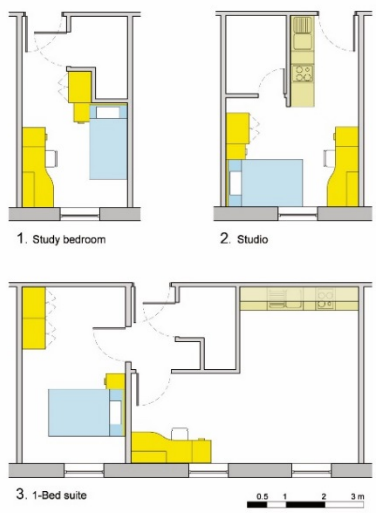

Figure 3 Schematic plans showing typical layout of accommodation rooms in Mayflower halls of residence

Figure 2 Indoor environmental controls available to Mayflower residents; radiator control valve (left), top opening tilt window with trickle vent (right)

2.1 Sample

Participation was open to all residents with first contact being made by email a few weeks after their one year occupancy began in the last week of September 2015. Since the focus of the study was to investigate the impact of thermal history, the intention was to have one third UK students and two thirds residents who had moved into Mayflower from another climate. Non-UK participants are those who stated that for the two years prior to moving to Mayflower, they had "…mostly been living in X…" where X was not the UK. The final sample employed for the study consisted of 56 residents, however this reduced to 53 later in the study period following three withdrawals.

In order to investigate differences in thermal preference between occupants already adapted to the UK climate and those who are not, a method to categorise climate history was introduced. Category A (cool/cold) climates are those where the mean temperature of the coldest month is equal to or lower than that of the coldest month in Southampton (4.6^{o}C); this group is further divided into UK and NON-UK in order to identify occupants from climates which may have colder winters than southern England. The mean temperature of Southampton was used (as opposed the UK) as temperature can vary quite significantly between the north and south of the country (965km) and since all the residents in the sample from the UK are from southern regions, Southampton was taken to be a representative location. Category B (warm/hot) climate are those where the mean temperature of the coldest month is higher than that of the coldest month in Southampton. This classification is used throughout the paper.

2.2 Environmental monitoring

Air temperature and relative humidity were monitored in all participants' rooms starting in late October 2015 (a few weeks after residents had moved into the case study). This was done using MadgeTech RHTemp101A data loggers which provide measurement resolution of 0.01^{o}C and 0.1% humidity for temperature and relative humidity, respectively. The selected reading rate for this investigation was 5 minutes, as this allowed a detailed picture of temperature variation in the accommodation rooms. One data logger was placed in each of the investigated rooms. The locations of the data loggers were selected so as to avoid direct solar radiation or proximity to other heating sources.

2.3 Thermal comfort surveys

Thermal comfort surveys were carried out in the participants' rooms. Indoor environmental measurements of air temperature, relative humidity, globe temperature and air velocity were taken during the face to face questionnaire using the portable DeltaOhm HD32.3 instrument. The questionnaire included questions about general perception of environmental conditions (including temperature and air movement), frequency of controls use and details about location of previous residence, including details of space heating and cooling facilities and ventilation strategy. For the assessment of thermal comfort at the time of the questionnaire, the 7-point ASHRAE thermal sensation scale was used (ASHRAE 2013) with 5-point thermal preference scale. Also recorded were clothing levels and reported activity level for the 30 minutes prior to the questionnaire.

Two sets of survey data are used in this analysis, both from the 2015/2016 academic year and both conducted over the first three months of the occupants one year stay (October 2015 – December 2015). The first of the two questionnaires was carried out over a fifteen day period at the end of October 2015 and the second over a fifteen day period in early

December 2015. This allowed investigation of participants change in comfort temperature over time which can be considered to be evidence of adaptation.

3 Results & Discussion

3.1 Factors which could affect occupants' comfort temperature

The aim of this paper is to investigate the impact that thermal history has on comfort temperature in a new climate. However, to do this requires first that other factors that are known to impact comfort temperature and indoor climate are considered. Factors to be considered here are gender, age and building characteristics. Gender is also often considered important in understanding indoor environmental preferences (Karjalainen 2007; Wang 2006) however a previous study conducted in this building, using similar methods found it to be negligible and thus is not considered here in further detail (Amin et al. 2015).

The age distribution, shown in Figure 4, highlights a cluster of participants around the age of 18-19 (first year undergraduates) and again 22-25 (Masters). Thus, while we can see some variation in age and a few outlying values this is not deemed to be influential due to both the small number of outlying values and relatively small range in ages amongst the majority of the sample. Indeed some studies considering the effects of age on comfort typically consider groups of at least 10 years in range (Indraganti & Rao 2010) and in some cases greater, e.g. over 65 years and under 65 years (Del Ferraro et al. 2015).

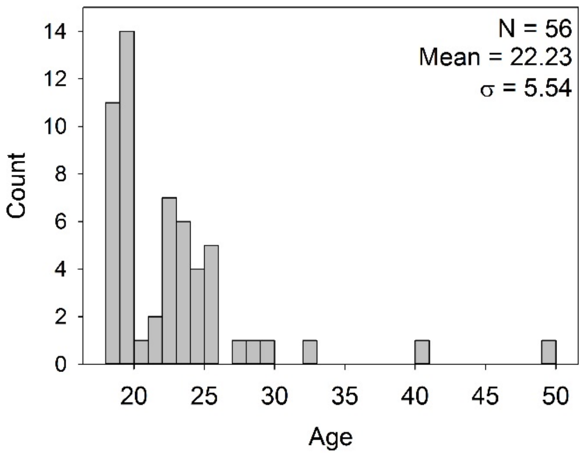

Figure 4 Histogram showing age distribution of study sample

Finally, considering building characteristics is key to understanding both user satisfaction and the indoor environment as they can have a strong influence on both of these factors. In some cases this could include building fabric but since all participants of this study are residents of the same building complex, this is negligible. In this instance, it is likely that floor level and orientation are likely to have the strongest influence on indoor temperature as the complex is split over 16 floors and the orientations of the rooms allow for vastly different levels of solar gain. Hence, rooms were clustered by orientation and floor level such that all rooms in a cluster are within three floor levels and on the same façade (within 6 rooms along) as each other. Plotting the mean monitored indoor temperature of two weeks at the end of November by cluster (Figure 5) shows the diversity in indoor temperature in rooms which cannot be explained by orientation and floor level alone; in one case (Cluster 1) a difference of over 6^{o}C. This period was chosen as it is during the heating season where occupants' are likely to have greater control to create the preferred indoor environment. This further serves to highlight both the diversity in thermal preference and that occupant behaviour is likely to be a determinant for indoor temperature.

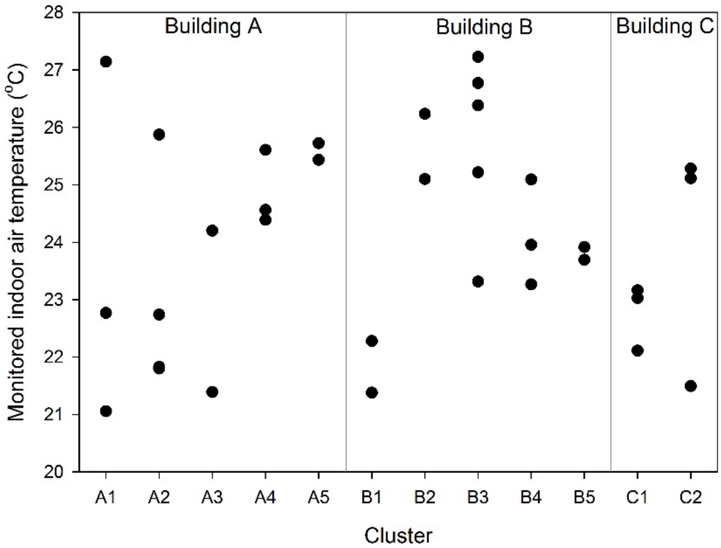

Figure 5 Mean monitored indoor air temperature for two week before second comfort survey (December 2015) clustered by orientation and floor level so that all rooms in a cluster are within 3 floor levels and on the same facade (within 6 rooms) as each other. Clusters are grouped by building (A, B, C – see Figure 1) where lower numbered clusters refer (approximately) to lower floor numbers.

Another interesting finding from the face-to-face questionnaire which is likely to have a strong influence in understanding the building occupants moving forward is that the range in number of hours spent in their accommodation rooms (including sleeping time) varies greatly; from 10-20 hours on weekdays and 0-22 hours on weekends. In terms of understanding the occupants from their monitored data this is likely to be of great importance in one of two ways. Either, those who spend longer in their rooms are likely to be controlling their environment to suit their preferences for much longer than their counterparts who spend fewer hours in the rooms. Alternatively, those who spend a greater number of hours in their room may adapt to their indoor environment and thus feel less of a need to take actions to modify it. In either case, monitored data from some rooms is likely to provide a more accurate picture of the occupant's preference than others.

3.2 General thermal sensation and preference

Thermal comfort surveys began shortly after the start of the 2015 Academic year in October with the first questionnaire and data logger installation taking place between 19th October and 3rd November 2015 and the second questionnaire from 30th November and 14th December 2015. The sample consisted of 56 participants, 23 males and 33 females which later reduced to 53. Figure 6 shows the distribution of thermal sensation votes and thermal preference votes across the two surveys. The thermal sensation vote (TSV) provides the participants current perception of temperature (on a 7-point scale) and the thermal preference vote (TPV) indicates their inclination to change their environment if they were able to. Figure 6 highlights a slight shift between the two surveys moving into the heating season where there is a noticeable decrease in people reporting 'neutral' or 0. This change comes despite the fact that the range in indoor temperatures were similar during both surveys, 20.8°C and 27.3°C in October and 19.4°C and 27.4°C implying that some adaptation has taken place such that expectation of the environment has changed. Furthermore, there is evidence for a change in desire to modify their environments for the cooler. For example, in the case of TSV=+1, the number of people casting this vote is the same in both surveys but there appear to be less inclination to prefer cooler in the second survey. This is also reflected in TSV=+2 where there is no longer a participant preferring 'much cooler'.

The fact that the range of mean globe temperature recorded during the face-to-face questionnaire was between 20.8°C and 27.3°C in October and 19.4°C and 27.4°C in December serves to highlight the diversity in comfort temperatures experienced by residents as in both cases the majority found the environment satisfactory (-1 ≤TSV≤1).

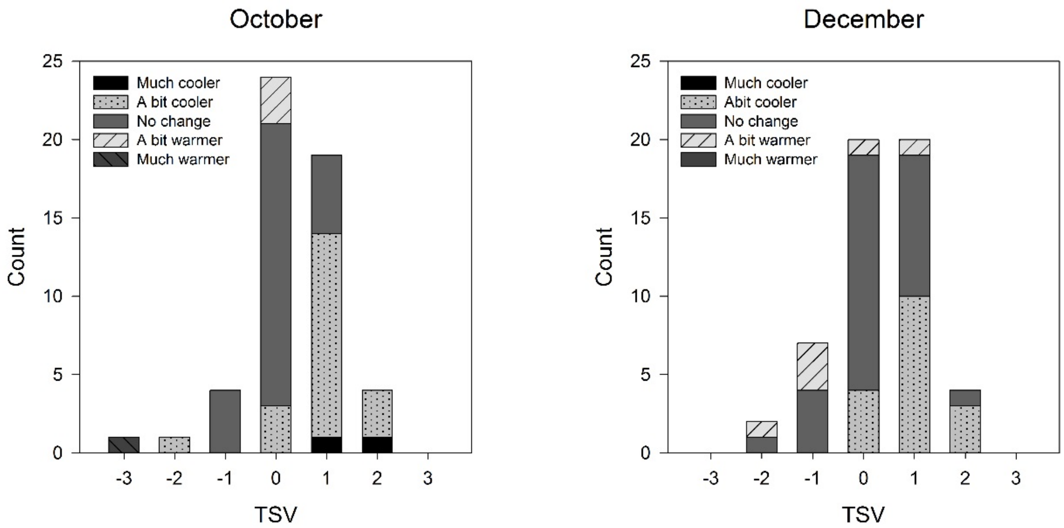

Figure 6 Histogram showing the distribution of Thermal Sensation Votes (TSV) in the October and December thermal comfort surveys along with proportion of thermal preference votes

3.3 Comfort temperatures

Comfort temperatures, T_{com}, were calculated using the Griffiths method which uses the globe (operative) temperature measured during the face-to-face questionnaire along with the thermal sensation vote. The Griffiths constant is taken to be 0.5 (Nicol & Humphreys 2010):

$$T_{com} = T_{op} + \frac{TSV}{0.5} \quad (1)$$

where T_{op} is the operative temperature at the time of the survey and TSV the thermal sensation vote.

The participants were then grouped by climate of previous residence as described in the Methodology (Section 2.1). Of the 56 participants, 23 had been living in the UK for two years prior to moving into Mayflower (Category A – UK), 19 had been in countries other than the UK that have climates as cold as or colder than the UK (Category A – NON UK) and 14 had been living in warm/hot climates (Category B).

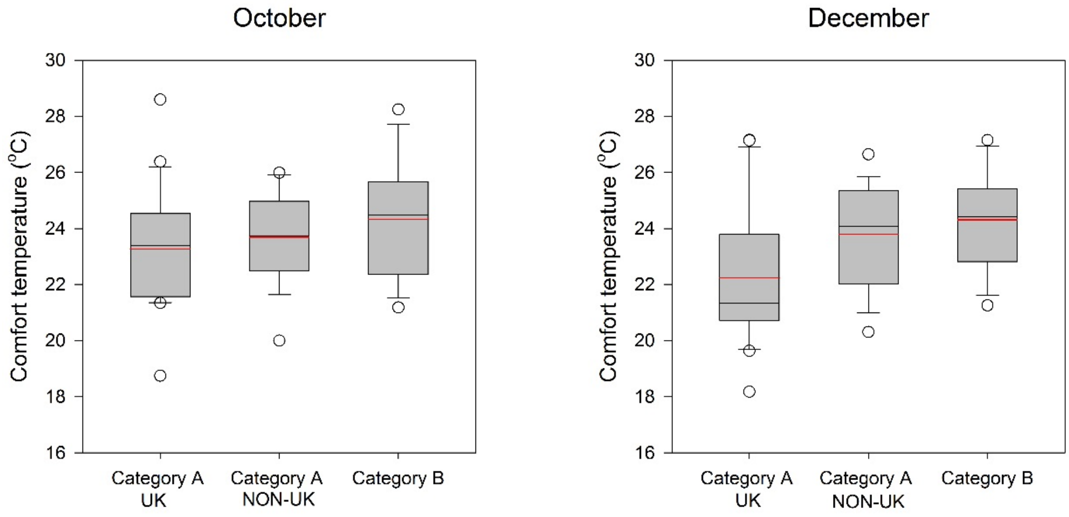

Figure 7 Box plots showing the mean (red line) median (black line), 10th, 25th, 75th, 90th percentiles and outliers (circles) of comfort temperature calculated in October where n=56 (left) and December where n=53 (right). Values are grouped by climate of residence two years prior to moving to the case study building.

Figure 7 shows box plots summarising comfort temperatures grouped by climate. The mean outdoor temperature during the October survey (n=56) was 10.6^{o}C (σ=1.7) and during the December survey (n=53) was 10.2^{o}C (σ=2.2). These mean outdoor temperatures are unusual for the UK, with December being 4.1^{o}C higher than the long term average (Met Office 2016). The means and standard deviations of the comfort temperatures for the three groups are shown in

Table 1. As can be seen, the mean comfort temperature of Category B group (warm/hot 'home' climates') is approximately 1^{o}C higher than that of the other two groups. No statistically significant difference was found between groups in the October survey (p=0.321). There was a statistically significant difference found between groups in the December survey (p=0.016), between Category A-UK and Category A NON-UK ($p<0.05$) and also between Category A-UK and Category B ($p<0.05$). It is possible that there is no statistical difference in mean comfort temperatures in the first survey as all the residents, regardless of their climate history, are adapting to very different living conditions in the halls of residence complex than they are likely to be used to.

Table 1 Summary table showing means and standard deviations of comfort temperature for October, comfort temperature for December and monitored air temperature for December (two weeks before comfort temperature calculation) for the three climate groups

	October T_{com} (°C)		December T_{com} (°C)	
	mean	**σ**	**mean**	**σ**
Category A- UK	23.3	2.2	22.2 $^{a, b}$	2.4
Category A – NON UK	23.7	1.6	23.8 ^{a}	1.8
Category B	24.3	2.1	24.3 ^{b}	1.7

a – statistically significant difference Category A-UK and Category A-NON UK, p<0.05
b – statistically significant difference Category A-UK and Category B, p<0.05

Between the first and second survey there is a decrease in mean comfort temperature in Category A- UK of over 1°C. The other two groups, Category A- NON UK and Category B demonstrate little to no change in mean comfort temperature from one survey to the other. This is illustrated in Figure 8, which shows the comfort temperatures of each participant in the three groups in October and December. While all groups contain individuals whose comfort temperature change (increase or decrease) dramatically (up to 4.5°C) between surveys, it is clear to see that the only groups that displays a change in mean is Category A – UK. This is an interesting finding given that the ambient temperature changed very little over this period, reinforcing the fact that comfort temperature is not only determined by outdoor temperature. Taking this further, the fact that only the residents who have been living in the UK before the start of the study showed a decrease in comfort temperature could be taken as evidence of psychological adaptation. That is, since these residents are accustomed to the seasonality of the UK, they have come to expect colder temperatures and therefore subconsciously prefer them. It is possible that this is driven by other environmental cues such as shorter daylight hours. In Southampton, sunrise typically occurs at 06:28 GMT and sunset at 17:17 GMT in mid-October compared to 08:02 GMT (sunrise) and 16:00 GMT (sunset) in mid-December (HMNAO 2011).

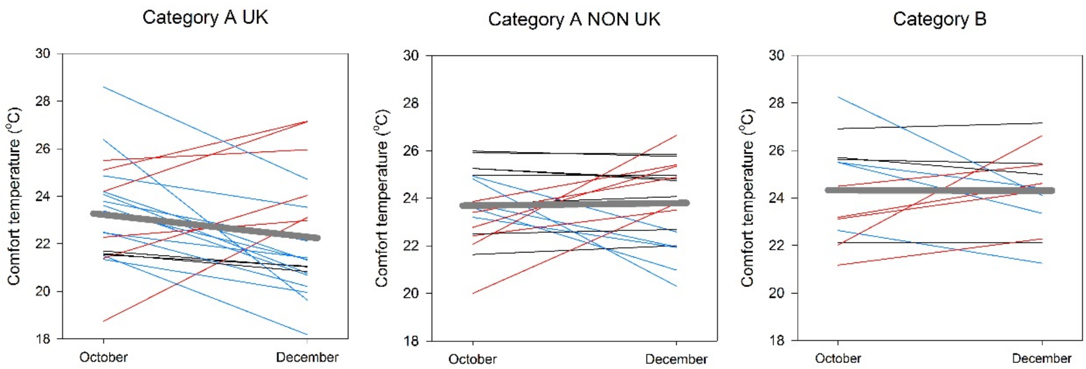

Figure 8 Change in comfort temperature from October to December and monitored indoor temperature in December grouped by climate of residence for 2 years prior to moving to Mayflower halls of residence. Red lines indicates increase in comfort temperature, blue lines indicates decrease in comfort temperature and black lines indicates negligible change in comfort temperature (<0.75°C). Bold grey line indicates change in mean comfort temperature.

Figure 9 shows the daily mean monitored indoor air temperature for the 53 participants who completed both thermal comfort surveys for the period between the two surveys (04/11/15 – 29/11/15) grouped by Category. Also shown is the ambient temperature. Most noticeable is the sharp drop in outdoor temperature on the 22nd November which corresponds to sharp drops in daily mean indoor temperatures in a few rooms which is likely to be a result of windows left open and radiator set on either low or off during this period. Considering that many of the rooms maintain very stable temperatures during this period, it is significant that the rooms with greatest drops in temperature are in Category A-UK, as leaving windows open is behaviour consistent with trying to achieve cooler temperatures. This agrees with the findings of the thermal comfort surveys and implies a move towards cooler temperature in the Category A-UK group and not in the other groups.

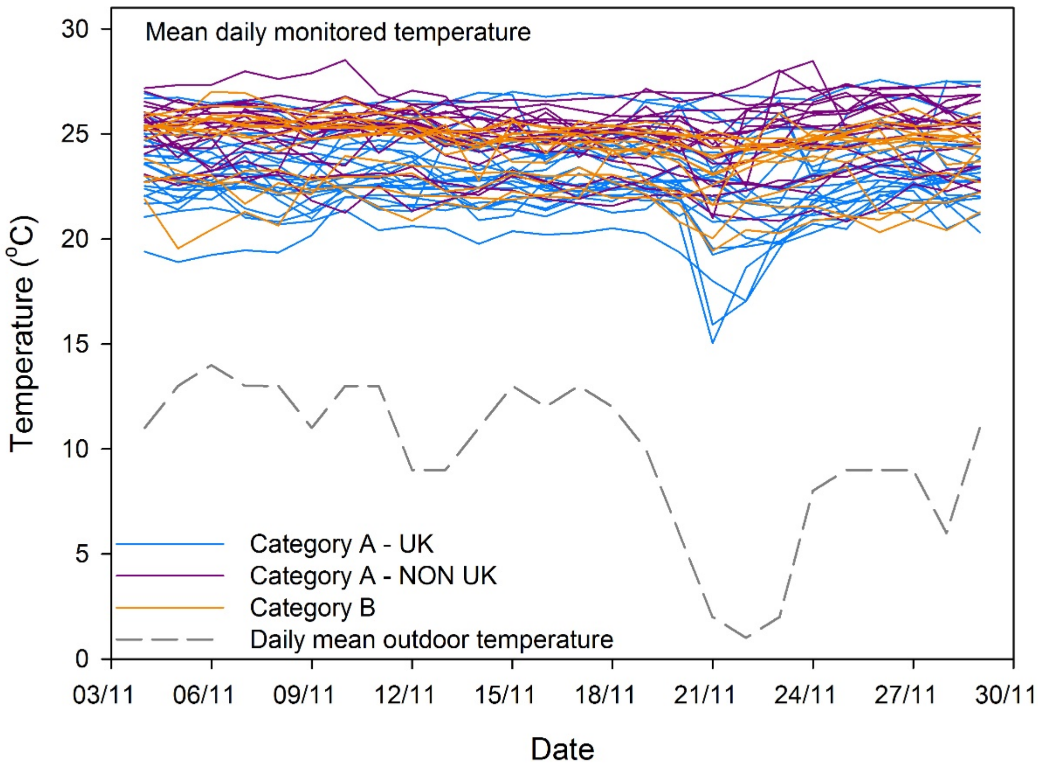

Figure 9 Mean daily monitored air temperature from 53 accommodation rooms in Mayflower Halls for the period between the first and second thermal comfort survey (04/11/15-29/11/15) coloured by climate of residence prior to moving to the case study building

The final relationship considered in this study was the fundamental adaptive relationship of indoor temperature and comfort temperature. Figure 10 shows a scatter plot of mean comfort temperature of the two surveys against mean indoor monitored temperature for the period between the two surveys. The correlation coefficient, r, for all data points was found to be 0.51 ($p<0.05$) however more interesting is the difference in correlation between the 3 categories. The correlation coefficients were found to be 0.69 ($p<0.05$), 0.14 ($p>0.05$) and 0.28 ($p>0.05$) for Category A UK, Category A NON UK and Category B, respectively. There is no significant relationship between comfort temperature and indoor temperature in either Category A NON UK or Category B but there is in Category A. This shows that indoor temperature is a good indicator of comfort temperature in residents who are already adapted to the UK conditions but not for residents who are not. Some of the scatter seen here may be due to the fact that both surveys considered here are early in the occupancy period and residents may still be familiarising themselves with their new environment. Furthermore, the data used to calculate the average indoor temperature included unoccupied periods; if the exact occupancy schedules were known, a stronger relationship may have been observed. However, it is evident that occupants from the UK are better able to control their environment to suit their comfort.

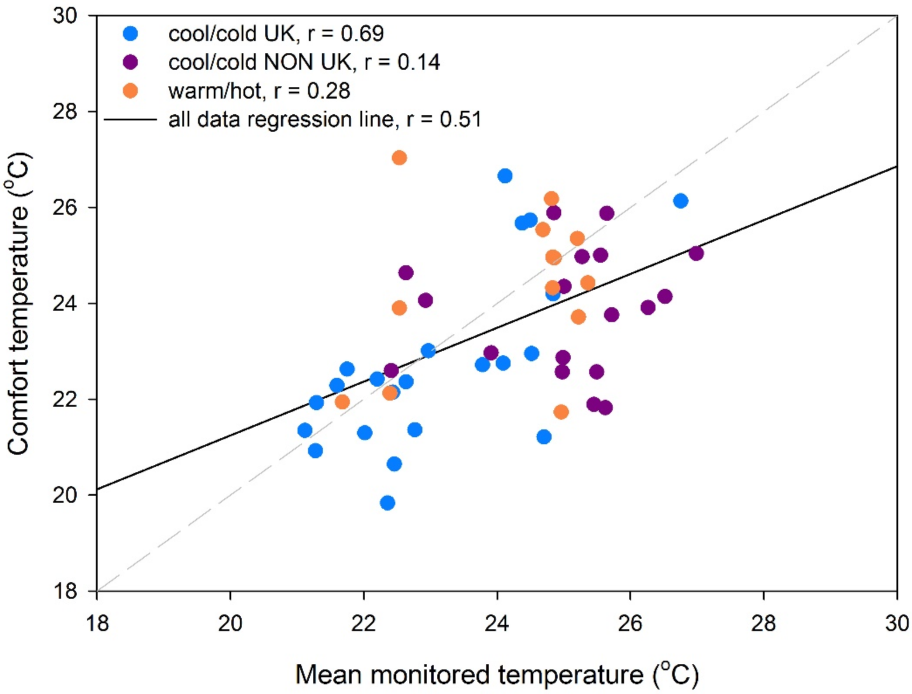

Figure 10 Relationship between comfort temperature and mean indoor temperature. The comfort temperature is the average of the two surveys and the mean monitored temperature is for the period between the two surveys. The solid line shows the regression line for all data values and the correlation coefficients for the individual groups are shown in the legend.

4 Conclusions

This study has investigated thermal preferences of occupants of Mayflower halls of residence complex in Southampton, UK using a mixed methods approach. It has been shown that variation in monitored air temperature cannot be attributed only to orientation and floor level in this case and furthermore that residents have reported feeling neutral (on a 7 point ASHRAE scale) within a wide range of measured globe temperatures. Differences in comfort temperature of over 10°C were found across two thermal comfort surveys conducted in October and December (within the first three months of the occupants stay). The first survey (October) found no statistically significant difference in comfort temperature of occupants when grouped by climate of residence for two years prior to moving to Mayflower, however a significant difference had emerged by the time of the second survey (December). One-way ANOVA revealed a statistically significant difference in comfort temperature between residents from Category A-UK and both Category A-NON UK and Category B, where the mean comfort temperature of the Category A-UK group had decreased by 1°C and the others had remained the same. This arose despite very little change in ambient temperature due to an unseasonably warm winter during the study period. This could be evidence of psychological adaptation, whereby residents accustomed to the seasonality of the UK expect cooler conditions and therefore come to prefer them. Cues here could include changes in daylight hours and perhaps wider media relating to this time of year. Furthermore, consideration of indoor temperature and comfort temperature revealed that this relationship is much stronger for residents from the UK, which indicates that their adaptation to the local conditions means that they are better able to control their environment to suit their comfort. While the limited number of surveys conducted so far mean that these findings are far from conclusive, it provides insight into thermal history and expectation in the context of a new climate.

Subsequent surveys to be conducted over the coming months will strengthen the evidence base.

Acknowledgements

The authors would like to thank the participants in this study for their ongoing cooperation. This work is part of the activities of the Energy and Climate Change Division at the University of Southampton and is also supported by funding from the Engineering and Physical Sciences Research Council (EPSRC) through a Doctoral Training Partnership and the Transforming Engineering of Cities Programme grant EP/J017298/1.

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SESSION 3

Comfort in Buildings

Invited Chairs: Yingxin Zhu and Maria Kolokotroni

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

The impact of seasonal climate variation on human thermal adaptation and evaluation of indoor thermal environment

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Abstract
The outdoor climate has regional and seasonal characteristics, and this affects the indoor thermal environment of naturally ventilated buildings directly. To understand the impact of seasonal climate variation on human thermal adaptation, approach of field survey of thermal comfort has been carried out in four seasons in cold climate zone of China. The values of adaptive coefficient were calculated based on the predicted mean vote (PMV) and mean thermal sensation vote (MTS) values proposed in adaptive PMV model（aPMV）and represented human adaptation levels, the values turned out to be various for each season, they are -1.24 for spring, 0.45 for summer, -0.38 for autumn and -0.23 for winter, respectively, varying from the given values in GB/T 50785-2012 (Evaluation standard for indoor thermal environment in civil buildings). The range boundaries of indoor thermal environment evaluation grades were proved to be different, especially when -1.3<PMV<0 in spring and autumn, then different evaluation results may occur. It proposed that the standard GB/T 50785-2012 should take account of the seasonal human thermal adaptations.

Keywords: human thermal adaptation, adaptive coefficient, aPMV model, different seasons, evaluation of indoor thermal environment

1 Introduction

The PMV model based on heat balance calculations was considered ignoring the psychological dimensions of adaptation, social and cultural aspects of an occupant. Worldwide field studies of thermal comfort carried out in the past few decades show that, there is a strong relationship between occupant's behavioral adaptation and thermal environment (de Dear et al, 2002; Becker et al, 2009). In some further studies, it was found that, PMV worked fairly well for conditioned buildings and deviated widely when applied to naturally ventilated buildings (Fanger PO. et al, 2002; Nicol F. et al, 2009; Peeters L. et al, 2009; Corgnati SP. et al, 2009). Adaptive thermal comfort can explain this well, it believed that thermal comfort is a neutral state, affected by behavioral, physiological and psychological adaptation. These thermal adaptations are the most important reasons that cause the differences between PMV and AMV (actual mean thermal sensation vote) in the field study. Brager and de Dear claimed that the adaptive and heat balance approaches to modelling thermal comfort are complementary rather than contradictory (Brager GS. et al, 1998). It is believed that only a combination of the features of both these modelling approaches will eventually be able to account for both the thermal and non-thermal influences on occupant response in real buildings (de Dear et al, 2002).

It is well known that the prevailing indoor air temperature, to a great extent, is influenced by the outdoor climate, especially in naturally ventilated buildings. Adaptive approach (de Dear RJ. et al, 1998; Brager GS. et al, 1998; Nicol JF. et al, 2002) reveals that the thermal comfort temperature is a function relating to the outdoor air temperature in free-running buildings (Nicol F. et al, 1996). Because climate has regional and seasonal characteristics, many studies prove that the human thermal adaptation also has the regional and seasonal differences (Nicol F. et al, 1996). In China, there have also been a number of thermal comfort studies in different regions (e.g. residential buildings in five major cities (Yoshino H. et al, 2004; Yang L. et al, 2015), in severe cold climate region (Wang Z., 2006), in cold climate region (Cao B. et al, 2011), in hot-humid climate region (Han J. et al, 2007)). For China's regional climate characteristics, the national standard GB/T 50785 was issued in 2012, which emphasizes the evaluation of indoor thermal environments. For different regions, the standard gives out different evaluation criterion. However, in China, most studies focused on the thermal adaptation in summer and winter, but ignored the impact of seasonal climate variation on thermal adaptation in the same region during a whole year. Therefore, this work will study the seasonal thermal adaptation and its impact on evaluation of indoor thermal environment.

2 The climate of the investigation region

The investigation of this work was carried out in Guanzhong plain, the central region of Shaanxi province of China. The region includes five cities of Xi'an, Xianyang, Weinan, Baoji and Tongchuan. It is a typical cold climate region with warm and semi-humid continental monsoon climate, and its four seasons are distinct, hot and rainy in summer (June to August), cold and less snow in winter (December to February), and moderate in Spring (March to May) and Autumn (September to November). The hottest month is July, with a monthly average temperature of 26.1-26.3 ℃, and the coldest is January, the monthly average temperature is between -0.3- -1.3 ℃, the annual average temperature is between 13.1 and 13.4 ℃. Seasonal distribution of rainfall is very uneven, with 78% concentrating in the May to October. The annual average relative humidity is about 70%, the annual average wind speed is 1.8 m/s, and annual prevailing wind direction is northeast.

Table 1. Outline of the investigated occupants.

	Spring	Summer	Autumn	Winter
Number of subjects	31	64	65	66
Number of residential units	17	35	30	36
Age (year)	26.5	43.9	25.7	42.3
Height (cm)	172.1	163.2	170.7	161.6
Weight (kg)	64.3	57.3	63.6	58.2
Metabolic Rate (met)	1.2	1.2	1.2	1.2
Clothing insulation (clo)	0.94	0.5	1.11	1.97

3 Investigation method

The field study was conducted in Xi'an (for spring and autumn) and Weinan (for summer and winter). Both subjective questionnaire survey and objective on-site measurements were carried out. During all field study period, the buildings are running freely. The general background information such as age, gender, weight and height of each participant was recorded at the beginning of the survey (Table 1). Each occupant was asked to provide information on (i) clothing and activity, and (ii) his/her perception of the thermal environment, humidity and air movement three times a day (in the morning, afternoon and evening). Since people were sitting idle for about 20 min, metabolic rate was fixed at 1.2 met. The ASHRAE seven-point thermal sensation scale was adopted for this survey to quantify people's thermal sensation. The indoor air temperature, relative humidity, radiant temperature and air velocity were measured using temperature and humidity electronic recorder and indoor thermal comfort data recorder. The instruments were positioned at a height of 0.6 ‑ 1.1 m from the finished floor, close to the occupants. Readings were recorded simultaneously during the questionnaire interview, so that the objective measurements could be related to the subjective perception of the indoor environment.

4 Analysis

4.1 Clothing level adjustment

Clothing level adjustment is the important adaptation process to maintain the comfort at different temperature. The thermal insulation provided by the clothing was estimated based on the information given by the participants and the clo values provided in ASHRAE Standard 55-2010. Figure 1 shows a summary of the clothing insulation value, and the values of minimum, maximum and mean were shown in figure 2. The rather wide range of clo values indicated, to a certain degree, some behavioural adaptation in response to the variations in the indoor air temperature (de Dear RJ. et al, 1998; Mui KWH. et al, 2003). To ascertain this, the clothing insulation (I_{cl}) was correlated with the corresponding indoor operative temperature (top), and a summary is shown in figure 3. To study the dependence of clothing level on indoor operative temperature, linear regression analysis is carried out. Eqs. (1) to (4) represents the linear regression equations for four seasons respectively. It can be conclude that clothing level adjustment in four seasons is different from each other. Clothing level in autumn and winter was greater affected by temperature changes, in spring and autumn, clothing level were both affected by temperature changes less, especially in autumn. This shows that the clothing level adjustment is not a linear relationship with indoor temperature in a whole year, it should be seasonal.

$$\text{Spring: } I_{cl} = -0.0515t_{op}+1.9556,\ R^2=0.551 \tag{1}$$

$$\text{Summer: } I_{cl} = -0.024t_{op}+1.1199,\ R^2=0.8629 \tag{2}$$

$$\text{Autumn: } I_{cl} = -0.075t_{op}+2.4785,\ R^2=0.9039 \tag{3}$$

$$\text{Winter: } I_{cl} = -0.075t_{op}+2.8153,\ R^2=0.9508 \tag{4}$$

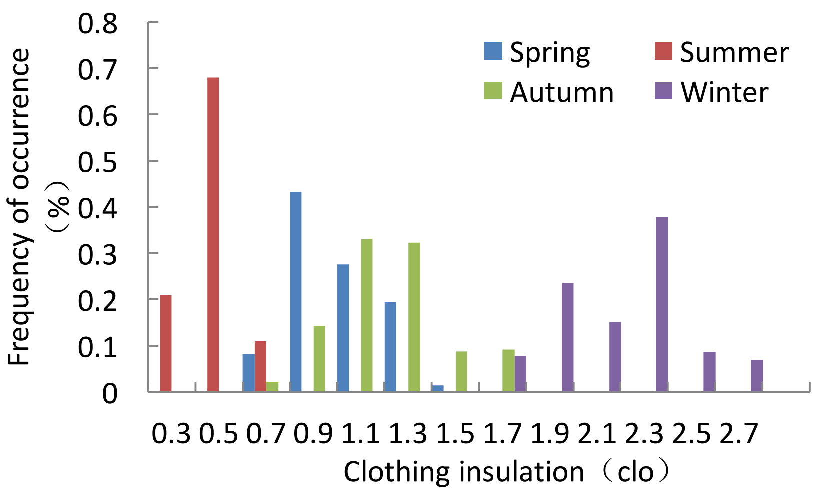
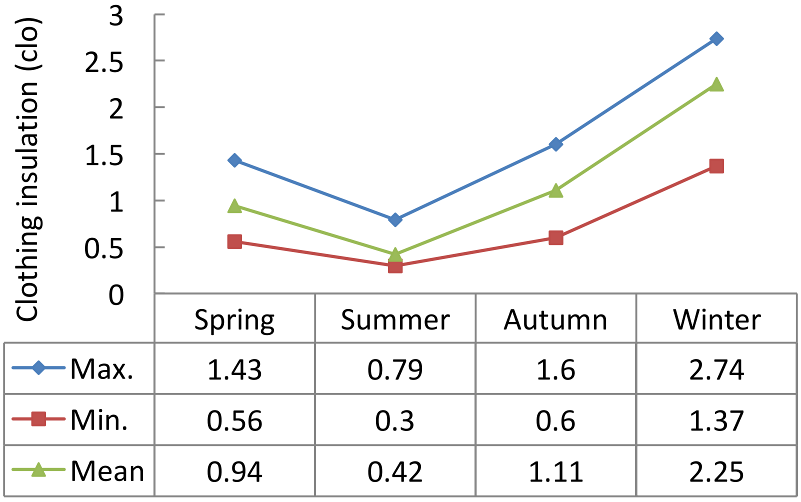


Figure 1. Seasonal distribution of the clothing insulation values.



	Spring	Summer	Autumn	Winter
Max.	1.43	0.79	1.6	2.74
Min.	0.56	0.3	0.6	1.37
Mean	0.94	0.42	1.11	2.25

Figure2. Seasonal minimum, maximum and mean clothing insulation values.

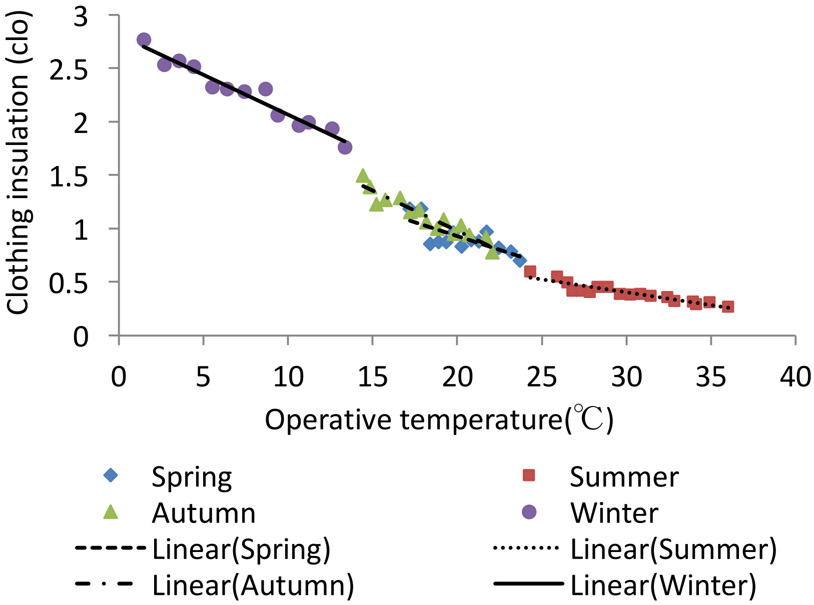


Figure3. Correlation between the clothing insulation value and the operative temperature.

4.2 Thermal sensation and neutral temperatures

Mean Thermal Sensation Vote (MTS) was used to analyze the correlation needed, which is the mean value of Thermal Sensation Vote (TSV) at a temperature range .We chose 0.5°C as the interval of the mean operative temperature (t_{op}), then got the linear relationship between top and MTS which is shown as a formula: MTS=a+b·t_{op}. In the same way, a formula of PMV=a+b·t_{op} can be obtained as well, PMV value in which is calculated using a program based on Fanger's PMV equation (Yang L. et al, 2015). The profiles obtained from the field study of four seasons are presented in Figure 4, and the Table 2 shows the equations of the relationship between top and MTS/PMV. It is clear from the plots that for spring, autumn and winter, for the same level of indoor temperature, the MTS values are greater than corresponding PMV, but in summer, the MTS values are lower than the corresponding PMV values. Meanwhile, the deviation in the values of MTS to that of corresponding PMV is different in four seasons due to various adaptation processes adopted by the occupants to make themselves comfortable in the indoor environment, such as opening windows, switching on fans, and so on in spring, summer and autumn, or closing windows, using the stove in winter. Besides, the trend of MTS/PMV with temperature changes is different between each season, in summer it is the greatest, and lowest in autumn. Let MTS=0 and PMV=0, respectively, the actual neutral temperature and predicted neutral temperature can be obtained, the results are shown in figure 5. The results indict that the predicted neutral temperature is higher than the actual except in summer, and the difference between these two values are also different.

All of the above illustrate that the human thermal adaption in different seasons vary from each other, and with an obvious seasonal feature.

Table 2. The equations for relationship between top and MTS/PMV.

Seasons	Relationship of t_{op} against MTS		Relationship of t_{op} against PMV	
	Equations	R^2	Equations	R^2
Spring	MTS = 0.176t_{op} – 3.696	0.536	PMV = 0.216t_{op} – 4.662	0.902
Summer	MTS = 0.2885t_{op} – 7.4238	0.8708	PMV = 0.331t_{op} – 8.0605	0.9531
Autumn	MTS = 0.076t_{op} – 1.485	0.512	PMV = 0.144t_{op} – 3.072	0.680
Winter	MTS = 0.265t_{op} – 2.8752	0.7387	PMV = 0.2404t_{op} – 2.9523	0.8124

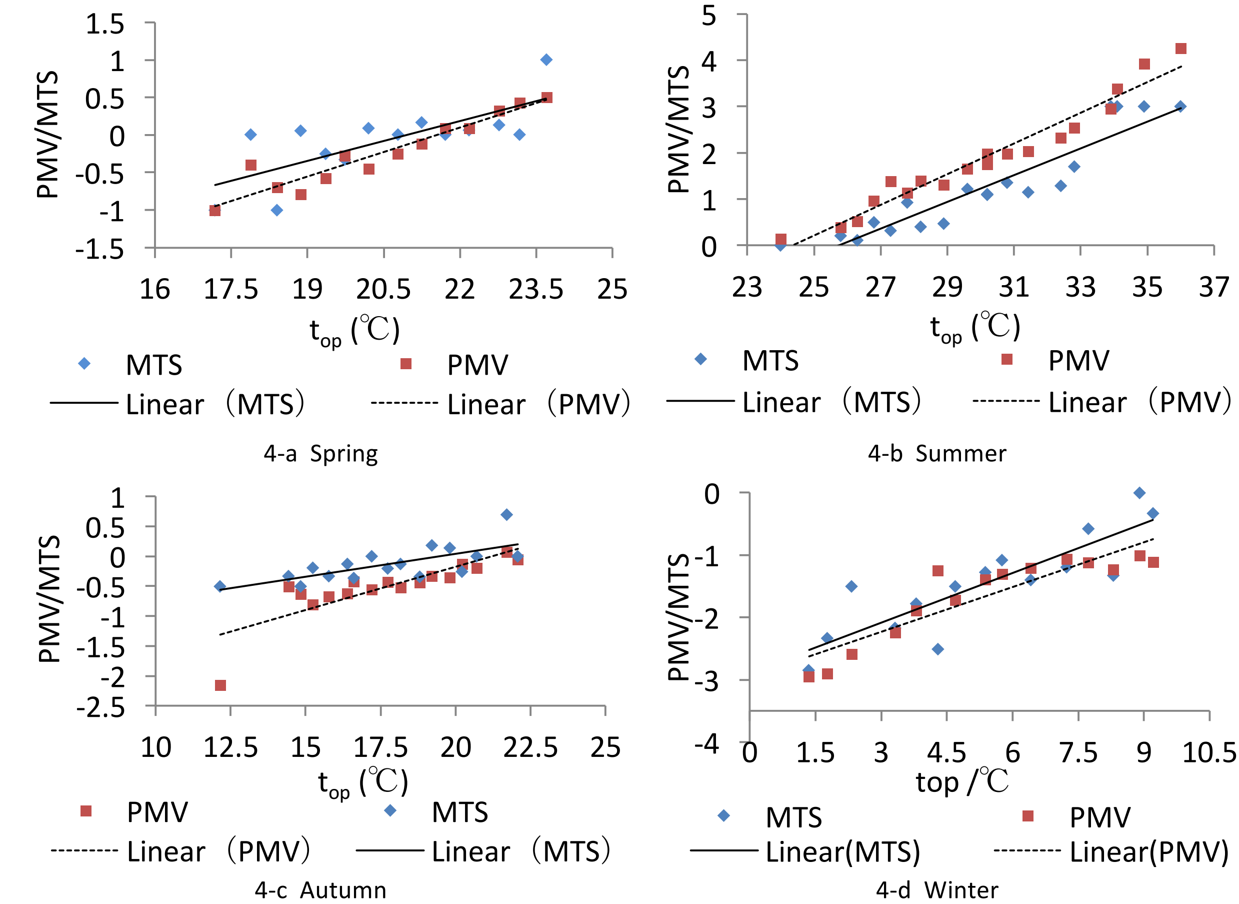


Figure4. Correlation between PMV/MTS and the operative temperature.

5 Impact on evaluation of indoor thermal environment

5.1 Evaluation of indoor thermal environment in China

Thermal comfort international standards such as ASHRAE standard-55, ISO standard-7730, and the European standard EN15251 play an important role in achieving building energy efficiency. Since an adaptive model was established, the adaptive model for the thermal comfort assessment has been amended to the ASHRAE Standard-55 2010 and the ISO standard-7730 2005. These international comfort standards are almost all based on North American and northern European subjects (Olesen B.W. et al, 2002), However, it has not been clarified in the aforementioned standards whether they are applicable to different environmental conditions especially China with a set of entirely different climate zones (Li B., et al, 2014). Therefore, Chinese Evaluation standard for indoor thermal environment in civil building GB/T 50785 was issued in 2012 (GB/T. 2012). The Chinese standard emphasizes the evaluation of indoor thermal environments, taking into account the great diversities of climatic characteristics and significant sensation variations and human adaptations in China. The Evaluation Standard for the indoor thermal environment was expected to be suitable for heated, cooled and free-running buildings in different climate zones and to provide a concept and methodology to create an acceptable and energy-efficient indoor thermal environment (Li B., et al, 2014). For the evaluation of free running buildings, a calculation method based on the model developed by Yao (Yao R. et al, 2009) called the adaptive predicted mean vote (aPMV) was involved in. There exists a relation between aPMV and PMV, the formula is as following:

$$\mathrm{aPMV}=\frac{\mathrm{PMV}}{1+\lambda\times\mathrm{PMV}} \tag{5}$$

where λ is the adaptive coefficient, which has a positive value when in warm conditions and a negative value when conditions are cool. In aPMV model, adaptive level can be measured by the adaptive coefficient (λ). When λ=0, aPMV=PMV, people don't adapt to the local climate; when λ>0, then, aPMV is smaller than PMV, people adapt to the warmer local climate; when the opposite result appears, people adapt to the cooler local climate.

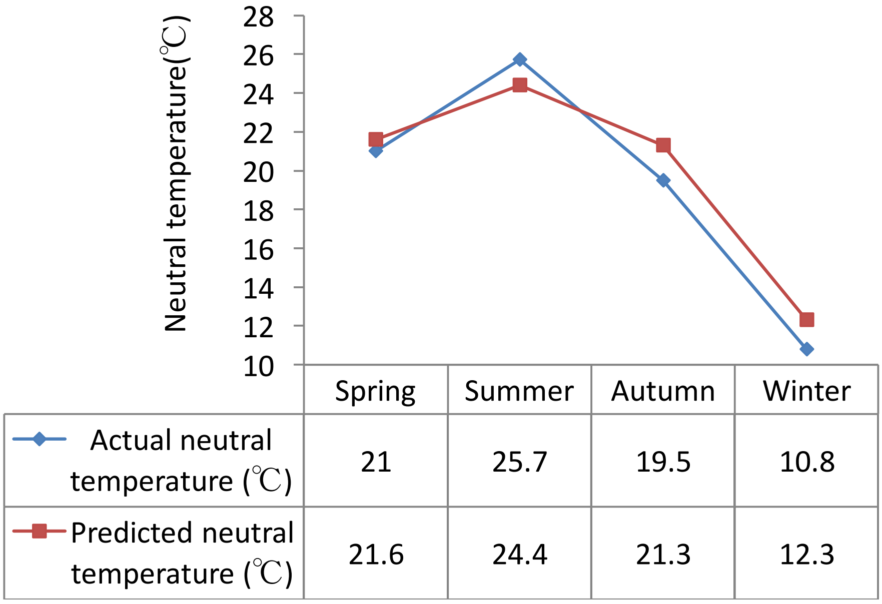


Figure 5. The actual and predicted neutral temperature.

The empirical values of the adaptive coefficients, λ, for cold zone in China were obtained listing in Table 3. In free-running buildings, the thermal environment evaluation grades I, II, III can be assessed according to the value of aPMV, which is illustrated in Table 4.

Table 3. Values of the adaptive coefficient λ in GB/T. 2012.

Climate zones		Types: Residential buildings, small department store, lodge, office	Types: Meeting room, classroom
Very cold, cold zones	PMV ≥ 0	0.24	0.21
	PMV < 0	-0.50	-0.29

Table 4. Assessment category for indoor thermal environments in free-running buildings and the corresponding calculated PMV scale for cold zone.

Category	Assessment index	PMV scale	
		λ=0.24（PMV≥0）	λ= -0.5（PMV<0）
Ⅰ 90% satisfactory	-0.5≤aPMV≤0.5	0≤PMV≤0.57	-0.67≤PMV<0
Ⅱ 75% satisfactory	-1≤aPMV<-0.5 or 0.5<aPMV≤1	0.57<PMV≤1.32	-2≤PMV<-0.67
Ⅲ unacceptable	aPMV<-1 or aPMV > 1	PMV > 1.32	PMV<-2.0

5.2 Seasonal aPMV models and Impact on the evaluation of indoor thermal environment

Figures 4a-d show that for the same level of indoor air temperature, the PMV is greater than the MTS in summer and is less than the AMV in other three seasons. Substituting the data from the seasonal field surveys into equation (5), the Yao's calculation method (Yao R. et al, 2009) is applied to calculate the value of the adaptive coefficient λ in the thermal comfort adaptive model, and λ for spring, summer, autumn and winter are -1.24, 0.45, -0.38 and -0.23 respectively. Seasonal adaptive coefficients are not the same, indicating that the adaptation levels of the occupants in different season are different. For spring and summer, the values of adaptive coefficient are relatively higher as compared to the values in autumn and winter. This is because there are more adaptive ways to adapt to warm and hot climate, such as opening windows, using fans and so on. Eqs. (6) to (9) represented the aPMV models for four seasons, and Figure6a-d illustrate the relationships between the PMV, aPMV and the MTS in four seasons in cold zone of China, respectively.

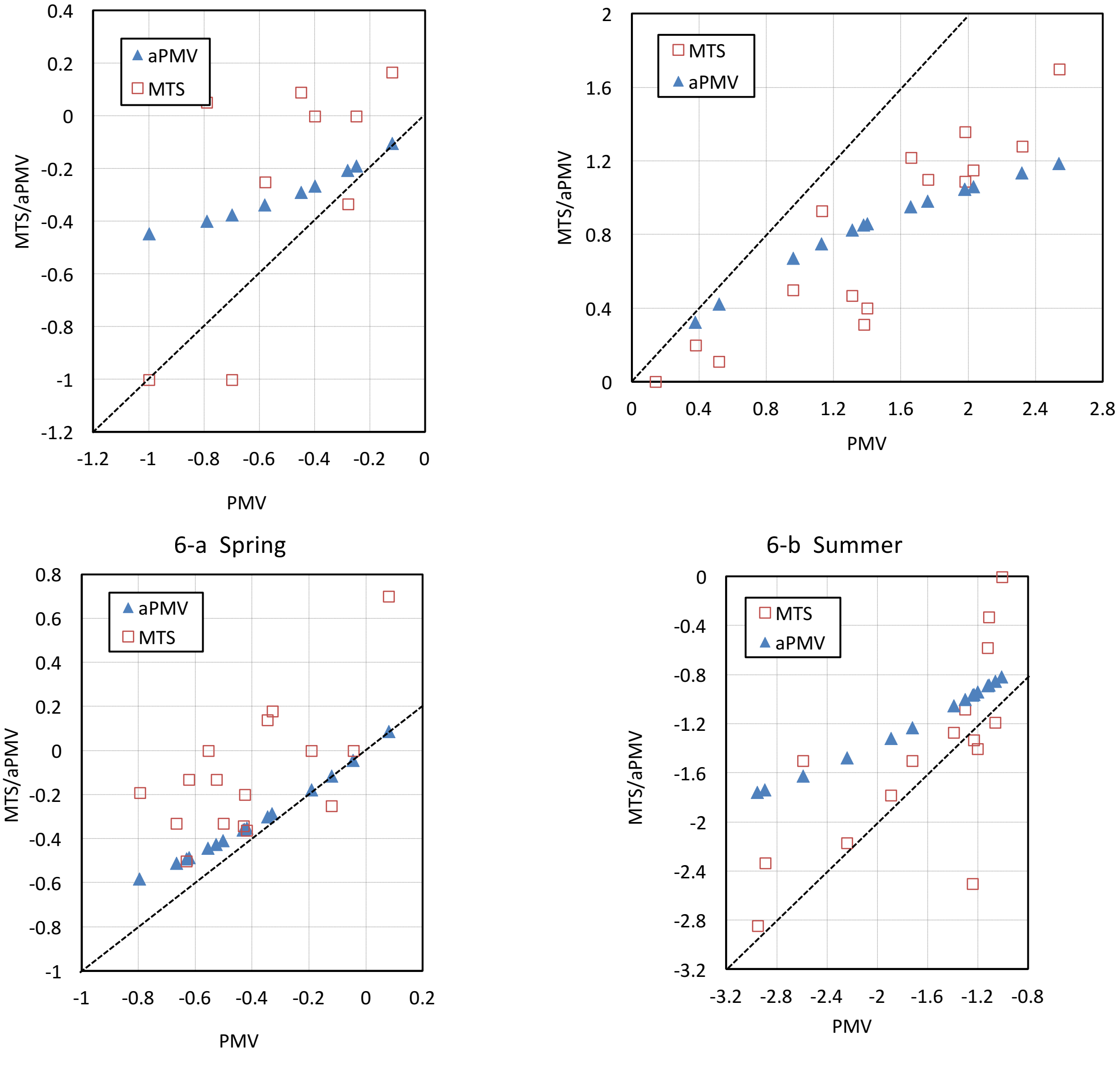
$$\text{Spring: aPMV} = \frac{\text{PMV}}{1 - 1.24\times\text{PMV}} \tag{6}$$

$$\text{Summer: aPMV} = \frac{\text{PMV}}{1 + 0.45\times\text{PMV}} \tag{7}$$

$$\text{Autumn: aPMV} = \frac{\text{PMV}}{1 - 0.38\times\text{PMV}} \tag{8}$$

$$\text{Winter: aPMV} = \frac{\text{PMV}}{1 - 0.23\times\text{PMV}} \tag{9}$$

According to table 3 and 4, the ranges of three evaluation grades in the standard GB/T 50785-2012 can be drawn (Figure7), and figure8 is the range calculated using adaptive coefficient (λ) obtained above. Comparing figs. 7 and 8, the range of thermal environment evaluation grades I, II, III are more or less different with standard: when PMV≥0, the PMV range boundary for three grades are 0.68 and 1.82, the former is slightly greater than that in the standard (0.57), and the later one is much greater than the one in standard (1.32). When PMV<0, there are two PMV range boundaries for grades I-II, they are -0.62(in autumn) and -1.32(in spring), PMV range boundaries for grades II-III is -1.30 which is very close to the I-II boundary in spring. This phenomenon will cause a different evaluation result when carrying out the evaluation work on the same building in different seasons, especially when -1.3<PMV<0. Therefore, it concluded that seasonal human thermal adaptation would affect the evaluation of indoor thermal environment.



6-a Spring

6-b Summer

6-c Autumn

6-d Winter

Figure 6. Relationship between MTS/aPMV and PMV.

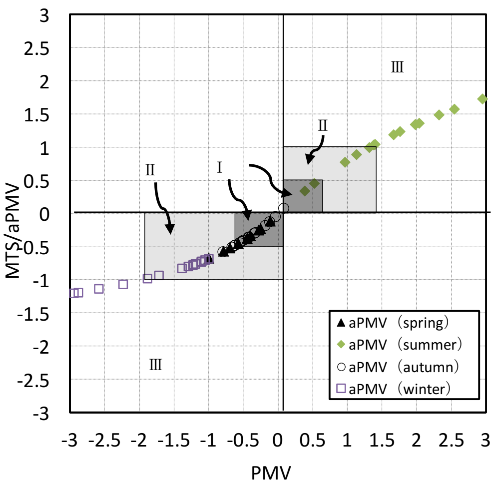


Figure7. The aPMV values and ranges of evaluation grades I, II, III using the adaptive coefficient given in standard GB/T 50785-2012.

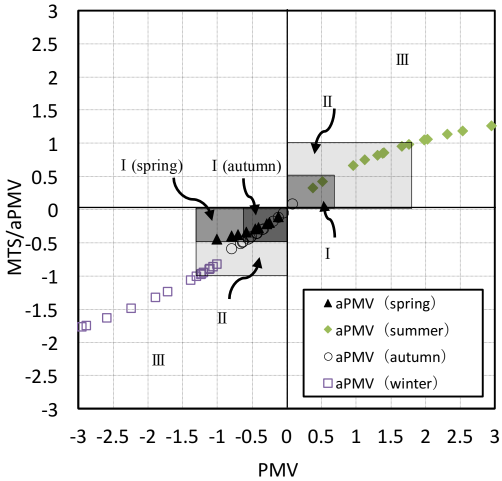


Figure8. The aPMV values and ranges of evaluation grades I, II, III using the adaptive coefficient given in this article.

6 Conclusion

This study is based on subjective questionnaire survey and objective on-site measurements of 226 occupants in naturally ventilated buildings in cold climate zone of China. The field studies were conducted in four seasons of the year to find out the seasonal human thermal adaptation and its impact on evaluation of indoor thermal environment. The results show that the thermal adaptations in four seasons are different, such as the differences in clothing level adjustment, thermal sensation (both MTS and PMV) and neutral temperature. Calculation method of adaptive coefficient (λ) in aPMV model developed by Yao was applied, and λ for spring, summer, autumn and winter are -1.24, 0.45, -0.38 and -0.23 respectively. The different λ values suggest that the occupant adopts different level of adaptations in different seasons. For spring and summer, the λ values are relatively higher as compared to the values in autumn and winter. Through calculating the ranges of three evaluation grades using seasonal λ values and comparing with the standard GB/T 50785-2012, it concluded that the evaluation of indoor thermal environment would be affected by seasonal human thermal adaptations.

Acknowledgements

This research was supported by the National Science Foundation for Distinguished Young Scholars of China (No. 51325803).

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Towards an adaptive model for thermal comfort in Japanese offices

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Abstract

This study was undertaken to investigate seasonal adaptation to temperature in Japanese offices, with a view to suggesting an adaptive model for them. We measured temperatures in 11 office buildings and conducted thermal comfort transverse surveys of occupants for over a year in the Tokyo and Yokohama areas of Japan. We collected 4,660 samples from about 1350 people. The occupants were found to be highly satisfied with the thermal environment in their offices. Even though the Japanese government recommends the indoor temperature setting of 28 °C for cooling and 20 °C for heating, we found that the comfort globe temperature was 2.6 °C lower in cooling mode and 4.3 °C higher in heating mode, in line with the actual indoor temperatures. The monthly and seasonal variation in the temperature in the investigated offices was significantly lower than had been found in dwellings. The comfort temperature is related primarily to the indoor temperature, but an adaptive relationship can be derived to estimate the indoor comfort temperature from the prevailing outdoor temperature for similar office buildings.

Keywords: Office building; Field survey; Griffiths' method; Indoor temperature; Comfort temperature; Adaptive model

1 Introduction

Thermal adaptation is one of the most important factors in creating a comfortable office environment. Investigating and establishing the comfort temperature of the occupants can suggest customary temperatures for office buildings, which may reduce energy use and save overall energy costs.

Comfort temperatures in Japanese offices based on field surveys have been investigated by Goto et al. 2007, Indraganti et al. 2013, Tanabe et al. 2013. However there are limitations in the research to date because of short time-periods or small samples. Comfort temperatures are likely to vary according to month and season, requiring long-term data to fully describe the occupants' perceptions and behavioural responses to the thermal environment in their offices.

In 2004 ASHRAE introduced an adaptive standard for naturally ventilated buildings (ASHRAE 2004) and CEN (2007) proposed an adaptive standard for free-running naturally ventilated buildings. However, Japanese data were not included in the data upon which they rest. The Japanese government recommends an indoor temperature setting of 28 °C for cooling and 20 °C for heating, and, while not unreasonable, the recommendation lacks supporting evidence from any field survey.

In order to explore seasonal differences in the comfort temperature and perhaps develop an adaptive model for Japanese offices, thermal measurements and a thermal comfort surveys were conducted for more than 1 year in 11 office buildings in Tokyo and Yokohama areas of Japan.

2 Field investigation

Thermal comfort surveys were conducted and corresponding thermal measurements made in 11 office buildings in the Tokyo and Yokohama areas of Japan from August 2014 to October 2015 (see Table 1). The indoor air temperature, globe temperature, relative humidity and air movement were measured 1.1m above floor level, away from direct sunlight, using a data logger (Figure 1, Table 2). Outdoor air temperature and relative humidity were obtained from the nearest meteorological station.

The subjective scales are shown in Table 3. The ASHRAE scale is frequently used to evaluate the thermal sensation, but the words 'warm' or 'cool' imply comfort in Japanese, and thus the SHASE scale (The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan) is also used to evaluate the thermal sensation (Table 3). To avoid a possible misunderstanding of 'neutral', it was explained in the questionnaire as 'neutral (neither cold nor hot)' (SHASE scale) or 'neutral (neither cool nor warm)' (ASHRAE scale). It is also said that the optimum temperature occurs on the cooler side in summer and on the warmer side in winter (McIntyre 1980), and so the scales of warmth sensation were supplemented by a scale of thermal preference.

We conducted both transverse and longitudinal surveys in open-plan offices. This paper analyses only the data from the transverse surveys. Respondents completed the questionnaire once a month for the transverse survey. As for the method of collecting the data, the instruments were set up on the office table, and questionnaires distributed to the people seated near to the instruments (Figure 1). While people were filling the questionnaire, the researcher recorded the environmental controls and the physical data. However, a few people did not provide responses due to their busy schedule, and others were not in the office at the time of the monthly visit. We collected 4,660 thermal comfort votes from about 1350 people.

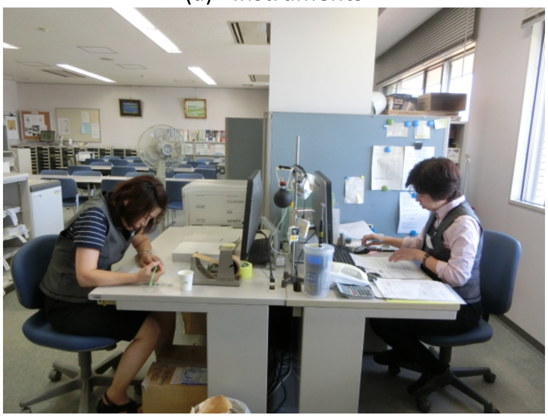
Table 1. Description of the investigated buildings

Building code	Location	Mode	HVAC control	Window	Natural ventilation opening	Number of survey months	Investigated floor*
B1	Tokyo	HVAC	Central	Fixed	Manual	13	4F, FF
B2	Yokohama	MM	Central	Openable	None	13	1F, 5F
B3	Tokyo	HVAC	Central	Fixed	None	13	3F
B4	Yokohama	MM	Local	Openable	None	13	1F, 2F
B5	Yokohama	MM	Local	Openable	None	13	5F
B6	Yokohama	MM	Local	Openable	None	13	1F
B7	Tokyo	MM	Local	Openable	None	13	1F, 4F
B8	Tokyo	MM	Local	Openable	None	13	1F
B9	Tokyo	HVAC	Central	Fixed	None	13	8F
B10	Tokyo	HVAC	Central	Fixed	Automatic	12	6F, 7F
B11	Tokyo	HVAC	Central	Fixed	None	12**	11F, 12F, 13F, 21F, 22F, 23F

HVAC: Heating, ventilation and air conditioning, MM: Mixed mode (heating in winter and cooling in summer), *: The floor is counted by American system, **: We have divided the floors in A, B & C groups (A: 22F, B: 21F, 23F, C: 11F, 12F, 13F) for monthly survey and each group is visited every 3 month i.e. each season. One small room of 21F is visited only once.

(a) Instruments

(b) Respondents, reseacher and instruments



(c) Respondents and instruments

(d) Respondents and instruments

Figure 1 Photograph of the instrumentation and thermal comfort survey

Table 2. Description of the instruments

Parameter Measured	Trade Name	Range	Accuracy
Air temperature, Humidity, CO_2	TR-76Ui	0 to 55 °C, 10% to 95% RH, 0 to 9,999 ppm	±0.5 °C, ±5%RH, ±50 ppm
Globe temperature	Tr-52i	−60 to 155 °C	±0.3 °C
	SIBATA 080340-75	Black painted 75 mm diameter globe	
Air movement	Kanomax, 6543-21	0.01 to 5.00 m/s	±0.02 m/s
Illuminance	TR-74Ui	0 to 130 klx	±5%

Table 3. Questionnaires used in the thermal comfort surveys

No.	SHASE scale	ASHRAE scale	Thermal preference
1	Very cold	Cold	Much warmer
2	Cold	Cool	A bit warmer
3	Slightly cold	Slightly cool	No change
4	Neutral (neither cold nor hot)	Neutral (neither cool nor warm)	A bit cooler
5	Slightly hot	Slightly warm	Much cooler
6	Hot	Warm	
7	Very hot	Hot	

3 Results and discussion

The data were divided into three groups. If heating was in use at the time of the survey visit, the data were classified as being in the heating mode (HT). If cooling was in use at the time of the visit, the data were classified as being in the cooling mode (CL). If neither heating nor cooling were in use, the data were classified as being in the free-running mode (FR). The CL and HT modes are distinct groups of data (generally CL used in summer and HT is used in winter), and need to be analysed separately. Thus the classification differs from that used in the CIBSE Guide (CIBSE 2015), and in current standards ISO Standard EN 15251 and ASHRAE Standard 55.

3.1 Distribution of outdoor and indoor temperature

The mean outdoor air temperatures during the voting were 20.7 °C, 24.9 °C and 10.4 °C for FR, CL and HT modes respectively. As shown in the Figure 2 and Table 4, the globe temperature is highly correlated with the indoor air temperature, and so the results can be presented using the indoor globe temperature alone.

The mean globe temperatures during the voting were 25.0 °C, 25.9 °C and 23.9 °C for FR, CL and HT modes respectively (Figure 3). The Japanese government recommends indoor temperature settings of 20 °C in winter and 28 °C in summer respectively. The results show that the mean indoor temperatures during heating and cooling were quite different from those recommended. The seasonal range of the indoor temperature was quite small, while there was a wide seasonal range of outdoor temperature.

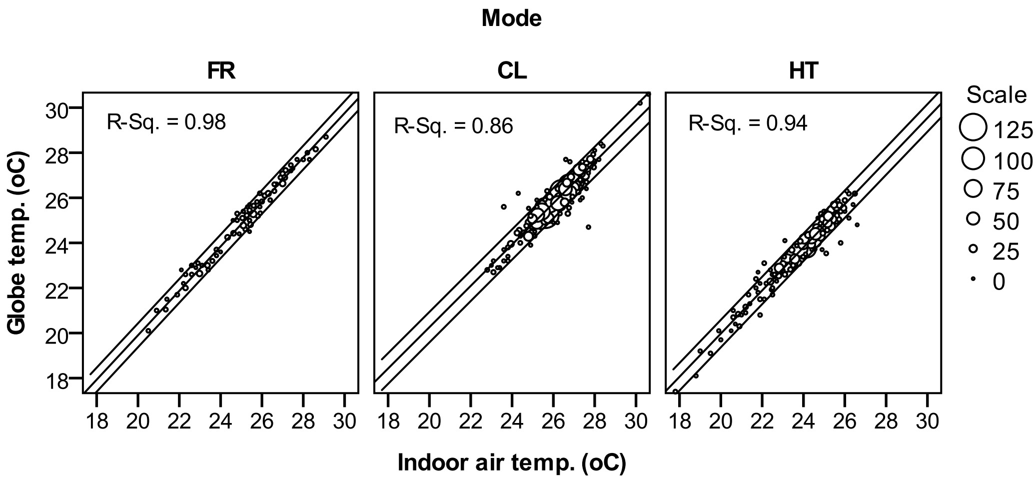


Figure 2 Relation between the globe temperature and indoor air temperature.

Table 4. Correlation coefficients for globe temperature and indoor air temperature or outdoor air temperature.

Mode	T_g:T_i		T_g: T_o	
	Number of sample (n)	Correlation coefficient (r)	Number of sample (n)	Correlation coefficient (r)
FR	422	0.99	422	0.76
CL	2,537	0.93	2,514	0.25
HT	1,699	0.97	1,699	0.28
All	4,658	0.98	4,635	0.64

T_g: Globe temp. (°C), T_i: Indoor air temperature (°C), T_o: Outdoor air temperature (°C), The correlation coefficient is statistically significant (p<0.001)

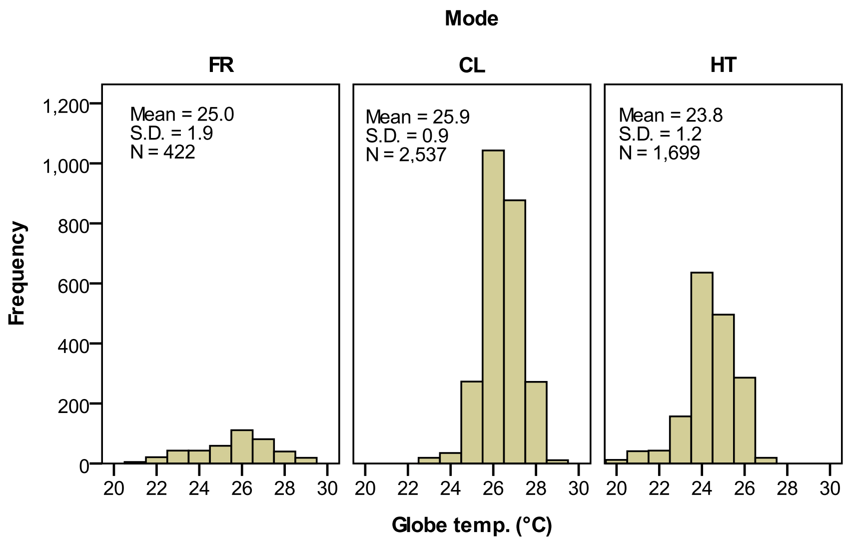


Figure 3 Distribution of globe temperature in various modes.

3.2 Comparison of the scales

We compared the performance of ASHRAE and SHASE scales by regressing the thermal response on the globe temperature. Table 5 compares the relevant regression statistics.

It is apparent that the thermal sensation when expressed on the SHASE scale correlates more closely with the globe temperature than it does when expressed on the ASHRAE scale. It also has a smaller residual standard deviation, which indicates that people agree more closely about their sensation at any particular temperature (their responses are more similar) when this scale is used. The regression coefficients are similar on the two scales. It can be concluded that the SHASE scale is better for these data, and should be used to present the results. This superiority of the SHASE scale had previously been found in our surveys in dwellings (Rijal et al. 2014, Humphreys et al. 2016).

The preference scale has fewer categories (5 rather than 7) and so its statistics are not directly comparable with those of the seven-category scales. Its purpose is different from that of the SHASE scale, and so it is retained.

Table 5 Regression analysis of thermal sensation and thermal preference on the globe temperature

Scale	Number of votes	Regression coefficient/K	Correlation coefficient	Residual standard deviation	Overall standard deviation of thermal sensation
ASHRAE	4,379*	0.232	0.38	0.84	0.91
SHASE	4,658	0.213	0.42	0.69	0.76
Preference	4,658	0.191	0.43	0.61	0.67

*We did not ask the ASHRAE scale in August 2014, and thus the number of votes is less than SHASE scale.

3.3 Distribution of thermal sensation

Mean thermal sensation vote was 4.0, 4.2 and 3.7 in FR, CL and HT modes respectively. Occupants sometimes felt hot (greater than 5) in CL mode and sometimes felt cold (less than 3) in HT mode (Table 6), despite the use of heating or cooling. As there are many '4 neutral' votes in each mode, it can be said that occupants were generally satisfied in the thermal environment of the offices. It is conventional to consider as comfortable responses that fall in categories 3, 4 and 5. These percentages are very high, as shown in the last column of the table.

To locate the thermal comfort zone, Probit regression analysis was conducted for the thermal sensation vote (TSV) categories and the temperatures for each mode. (The analysis method is Ordinal regression using Probit as the link function and the temperature as the covariate.)

The results of the Probit analysis is shown in Table 7. The temperature corresponding to the median response (Probit = 0) is calculated by dividing the constant by regression coefficient. For example, the mean temperature of the first equation will be 6.2/0.359 = 17.3 °C (Table 7). The inverse of the Probit regression coefficient is the standard deviation of the cumulative Normal distribution. For example, the standard deviation of air temperature of the FR mode will be 1/0.359 = 2.8 °C (Table 7). These calculations are fully given in Table 7. Transforming the Probits using the following function into proportions gives the curve of Figure 4 a–c. The vertical axis is the proportion of votes.

Probability = CDF.NORMAL (quant, mean, S.D.) (1)

where 'CDF.NORMAL' is the Cumulative Distribution Function for the normal distribution, 'quant' is the globe temperature (°C); the 'mean' and 'S.D.' are given in the Table 7.

The highest line is for category 1 (the margin between 'very cold' and 'cold') and so on successively. Thus it can be seen that the temperatures for thermal neutrality (a probability of 0.5) is around 25 °C (Figure 4 a–c).

Reckoning the three central categories as representing thermal comfort, and transforming the Probits into proportions gives the bell-curve of Figure 4 d. The result is remarkable in two respects. The proportion of people comfortable at the optimum is very high, only just less that 100%, and the range over which 80% are comfortable is wide—from around 20 to 30 °C.

Table 6 Percentage of thermal sensation in each mode

Mode	Items	Thermal sensation							Total	Central 3 categories
		1	2	3	4	5	6	7		
FR	N	-	4	77	260	76	7	-	424	413
	Percentage (%)	-	0.9	18.2	61.3	17.9	1.7	-	100	97.4
CL	N	5	29	251	1424	747	66	15	2537	2422
	Percentage (%)	0.2	1.1	9.9	56.1	29.4	2.6	0.6	100	95.4
HT	N	9	72	436	1027	150	5	-	1699	1613
	Percentage (%)	0.5	4.2	25.7	60.4	8.8	0.3	-	100	94.9

N: Number of sample

Table 7 Results of the probit analysis

Mode	Globe temperature T_g (°C)					
	Equation*	Median	S.D.	N	R^2	S.E.
FR	$P(\le 2)=0.359T_g-6.2$	17.3	2.8	422	0.25	0.034
	$P(\le 3)=0.359T_g-7.9$	22.0				
	$P(\le 4)=0.359T_g-10.0$	27.9				
	$P(\le 5)=0.359T_g-11.5$	32.0				
CL	$P(\le 1)=0.353T_g-6.1$	17.3	2.8	2,537	0.08	0.024
	$P(\le 2)=0.353T_g-6.8$	19.3				
	$P(\le 3)=0.353T_g-7.9$	22.4				
	$P(\le 4)=0.353T_g-9.6$	27.2				
	$P(\le 5)=0.353T_g-11.1$	31.4				
	$P(\le 6)=0.353T_g-11.8$	33.4				
HT	$P(\le 1)=0.270T_g-3.7$	13.7	3.7	1,699	0.08	0.022
	$P(\le 2)=0.270T_g-4.7$	17.4				
	$P(\le 3)=0.270T_g-5.9$	21.9				
	$P(\le 4)=0.270T_g-7.8$	28.9				
	$P(\le 5)=0.270T_g-9.3$	34.4				

*: All regression coefficients are significant (p<0.001), $P_{(\le 1)}$ is the Probit of proportion of the votes that are 1 and less, $P_{(\le 2)}$ is the Probit of the proportion that are 2 and less, and so on., S.D.: Standard deviation, N: Number of sample, R^2: Cox and Snell R^2, S.E.: Standard error of the regression coefficient.

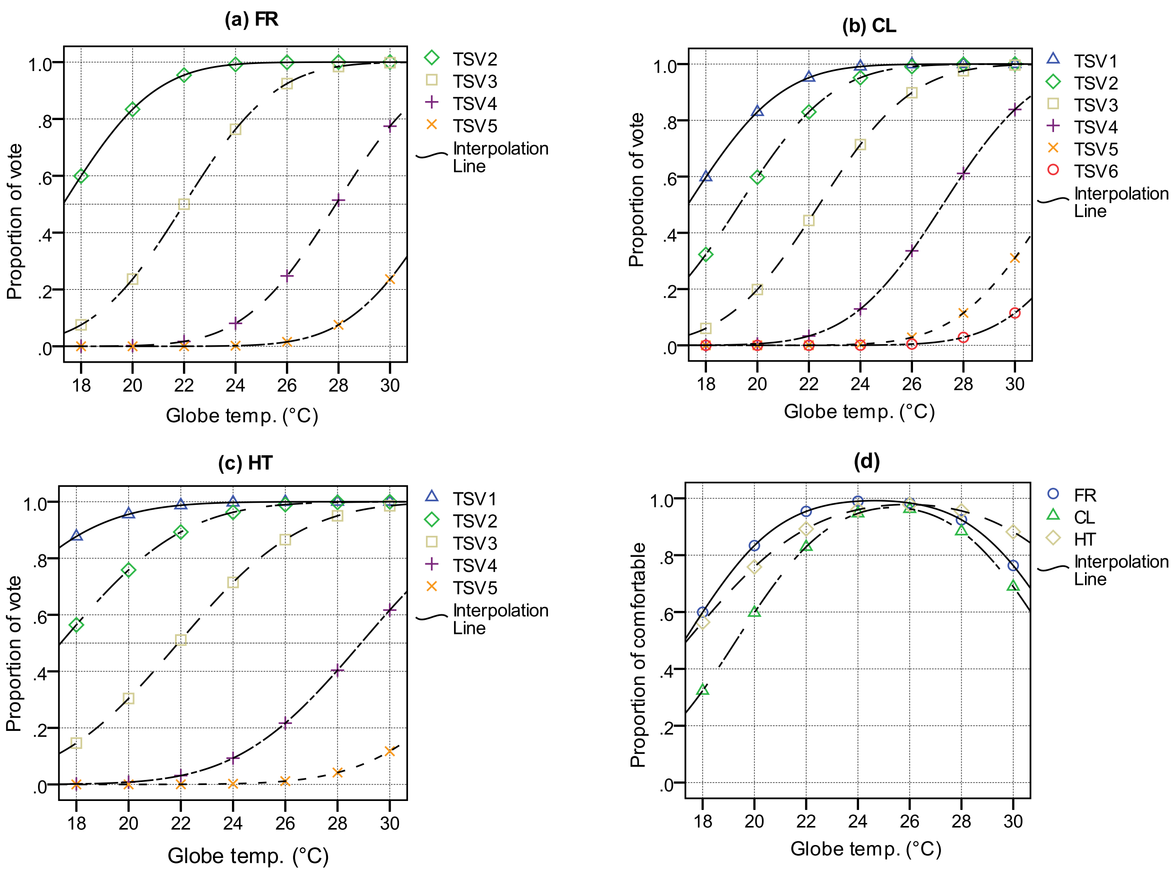


Figure 4 Proportion of thermal sensation vote (TSV) or comfortable (TSV 3, 4 or 5) for globe temperature.

3.4 Prediction of the comfort temperature

3.4.1 Regression method

Linear regression analysis was conducted to predict the comfort temperature. Figure 5 shows the relation between thermal sensation and globe temperature. The following regression equations are obtained for the thermal sensation (C) and temperatures.

FR mode $C=0.183T_g-0.6$ (n=422, $R^2=0.25$, S.E.=0.015, $p<0.001$) (2)

CL mode $C=0.228T_g-1.7$ (n=2,537, $R^2=0.08$, S.E.=0.015, $p<0.001$) (3)

HT mode $C=0.168T_g-0.3$ (n=1,699, $R^2=0.08$, S.E.=0.013, $p<0.001$) (4)

T_g: Globe temperature (°C); n: Number of sample; R^2: Coefficient of determination; S.E.: Standard error of the regression coefficient; p: Significance level of regression coefficient.

When the comfort temperature is predicted by substituting '4 neutral' in the equations (2) to (4), it would be 25.1 °C, 25.0 °C and 25.6 °C in FR, CL and HT modes respectively. As shown the Figure 5, the comfort temperature of the HT mode is higher than the CL mode. This might be due to the problem of applying the regression method in the presence of adaptive behaviour, where it can be misleading when used to estimate the comfort temperature, as has been found in previous research (Rijal et al. 2013). So to avoid the problem the comfort temperature is re-estimated using the Griffiths method.

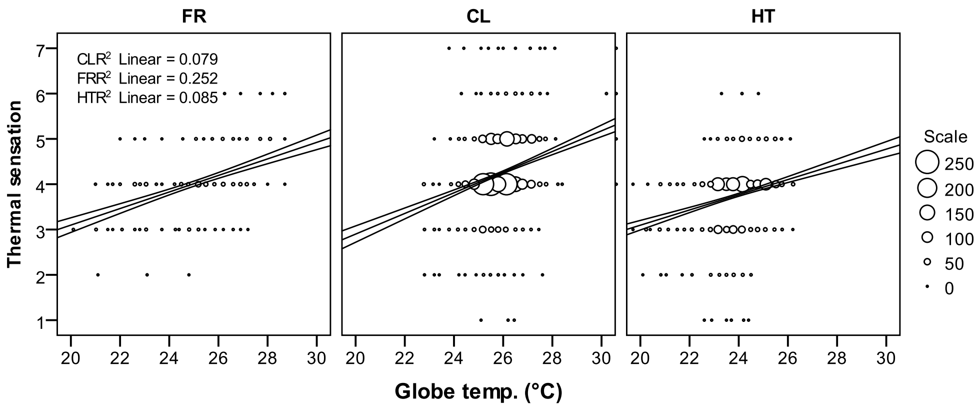


Figure 5 Relation between the thermal sensation and indoor globe temperature

3.4.2 Griffiths' method

The comfort temperature is predicted by the Griffiths' method (Griffiths 1990, Nicol et al. 1994, Rijal et al. 2008).

$$T_c = T_g + (4 - C) / a \quad (5)$$

T_c: The comfort temperature by Griffiths' method (°C); T_g: globe temperature (°C); C: Thermal sensation vote; a: The rate of change of thermal sensation with room temperature.

In applying the Griffiths' method, Nicol et al. (1994), Rijal et al. (2010, 2013) and Humphreys et al. (2013) used values for the constant, a, of 0.25, 0.33 and 0.50 for a 7 point thermal sensation scale. We investigated the comfort temperature using these regression coefficients. The mean comfort temperature with each coefficient is similar (Table 8), so it matters little which coefficient is adopted. The comfort temperature calculated with the coefficient 0.50 is used for further analysis. In our data powerful adaptation to the seasonal variation of indoor temperature necessitates the use of the Griffiths method.

The mean comfort temperature by the Griffiths' method is 25.0 °C, 25.4 °C, 24.3 °C in FR, CL and HT modes respectively (Figure 6). The correlation between the comfort temperature and globe temperature is quite high (Figure 7), showing that fundamentally the people had adapted to a large extent to the temperatures that were provided. Had more seasonal drift of indoor temperature been provided, it is likely that people would have adapted to that temperature. Even though, the Japanese government recommends an indoor temperature setting of 28 °C for cooling and 20 °C for heating, we found that in these buildings the comfort-temperature was 2.6 °C lower in CL mode and 4.3 °C higher in HT mode.

Table 8 Comfort temperature predicted by Griffiths' method

Regression coefficient	Comfort temperature, T_c (°C)								
	FR			CL			HT		
	N	Mean	SD	N	Mean	SD	N	Mean	SD
0.25	422	25.0	2.4	2537	24.9	2.9	1699	24.9	2.7
0.33	422	25.0	2.0	2537	25.2	2.2	1699	24.6	2.1
0.50	422	25.0	1.7	2537	25.4	1.5	1699	24.3	1.6

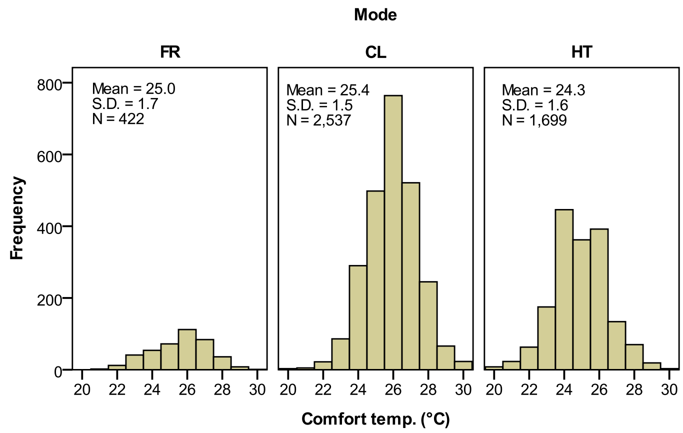


Figure 6 Distribution of comfort temperatures from each observation using the Griffiths' method in each mode.

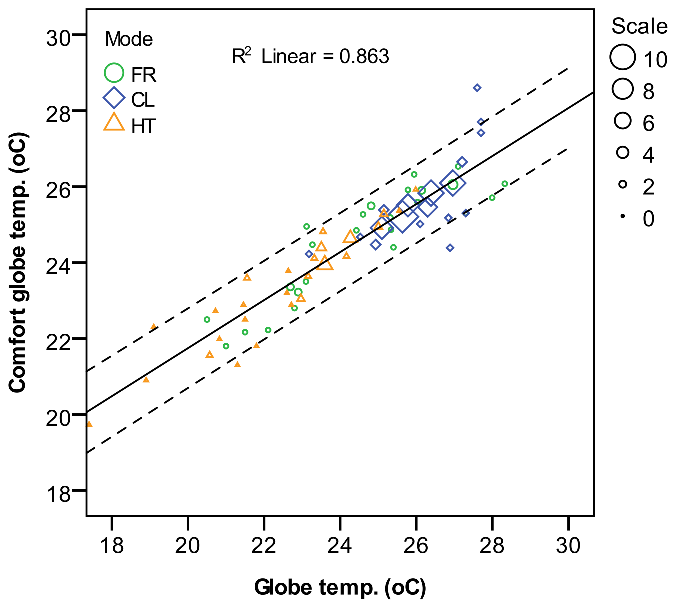


Figure 7 Relation between the comfort temperature and globe temperature. Each point represents the monthly mean comfort temperature in each office building.

3.4.3 Monthly and seasonal difference in comfort temperature

We would like to clarify the monthly and seasonal difference of the comfort temperature as shown in the Figures 8 and 9. It is evident that the comfort temperature closely tracks the mean indoor globe temperature over the year, the difference between them never exceeding 1K in any month or season. The comfort temperature and the indoor globe temperature both show rather little monthly and seasonal variation. The comfort temperature is 22.1 °C in March, 26.0 °C in September in FR mode. Thus, the monthly difference of the mean comfort temperature is 3.9 K. The comfort temperature is 24.2 °C in spring, 25.7 °C in summer and 24.9 °C in autumn in FR mode. Thus, monthly and seasonal difference in comfort temperature is significantly less than was found in dwellings (Rijal et al. 2013). When we compared the summer comfort temperature with previous research, it is similar in FR mode and slightly lower in CL mode (Table 9).

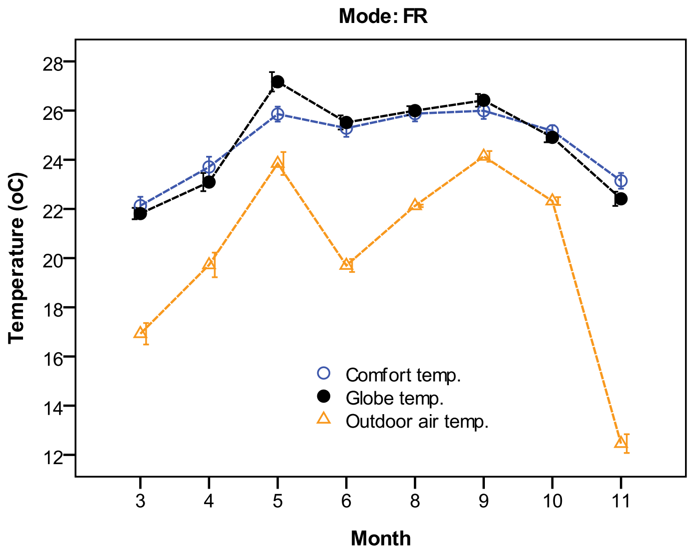


Figure 8 Monthly mean comfort temperature with 95% confidence intervals predicted by Griffiths' method (March to November)

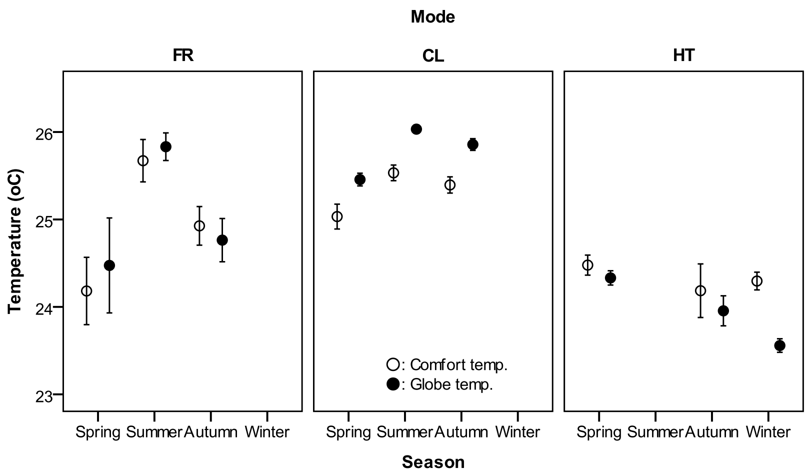


Figure 9 Seasonal difference of comfort temperature with 95 % confidence intervals by Griffiths' method

Table 9 Comparison of comfort temperature with previous research

Area	Reference	Season	Temperature (°C)	Mode		
				FR	CL	FR, CL, HT
Tokyo, Yokohama	This study	Summer	Comfort temperature (T_g)	25.7	25.5	-
Tokyo	Tanabe et al. (2013)	Summer	Comfort temperature (T_i)	-	26.2	-
Tokyo	Indraganti et al. (2013)	Summer	Comfort temperature (T_g)	25.8	27.2	-
Sendai, Tsukuba, Yokohama	Goto et al. (2007)	4 seasons	Preferred SET*	-	-	26.0

T_g: Globe temperature, T_i: Indoor air temperature

3.5 Relating the comfort temperature to the outdoor temperature

3.5.1 Running mean outdoor temperature

The running mean outdoor temperature is the exponentially weighted daily mean outdoor temperature, and it is calculated using the following equation (McCartney & Nicol 2002).

$$T_{rm} = \alpha T_{rm-1} + (1-\alpha)T_{od-1} \quad (6)$$

Where, T_{rm-1} is the running mean outdoor temperature for the previous day (°C), T_{od-1} is the daily mean outdoor temperature for the previous day (°C). So, if the running mean has been calculated (or assumed) for one day, then it can be readily calculated for the next day, and so on. α is a constant between the 0 and 1 which defines the speed at which the running mean responds to the outdoor air temperature. In this research α is assumed to be 0.8.

3.5.2 Linear regression equations

An adaptive model relates the indoor comfort temperature to the outdoor air temperature (Humphreys 1978, Humphreys & Nicol 1998, ASHRAE 2004, CEN 2007). Figure 10 shows the relation between the comfort temperature (calculated by the Griffiths' method) and the running mean outdoor temperature. The regression equations are given below.

FR mode $T_c=0.206T_{rm}+20.8$ ($n=422$, $R^2=0.42$, S.E.=0.012, $p<0.001$) (7)

CL&HT mode $T_c=0.065T_{rm}+23.9$ ($n=4,236$, $R^2=0.10$, S.E.=0.003, $p<0.001$) (8)

T_c: Comfort temperature by Griffiths' method (°C); T_{rm}: the exponentially-weighted running mean outdoor temperature for the day (°C); S.E.: the standard error of the regression coefficient.

The regression coefficient and the correlation coefficient in the FR mode are higher than in the CL and HT modes. The regression coefficient is lower than that in the CEN standard (FR=0.33) and CIBSE guide (CL&HT=0.09). It is lower than found for Japanese dwellings (Rijal et al. 2013). It is probable that the low gradients which we find for the 'adaptive models' just reflect the small seasonal trends of the indoor temperatures in our sample of office buildings. 90% of data of this study is from the CL&HT mode, and thus we need to increase the sample size of the FR mode to obtain a reliable estimate. In view of the climatic variation across Japan, we also need to conduct the field survey in various parts of Japan.

The equations can be used to predict the indoor comfort temperature for these buildings. For example, when the running mean outdoor temperature is 25 °C, 28 °C and 10 °C in the equations (7) & (8), the comfort temperature would be 26.0 °C, 25.7 °C and 24.6 °C for the FR, CL and HT modes respectively. The results indicate that the range of the month-mean comfort temperature for HT & CL mode is small – less than 2k – probably because the occupants adapted only to the small seasonal variation of the temperature setting in these particular offices. (Had the government recommended temperatures been provided, the occupants could perhaps have adapted to the summer or winter environment of the office without compromising comfort or productivity, but further surveys would be needed to explore the question.)

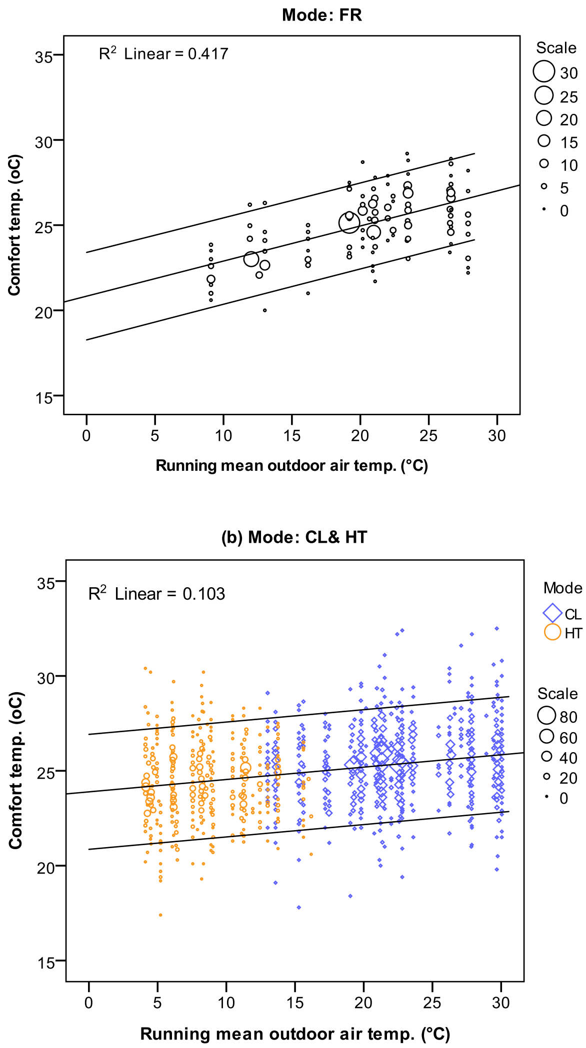


Figure 10 Relation between the comfort temperature and the running mean outdoor temperature.

3.5.3 Comparison with adaptive model in the CEN standard

Figure 11 shows the variation of the comfort temperature in the CEN standard (Nicol & Humphreys 2007) and in this research. The scatter of the comfort temperature is quite similar in two surveys, but the gradients are very different, probably reflecting the smaller seasonal variation of temperature found in the Japanese offices.

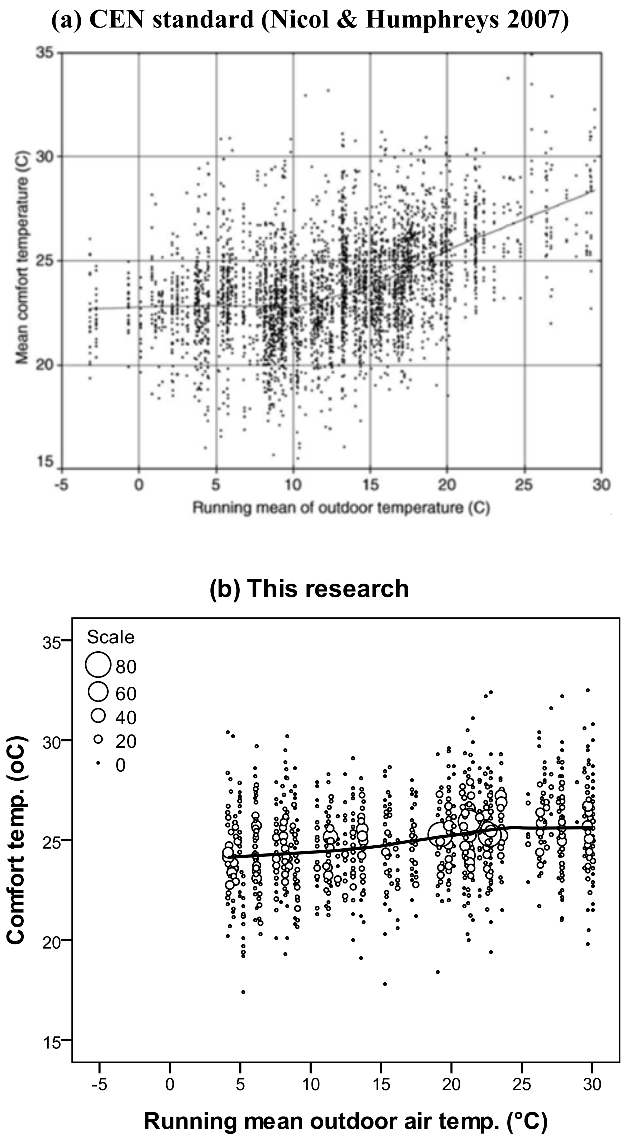


Figure 11 Variation of the comfort temperature in previous and this research.

4 Conclusions and discussion

A thermal comfort survey of the occupant of the Tokyo and Yokohama areas of Japan was conducted more than a year in 11 office buildings. The following results were found:

- The occupants proved to be highly satisfied with the thermal environment of their offices, as indicated by the high proportion of 'neutral' responses.
- The average comfort temperature was found to be 25.4 °C when cooling was used, 24.3 °C when heating was used, and 25.0 °C when neither heating nor cooling were used (the FR mode). The comfort temperature for heating mode is surprisingly high.
- The seasonal variation in comfort temperature in offices is significantly lower than in had been found in Japanese dwellings.
- The seasonal variation of the comfort–temperatures tracked those of the concurrent mean indoor globe temperatures, to the extent that the difference between them never exceeded 1K.

This last finding, which is in agreement with the findings of the great majority of other field-surveys of thermal comfort, in all but the more extreme indoor temperatures, strongly suggests that the fundamental adaptive relation is between the comfort temperature and the prevailing *indoor* temperature and not between the comfort-temperature and the prevailing *outdoor* temperature. People become adapted to the indoor temperatures they experience, while at the same time they adjust the indoor temperature to make themselves comfortable.

It follows that the relation between the comfort temperature and the outdoor prevailing mean temperature is not fixed, but depends on the thermal properties of the building envelope, and on the temperatures at which heating and cooling are set to operate. The 'adaptive model' obtained from this survey therefore should not be generalised to apply to all offices in Japan. It is, however, expected to apply to other Japanese offices with similar thermal properties and similar patterns of temperature control.

Acknowledgements

We would like to thank to all the people who participated in the survey, to the Gotoh Educational Corporation, Hulic Co., Ltd., Nikken Sekkei Ltd., Panasonic Corporation, Tokyo City University, Tokyu Fudosan Next Generation Engineering Center Inc., Tsuzuki Ward for their cooperation and to all students for data entry. This research was supported by Grant-in-Aid for Scientific Research (C) Number 24560726 and (B) Number 25289200.

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Assessing overheating risk and preparedness in care facilities in the UK

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Abstract

Research in the UK and elsewhere has highlighted that older people are particularly vulnerable to negative health effects of overheating. Funded by Joseph Rowntree Foundation, this study empirically assesses the risk of summertime overheating across four care home facilities in the UK, using continuous monitoring of indoor (and outdoor) temperatures from June to September 2015, and building surveys to identify design features that can enable or prevent occupants and their carers to control their thermal environment. Qualitative feedback was gathered through semi-structured interviews with designers and senior managers of the care facilities.

The results from the monitoring study indicate a high risk of summertime overheating across all the case study settings, especially during short-term peaks in outdoor temperatures. Nevertheless managing the risk of overheating in care homes is found to be under-prioritised by designers, care home managers and front-line staff, due to the perception that 'older people are vulnerable to cold, and not heat'. Insights from building surveys showed under-ventilation due to single-aspect rooms, window restrictors and sealed trickle vents in windows. The separation of care service management and building maintenance team resulted in confusion amongst care staff and residents about how the ventilation systems work, and whose responsibility it was to turn them on or off. Institutional factors such as relatively short-term development strategies affected the willingness to adapt designs against overheating. This makes vulnerable care facilities even more exposed to overheating risk, now and in the future.

Keywords: overheating; care sector; monitoring; indoor environmental conditions

1 Introduction

Anthropogenic climate change is expected to result in hotter and drier summers with heatwaves with greater frequency, intensity and duration; milder and wetter winters with more storms and flooding in the UK (DEFRA 2011; Gupta and Gregg 2013). This has serious implications for future heat-related mortality, given that there are currently around 2,000 premature heat-related deaths in the UK each year (CCC, 2014). Specifically for older people in care homes, research has shown that in England and Wales these are the most vulnerable to negative health effects of summer overheating (AECOM 2012; Lindley et al 2011).

Physiological studies show that the body's response to heat is impaired with age (Klenk et al, 2010), and chronic or severe illnesses (PHE, 2014; Koppe et al, 2004). Relatively healthy older people can also be at risk, particularly in extremely hot weather (PHE, 2014; Tran and Petrokofsky, 2013; Klenk et al, 2010), partly because they do not necessarily perceive themselves to be vulnerable (Abrahamson et al, 2009). It is also likely that heat-related mortality rates are mediated by people's ability to adapt to local conditions as well as physiological changes over time (PHE, 2014). This indicates that both *care practices* and *environmental factors* can affect people's vulnerability especially in heatwaves (Brown and Walker, 2008). The need to adapt to ongoing climate change has been highlighted by the

National Health Service (NHS) Heatwave Plan for England (NHS England & Public Health England (PHE), 2013) and the recently published report by the UK's Adaptation Sub-Committee on the potential climate change risks to population well-being (CCC, 2014).

However there is growing evidence that many new-build care and extra-care housing schemes are already too warm for occupants and 'overheating' (Barnes et al, 2012; Lewis, 2014; Guerra-Santin and Tweed, 2013). Given that UK Climate Projections 2009 (UKCP09) indicate that by the 2080s mean daily maximum temperatures will increase even further (Jenkins et al, 2009), such rises in ambient temperature are likely to lead to even more overheating in care settings. Moreover care and extra-care housing schemes are generally hybrid building-types, simultaneously functioning as long-term residences, sometimes nursing environments, and workplaces. This hybridity is reflected in the design of care and extra-care buildings, and there are many other aspects to be considered within the design of care and extra-care housing that can all impact (positively and negatively) on the building's risk of summertime overheating; including safety issues, diverging needs and preferences (particularly between staff and residents), user-technology interaction, and questions about who is responsible for thermal conditions (van Hoof et al, 2010).

Within this context, this paper seeks to investigate the current risk of summer overheating in two care homes and two extra care settings, and assess how prepared the care sector is to tackle this risk through appropriate design, management and use. The research is part of a wider study funded by Joseph Rowntree Foundation to examine how far existing care homes and other care provision in the UK are fit for a future climate, and to consider the preparedness of the care sector in light of the consequences of climate change with a focus on overheating.

2 Care and extra-care homes: physical and institutional context

It is important to note that there are differences between care and extra-care settings, such as a care home is a residential setting, where a number of older people live, usually in single rooms but with access to communal social spaces, and have access to on-site care services with meals provided and staff on call 24 hours a day. In contrast, extra-care housing is a different type of housing and care scheme designed to accommodate older people who are becoming frailer and less able, but who still require and/or desire some level of independence. Extra-care housing schemes provide varying levels of care and support; at a minimum, there will be some kind of on-call assistance for people in an emergency, but not necessarily a 24 hour a day physical presence, as is available in care homes. Extra-care schemes also usually provide self-contained units, consisting of a kitchen, living/dining area, bathroom and one or two bedrooms, in addition to communal social facilities similar to those within a care home.

In both care and extra-care settings existing research indicates that warmth is generally seen as something that is positive and the cold in turn as something negative; achieving thermal comfort is strongly related to keeping residents warm (Brown 2010, Walker et al. 2015, Neven et al 2015, Lewis 2015). The status of warmth is reinforced by two institutional aspects that are important for care homes: the regulatory context and business considerations. Neven et al. (2015) describe the degree of scrutiny and regulation that care homes are under and emphasise that the temperature and thermal comfort of the home are part of this scrutiny, with Care Quality Commission (CQC) inspectors checking room temperatures and scrutinizing staff responsiveness to complaints from residents about being cold. Furthermore, many care homes are run as a business and the success of this business relies heavily on keeping occupancy rates high; being labelled as a care home that is too cold can be very damaging as this is quickly associated with poor care standards (Neven et al., 2015).

Research by Brown (2010) in care homes suggests that there are several institutional aspects which can limit responsiveness to heatwave risks such as the *hierarchical power structures* preventing junior staff and residents from interacting with certain aspects of the heating and cooling infrastructure; *the way in which hot and cold weather are perceived*; carers, care home management and care home inspectors alike have a particular view of indoor temperatures, with the cold seen as problematic and dangerous but heat is not and even during hot weather measures are still employed to maintain a high indoor temperature. Moreover the immobility of residents and the way in which they are actively prevented from moving around, in part due to safety and control, leads to inactivity and therefore to a drop in body temperature, which is then combated by measures leading to an increase in body temperature, making residents drowsy and even more immobile. Also the timetable of the care home and the temporal routines it generates can introduce inertia and inflexibility which may make adapting to needs generated by hot weather difficult.

3 Methods, case studies and overheating metrics

The methodological approach was case study based (focussing on two care homes and two extra-care facilities), socio-technical and interdisciplinary, drawing from building and social science methods. The study included: ***analysis of design features using building surveys*** (to *assess building design features that could contribute to the avoidance/exacerbation of overheating and enable or prevent occupants control over their thermal environment*), ***continuous monitoring of indoor and outdoor temperatures in different spaces*** (*to assess current overheating risk*), and ***semi-structured interviews with a selection of designers and managers*** ((*to assess how building design and management practices address overheating risks and vulnerabilities*).

3.1 Overview of the case studies

The four case study buildings (two care homes and two extra-care facilities) are located in Yorkshire & Humber (one care home), the South West of England (one extra-care), and two in the South East of England (one care home and one extra-care). Table 1 outlines the key characteristics of the case studies. It must be noted that due to issues with recruitment, the case studies were relatively self-selecting which may mean that they have some degree of pre-existing interest in questions of overheating and climate change.

Table 1. Main characteristics of case study care facilities.

Characteristic	Case Study A	Case Study B	Case Study C	Case Study D
Region	Yorkshire & Humber	South East England	South West England	South East England
Location	Suburban	Rural	Suburban	Suburban
Type of facility	Integrated care community[1] (care home with extra-care facilities) (purpose built)	Care home (renovated)	Extra-care (purpose built)	Extra-care (purpose built)
Ownership	Not-for-profit RSL	Private company	Not-for-profit RSL	Not-for-profit RSL
No. of beds/dwellings	42 (plus 10 2-bed cottages)	22 beds	50 flats (1 and 2 bed)	60 flats (1 and 2 bed)
Date of construction completion (Building regulations year)	2005 (2000)	Pre-1900s (n/a)	2006 (2002)	2012 (2006)
Predominant construction type	Brick/stone and block insulated cavity	Solid brick	Brick and block insulated cavity/rendered insulation with block	Brick/render and block insulated cavity/rendered insulation with block
Ventilation and/or cooling strategy	Mixed mode: Natural ventilation with MVHR in residential and communal kitchen and sanitary areas	Natural ventilation with some extract ventilation in communal kitchen and sanitary areas	Mixed mode: Natural ventilation with some extract ventilation in residential and communal kitchen and sanitary areas; air conditioning in lounge and dining area	Mixed mode: Natural ventilation with some extract ventilation in residential areas; MVHR in communal kitchen and sanitary areas; air conditioning in office area
Standards	-	-	-	BREEAM Excellent

Notes:-
[1] Only the care home building was involved in the study.

3.2 Overheating metrics

There are several methodologies and overheating metrics used to assess buildings (domestic and non-domestic) in England and Wales. This is mainly due to the fact that overheating, whilst a widely used term, is currently neither precisely defined nor understood, particularly in the building sector. The metrics used to assess the thermal comfort and overheating risk within this study included both the static CIBSE Guide A (2006) overheating and thermal comfort criteria (referred to as the static method) and the adaptive overheating and thermal comfort method outlined in BS EN 15251:2007, CIBSE TM52 (2013) and CIBSE Guide A (2015) (Nicol et al., 2012).

The static method enables simple calculations to be undertaken when assessing the performance of a building, however it does not account for the adaptation of the occupants to their environmental context such as external temperatures. The adaptive approach was developed by Humphreys and Nicol (1998) through field studies of people in daily life, and is particularly relevant to free-running buildings. Research (CIBSE, 2015) suggests that people are less sensitive to temperature changes in their own home than at work, and, generally, people have more adaptive opportunity at home. Understanding the sensitivity of people to environmental conditions is particularly pertinent when studying the care sector context, where the residents may still be relatively sensitive due to their physiological state, and the conflicts between control and health, safety and security that were evident in this study, and others (PHE, 2014).

Furthermore, despite a focus on the need to use the adaptive method when assessing overheating risk, the current CIBSE Guide A (2015) states; *“Available field study data for the UK (Humphreys, 1979) show that thermal discomfort and quality of sleep begin to decrease if the bedroom temperature rises much above 24 °C. At this temperature just a sheet is used for cover. It is desirable that bedroom temperatures at night should not exceed 26 °C unless there is some means to create air movement in the space, e.g. ceiling fans.”* Due to this, and Public Health England guidance that suggests that certain areas within a care home should be retained at a maximum of 26°C in order to provide ‘cool areas’ for residents, it was felt appropriate to include the static overheating metric as defined in the superseded 2006 CIBSE Guide A, and which is based on CIBSE TM36: 2005.

It must be noted that whilst the authors acknowledge the requirement for the operative temperature (T_{op}) to be calculated in order to undertake the above overheating risk methodologies, due to practical constraints, air temperature (dry bulb) was used as a proxy for T_{op}. According to Mavrogianni *et al.,* (2015) this is a common limitation of monitoring studies due to cost constraints. The gap between T_{op} occurs in indoor spaces with higher levels of exposed thermal mass or high indoor air velocity (Mavrogianni *et al.,* 2015); neither of which were prevalent in the case study buildings.

4 Analysis of building design features and controls

The case study buildings included a number of design features that could impact upon the risk of overheating within them, both negatively and positively, as detailed in Table 2. Of particular note in terms of good practice, all case studies had well designed soft landscaping (Figure 1), which can provide cooler microclimates, and some had external shading measures such as brise soleil and large overhanging eaves (Figure 2), fixed vertical panels and balconies (Figure 3). Furthermore, the case studies generally had openable windows or doors at the end of residential corridors, which increases potential for cross-ventilation and air circulation.

However there were also some features that could exacerbate the risk of overheating, such as the residential areas were all single aspect which can limit the potential for cross-ventilation. Spatial requirements of care home and extra-care buildings make dual aspect residential spaces difficult to implement. Both Case Study A and D have openable windows in the corridors adjacent to the residential areas. Whilst this does enable cross-ventilation to happen, it relies on the resident’s leaving their doors open, which can have security and privacy implications.

Figure 1. Soft landscaping in Case Study B can help provide a cooler microclimate during periods of hot weather.

Figure 2. Brise soleil and large overhanging eaves on south façade of Case Study C to provide additional shading.

Figure 3. Wide balconies in Case Study D provide additional shading to rooms below, as well as space for planting.

Table 2. Identified design features that contribute to/reduce the overheating risk in case study buildings.

Design feature	Hazard relevance	Findings
Landscaping	Landscape design features can play a significant role in reducing overheating risk as green space and trees can create cooler microclimates (Gill *et al.*, 2007).	• All of the case study buildings appear to have maximised areas of secure green space with limited hard surfaces (only where paths and terraces are required for access). • *By providing secure spaces with green vegetation, the buildings are not only minimising the effects of external heat gain but also enabling the use of windows due to reduced noise, pollution and security concerns.* • *The balconies in Case Study D also provide further space for planting and green vegetation in a suburban context (Figure 3).*
Building orientation	Orientation can have a significant effect heat gains in summer, as the direction faced by a window, relative to south, affects how much direct sunlight it receives (Gething and Puckett 2014).	• The orientation of the case studies varies, mainly due to the tight configuration of the overall sites and certain internal layout requirements. However, all have a north or north-west facing entrance which affords privacy to the rest of the building. • *In Case Study A, the corridor spine, switches access to resident's bedrooms from left to right, ensuring the majority of bedrooms have either a southerly orientation or are inwardly facing onto the internal courtyard. Whilst this enhances the visual aspects of the spaces, it could also increase the risk of overheating; particularly as there are no external shading devices on the south-facing façade.*
Internal layout	Single aspect apertures can reduce natural ventilation capability whilst cross ventilation increases air flow velocity improving effect of ventilation (Santamouris and Allard, 1998, p.69).	• All case studies have only single-aspect residential areas, which can limit the potential for cross-ventilation. Spatial requirements of care home and extra-care buildings make dual aspect residential spaces difficult to implement. • *Both Case Study A and D have openable windows in the corridors adjacent to the residential areas. Whilst this does enable cross-ventilation to happen, it relies on the resident's leaving their doors open, which can have security and privacy implications.*
Construction type and materials	Heavyweight construction and light (high albedo) surface materials can reduce the effect of incident solar gain in a building (Gupta and Gregg 2012).	• All case studies except Case Study B are predominantly cavity insulated wall construction with mix of external finishes (brick, render and timber cladding) and heavyweight floor construction. • *The roof finish on Case Study D is light in surface colour which is likely to reduce solar gain.*
Passive shading measures	Shading reduces incident solar gain (Gupta and Gregg, 2012; 2013).	• Fixed external shading: Brise-soleil (fixed louvres) and overhanging roof eaves provide additional shading in Case Study C. • Internal shading: All buildings have either internal blinds or curtains (or both) in all residential, communal and office areas. • Balconies: Case Studies A and D have balconies that provide shading to rooms below.
Lighting and appliances	Lighting and appliances can add to internal heat gains within the building.	• Generally all fixed lighting in the 'new' case studies designed for and installed with low wattage bulbs, with lighting being replaced in all areas of Case Study D with LEDs as and when the bulbs went. Although not intended design features, it is worth noting that: • It appeared that often the residents brought their own lamps, which on some occasions noted, were not low energy, for example in Case Study B where a resident had a high watt halogen bedside lamp. • In terms of appliances, only the extra-care case studies had a significant number of appliances in the residential areas, including ovens, microwaves and washing machines; but these were not always used regularly (dependent on occupant/s).
Building services	Mechanical ventilation, community heating systems and hot water systems can contribute significantly to internal heating gains	• All case studies had centralised hot water systems that ran 24/7. Where it was possible to review, often the route of these systems followed corridors, and as such, unless adequately insulated, could be contributing to internal heat gains throughout the building.

4.1 Controls for managing the indoor environment

Occupant management of their thermal environment can be greatly influenced by the controls afforded to them through the design of both the building itself and the actual user controls for building services. Within the case studies, it became apparent that there was a difference in user requirements of care and extra-care schemes; the thermal environment of residents in care homes was generally controlled by the carers, whilst the more independent residents of the extra-care schemes able, and desiring, to self-control their environments. The building survey also highlighted conflicts in design for appropriate user thermal environment control and other priorities such as safety and security.

In all case studies, the need to provide security led to restrictors being placed on nearly all windows; which limits the ability of even staff to open the windows. In the extra-care settings, the restrictors were able to be removed, which did afford slightly more personal control over ventilation. The design of the window handles in residential areas was also highlighted as a potential issue; in Case Study D, the installed handles were inoperable by occupants with severe, but common physical complaints (e.g. arthritis) and in one flat the handles had been adapted using a bike handle to provide a longer handle and enable the occupant to actually open and close the window.

The occupants also displayed signs of adapting the building to suit their thermal comfort needs, whether this be through propping doors open or creating their own window 'controls' (Figure 4) or having electric mobile fans to aid in thermoregulation during periods of hot weather. Yet there were examples of where insufficient consideration of services and systems hampered the ability of residents, in particular; the location of TRVs in the case study buildings were nearly always at floor level, which, for frailer and less mobile residents, prevents easy access. It was also obvious that whilst the majority of the controls for building services were relatively simple, this did not necessarily mean they were being used in an efficient manner; an example of this was the fact that the heating settings in the corridor areas were very high. In Case Study D, more complex controls were used (each flat has a programmer and individual room thermostats), and issues with the heating system meant that the thermostat in the bathrooms of most flats had to be left on 'max', which further reduced the ability of the residents to control their own thermal environment. Trickle vents were present in the three 'modern' case studies (A, C and D). However, in Case Study A, it was found that many of the trickle vents had been painted over, rendering them inoperable.

Figure 4. Window propped open using block of wood to provide background air flow.

5 Measuring indoor temperature conditions

In order to understand the current overheating risk in the case study buildings, data loggers measuring temperature, relative humidity and, in some areas, CO_2 levels were installed in key residential, communal and office areas. Readings were taken every 15 minutes over, approximately, a four month period (June – September 2015). The analysis of indoor and outdoor temperatures is presented here.

5.1 Residential areas

Overall, 17 residential rooms were monitored across the four case studies, including six living rooms and 11 bedrooms, of which six living rooms and five bedrooms were monitored in the extra-care homes. Figure 5 shows the temperatures within the bedrooms in all the case studies across the monitoring period. As can be seen, for a significant amount of the monitored time, temperatures in all of the bedrooms were above 24°C throughout the monitoring period (dotted horizontal red line) and most also went above 26°C (solid horizontal red line). Furthermore, the average mean temperature across all bedrooms monitored was 24.5°C (Table 3); which is above recommended thermal comfort levels (CIBSE Guide A, 2015). In relation to the static 'comfort' range(CIBSE Guide A, 2006) for non air-conditioned private living rooms (only in Case Study C and D), the temperatures in Case Study C were mainly within the 'comfort' range (25°C ±3K), although there were some instances of temperatures above 28°C, and below 22°C. In Case Study D, temperatures were significantly higher throughout the period with several periods in which the temperature was above 28°C, and never below 22°C. The average mean temperature across the six living rooms was 25.5°C.

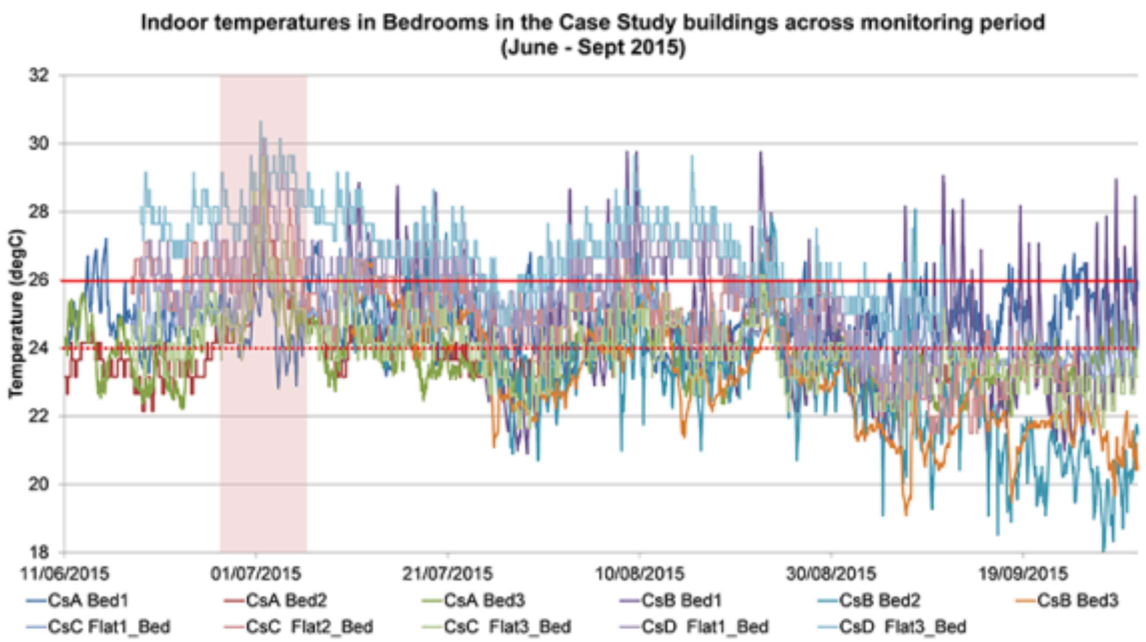

Figure 5. Temperatures within bedrooms in the four case study buildings across the monitoring period.

Table 3. Minimum, mean and maximum indoor temperatures in monitored bedrooms and living rooms in the case study buildings across the monitoring period.

	Temperature (°C)				Temperature (°C)		
	Minimum	Mean	Maximum		Minimum	Mean	Maximum
Case Study A				**Case Study B**			
Bed 1	22.8	24.7	27.2	Bed 1	18.0	23.1	28.1
Bed 2	22.2	24.0	28.0	Bed 2	19.1	23.0	26.6
Bed 3	21.7	23.8	28.8	Bed 3	20.8	24.3	29.8
Case Study C				**Case Study D**			
Flat 1 (Bed)	22.9	24.7	28.3	Flat 1 (Bed)	22.5	25.9	30.2
Flat 1 (Living)	23.1	25.0	29.1	Flat 1 (Living)	23.3	26.7	30.9
Flat 2 (Bed)	21.5	24.9	29.6	Flat 2 (Living)	22.0	25.4	30.6
Flat 2 (Living)	20.8	24.4	30.0	Flat 3 (Bed)	24.0	26.9	30.6
Flat 3 (Bed)	21.2	24.0	30.1	Flat 3 (Living)	24.9	27.1	30.7
Flat 3 (Living)	20.3	24.4	29.4				

As the red vertical band in Figure 5 demonstrates, there were 'spikes' in indoor temperatures within the monitored bedrooms and living rooms, across the four case study buildings. When cross-related with external data, it was apparent that these spikes correlated with outdoor temperatures, and highlighted the impact of short-term heatwaves on the overheating risk within the buildings. In two case study areas (A and D), the recorded outdoor temperatures during this period were above the PHE Heat-Health Watch (PHE, 2015) system's threshold temperatures (day and night). Although the period in which outdoor threshold temperatures were reached was relatively short, as Figure 6 demonstrates, they did appear to affect indoor temperatures in the residential areas significantly. Using the residential areas within Case Study A as an example, within the first day, indoor temperatures did not rise significantly, but on the second and third day, significant increases in temperatures can be seen; with indoor temperatures over PHE's 'cool area' temperature threshold of 26°C (red dot-dash line on Figure 6)), and as such, potentially putting the residents at risk of heat-related illness. Such increases in indoor temperatures during the short-term heatwave periods was found to occur across most of the case study buildings; indicating that this is a potentially widespread issue.

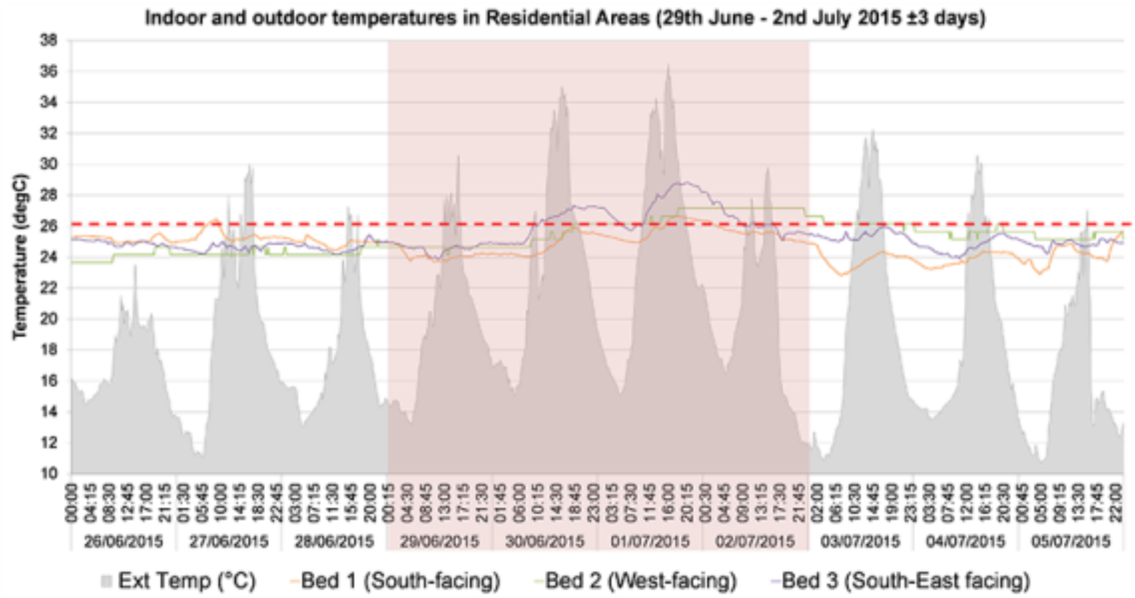

Figure 6. Indoor and outdoor temperatures in the residential areas in Case Study A over short-term heatwave period (red vertical band indicates period in which outdoor temperatures were above PHE's Heat-Health Watch threshold temperatures.

5.2 Communal areas

Overall, eight communal areas (shared lounges and dining areas) were monitored. Figure 7 shows the temperatures within these areas across the monitoring period. The blue dotted line indicates CIBSE Guide A's (2006) 'comfort' indoor summer time temperature (25°C) for non air-conditioned living areas, with the blue band indicating the ±3K temperature range that is seen as the acceptable range. As can be seen, the communal areas were generally within this 'comfort' range, and the average mean temperature across them is 24.7°C (Table 4). However, Figure 8 also demonstrates that during specific periods, the indoor temperatures 'spike' significantly (vertical red band in Figure 7), even more so than seen in the residential areas.

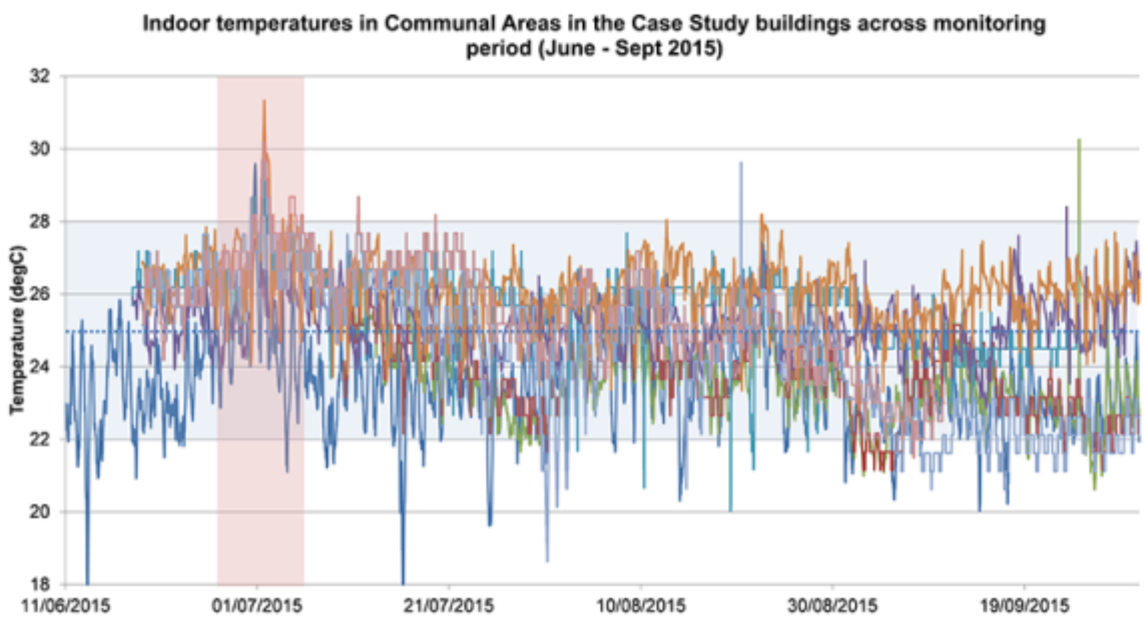

Figure 7. Indoor temperatures in monitored communal areas in all case study buildings across the monitoring period.

Table 4. Minimum, mean and maximum indoor temperatures in communal areas in case study buildings across the monitoring period.

	Temperature (°C)						
	Minimum	Mean	Maximum		Minimum	Mean	Maximum
Case Study A				**Case Study B**			
Lounge / Dining	16.4	23.5	31.2	Lounge 1	20.6	23.5	30.3
				Lounge 2	21.2	23.7	26.7
Case Study C				**Case Study D**			
Lounge 1*	22.9	25.2	28.4	Lounge 1	22.8	26.1	31.3
Lounge 2	20.2	25.8	30.2	Lounge 2	18.6	24.4	29.6
** This lounge has air-conditioning and electric fans. The appropriate comfort range (CIBSE Guide A, 2006) for such an area is 23-25°C.*				Dining	21.5	25.6	30.2

Using Case Study D as an example, when cross-relating the indoor temperatures to external temperature data, it is again apparent that these 'spikes' are happening during periods of short-term heatwaves. As Figure 8 indicates, the indoor temperatures increase particularly on the second day of the heatwave, which suggests that the ventilation and cooling strategies do not provide adequate overnight cooling in order to reduce indoor temperatures, and even perhaps a lack of adequate preparation for heatwaves in terms of heat and ventilation management. Also demonstrated by Figure 8 is the fact that in Case Study D, temperatures within the communal areas were all generally above 26°C before, during and after this period; which means these rooms could not be used as 'cool areas' as recommended by the Heatwave Plan for England without additional heat management arrangements.

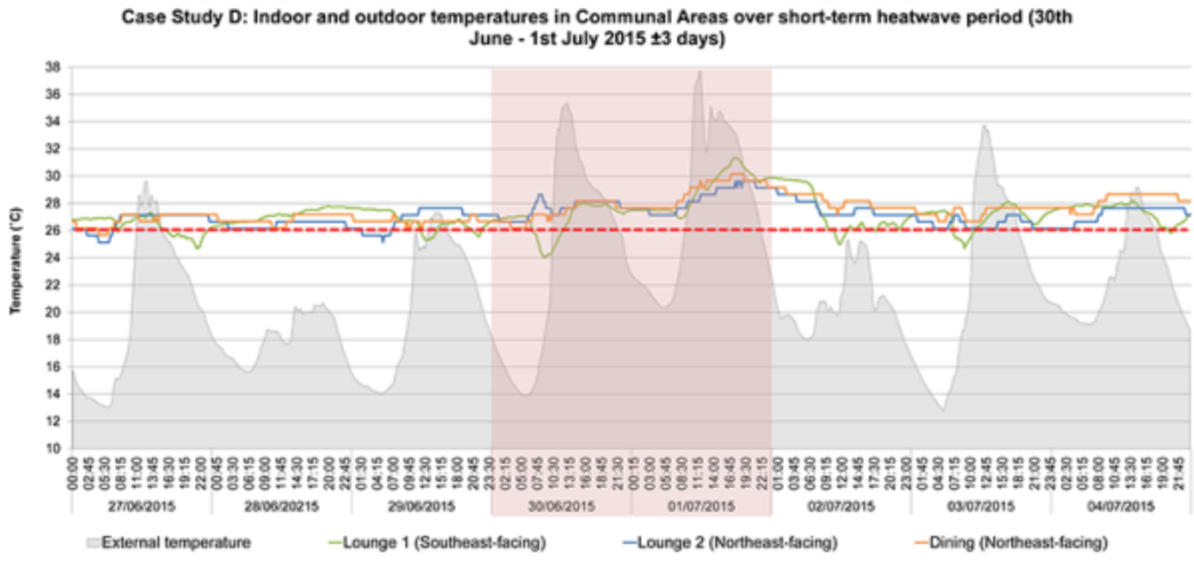

Figure 8. Indoor and outdoor temperatures within communal areas in Case Study D over short-term heatwave period.

5.3 Office areas

In total, eight offices were monitored. Figure 9 shows the temperatures within the offices across the monitoring period, in relation to the static indoor summertime comfort range for non air-conditioned offices (CIBSE Guide, 2006: 25°C ±3K, as highlighted by horizontal blue dotted line and band). As can be seen, the temperatures were towards the higher end of the 'comfort' range, and there were several office areas (across the four case studies) that were over the maximum threshold temperature of 28°C for periods of time. The average mean temperature across them was 25.7°C (Table 5).

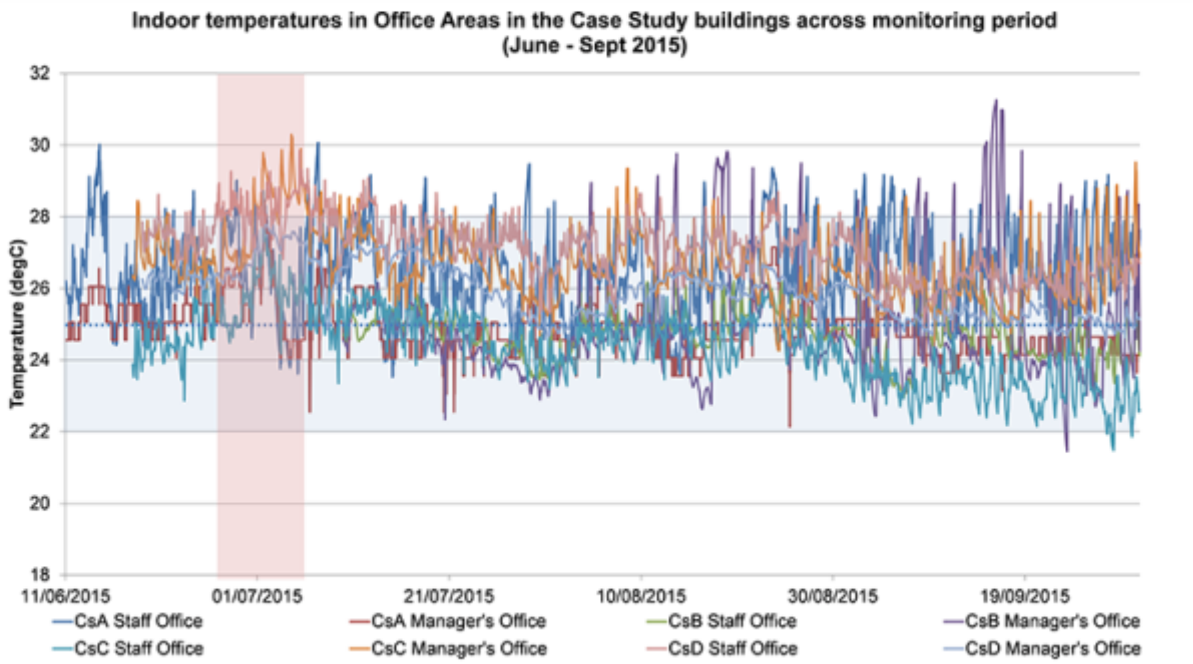

Figure 9. Indoor temperatures within offices areas in all case study buildings across the monitoring period.

Table 5. Minimum, mean and maximum temperatures in office areas in case study buildings across monitoring period.

	Temperature (°C)				Temperature (°C)		
	Minimum	Mean	Maximum		Minimum	Mean	Maximum
Case Study A				**Case Study B**			
Staff Office	23.5	26.4	30.1	Staff Office	22.9	24.8	26.9
Manager's Office	22.1	24.9	28.1	Manager's Office	21.5	24.9	31.3
Case Study C				**Case Study D**			
Staff Office	21.5	24.4	28.7	Staff Office	24.8	27.1	29.8
Manager's Office	24.3	26.6	30.3	Manager's Office*	24.6	25.9	27.8

* This office has air-conditioning and electric fans. The appropriate comfort range (CIBSE Guide A, 2006) for such an area is 22-24°C.

Although there is a slight 'spike' in the offices (highlighted in Figure 9 by vertical red band), it is not as obvious as that in the residential and communal areas. Figure 10, using Case Study A as an example, demonstrates that high outdoor temperatures are not necessarily indicative of high indoor temperatures in the office areas; the Staff Office in Case Study A reaches higher temperatures the day before peak outdoor temperatures are reached. This suggests, as expected, that internal heat gains play a significant role in the overheating risk in these areas. It is also worth noting that the majority of the office areas in the case study buildings are more northerly-facing than communal and residential areas.

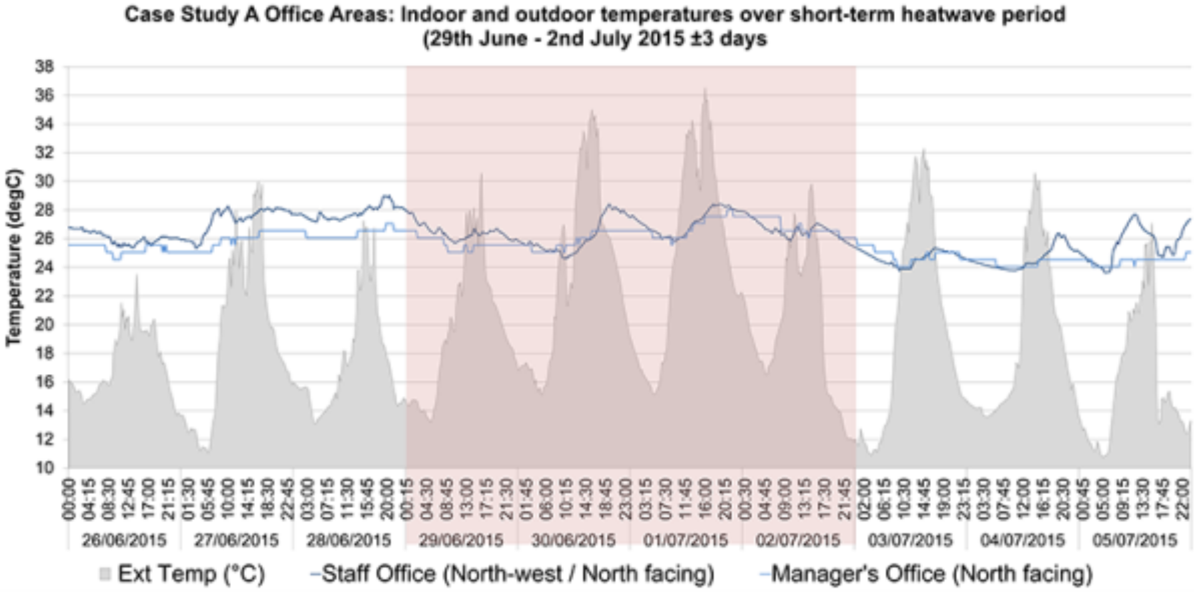

Figure 10. Indoor and outdoor temperatures within office areas in Case Study A over short-term heatwave period.

6 Assessing overheating risk

The overheating risk within the monitored areas was calculated using both the static and adaptive methods; as outlined in an earlier section.

6.1 Static method: residential, communal and office areas

The static method criteria, as outlined in CIBSE Guide A (2006), states that overheating is likely when the temperature in the room exceeds a threshold temperature more than 1% of occupied hours (bedroom threshold temperature is 26°C and living room threshold temperature is 28°C). The occupied hours of the individual rooms was based on the findings of the building survey to ensure accuracy. Using the static method to assess the overheating risk, the findings indicate that all except one of the residential areas are overheating (Table 6). Case Study D residential areas show the highest levels of overheating; most likely, in part, due to the fact that the heating was on (due to a fault with the system) during the summer months. However, it is worth noting that Flat 3 (south-east facing and on the third floor) has the highest percentage of occupied hours over the temperature threshold; Flat 3 is on the top floor and as such has no additional shading from the balcony of a flat above.

In the communal areas, overheating occurs in all case study buildings, except for Case Study B, and the south-facing Lounge 1 in Case Study C (five out of eight rooms). Lounge 1 (Case Study C) has significant additional passive measures such as brise soleil, large roof overhang and controllable cross-ventilation as well as active measures including electric ceiling fans and an air conditioning unit. Out of the eight offices monitored, there is evidence of overheating in four; spread across the four case study buildings. All of the offices that showed signs of overheating were either south-west or south-east facing except one (Case Study A); this room was relatively crowded in terms of both occupants and office equipment, which most likely add substantially to the internal gains in this room. In total, 25 out of the 33 rooms monitored overheated during the monitoring period, according to the static method.

6.2 Adaptive method: residential, communal and office areas

The adaptive comfort and overheating methodology used within this study is that outlined in CIBSE TM52. Table 7 outlines the results for all monitored rooms. As can be seen in this table, fewer rooms showed signs of overheating, in comparison to the results of the static method. Only three residential areas (Case Study C) were overheating during the monitored period, although a further six rooms (mainly in Case Study D) did fail Criterion 1. In the communal areas, all three communal areas in Case Study D failed both Criterion 1 and 3, and as such are deemed to have overheated during the monitoring period. Within the monitored offices, only one failed two or more criteria; the Manager's Office in Case Study B. In total, only seven out of the 33 monitored rooms overheated, according to the adaptive method analysis.

7 Assessing preparedness: design intent and management practices

In total, five designers and three managers (ranging from sustainability managers to housing managers) involved in the design practices and care organisations responsible for the four case study buildings were interviewed. The semi-structured interviews lasted approximately one hour and involved questions on the design, briefing, procurement and management of the building, along with wider questions on design and strategizing for future climate change and overheating in the care sector.

The interviews highlighted the need for an increase in awareness of, and change in attitudes towards overheating; the majority did not see it as a 'current' issue, which is likely to be problematic in light of the findings from the temperature monitoring in the study which indicated that overheating is happening in care facilities, particularly during short-term heatwaves. The interviews also highlighted the disconnect between design intent and operation of heating and ventilation systems, either through the low prioritisation of the overheating mitigation strategies; procurement processes removing the design team from what is built on site and/or handover of the building being undertaken by separate management and maintenance teams within the organisation, and not given directly to the on-site staff.

This limited the ability of the on-site users of the systems from effectively managing their environment; an example of which can be found in Case Study D where the heating system itself is on 24/7 throughout the summer, and has not been working correctly since it was installed. Yet the on-site manager is not fully aware of how to use it, and as such has advised the residents to simply leave the system alone. The impacts of this are clear in the monitoring results, with temperatures in this case study generally much higher than the other case studies, and generally towards the high end of expected comfort levels. Furthermore, particularly in the medium-to-large organisations, there appeared to be a conflict between providing on-site user control and ensuring a more centralised management system to enhance effective and efficient energy and maintenance management. Such institutional factors are likely to have an effect on how heatwave action plans can be effectively implemented, as well as how much occupants feel able to manage and control their own thermal environment.

Table 6. Results from the static (CIBSE Guide A, 2006) overheating method analysis of all monitored areas within the case study buildings.

	Monitored Area	Percentage of occupied hours over temperature threshold (%)	Monitored Area	Percentage of occupied hours over temperature threshold (%)
Residential Areas	**Case Study A**		**Case Study B**	
	Bed 1 (GF, South-facing)	6.3	Bed 1 (GF, North-west facing)	7.9
	Bed 2 (GF, West-facing)	2.7	Bed 2 (FF, North-east facing)	1.4
	Bed 3 (FF, South-east facing)	2.2	Bed 3 (FF, South-west facing)	16.7
	Case Study C		**Case Study D**	
	Flat 1 (Bed) (GF, South-west facing)	6.0	Flat 1 (Bed) (FF, South-east facing)	49.9
	Flat 1 (Living) (GF, South-west facing)	1.4	Flat 1 (Living) (FF, South-east facing)	9.3
	Flat 2 (Bed) (FF, East facing)	24.1	Flat 2 (Living) (SF, South-east facing)	3.2
	Flat 2 (Living) (FF, East facing)	1.0	Flat 3 (Bed) (TF, South-east facing)	76.0
	Flat 3 (Bed) (FF, West facing)	5.0	Flat 3 (Living) (TF, South-east facing)	17.6
	Flat 3 (Living) (FF, West facing)	0.2		
Communal Areas	**Case Study A**		**Case Study B**	
	Lounge / Dining (FF, North/North-west facing)	1.0	Lounge 1 (GF, South-west facing)	0.0
			Lounge 2 (GF, North-east facing)	0.0
	Case Study C		**Case Study D**	
	Lounge 1 (GF, South-facing)	0.0	Lounge 1 (UGF, South-east/South-west facing)	1.1
	Lounge 2 (GF, South-east facing)	1.1	Lounge 2 (SF, North-east facing)	1.4
			Dining (LGF, North-east facing)	4.4
Office Areas	**Case Study A**		**Case Study B**	
	Staff Office (GF, North-west/North facing)	1.6	Staff Office (Basement, North-west facing)	0.0
	Manager's Office (GF, North-facing)	0.0	Manager's Office (Basement, South-west facing)	14.6
	Case Study C		**Case Study D**	
	Staff Office (GF, North-east facing)	0.4	Staff Office (SF, South-west facing)	4.1
	Manager's Office (GF, South-east facing)	10.6	Manager's Office (LGF, no external windows)	0.0

Note:- Boxes shaded green did not show signs of overheating, boxes shaded red showed signs of overheating.

Table 7. Results from the adaptive overheating method analysis of all monitored areas within the case study buildings.

	Monitored Area	TM52 criteria failed	Monitored Area	TM52 criteria failed
Residential Areas	**Case Study A**		**Case Study B**	
	Bed 1 (GF, South-facing)	-	Bed 1 (GF, North-west facing)	-
	Bed 2 (GF, West-facing)	-	Bed 2 (FF, North-east facing)	-
	Bed 3 FF, South-east facing)	-	Bed 3 (FF, South-west facing)	1
	Case Study C		**Case Study D**	
	Flat 1 (Bed) (GF, South-west facing)	-	Flat 1 (Bed) (FF, South-east facing)	1
	Flat 1 (Living) (GF, South-west facing)	1,2,3	Flat 1 (Living) (FF, South-east facing)	1
	Flat 2 (Bed) (FF, East facing)	1,2,3	Flat 2 (Living) (SF, South-east facing)	1
	Flat 2 (Living) (FF, East facing)	1,2	Flat 3 (Bed) (TF, South-east facing)	1
	Flat 3 (Bed) (FF, West facing)	-	Flat 3 (Living) (TF, South-east facing)	1
	Flat 3 (Living) (FF, West facing)	-		
Communal Areas	**Case Study A**		**Case Study B**	
	Lounge / Dining (FF, North/North-west facing)	-	Lounge 1 (GF, South-west facing)	-
			Lounge 2 (GF, North-east facing)	-
	Case Study C		**Case Study D**	
	Lounge 1 (GF, South-facing)	-	Lounge 1 (UGF, South-east/South-west facing)	1, 3
	Lounge 2 (GF, South-east facing)	1	Lounge 2 (SF, North-east facing)	1, 3
			Dining (LGF, North-east facing)	1, 3
Office Areas	**Case Study A**		**Case Study B**	
	Staff Office (GF, North-west/North facing)	1	Staff Office (Basement, North-west facing)	-
	Manager's Office (GF, North-facing)	-	Manager's Office (Basement, South-west facing)	1,2
	Case Study C		**Case Study D**	
	Staff Office (GF, North-east facing)	-	Staff Office (SF, South-west facing)	-
	Manager's Office (GF, South-east facing)	1	Manager's Office (LGF, no external windows)	-

Note:- Boxes shaded green did not show signs of overheating, boxes shaded red showed signs of overheating.

8 Discussion

The findings from the study indicate that there is significant risk of overheating, particularly during short-term heatwaves, but also at times when there is no assessed heatwave risk. The monitoring of indoor environmental conditions revealed that, generally, indoor temperatures were high. In particular, the residential areas were higher than recommended comfort levels; but were lower than findings from other studies on comfort temperatures for older people (Mendes et al., 2013). Indoor temperatures significantly increased in the residential and communal areas in all case studies during periods of hot outdoor temperatures (short-term heatwaves). Indeed, during the short-term heatwave periods, none of the residential or communal areas in the case studies remained below 26°C; the temperature at which PHE's Heatwave Plan for England recommends at least one area within the care facility to remain below in order to provide a 'cool area' to reduce the likelihood of heat-related illness. However, outdoor temperatures did not appear to have such an impact on office areas.

In terms of overheating, three out of the 17 residential areas (Case Study C), three out of the eight communal areas (Case Study D) and one of the eight office areas (Case Study B) monitored overheated according to the adaptive method. This suggests that overheating is currently happening in the case study buildings, and indicates that overheating is potentially a more significant risk in extra care buildings than care homes.

Whilst the buildings themselves include a variety of passive strategies that help to mitigate the overheating risk, more could be undertaken, such as fixed louvres and shutters. However, the designers highlighted the fact that often passive strategies, such as fixed louvres and shutters are dismissed during the early design and planning stages, in part due to their aesthetics not being common in the UK, and a lack of awareness of the current and future overheating risk in UK buildings throughout both the construction industry and care sector. The conflicts between priorities, such as health and safety, financial and quality assurance, combined with the pervading culture of warmth within the care sector can also often make it difficult to 'design-in' passive overheating strategies, and further exacerbate the overheating risk. This is a significant finding in terms of enabling effective adaptation strategies, not just in existing care facility buildings but also in terms of future developments.

There also appears to be a lack of adequate management of ventilation and heating within the case study buildings, other than installing and using temporary electric fans during particularly hot weather, which is likely to also contribute to the current overheating of the case study buildings. The building surveys uncovered a number of areas in which this lack of management and control was evident; the painting over of trickle vents in Case Study A, and the lack of understanding as to what their use was by both residents and staff was notable, as was the fact that in all the case studies the heating system was left on 24/7, all year round. This was a key finding of this study and highlighted the impact of both design and management of the services and systems on the overheating risk. Whilst this was in part to give flexibility to the residents, as well as provide them with hot water, the design meant that the pipework for these systems followed corridors, and was likely to be contributing to the internal heat gains throughout the buildings; again emphasising the need for joined-up design in relation to the services of complex buildings such as care facilities.

In addition, it appeared that there was little 'ownership' over the heating controls within the care facilities, and few onsite staff were fully aware of how to control and manage the system most effectively. This, in part, appears to be due to the fact that separate management and maintenance teams have overall responsibility for the systems, and the on-site staff focus solely on provision of care rather than the intricacies of the services and systems on-site.

9 Conclusions

This study provides evidence on the risks and experiences of overheating in both care and extra-care settings. This is particularly vital as there is currently little research on heat management, overheating and thermal comfort, specifically during the summer months in the care sector. Such research is essential if adequate facilities are to be provided and maintained for such an aging and subsequently vulnerable population such as that of the UK.

Findings from the study also suggest that overheating during summer months *is* a current risk in the case study buildings, particularly during short-term heatwaves, yet there appears to be a lack of recognition and awareness within the care sector about this. This is in part due to aspects of the design, management and use of the buildings, as well as the services and systems installed.

A lack of prioritisation of the overheating risk, both current and future, throughout the design and management of such buildings appears to be deep-rooted in both the care sector itself and emphasises the need for a culture change within the care sector itself in order to ensure 'cooling' is prioritised as much as 'warmth'. Whilst individual organisations can seek to provide better management and incorporate appropriate design strategies, for a wholesale change in the culture and awareness of the care sector, input and support is required from governmental departments and national care sector bodies in terms of providing enhanced and focused regulations, standards and guidance. Without this policy support, vulnerable care facilities would be even more exposed to overheating risk, now and in the future.

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Acknowledgements

We are grateful to Joseph Rowntree Foundation for funding this research study. Our sincere thanks to the occupants, staff, managers and designers involved in the case study buildings for their time and involvement in the project. We also wish to thank our academic partners, Dr Alan Lewis of the University of Manchester and Professor Gordon Walker and Dr Louis Neven of Lancaster University for their invaluable work and input into the study.

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Comfort Preferences for Passive Chilled Beams Vs Variable Air Volume Vs Under Floor Air Distribution

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Abstract

This paper presents lab-based evaluations of indoor thermal preferences from human subjects, under three different air conditioning systems, namely Passive Chilled Beams (PCB), Variable Air Volume (VAV) and Under Floor Air Distribution (UFAD).

The preference data was collected using an A-B comparison research design. The study included structured feedback from a sample of 30 participants who spent a day in the Indoor Environment Quality (IEQ) Laboratory carrying out their normal work. Subjects provided feedback at specified intervals on comfort vectors and room preferences (which related to different HVAC systems). Room environmental data together with forehead, hand and ankle skin temperatures were recorded at regular intervals.

The findings indicate a thermal preference for PCB (62%, 0.95CI = 70%, 53%) when compared to VAV (38%, 0.95CI = 51%, 26%) and PCB (63%, 0.95CI = 71%, 54%) versus UFAD (37%, 0.95CI = 50%, 25%). Thermal preference was negligibly different between VAV (48%, 0.95CI = 60%, 35%) compared to UFAD (53%, 0.95CI = 61%, 44%).

Logistic Regression analysis, similar to that carried out in the food and wine industry, was used to understand the parameters that contributed to these preferences. Skin temperature difference between head and ankle of the subjects was found to be significant when comparing PCB with UFAD ($p = 0.003$) and when comparing PCB with VAV systems ($p = 0.032$). This confirms the thermal comfort adage about cooler head and warmer feet being preferable.

Keywords: Indoor Thermal Comfort, VAV, UFAD, Passive Chilled Beams, Thermal Preference

1 Introduction

Architecture is more than the art of constructing individual buildings. It is also the creation of environment. Buildings do not exist in isolation. They not only impose their character on their surroundings but also have an incalculable effect on the lives of human beings who inhabit them. Conti (1978)

International attention continues to focus on the way buildings are built and operated in response to the challenges of greenhouse gas reductions and associated climate change implications. With the building sector contributing 34% of global carbon dioxide (CO^2) emissions (IPCC Report Chap. 9 - 2013), sustainable building technologies have been identified as one of the most cost-effective approaches for improving energy efficiency and reducing the operational carbon footprint. In modern day office building, Heating, Ventilating and Air-Conditioning (HVAC) systems strive to provide a healthy and comfortable environment for the occupants. Typical energy consumption of an air based air conditioning system in a commercial building can be broken down to Fans (34%), Cooling (27%), Heating

(17%), Pumps (16%) & Cooling Towers (6%) as per Factsheet HVAC Breakdown – industry.gov.au. This forms a significant component of the operational carbon footprint.

Legislative requirements related to energy combined with intense market driven competition to strive for the highest energy ratings for commercial buildings have, in most cases, become the key drivers for improving thermal performance of the building envelopes and enhancing the energy efficiency of building services. Both these initiatives carry implications for the indoor environmental conditions particularly on building occupants. To achieve the high building and energy ratings, design and operational strategies are often pushing the comfort parameters into ranges previously not considered. It is no surprise that addressing occupant complaints, related to HVAC and thermal discomfort, also rank highly in the daily activity of every Facility Manager. A Facility Manager has to face daily the dilemma of satisfying the objectives of the Building Owner versus the requirements of the Tenants, that is reducing carbon footprint versus maintaining acceptable occupant thermal comfort.

So how does one distill out the dominant complaints in commercial buildings? One of the most commonly complained items in commercial buildings universally is related to indoor temperature. It seems to have the most impact on occupants largely due to expectations and personal preferences. When it comes to HVAC and the resulting thermal comfort the psychological and, in some instances, the physiological aspects also contribute to this complex issue. For office buildings where energy efficiency measures have been adopted indiscriminately, it is becoming more evident that there is increased risk of compromising Indoor Environmental Quality (IEQ) for building occupants (Thomas L E, 2012).

Against this backdrop it is not surprising that there is an intensification of research activity on the topic of IEQ in recent years. The IEQ aspect relevant to this study involves HVAC systems and thermal comfort. There are several papers written on HVAC and Comfort. The three types of air conditioning systems prevalent in commercial buildings in Australia are:

- **Variable Air Volume (VAV),** where the conditioned air volume, generally supplied via the ceiling, varies in response to the heating or cooling load requirements in an occupied zone. Return air, back to a central air handling unit, is normally via the ceiling space as well.
- **Under Floor Air Distribution (UFAD),** where conditioned air is supplied to an under floor plenum created by raised flooring. Air diffusion is through floor-mounted diffusers that can be located to suit the furniture layout. The return air, back to a central air handling unit, is at a higher level, usually via grilles or slots in the ceiling.
- **Chilled Beams** (also referred to as Radiant Cooling), where cooling is through a cold medium, commonly a chilled water coil, utilising the heat transfer principles of convection and radiation (where exposed). Heating in that case is through heated fresh air or room mounted radiant hot water heaters.

  There are two types of chilled beam systems:

- **Active Chilled Beam (ACB)-** a ceiling mounted unit which has supply air outlets (generally conditioned outside air) as an integral component that facilitates, via nozzles, induction of room air over the cooling coil and thereby increasing the cooling capacity; and
- **Passive Chilled Beam (PCB)** – a ceiling mounted unit comprising a cooling coil. There is an independent outside air supply system.

In both cases, conditioned outside air caters for the mandatory fresh air requirements and latent cooling aspects. In most applications, active chilled beams, which can handle higher cooling capacities, are located on the perimeter of buildings whilst passive chilled beams are installed in the interior zones.

VAV systems became more popular in the 70s and 80s, resulting from the 'oil related energy crisis'. These systems have become standard HVAC applications in a majority of high-rise buildings in Australia and have generally performed well with regards to provision of acceptable indoor environment. They have also been very energy efficient, achieving reasonably good energy ratings, around 4 to 5 Stars in the National Australian Building Environmental Rating System (NABERS) scheme (Rating Register - Sydney Building - nabers.gov.au). Research associated with VAV has centred around different types of applications such as occupancy based control strategy for VAV terminal box systems (Liu and Brambley, 2011), optimal terminal box control algorithms for single duct air handling units (Cho and Liu, 2009) and techniques for measuring and controlling outside air intake rates in variable air volume systems (Krarti et al, 2000). There do not appear to be any direct research addressing VAV systems with regards to evaluation of indoor comfort.

On the other hand, with regards to more recent advancement in Chilled Beams and UFAD, there has been a proliferation of research literature involving investigation of these newer technologies and, in some instances, comparing them with the VAV system.

Passive chilled beams are gaining in popularity due to the obvious efficiency of not having to transport large volumes of conditioned air around the building. Space efficiency, combined with their energy efficiency and quieter operation, is making them a regular feature of many "green buildings." The performance characteristics of a passive beam convective regime within the occupied zone have been investigated (Fredrikkson *et al*, 2001) using a full-scale simulated office, complete with fluorescent tube lighting, a personal computer, and thermal manikin providing "typical" heat loads. The experiment did not include any evaluations from human subjects, so conclusions about the impact of passive chilled beams' intermittent flow characteristics on comfort were based purely on the theoretical "draft risk" model. The interaction of flows in rooms ventilated by active chilled beams and its importance for the air distribution and occupants' thermal comfort was studied by Melikov, A. et al (2007) in a full-scale room experiments. The impact of the supplied flow rate of primary air (1.5 L/s/m ^{2} and 3 L/s/m ^{2}) and the heat load strength (50 and 80 W/m ^{2}) on the thermal environment generated in the occupied zone was the focus of this study. It did not involve human subjects. Two thermal manikins, two desk computers, two artificial windows with controlled heat load and ceiling lights were used as heat sources. The results showed that the heat load and the supplied flow rate have substantial impact on the air distribution in rooms with chilled beams.

Laboratory based experiments carried out by Ma J and Zhang Z (2012) provides details of involving combined cooling ceiling (CC) and displacement ventilation (DV) system, with different supply air temperature, various supply air velocity and changeable temperature of supply water by simulating to cool a small office in summer. Based on similarity theories, some suggestions are given for the numerical area of cooling parameters under some laboratory conditions. However, it does not address any direct comfort issues. Behne (1999) argues, in his paper "Indoor air quality in rooms with cooled ceilings. Mixing ventilation or rather displacement ventilation?" that if the air quality in the occupied zone is top priority and the cooling capacity of a single displacement ventilation system is not satisfying the load, a cooled ceiling can be combined with a displacement ventilation system. And if the favourable characteristics of a radiant cooled ceiling with respect to thermal comfort are most important, an air-conditioning concept can be realized with mixing ventilation and a cooled ceiling. Such investigations and outcomes demonstrate a lack of understanding of practical applications, as it is more than likely that such hybrid systems may not be cost effective and have a higher risk of condensation.

Experimental measurements were conducted in South Africa by Madyira, D.M. and Bhamjee, M (2010) in a specially designed test chamber incorporating UFAD supplied from a split HVAC system. Focusing on energy efficiency and thermal comfort**,** the results of the investigation showed that UFAD **(**displacement ventilation) had superior performance over conventional ventilation for the cooling period. The paper, however, does not contain detailed methodology or comprehensive findings.

Following are additional examples of use of manikins in experiments, which lack the "human" factor. A study of the air quality in the breathing zone in a room with displacement ventilation by H. Xing et al (2001) examined the difference in the air quality that is perceived by the occupants (breathing zone) and that existing in the occupied zone as a whole. An environmental chamber with displacement ventilation system was utilised to carry out the measurements with the presence of a heated manikin and other heat sources. Measurements of the age of air distribution, the air exchange index and the ventilation effectiveness were carried out at different points in the chamber for different room thermal loads. CFD simulations were also carried out for the purpose of low visualisation as well as the calculation of air velocity, temperature and age of air distribution. Wyon and Sandberg (1990) also employed thermal manikin to predict discomfort due to the displacement ventilation. Cheong et al. (2006) presents findings of a thermal comfort study using a thermal manikin in a field environment chamber served by the UFAD or Displacement Ventilation (DV) system. It was concluded that the local discomfort was affected by overall thermal sensation and was lower at overall thermally neutral state than at overall cold and cool sensations. In a set of experiments, (Neilson et al. 2006) conditioned air distribution generated by a radial ceiling-mounted diffuser and a diffuser generating flow with swirl were compared with the air distribution obtained by mixing ventilation from a wall-mounted diffuser, vertical ventilation**,** and UFAD **(**displacement ventilation)**.** The air distribution generated by a radial diffuser was partly controlled by the momentum flow from the diffusers and partly from gravity forces where the thermal load and the temperature difference between room air and supply air deflect the radial wall jet down into the occupied zone. The ceiling diffuser with swirling flow generated a flow pattern in the room that was stated as uninfluenced by the thermal load. The airflow was observed to be highly mixed above the occupied zone, and the air movement apparently penetrated the occupied zone close to the walls. All systems were tested in the same room with a load consisting of two manikins, each sitting at a desk with two PCs and two desk lamps, producing a total heat load of 480 W. The comparison was extended by considering both, the local discomfort caused by draught and the percentage of dissatisfied due to the temperature gradient when this is relevant to the system.

Field survey of occupants' response to the indoor environment in ten office buildings with UFAD was carried out by Melikov et al, (2005), whereby response of 227 occupants (94 males and 133 females) was collected and analysed. A neutral thermal sensation was reported by 37% of the occupants, and between slightly cool and slightly warm by more than 85% of the occupants. According to the publication, the occupants' thermal sensation was close to the predictions by the PMV index. Field measurements (Melikov et al, 2005) carried out in buildings with UFAD (displacement ventilation) also identified mean velocity as high as 0.48 m/s and an air temperature as 18.2°C near the floor in the occupied zone. It is appreciated that large sample sizes are necessary for any field studies. Hence the approach outlined later concentrates on data to be obtained in the laboratory but with HVAC set up information from field studies.

The above highlights that a majority of investigations to date have concentrated on use of analytical tools and/or manikins.

The aims of this study include:

1. Investigating thermal preferences of Passive Chilled Beams Versus VAV & UFAD in an IEQ Laboratory, which incorporates these types of HVAC systems. Passive Chilled Beams have been selected because in a typical commercial application in an interior zone of building they serve a majority of the office population. Passive Chilled Beams also have a more stable cooling load as compared to Active Chilled Beams, which vary considerably in line with solar loads, as they typically serve the perimeter areas due to their ability to handle increased cooling capacities.
2. Using human subjects to provide their preferences as opposed to thermal manikins
3. Selecting samples of human subjects who spend a majority of their working lives in air conditioned offices from the working population.
4. Carrying out field studies of exemplar buildings to ascertain HVAC related parameters that could be applied in the Lab.
5. Ensuring that indoor environments, especially the air occupied temperature, is maintained within the limits as observed in field studies
6. Carrying out statistical analysis using the techniques utilised by industries that sample preferences such as food and wine tasting applications.

2 Methodology

2.1 Field studies

During the summer of 2013-2014, field studies were carried out in nine exemplar buildings in Sydney – three air conditioned with VAV, three with UFAD and three with Chilled Beams air conditioning systems, with the express aim to gather the following data that would be used to set up subsequent Lab studies:

- Zone temperatures and humidity levels
- Zone air velocities
- Zone radiant temperatures
- Control strategies and respective system set-points
- Occupant feedback, as relayed to Facility Managers, on zone conditions
- Energy Ratings of the building
- Maintenance issues
- Annual Operating costs

Miniature data loggers were utilized to record the zone temperatures (perimeter and interior areas) every 15 minutes, over a period of two weeks (minimum) in each case, to ensure that the respective air conditioning control strategies were achieving required zone conditions uniformly. Information obtained from the filed studies was applied to the systems set-up in the IEQ Laboratory, where comfort related evaluations were carried, through feedback from human subjects.

2.2 IEQ Lab

Comfort evaluations were carried out in the Indoor Environment Quality (IEQ) Laboratory at the University of Sydney's Faculty of Architecture, Design and Planning. Technical and physical details of the IEQ Lab are covered by de Dear et al, (2012). The Lab chambers' fit-out resembles grade-A commercial office spaces. The perimeter zone of each chamber is adjacent to an "environmental corridor" that is able to simulate "outdoor" ambient conditions that could create a selected climate. In this case it was Sydney, Australia.

Chamber 1 (Ch 1) has two air conditioning zones – approximately 35 sq m on the left hand side and approximately 25 m^2 on the right hand side. It was partitioned, using moveable screens, to enable the right hand side of Ch 1 to be utilised for the evaluation whilst the left hand side provided space for acclimatisation, by the subjects, prior to commencement of the evaluations.. Partitioning of the right hand side of Ch 1 made it the same size as Ch 2 – approximately 25 m^2. Chamber 2 (Ch 2) is served by Chilled Beams air conditioning systems.

The outside air corridor was set to a mean summer temperature of 32^0 C, as experienced in Sydney, Australia. The system settings within each room, for each HVAC mode, were replicated from the data gathered during field studies.

A state-of-the-art Building Management & Control System (BMCS), incorporating Direct Digital Controls (DDC), controls the indoor environment in the IEQ Laboratory

IEQ HVAC Details

Chamber 1 is served by a chilled water fan coil unit FCU-1, which serves the two independently controlled zones LHS (35 m2) and RHS (25 m2). The air conditioning in Ch 1 can be switched between UFAD) and VAV systems through the BMCS. FCU-1 has a variable speed drive and hence has the ability to have different airflows depending on the system selection.

Chamber 2 is conditioned by Chilled Beams - Active or Passive - depending on system selection via the BMCS. The Fresh air supply can be through an overhead or and under floor arrangement.

FCU- 2 is a separate fan coil unit that can be set to supply the required outside (fresh) air to Ch 1 and Ch 2. It has a variable speed drive as well as cooling and heating coils. Hence the fresh air quantity can be set to required level.

Technical details:

<u>Ch 1 (RHS)</u>.

- Room Sensible Heat = 96 W/m^2
- Room Total Heat = 120 W/m^2

VAV system settings:

- Airflow range: 13.2 to 4.0 L/s m^2, supply air temperature: 16^0 C, Control setting: P+I.
- Outside Air = 1.2 L/s m^2.

UFAD system settings:

- Airflow fixed: 17.5 L/s m^2 , supply air temperature based on re-set schedule:

Zone Temp = 22^0 C, SA Temp = 19^0 C & Zone Temp = 24^0 C, SA Temp = 18^0 C

- Outside Air = 1.2 L/s m^2.

Ch 2

- Passive Chilled Beams (sensible): 82.5 W/m^2
- Outside air (sensible and latent): 28.6 W/m^2
- Note: Outside Air = 1.2 L/s m^2

2.3 Indoor Environment

Following items were recorded, every 15 minutes, on the BMCS:

- Air temperature in Occupied Zone at 1.1 m
- Air temperature in Occupied Zone at 0.1 m
- Globe temperature in Occupied Zone at 0.6 m – converted to MRT
- Air temperature – wall sensor - at 1.7 m
- Air temperature – wall sensor - at 1.1 m.
- Air temperature – wall sensor - at 0.6 m.
- Air temperature – wall sensor - at 0.1 m.
- Air Humidity – wall sensor – at 1.7 m. This was converted to Absolute Humidity.

Using dedicated sensors and recording equipment – air velocities were recorded at 1.1 m and 0.1 m in two locations – between the three subjects – in each of the rooms.

The set-point for the zoned mounted temperature sensors – (Thermister, Precon Type 11 - 10k@25^0C) was 22.5 ^{0} C +/- 0.5^0 C – in line with observations made during the field studies.

The lighting levels in each of the chambers were set to 340 lux in line with observations made during field studies.

Subjects

Thirty (30) subjects took part in the evaluation in the Lab. Subjects were selected on a random basis from the property sector. The selection of the subjects involved listing all the likely candidates (typically office workers who generally spend most of their time in air conditioned offices) from random firms in Sydney, based on availability of the subjects to attend the full day session at the IEQ Lab and be able to carry out their 'normal' office work remotely. Firms dealing in air conditioning aspects of the property sector were avoided as it was believed that there could be potentially pre-existing bias by the employees for specific air conditioning system types. Once the final list of participants was compiled, each participant was allocated a day to attend through randomization. The seating of the subjects in the two rooms was also randomized. Three (3) subjects attended per day over a period of ten (10) days. Details for each subject were recorded. These included age, weight, gender and the method of travel to the IEQ Lab. Clothing value was assessed by observation. Photos were taken of each subject to ascertain the clothing (clo) value and keep a record of the clothing worn. There were 15 males and 15 females. The age ranged from 20 to 60 years– mean was 36.The mean height of the subjects was 168 cm. The mean weight of the subjects was 68 kg.

Three (3) workstations were set up in each of the chambers, as shown below for Lab 2.

Participation, with three subjects per day, was from 8.30 am to 6.00 pm. The evaluation was over ten (10) days. The position of each participant was identified with a code such that the responses corresponded to their physical location, within the respective chambers.

Fig. 1 IEQ LAB - Chamber 2 – Seating Arrangement (Chamber 1 was set in the same configuration)

2.4 Laboratory Procedure

Subjects were requested to wear normal office attire suitable for summer time. The data was obtained using an A-B comparison research design. The design required subjects to spend 1 hour in each of the two chambers, where the air conditioning system differed.

The procedure and sequence of movements between the Chambers was as follows:

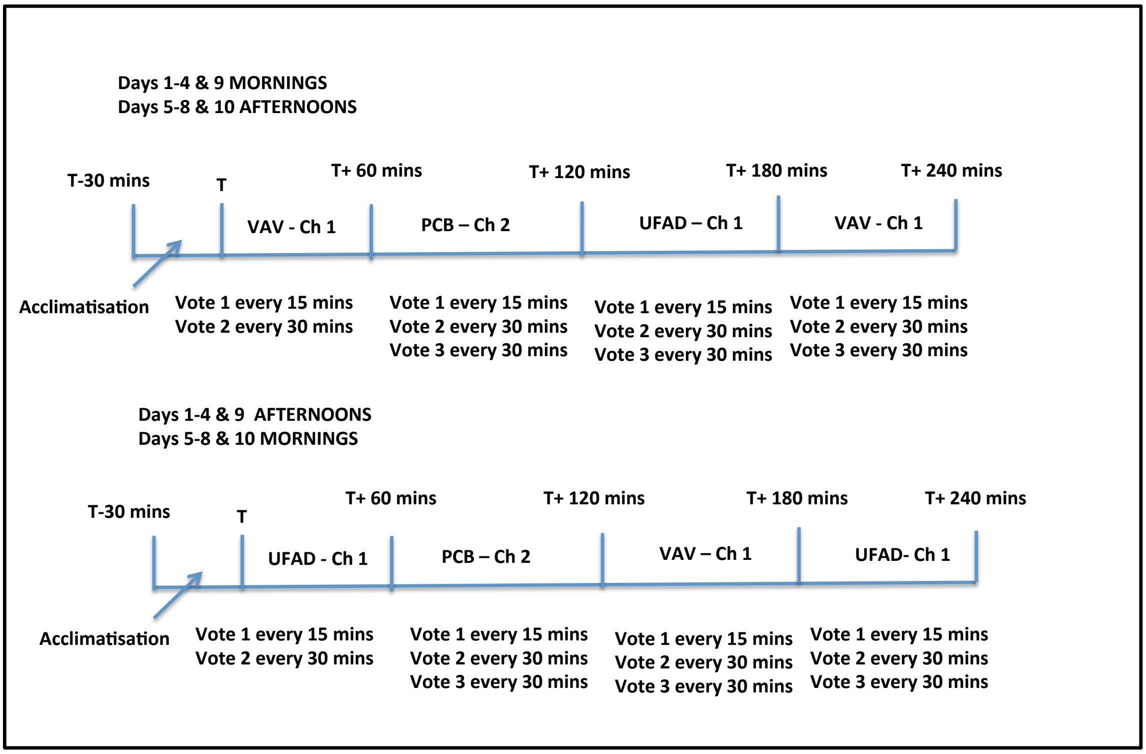

Fig 2. IEQ LAB - Chambers 1 & 2 – Experiment Procedure

Notes:
Vote 1 (every 15 minutes):
(i) Indication of how the subject felt from thermal comfort perspective, by sliding the pointer on the 7 points thermal sensation scale.
(ii) Indication of whether the subject preferred to be cooler or warmer or remain the same by sliding the pointer on a 3 points scale.

Vote 2 (every 30 minutes):
(i) Indication of how the participant felt around the ankle by sliding the pointer on the 7 points thermal sensation scale.

(ii) Indication of how the participant felt around the head by sliding the pointer on the 7 points thermal sensation scale.

Vote 3 - was asked after 30 mins and 60 mins after moving from one chamber to another as to whether the subject preferred the environment the subject was in compared to the environment the subject came from.

Subjects were required to spend a minimum of 0.5 hour in Ch 1 (left side area) to acclimatise. Randomisation techniques were employed for the seating arrangements in Ch 1 (right hand side area) and Ch 2. The subjects were not made aware of the type of air conditioning system in operation during any of the evaluations. Subjects were requested to carry out their normal work, generally using the allocated Desktop Computers or their own Laptops. The time period was 1.0 hour for each of the air conditioning modes in the two chambers, during which the subjects were required to respond to Vote 1 and Vote 2 questions via IPads. The air conditioning system sequencing in Ch 1 was either VAV or UFAD depending on the day and whether it was morning or afternoon session, in line with the randomisation strategy.

After 1 hour the subjects were required to go to Ch 2. The air conditioning system selection was Chilled Beams (passive). Once again the subjects were required to spend another hour and respond to Vote 1 and Vote 2 questionnaires. In addition to that, a room preference question was asked after 30 minutes and 60 minutes. After 1.0 hour, the subjects were requested to return to Ch 1. The system setting was UFAD or VAV, once again, depending on the day and the session. The subjects were required to spend another 1.0 hour and respond to Vote 1, Vote 2 and Vote 3 questionnaires. After 1.0 hour the air conditioning setting was changed in Ch 1 to VAV and after half hour and one hour a question was asked in relation to environment preference between the prevailing and the previous environments. The same process was repeated in the afternoon but in reverse i.e. starting with UFAD instead of VAV or starting with VAV instead of UFAD in line with the randomisation selection as described as above.

2.5 Skin Temperature Measurement

Every half hour skin temperatures were taken using an Infrared Digital Camera.

Various options were investigated for obtaining Skin Temperature and use of FLIR Infrared Digital Camera was chosen on the basis that it was least obtrusive for the subjects. This also suited the overall objective to make the subjects feel that they were in an "office" environment rather than in a laboratory should other options, such as attachment of sensors on the body, were to be used.

Research Assistant carried out the skin temperature measurements. This provided uniformity and consistency in taking the readings. The measurements were taken of the forehead, back of hand and ankle of each subject and recorded every 30 minutes.

Following are examples of the technique adopted:

Fig 3. Skin Temperature Measurement using FLIR Infrared Camera .

3 Data Analysis & Outcomes

HVAC System Preferences

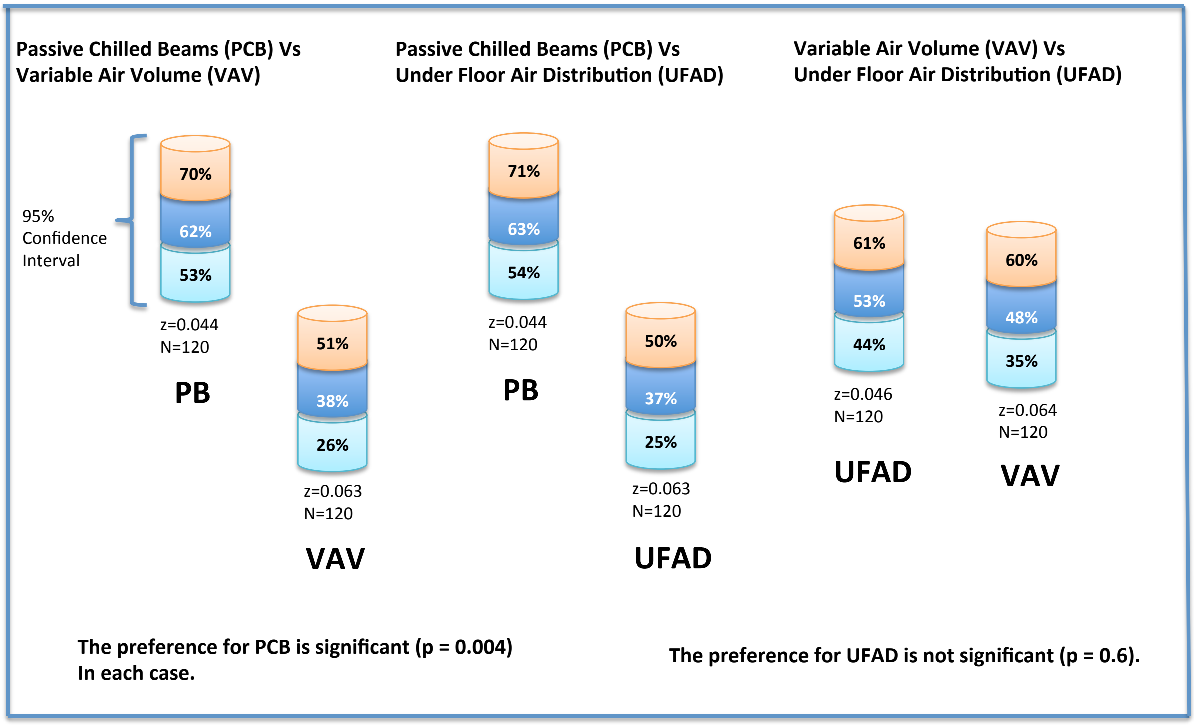

Fig. 4 Summary of Thermal Preferences based on A-B Comparisons

The results indicate a significant preference ($p = 0.004, 0.004$) for Passive Chilled Beams system when compared to VAV and UFAD. However there is negligible difference between the UFAD and VAV preferences ($p = 0.6$).

Since the preferences were based on feedback from human subjects, Logistic Regression analysis, similar to that used in wine and food tasting, was utilised to investigate as to which of the parameters were contributing to the choice of the preferences.

The following is a summary of the outcomes:

Table 1 – Impact of key parameters on thermal preferences

Parameter	PCB Vs VAV	PCB Vs UFAD	UFAD Vs VAV
Skin Temp - Head minus Ankle	P = 0.041	P= 0.001	P = 0.786
Skin Temp – Head	P = 0.203	P = 0.003	P = 0.554
Skin Temp – Hand	P = 0.643	P = 0.406	P = 0.512
Skin Temp – Ankle	P = 0.192	P = 0.050	P = 0.181
Occupied Room Temp @ 1.1 m	P = 0.500	P = 0.091	P = 0.098
Air Velocity @1.1 m	P = 0.885	P = 0.759	P = 0.089
Air Velocity @ 0.1 m	P = 0.787	P = 0.856	P = 0.092
Abs Humidity	P = 0.465	P = 0.136	P = 0.023
Mean radiant Temperature	P = 0.214	P = 0.196	P = 0.261

For both these AB comparisons, the most significant contributor to the preferences is the Skin Temperature difference between Head and Ankle. Passive Chilled Beam system, through a combination of convective and radiant energy exchange at ceiling level, cools the head whilst allowing the ankle area to remain at a stable temperature. UFAD system has air circulation at lower body areas and hence the difference between the head and the ankle area is greater than that experienced under PCB. In UFAD the energy exchange is at the lower level whilst for PCB the heat exchange is from above

The skin temperature difference between Head and Ankle during VAV is similar to that for UFAD. This is because the air movement under VAV was comparable to UFAD at lower levels. Air velocities at 0.1 m were UFAD mean = 0.040 m/s (note: nearest UFAD outlet was approximately 1.5 m from occupants and the velocity sensor) and VAV mean = 0.047 m/s. This can be explained by the fact that under VAV operation the supply air “hugged” the walls and partitions and flowed to the floor. The requirement of the partitions was to match the physical size of RHS of Ch 1 to Ch 2. This airflow was evident during commissioning of the VAV system when tracer gas confirmed such a pattern. The air velocities at 1.1 m were also similar between these systems - UFAD mean = 0.056 m/s versus VAV mean = 0.051 m/s.

Turbulence Intensities were calculated from measurements taken, using Dantec Innova instrumentation (10 Hz) and it was established that the Draught Rate (DR) values were negligible (ranging between 0% to 3%) for all the three systems. Hence it can be confirmed that the velocities have no impact on system preferences – as indicated in Table 1. However, in the filed studies, it was observed that VAV had higher air velocities at 1.1 m (range: mean = 0.15 to 0.35 m/s) depending on the system demand. Therefore it is possible that VAV in practice could have higher DRs, which could influence the system preference.

There is no significant difference between UFAD and VAV systems from comfort perspective. Humidity difference, due to dehumidification with lower supply air temperature of a VAV system compared to UFAD (which generally provide higher humidity levels), shows a significant impact but not sufficient to create a noticeable difference between these two systems from overall comfort view point.

Following are graphs indicating the skin temperature differences for three clothing levels and the occupied zone temperatures:

Fig. 5 Skin Temperatures, TD = Mean Head minus Ankle Temperature Deg K and Occupied Zone Temperature Deg C for clo values = 0.4, 0.5 & 0.6

As can be seen the clothing levels have an impact on skin temperatures. As the level of clothing increases the mean head minus ankle temperature (TD) decreases. This is because the body temperature will remain higher around the ankle with increased clothing and vice versa.

The clothing value, the gender difference or the number of participants with bare ankles did not have significant impact on the thermal preferences.

A high level of the consistency of zone temperature was maintained during the operation of each of the air conditioning system. It was important to ensure that there were minimum variations (plus or minus 0.5 degrees of the set-point) in zone temperatures between the three systems. Hence the occupied room temperatures at 0.1 m and 1.1 m did not have significant impact on the thermal preferences. This was one of the aims of the experiment.

It was observed that there was a noticeable difference between the occupied zone temperatures at 1.1 m and the wall sensor at 1.7 m. Wall mounted thermostats / temperature sensors are typically located at 1.7 m in most commercial buildings. The results show that variation in the difference of these temperatures depended on the type of air conditioning system in operation – for VAV the mean = 0.6 ^{0}K, for UFAD the mean = 0.4^{0} K and for PCB, the mean = 0.2^{0} K. This could be useful information for commissioning of these types of systems in setting the control set points and checking against occupied zone conditions.

4 Conclusion

There is no significant difference between Under Floor Air Distribution and Variable Air Volume systems with regards to indoor thermal comfort. This is mainly due to the fact that both are air based systems with similar heat exchange and air distribution characteristics.

Passive Chilled Beam (PCB) system offers a higher level of comfort when compared to both Variable Air Volume (VAV) and Under Floor Air Distribution (UFAD) systems. This is primarily due to the fact that Passive Chilled Beam system has the ability to cool the head without have a significant impact on the ankle area temperature. This confirms the adage of warm feet and cool head providing better comfort.

Acknowledgement

Sincere appreciation is extended to the following for their support and assistance:

- Professor Richard de Dear
- Mrs Samim Nathwani
- Dr Jungsoo Kim
- Dr Christhina Candido
- Miss Jessica (Fan) Zhang
- Mrs Maryam Likhouhi

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

The impact of increasing temperatures in transition zones in Abu Dhabi on thermal comfort

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Abstract
The application of western comfort standards to buildings in the Arabian Gulf has resulted in mass-use air-conditioning. Buildings are cooled to temperatures that are excessive compared to historic expectations in Abu Dhabi. This paper raises the question of whether these thermal conditions are appropriate. If not, is there scope for adjustment of indoor standards to broaden thermal comfort parameters whilst retaining thermally satisfied occupants. This paper investigates the entrance lobby, a form of transition zone, cooled identically to occupied zones, that provides occupants with a bridge between external and internal environments. If transition zones have different comfort conditions to steady state environments, they may allow occupants to acclimatize before reaching their destination inside the building.. In 2012, twenty existing mixed-use, case study buildings were tested using passive methods to widen comfort parameters indoors. Buildings were measured to provide occupant feedback from an intervention of raising the indoor transition zone temperature by 1ºC. A pre intervention and post intervention survey was used in the entrance transition zone. The results show there are some changes in buildings that can be associated to the intervention study.

Keywords: Thermal Comfort; Transition Zone; Abu Dhabi;

1 Introduction

The widening of the indoor thermal comfort parameters could lead to an opportunity to study how to improve the performance of existing buildings in Abu Dhabi using simple techniques of changing the temperature inside the transition zone. Meanwhile, occupants may provide feedback for a potential change in behaviour toward accepting more ambient environments. Thermal comfort is the psychophysical experience of one's immediate environment. Transition zones are designed to be steady-state environments but they do not need to be designed to deliver steady-state conditions. There is little empirical information about how much time is spent in transition zones and more information is required. This shows, that on average, occupants do not spend more than 10 minutes in transitional areas and as such the traditional method of Predicted Mean Vote (PMV) may not be applicable to thermal comfort assessments in Abu Dhabi.

The transition zones bridge the external and internal environments of the building. The exchange of air between the outdoors and indoors is a significant factor in these spaces. These spaces are currently cooled continuously throughout the year. Further analysis is needed to understand how the thermal comfort in these areas may be tested and by widening the comfort parameters what impact this may have on occupant received comfort.

2 Literature Review

2.1 Transition Zones

Transition areas may be characterised by their physical location; features (glazing walls orientation and fenestration); varying levels of access to the public, workers and residents; occupancy (schedules and use) and their fluctuating thermal parameters. Chun et al describe three particular types of transitional environments (Chun, Kwok, & Tamura, 2004), these are:

TYPE 1: A transitional spaces contained within a building, where conditions are constantly mixed as people move in and out of the building.

TYPE 2: An attached covered space connected to the building (balcony)

TYPE 3: A separate space with no attachments to buildings (bus stations)

Types 1 and 2 are areas that are influenced by the outdoor climate whilst architecturally bound to the building. Pitts description of transitional areas includes entrance zones, circulation zones, and zones of longer residence (Pitts, 2013). Pitts argues there is a weak separation between the external and internal environments in the entrance zones. His suggestion is to widen the PMV to operate the entrance zone between +0.5 to -0.5 (Pitts, 2013). Occupants pass through a variety of thermal environments as they journey through a building. These are referred to as thermal step changes. The largest step change in Abu Dhabi is between the external environment in the summer season and the entrance zone.

The entrance transition areas have a function more akin to free running spaces because of the link to the external environment. Here MET values are expected at 1.7-2.0 (Pitts, 2013). Despite the numerous features of transition zones, the focus should be on the entrance zone where there is a high rate of infiltration from the outdoors and occupants expect a short transit, see Fig. 2.1. This is typically where heat exchange between man and environment does not reach steady-state but the increased thermal flexibility improves comfort (Humphreys & Nicol, 1998) and the increase in perceived control delivers a higher rate of occupant satisfaction (Williams, 1995).

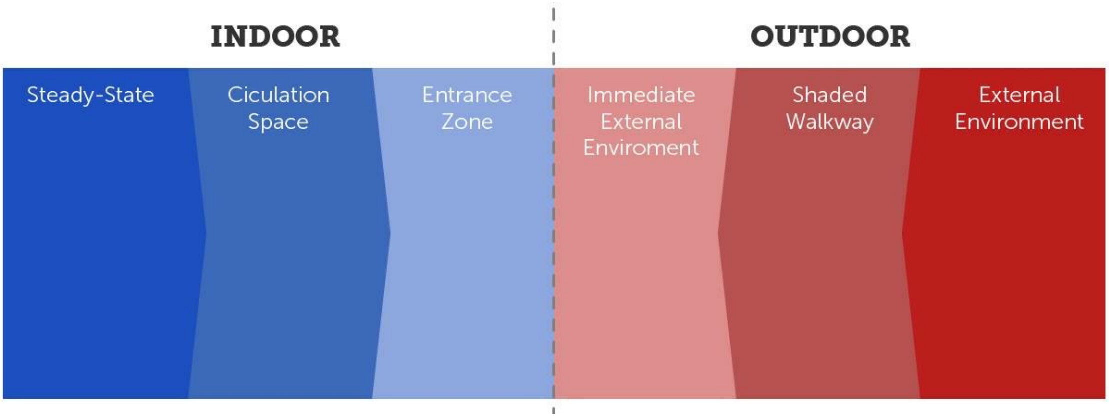


Figure 2:1 Concept of transitional environments indoors and outdoors

2.2 Thermal Comfort in Transition Zones

Thermal comfort is the human psychological sense of satisfaction in one's physical environment. Research divides into subjective (satisfaction, productivity, health, wellbeing, and approval) and objective factors (Temperature, Humidity, Air speed, Clothing Factor - CLO and Metabolic rate - MET). The physical, physiological and increasingly the psychological constructs have determined both quantitative and qualitative parameters of thermal comfort. Although the quantitative measurements are favoured (Meir, I. A., Motzafi-Haller, W., Krüger, E. L., Morhayim, L., Fundaminsky, S. and Oshry-Frenkel, 2007) there remains an opportunity to research qualitative measures of subjective states.

The heat balance model is best used in a steady-state environment; however, transitional zones are by definition, not steady-state environments. They are areas that connect occupants to the outdoors and indoors, as well as connecting occupants between different steady-state environments indoors. Further articulation of the needs of the transition zones may close the gap, which exists between the design-stage and actual construction of the building's thermal environment. It is rare to find indoor environments that have uniform conditions throughout the building (Schiavon et al., 2014, p. 329). Traditional heat balance models use a single set of conditions to compare occupant experiences and the result is a variety of responses even though occupant may be wearing the same level of clothing and activity and exposed to the same zone (Schiavon et al., 2014, p. 329).

Mechanical control of the physical environment to standardise indoor comfort has dominated comfort research (Richard De Dear, 2012). Despite work to introduce thermal delight to highlight the significance of broadening the parameters of thermal comfort (Heschong, 1979), environmental engineering applications of comfort, such as heating and cooling, are the main focus of the building industry (Fanger, 1970, p. 14). Fanger's analysis shows that applying an inter-disciplinary approach to comfort, including heat and mass transfer, thermal physiology, psychophysics, ergonomics, biometeorology, architecture and textile engineering, one can increase the understanding of ones immediate environment. These evaluations are useful to learn from in order to construct better buildings in the future.

There is little empirical information about how much time is spent in transition zones and more information is required. Research completed by the author in 2011 showed that on average, occupants do not spend more than 10 minutes in transition zones. If this is the case on a wider scale, the traditional method of PMV may not be applicable to thermal comfort assessments and is supported by the work of Schiavon et al. suggesting traditional models are "far from reality during building operation and in building performance simulations" (Schiavon et al., 2014, p. 329).

The adaptive method of thermal comfort analysis requires a building to be passively, or naturally ventilated. The transition zones are cooled continuously throughout the year. Often this means, there is no scheduling of air conditioning and the adaptive method of thermal comfort may not be applicable to the transition zones indoors. However, of the two transition zone connectors, the space that bridges the indoors to the outdoors is of significant concern as the air exchange with the outdoors is at its highest.

Thermal comfort theory recognises that there is no exact set condition that will satisfy all occupants, as each occupant has a distinct perception of 'too hot', 'too cold', and 'comfortable'. One's perception is fed by feelings, reasoning and how we react to our environment. The objective in designing a common thermal environment is to satisfy the majority of occupants and to minimise those who are dissatisfied. PMV studies have been used in transition zones but due to the short period of time spent in such non steady state environments, the continuation of PMV may not be ideal.

Standards for building construction specify characteristics of the design for steady-state environments. The American Society of Heating, Refrigerating and Air-Conditioning Engineers – ASHRAE (Paliaga et al., 2013) as well as the British Standard/European Standard/International Standards Organization – BS EN ISO 7730, two of the most-used standards, both define comfort conditions for steady-states. However, separate and more appropriate comfort parameters for transitional spaces are lacking in current literature (Hwang, Yang, Chen, & Wang, 2008). Abu Dhabi's standard for the built environment - the Pearl Rating System (PRS - introduced in 2010 by Emiri Decree) uses ASHRAE, ISO and Chartered Institute for Building Services Engineers (CIBSE) standards for designing buildings.

These rating systems as well as the local statutes lack any transition zone-specific comfort conditions or design parameters. There is also an absence of analytical studies on the traditional transition zones of the Emirati and international standards are unsatisfactory. This places the discussion on the comfort-design of these environments as a timely framing of the subject in this paper. Fanger mentioned there are "unhealthy shocks" upon entry into a building (Fanger, 1970, p. 93). This occurs in the entrance, when one moves from the hot outdoors to the air conditioned indoors, which is often the case in Abu Dhabi, throughout the year, but particularly during the summer. There is information on the impacts of the sudden shift in temperature on the occupant, but there is little research on the exact amount of time an occupant spends in the different parts of the building's circulation areas and corridors.

ISO 7730 mentions the PMV is applicable for an environment after 30 minutes of exposure (ISO, 2005). Tham and Willem (2010) researched the timeframe for changes to be noticed in the reduction of whole body thermal sensation. They concluded that most noticeable changes in the body could be perceived within the first hour of exposure at 20ºC (Tham & Willem, 2010). Further research on the exact time difference between steps as well as the time constant of the human body are required.

Literature suggests it takes up to 20 minutes to adjust to a steady state environment (Hwang et al., 2008; Nagano, Takaki, Hirakawa, & Tochihara, 2005; Ring, de Dear, & Melikov, 1993). Occupants spend shorter amounts of time than this in transitional areas. Therefore, it is inappropriate to use the PMV model to calculate comfort. Chun et al. argue transitional spaces should be considered as 'dynamic, variable and unstable' (Chun, Kwok, & Tamura, 2004). With this definition, traditional standards are far from addressing the requirements for these spaces. Humans can adjust effectively to a different internal environment (de Dear, Ring, & Fanger, 1993; Hwang et al., 2008; Nagano et al., 2005). The transition zones are psychologically and physically halfway between the outdoors and indoors. The design of such places should be congruent with the patterns created with the surrounding building, all to aid the relationship with the external elements (Alexander, 1979).

In Abu Dhabi it is unlikely the occupants will have spent more than 1 hour outside, without any artificial cooling e.g. walking outside, or in a car without it. This may change the expectation of cooling they require upon entry, depending on their acclimatisation to the summer heat. In 2011, the author found that the average time occupants passed through the building to arrive at their destination was ten minutes. Further analysis on transition zones shows how subjects move from discomfort to comfort when moving from cold to warm environments (Hardy & Stolwijk, 1966). However, the converse where analysis is completed on subjects moving from hot environments (outside) to cooler environments (inside) has yet to be researched.

2.3 Adjusting transition zones temperature setpoint

The ASHRAE standards have been important for the design of healthy, liveable buildings, however, as De Dear suggests, they indirectly promote excessively cold temperatures (de Dear, 2012). Further research is needed on the changes to the transition zone's comfort conditions to test how occupants react to these changes. This is especially the case if the temperature is increased to widen the thermal comfort parameters and reduce energy consumption. De Dear and Brager (1998) interviewed occupants in Naturally Ventilated buildings, their findings showed occupants preferred wider diversity in temperatures to mimic the outdoors (Brager & de Dear, 1998). However, these studies were undertaken in non-air conditioned buildings, case studies used in this research are all mechanically cooled.

The application of widening the comfort parameters at the entrance area of buildings where there is contact with the external climate may prove fruitful. Testing the perceived comfort of occupants in these spaces could provide an advancement of knowledge and literature. According to Huang, Lu and Ma further research would be needed to identify where the conditions of the circulation spaces could change to improve comfort according to (Huang, Lu, & Ma, 2011). Chun et al. suggests that buildings with considerable circulatory spaces may face higher operational costs per unit indoor area in comparison to steady-state environments (Chun et al., 2004). For example, Saleh and Pitts discuss four notional examples of geometries to indicate energy use of these spaces (bin Saleh & Pitts, 2004). They modelled what a change in temperature (±5ºC) could do to the transition zones. The results of their models showed a notional 10% or more decrease in energy use over the year, if glazing ratio, building configuration and building design are taken into consideration alongside set point changes. There are a number of examples around the world that illustrate a wider temperature band in buildings. The UK Health and Safety Executive (Corrosion, Of, Steels, & Swimming, 2006) suggests an indoor environment can range from 13- 30°C, according to the level of activity indoors (Nicol, Humphreys, & Roaf, 2012). The Australian standard AS 1837-1976 (1976) recommends between 21- 24°C for offices and the British Council for Offices (British Council, 2010) recommends between 20- 26°C during the summer.

Studies challenging the BS EN ISO 7730: 2005 in Ilam, Iran, found that occupants were willing to accept comfort at a higher temperature than offered in BS EN ISO 7730: 2005 (Heidari & Sharples, 2002). In an experiment with 18 males and 18 females, subjected to a range of temperatures of 22-32ºC, Cui et al. found that performance of the workers was greatly affected by discomfort (Cui, Cao, Park, Ouyang, & Zhu, 2013). The tests showed that the optimum temperature range for performance was 22-26ºC.

Schiavon et al. propose indoor setpoints to remain between 18ºC and 27.3ºC if occupants are allowed to adapt their clothing to achieve thermal comfort (Schiavon, Hoyt, & Piccioli, 2014, p. 331). Additionally, if occupants do not have the ability to change their clothes, setpoints should remain between 21.3ºC and 25ºC (Schiavon, Hoyt, & Piccioli, 2014, p. 331).

The Abu Dhabi Energy Codes, recommend a maximum of 22°C for heating and a minimum 24°C for cooling with a relative humidity of 50% ±5% (International Code Council, 2012 Article 302.1). In Malaysian offices, Ismail assessed the measured temperature was 23.1ºC but the Malaysian comfort temperature was found to be 24.6ºC (Budaiwi & Abdou, 2013). Jiang and Tovey (2009) modelled indoor thermal comfort by increasing the indoor temperature set point. They found that during the summer a 1ºC increase, from 25°C to 26°C could lead to energy saving in the building of 19% in Shanghai and 22% in Beijing (Jiang

& Keith Tovey, 2009). Al-Sanea and Zedan's research on increasing temperature set points showed there was a calculated reduction of yearly cooling of 10% (Al-Sanea & Zedan, 2008). Most literature shows the impact of the energy use from the change in the indoor temperature setpoint.

2.4 Evaluating Transition Zones

It is clear transitional areas are widely considered different from steady-state environments. Post Occupancy Evaluation, which has thus far provided method of assessing steady-state zone performance, occupant satisfaction and thermal comfort is a valid method to extend to transitional environments. Objective and subjective measures in transition zones show a variety of factors that point towards potential energy saving, primarily this is in widening the comfort parameter in the building (Alonso, Aguilar, Coch, & Isalguy, 2000; bin Saleh & Pitts, 2004; Chun et al., 2004; Chun & Tamura, 2005; Ghaddar, Ghali, & Chehaitly, 2011; Gulec, Cana, & Korumaz, 2013; Huang et al., 2011; Hwang et al., 2008; Jie Kwong & Adam, 2011; Kitchari Jitkhajornwanich, 2000; Nakano, 2003; Pitts, 2013). Whilst energy reduction in transitional areas is the main focus for studies done on transition zones, the main aim of this paper is thermal comfort of occupants and their approval of these changes to the transition zone. Hence, upon widening the comfort parameters of transition zones factors like thermal approval of occupants upon immediately entering the building, complements this investigation (Chun & Tamura, 2005; Jie Kwong & Adam, 2011). Transition zones are characterised by their location in bridging the indoor and outdoor environment; their occupancy time and use; their volume as a percentage of the whole building; architectural/engineering features and, for the purpose of this section, the methods used to analyse their thermal comfort.

A large percentage of the buildings are often ignored when conducting post occupancy evaluations. Transitional spaces offer occupants temporary refuge from the harsh summer of Abu Dhabi. Besides the influence from the external climate, they prepare one for the tightly controlled, indoor work environment (Nakano, 2003). In Abu Dhabi, the step change between the interior and exterior environment may reach upwards of 20°C. A thermal buffer, between natural and artificial spaces, if managed well, may lend itself increasing the preparatory step for occupants as they move to steady-state environments. Literature states it is difficult for occupants to achieve thermally steady states if they are exposed to these environments for less than 20 minutes (R.J. de Dear, Ring, & Fanger, 1993; Nagano, Takaki, Hirakawa, & Tochihara, 2005). Steady state environments target specific indoor thermal criterion independent of the external environment (Nakano, 2003). Transition zones are yet to be recognised by either of the two influential internationally recognised thermal comfort standards (Chun et al., 2004). These are International Organisation for Standardisation (ISO) or the American Society of Heating, Refrigerating, and Air Conditioning Engineers - ASHRAE (Nakano, 2003).

The heat balance model of thermal comfort assumes the occupant is a passive recipient of a controlled thermal environment. The adaptive model of thermal comfort in comparison, empowers occupants to maintain comfort by self-regulation. When Fanger's equation is not met, the occupant is experiencing thermal discomfort, in transition zones, this is the majority of the case. The transition zone analysis rests between artificially cooled environments and naturally ventilated buildings. The heat balance model does not apply to naturally ventilated buildings.

"(entrance) zones are so much more connected to the exterior ambient environment that they should be considered as free running spaces and therefore be categorised as such, and use of adaptive algorithm should be applied (that is based upon external condition)" (Pitts, 2013).

The heat balance models, pioneered by Fanger's predicted mean vote (1970) or the New Effective Temperature presented by Gagge et al. (1971) measure thermal comfort of steady-state air-conditioned indoor environments. Building transition zones are controlled identical to the steady-state conditions because there is not enough empirical research on what the comfort criteria should be of transition zones. It is also a result of the lack of practical thermal environment design, which leads to the default use of benchmarks specific to steady-states (bin Saleh & Pitts, 2004).

3 Method to change the Transition Zone temperature setpoint

Occupant adaptation takes place with the use of behavioural and physiological adjustments to maintain body heat balance. Psychological adjustment remains less documented as a method, despite the significance in its ability to illustrate differences between observed and predicted thermal sensation (Nakano, 2003).

3.1 Methods in literature

Some literature suggests a variety of surveys to use in the transition zone. Kong et al.'s (2011) research controlled the temperature in the lift lobby at 26ºC. The experiment aimed to measure human thermal perceptions in enclosed regions. Their experiment measured subjective (questionnaire: sensation and preference and acceptability) and objective thermal comfort in Malaysian educational buildings. The research took place in 2008, with four months of surveying between August and November, 113 respondents' data was collected. A split unit AC was installed in the lift lobby as an intervention and temperature was maintained using the thermostat. Occupants were not surveyed immediately upon entry but invited only after 30 seconds of waiting for the lift. There was 8°C higher temperature difference between the lift lobby and steady state indoors. Occupants were at 1.2 MET and below, with a resting time of 30 seconds before surveying (Jie Kwong & Adam, 2011). Using artificial chambers, Chun et al. found occupants' thermal comfort was closely associated to prior exposure to thermal environments (Chun et al., 2004). Long-term and short-term measurements were taken using objectives thermal measurements. They also suggest not using PMV to determine comfort. In field and laboratory experiments Chun and Tamura tested objective and subjective measurements on occupants walking into transition zones in Yokohama (Chun & Tamura, 2005). The data showed all of 36 subjects were comfortable and could adapt their thermal sensations "very widely" (Chun & Tamura, 2005). Studies show it is important the occupants know what to thermally expect (Nikolopoulou, Baker, & Steemers, 2001). This is because it will influence their clothing choices and their interpretation or expectation of comfort (Nikolopoulou et al., 2001). Brager (1998) states psychological adaptation remains the least studied of adaptive mechanisms, which may explain the discrepancy between the observed and predicted thermal responses.

Occupants of semi-outdoor environments were more tolerant of a wider thermal parameter than the PPD model suggests (Nakano, 2003). Pitts (2013) suggests an investigation into the non-physiological stimuli on perceptions of comfort and transition zones is warranted. This may be in the form of a broad scale parametric study of reaction. Pitts suggest that broadening of the PMV to between 16ºC-26ºC to ±1.0 and PPD from 10% to 26% under transition zone conditions. The challenge is isolating the adjustments to only the transition zones (Pitts, 2013).

A seminal study on thermal comfort in transition zones by Jitkhajornwanich (2000) surveys occupant thermal comfort whilst they move in and out of the main entrance (K. Jitkhajornwanich & Pitts, 2002). The experiment takes place in both winter (1996) and summer (1997) in Bangkok. Unlike Abu Dhabi, Bangkok's hot and humid tropical climate has small variation between the seasons (±10ºC). Jitkhajornwanich uses transverse design surveys to access subjective responses of occupants in transition zones. A total of 1143 office workers are surveyed (Kitchari Jitkhajornwanich, 2000). Jitkhajornwanich evaluates objective comfort; clothing insulation; metabolic activities, the Seven-point ASHRAE scale of thermal sensation; and the Three-point McIntyre scale for thermal preference. Jitkhajornwanich's results of the surveys show transition zones could be used to prepare occupants for the steady states indoors or outdoors (Kitchari Jitkhajornwanich, 2000).

A Taiwanese service centre was used to conduct thermal comfort surveys during the summer (June – September) on guests and staff. The results measured guests and staff entering and exiting the entrance zone. They found an obvious difference between staff and guest levels of thermal requirements, in that guests preferred cooler environments in the entrance area (Hwang et al., 2008). All interviews took place between 10 AM and 3:30 PM, excluding the hour following lunch (when the metabolic rate of respondents is considered unsteady). When interviewing, Hwang et al. explained the meaning of the questions but did not offer suggestions to bias occupant responses. There were 587 subjects interviewed. The survey was prepared in Chinese using transverse design, 11 staff were interviewed twice-daily during the data collection period. Objective thermal comfort measurements were taken in two locations, one at the main entrance the other in the waiting area further into the building. Objective thermal comfort was measured using an omnidirectional hotwire anemometer, a digital thermometer, with a 150mm diameter global thermometer. The indoor climate was continuously measured between 9:30 AM and 4 PM daily. The ASHRAE Seven-point thermal sensation scale and MyIntyre preference scale were used. The survey removed anyone walking hastily. This meant anyone in the immediate entrance zone was excluded.

Ghaddar et al. (2011) studied a workshop at the American University of Beirut during the summer. Occupants were administered surveys to record their local thermal sensation and comfort after three clothing changes. The air temperature of the transition zones ranged between 27ºC-30°C. To test for a warmer transition zone on occupant comfort, indoor entrance zone setpoints were increased from 26ºC to 30ºC. The questionnaire asked occupants their demographic and anthropometric characterisation and segmental thermal sensation and discomfort (Ghaddar et al., 2011). An acceptable range of comfort (PMV less than 0.5) was achieved by raising air velocity to 1.5m/s and dressing occupants with higher permeable fabric.

Building Heating Ventilation and Air Conditioning (HVAC) are designed to cater for a comfortable indoor environment whilst balancing the system to reduce any negative healthy affects. Intervention studies have shown positive effects on reducing energy use in the workplace (Siero, Bakker, Dekker, & Van den Burg, 1996). Neutral temperatures of the transition zone were discussed as a result of four groups under assessment by Jitkhajornwanich and Pitts in a variety of transition zones in Bangkok, although the city does not have large annual temperature variations (Jitkhajornwanich & Pitts, 2002), they reported neutral temperatures were comfortable for these groups and also suggested the use of air-conditioned and naturally ventilated transition zones for further testing. The four groups reported a neutral temperature of 27ºC in the cool season, and of 26.5ºC in the warm season (Jitkhajornwanich & Pitts, 2002).

Interventions within the realm of social and environmental psychology predominantly focus on voluntary behaviour change, rather than changing contextual factors, like temperature. This may determine occupant behavioural decisions and comparative feedback i.e. feedback about the performance of the transition zones (Abrahamse, Steg, Vlek, & Rothengatter, 2005). Gardner and Stern conducted thirty-eight studies, within the field of (applied) social and environmental psychology were reviewed, and categorised as involving either antecedent strategies (i.e. commitment, goal setting, information, modelling) or consequence strategies (i.e. feedback, rewards) (Gardner & Stern, 2002). Gardener and Stern's (2002) research on feedback on individual performance, relative to the performance of others, may be helpful in reducing building energy use (Gardner & Stern, 2002).

3.2 Intervention

The aim of the intervention was to understand the difference between the temperature increase on different groups of buildings. The following section describes methods found in literature as we as each of the intervention groups. The intervention took place over the month of August 2012, where the occupied zone temperature setpoint would increase by 1ºC, thus a reduction in cooling requirement by 1ºC. In Abu Dhabi, infiltration could lead to increased moisture content. This is because of the high levels of humidity outdoors. Above 60% RH indoor mould growth becomes a concern. Interventions were imposed on ten buildings (5 mixed-use and 5 prestige), a control group of buildings was also kept to compare results between the two group.

Intervention Group (10)

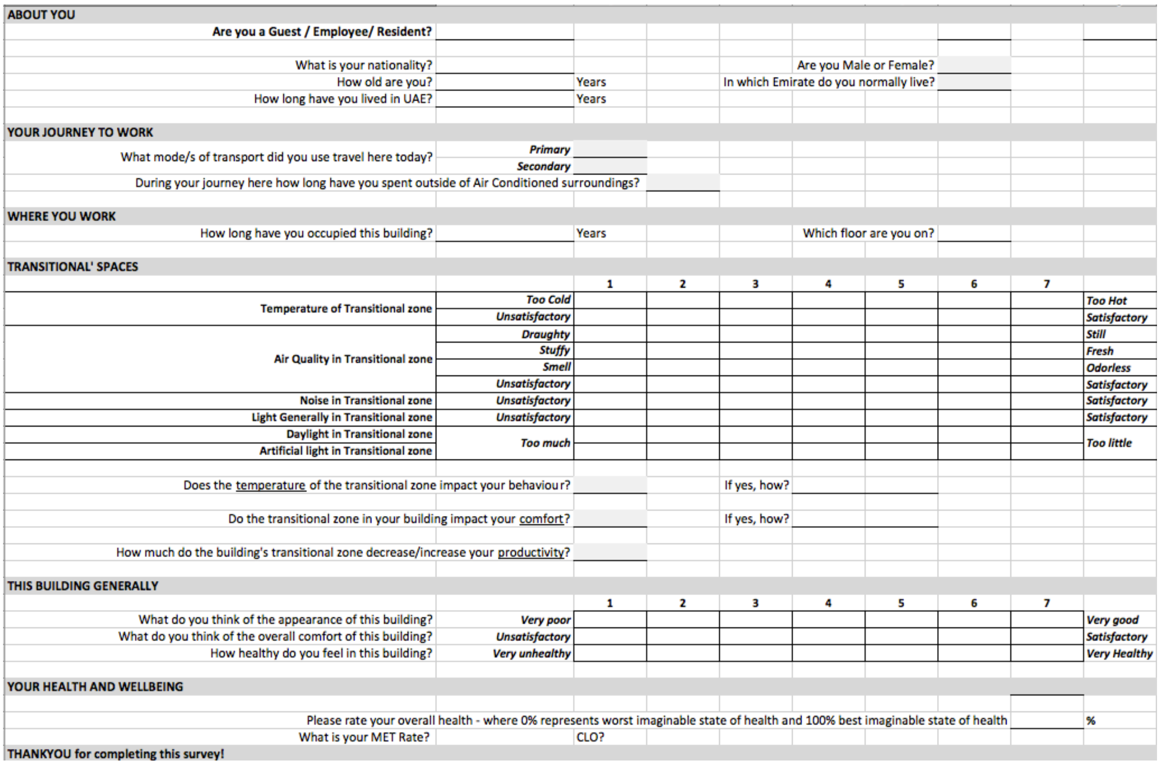
This is the test group, where a 1ºC change in transition zone temperature was made. This took place with the researcher physically going around the building and increasing the temperature of the occupied zone setpoint with the permission of the building owner and facilities management.

Control Group (4)

The control group had 5 mixed-use buildings. No intervention took place. The purpose of this group was to maintain a group of buildings consistent throughout the field study that would not be intervened on.

3.3 Pre/Post Intervention Survey

To conduct the survey of occupant perceived comfort and satisfaction, the researcher stood in the entrance lobby of the building and surveyed occupants entering the building. The aim here was to capture the effect of the building upon entry. The Pre and Post-Intervention survey was conducted using the same questions, where CLO and MET could also be collected. The survey was prepared in English, Hindi, Malayalam, Arabic and included a sheet with CLO and MET estimations.


ABOUT YOU

Are you a Guest / Employee/ Resident?

What is your nationality? | Are you Male or Female?

How old are you? Years | In which Emirate do you normally live?

How long have you lived in UAE? Years

YOUR JOURNEY TO WORK

What mode/s of transport did you use travel here today? *Primary* *Secondary*

During your journey here how long have you spent outside of Air Conditioned surroundings?

WHERE YOU WORK

How long have you occupied this building? Years | Which floor are you on?

TRANSITIONAL' SPACES

		1	2	3	4	5	6	7	
Temperature of Transitional zone	*Too Cold*								*Too Hot*
	Unsatisfactory								*Satisfactory*
Air Quality in Transitional zone	*Draughty*								*Still*
	Stuffy								*Fresh*
	Smell								*Odorless*
	Unsatisfactory								*Satisfactory*
Noise in Transitional zone	*Unsatisfactory*								*Satisfactory*
Light Generally in Transitional zone	*Unsatisfactory*								*Satisfactory*
Daylight in Transitional zone	*Too much*								*Too little*
Artificial light in Transitional zone									

Does the temperature of the transitional zone impact your behaviour? | If yes, how?

Do the transitional zone in your building impact your comfort? | If yes, how?

How much do the building's transitional zone decrease/increase your productivity?

THIS BUILDING GENERALLY

		1	2	3	4	5	6	7	
What do you think of the appearance of this building?	*Very poor*								*Very good*
What do you think of the overall comfort of this building?	*Unsatisfactory*								*Satisfactory*
How healthy do you feel in this building?	*Very unhealthy*								*Very Healthy*

YOUR HEALTH AND WELLBEING

Please rate your overall health - where 0% represents worst imaginable state of health and 100% best imaginable state of health %

What is your MET Rate? CLO?

THANKYOU for completing this survey!

Figure 3:1 Transition zone survey

The questionnaire to determine occupant thermal comfort in-situ, was administered twice, before the intervention in July 2012 and again during the intervention in each respective case study building in August 2012.

4 Results

The sample sizes for each building of the occupants were determined by the total occupant population of the building, without including external guests to the sample size, however, guests were included in the surveying as their interaction with the comfort of the transition zone was equally important, see Table 4-1.

Table 4-1 Summary of response rates of all self-reported questionnaires

CSB	Intervention Group	Occupancy sample	Responses Pre July 2012	Responses Post Aug 2012
1	Intervention Prestige	600	84	20
2	Intervention Prestige	340	55	20
3	Intervention Prestige	80	26	13
4	Intervention Prestige	630	10	16
5	Intervention Prestige	45	40	16
6	Control	25	14	5
7	Intervention	20	7	4
8	Intervention	32	16	8
9	Control	32	11	5
10	Control	32	6	3
11	Intervention	32	11	3
12	Intervention	24	15	8
13	Intervention	30	30	5
14	Control	32	24	5

The results of the comfort vote show there is a normal distribution around the neutral comfort from the intervention, see Fig. 4-1, where the majority of respondents showed they are comfortable in the transition zone with a 1ºC in temperature setpoint using the thermal sensation scale.

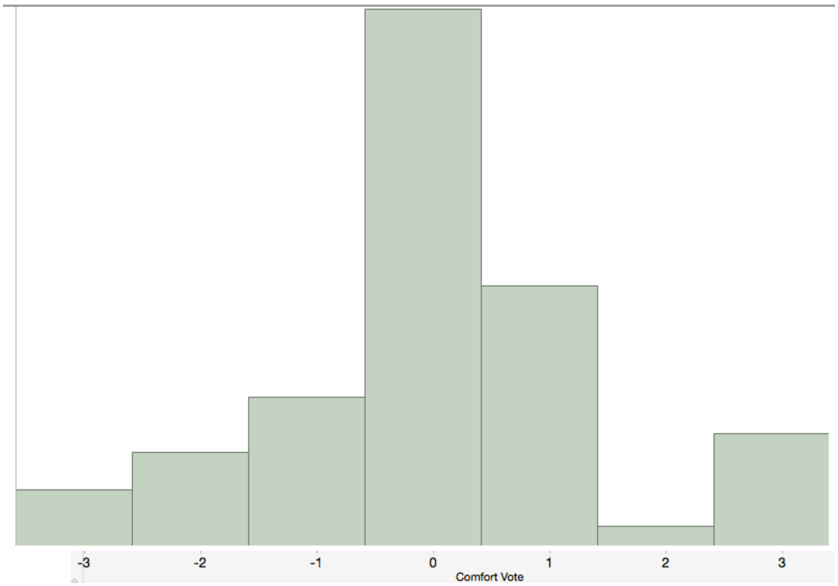


Figure 4:1 Intervention building comfort vote, post-intervention, -3=too cold, +3=too hot

Perhaps a 1ºC increase in temperature of the transition zone was not a significant change to the standard comfort of the occupants, in 6 of the 10-intervention building, there was a visible increase in the comfort satisfaction (1 to 7 scale) of the occupants from the pre-intervention results. However, in 3 of the 4 control buildings this also happened to be the case. It is unclear in the control buildings, whether there was any indirect impacts on the buildings that may not have been captured, see Table 4-2. The comfortable satisfaction

Table 4-2 Summary of mean self-reported comfort, 1= unsatisfactory, 7= satisfactory

CSB	Intervention Group	Pre Comfort Sat	Post Comfort Sat	Delta Comfort Sat	Pre Comf Sat STD	Post Comf Sat STD
1	Intervention Prestige	4	4.7	0.7	1.22	0.4
2	Intervention Prestige	4	5	1	1.12	1.5
3	Intervention Prestige	4.1	5.7	1.6		0.94
4	Intervention Prestige	5.4	5.6	0.2	1.1	1.45
5	Intervention Prestige	4.9	4.8	-0.1	1.73	0.47
6	Control	3.8	5	1.2	1.3	1.81
7	Intervention	4.3	4	-0.3	0.86	1.62
8	Intervention	5.6	4.6	-1	1.13	1.28
9	Control	4.9	3.8	-1.1	1.64	1.32
10	Control	3.7	4.3	0.6	1.69	1.33
11	Intervention	3.5	4.3	0.8	1.34	1.41
12	Intervention	3.4	5.6	2.2	0.86	1.26
13	Intervention	5.6	3.6	-2		0.56
14	Control	4.8	5.4	0.6	1.19	1.22

5 Conclusion

An intervention to increase in the transitional zone temperature shows that there was a positive response from occupants to the comfort satisfaction and comfort vote of the occupants. Research suggests there is potential for further analysis of this non-steady-state environment, which could lend itself as a bridge between the indoor and outdoor environments. Literature suggests there is potential to widen the comfort parameter of the transition zone, from the perspective of the occupant, there is a broad scale of comfort that the occupant manages.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
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Air-Conditioner Use Effects on Thermal Environment in Bedrooms and Sleep Quality during Summer – Analysis of University Students in Osaka

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Abstract

Analyses of thermal environment, thermal control behaviors, thermal sensations, and sleep quality yielded the following results indicating air conditioner (AC) use effects on sleep quality in 11 bedrooms during three periods of summer. 1) Outside temperatures were higher on AC use days but room temperatures during sleep were kept almost identical (25.7°C). 2) Sleep quality as evaluated by the OSA score was higher on AC use days. However, it was hotter and less acceptable on AC use days, although thermal comfort was not different. 3) On AC non-use days, the relation between thermal comfort and thermal sensation was stronger. Thermally acceptable ranges were wider on non-use days. 4) Relation between the OSA score and the degree of sound sleep was weaker on AC use days. The OSA score was more strongly related to thermal acceptability on AC use days than non-use days. 5) Differences in sleep quality were smaller between AC use days and non-use days than between the surveyed periods. Lower sleep quality in mid-summer was caused not by AC, but by higher room temperatures.

Keywords: Sleep Quality, Thermal Sensation, Air Conditioner use

1 Introduction

Sultry nights with temperatures that remain higher than 25°C have become increasingly common in the urban area of Osaka, Japan, perhaps because of global warming and heat island phenomena. There were 23, 27, 10, 50, 57, and 55 sultry nights, respectively, in 1960, 1970, 1980, 1990, 2000, and 2010.

Common households possess 2–3 air-conditioners (AC), using them during sleep times. Decreased sleep quality caused by heat might affect work performance and health. Recently, increased heat stroke risk has because become a matter of greater concern. AC use has become a heatstroke countermeasure. However, electrical power shortages related to the severe accident at the Fukushima Daiichi nuclear power plant caused by the Tohoku earthquake on March 11, 2011 possibly affected AC use. A government campaign of 'electricity conservation', *COOLBIZ*, calls for an AC temperature setting of 28°C.

Sakane et al. (2012) conducted a questionnaire survey of AC use by 362 residents in Osaka apartment houses in autumn 2012. Results show that 24.6% answered 'very frequently use' AC and 29.7% answered 'frequently use' AC on a four-point scale in daytime. In addition, 36.5% answered 'very frequently use' AC; 30.7% answered that they 'frequently use' AC during nighttime. However, 54.4% and 29.0% answered 'keep open' in daytime and nighttime on a five-point scale; 22.5% and 38.4% answered 'keep closed' windows in daytime and nighttime. Results show that people reported choosing AC use according to a daily preference.

In such circumstances, this study objects to clarify the followings. 1) How are indoor and outdoor thermal environment different between AC-use and non-use days? 2) How are sleep quality, thermal sensation, comfort, and acceptability improved by AC use? 3) How the relations between sleep quality and thermal senations different in between AC use and non-use days? 4) Are the relations different among periods in summer?

2 Methods

Eleven university students who lived in or near Osaka city participated in the survey during June 18–25 in early summer, August 27 through September 5 in mid-summer, and September 17–24 in late summer. Each survey was continued for more than seven successive days during the university summer vacation season. For that reason, some of them went outside their ordinary bedrooms because of travel or returned home or to work; thereby each became unable to attend the entire survey. Table 1 presents attributes of the subjects and the bedrooms.

The subjects measured the bedroom temperature at intervals of 10 min using data loggers. Relative humidity was recorded before and after sleep. Every morning, they filled questionnaire sheets related to the degree of sound sleep in four categories, thermal sensation in seven-point-scale, thermal comfort in four-point-scale, and acceptability in three-point-scale in bedrooms of the prior night. Sleep quality was also evaluated using OSA scales in mid-summer and late summer. At the same time, they kept a diary recording their absence or presence in bedrooms, personal AC use, window opening of the bedrooms and sleep at intervals of 30 min.

Table1 Attribute of the subjects and the bedrooms

Subject	Attendance in the survey			Boarder or commuter	Building type	Bedroom area (m^2)	Bedding type	Sleeping time (hrs.)
	early summer	middle summer	late summer					
no.1	○	○	○	boarder	apartment	n.a.	tatami mat	7.9
no.2	○	△	○	commuter	apartment	15	bed	6.4
no.3	○	○	○	commuter	detached	12	bed	6.4
no.4	○	○	○	boarder	apartment	13	bed	8.6
no.5	○	△	○	commuter	detached	12	bed	8.5
no.6	○	×	○	commuter	detached	9	tatami mat	8.8
no.7	○	×	×	commuter	detached	9	tatami mat	10.2
no.8	○	○	○	commuter	detached	12	bed	8.1
no.9	○	×	○	boarder	apartment	12	tatami mat	8.5
no.10	×	×	○	commuter	detached	n.a.	bed	7.0
no.11	○	×	×	commuter	apartment	n.a.	n.a.	4.7

Oguri et al. (1985) developed the OSA sleep inventory to evaluate subjective sleep quality. Yamamoto et al. (1999) revised it. Generally, OSA is used for clinical purposes in Japan. It is a standard deviation calculated from subjective rating scales of sleep quality. It evaluates sleep at the time of awakening, based on responses to 16 questions. Each question response is given on a four-response scale: very good, somewhat good, somewhat bad, very bad. These questions yield standard scores of five factors. Averaged standard scores of five factors are defined as the OSA score. The higher the score is, the higher the sleep quality is indicated. The five factors are Factor I (Drowsiness when waking such as 'I have the power of concentration', 'I feel a sense of liberation' and 'I feel clear-headed'), Factor II (Falling asleep and maintaining sleep such as 'I was able to sleep soundly', 'I dozed off until I finally fell asleep', 'I got to sleep easily', 'I often woke up from sleep' and 'The sleep was shallow'), Factor III (Dreaming, such as 'I had many nightmares' and 'I had many dreams'), Factor IV (Fatigue recovery such as 'Fatigue persists after waking up', 'I feel languorous' and 'I feel unwell'), and Factor V (Sleeping duration such as 'I have generally good appetite' and 'The sleep duration was long').

3 Results

3.1 Comparison among periods in summer

3.1.1 Thermal environment

An example of bedroom temperature and humidity, outdoor temperature and humidity, and behaviors in mid-summer for subject no.1 in mid-summer is presented in Fig. 1. We use outdoor temperature measured by local weather observatories. The respondent went outside the bedroom on the sixth and seventh night, so the survey was continued until the ninth day. He lived with his family in an RC apartment. He sometimes used AC, and sometimes opened windows. Indoor temperatures were sometimes lower than outdoor temperatures in daytime but usually higher than outdoor temperatures in nighttime.

Fig. 2 presents the mean daily indoor and outdoor temperatures for the surveyed periods. The mean indoor temperatures (during sleep) were 26.5°C (25.7°C), 27.7 °C (27.2°C) and 25.7°C (25.4°C) in early, middle and late summer. Mean outdoor temperatures (during sleep) were 24.1°C (21.8°C), 26.0°C (23.3°C) and 22.6°C (20.2°C) in early, middle and late summer.

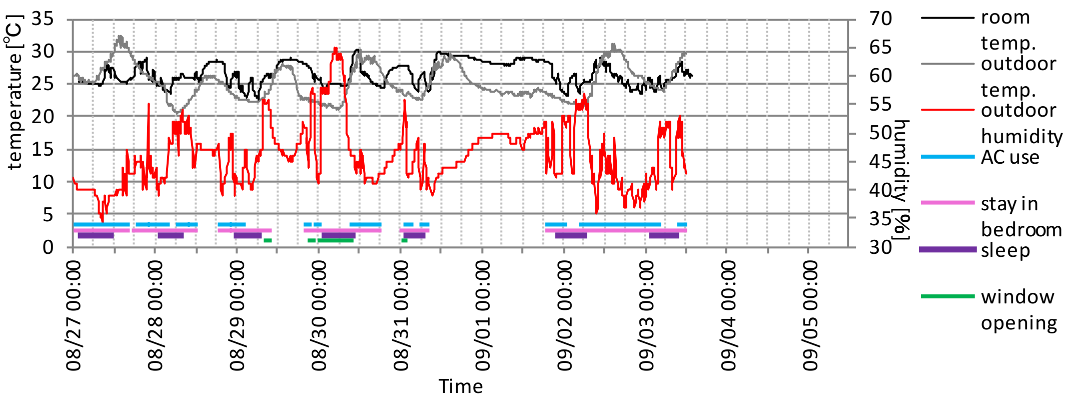


Fig.1 An example of the records of thermal environment and thermal control behaviors

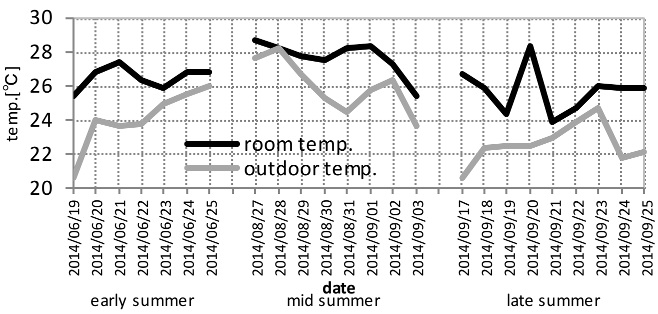


Fig.2 Daily mean temperatures for three periods

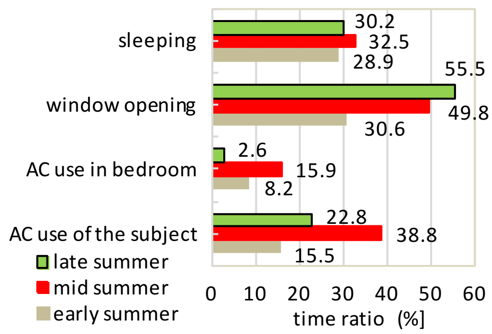


Fig.3 Time ratio of behaviors for the periods

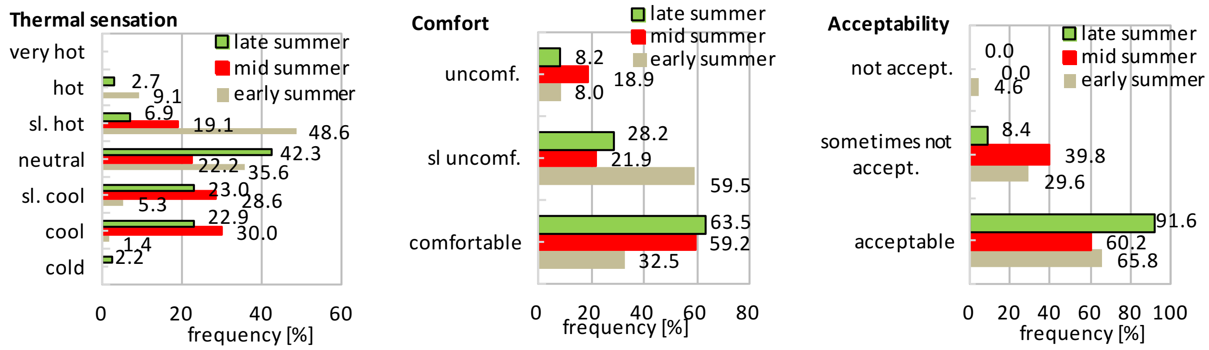


Fig.4 Frequency distribution of thermal sensation, comfort and acceptability for periods

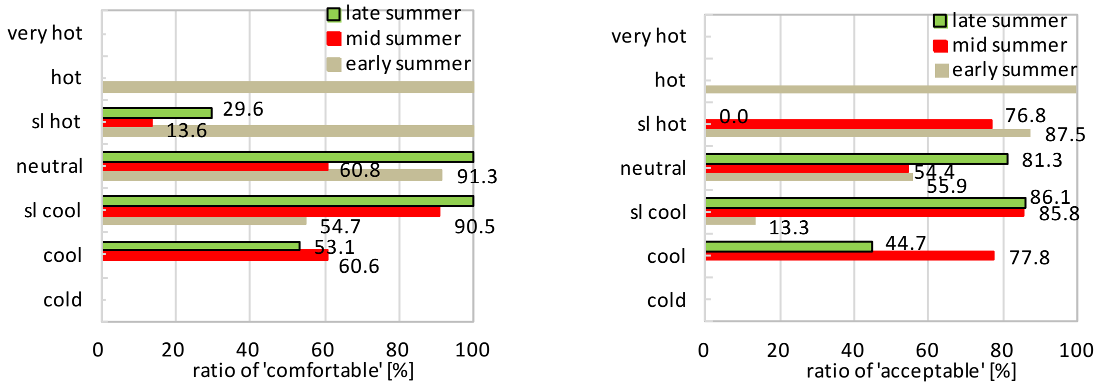
3.1.2 Behaviors

Fig. 3 shows the average time ratio of sleep, window opening and AC use in the bedroom and AC use of the respondents for 24 hours for different periods. These time ratios are based on records from diaries of respondents kept at 30 min intervals. The time ratio of presence in bedroom was 51.2%. Respondents rarely stayed in bedrooms during daytime. The time ratio of sleep was not different among periods. The time ratio of window opening in bedrooms was 30.6% in early summer, 49.8% in mid-summer and 55.5% in late summer. Windows of bedrooms were sometimes kept open during absence. The time ratio of AC use in bedrooms was 8.2% in early summer, 15.9% for mid-summer and 2.6% for late summer. Respondents did not usually use AC and did not open windows in early summer. The AC use days during sleep were 11 days in early summer, 15 days in mid-summer, and 4 days in late summer. The AC non-use days during sleep were 54 days in early summer, 27 days in mid-summer, and 48 days in late summer.

3.1.3 Thermal sensation

Fig. 4 shows a frequency distribution of thermal sensation, comfort, and acceptability in different periods. Results show that, ‘slightly hot’ was most frequent (48.6%) in early summer; ‘cool’ was most frequent (30.6%) in mid-summer; and ‘neutral’ was most frequent (42.3%) in late summer (in uniformity test among periods, p<.0001). It was hottest in early summer and most cool in mid-summer. ’Slightly uncomfortable’ was most frequent (59.5%) in early summer; ‘comfortable’ was most frequent (59.2%) in mid-summer, but 18.9% responded ‘uncomfortable’; ‘comfortable’ was most frequent (63.5%) in late summer (p=.007). ‘Comfortable’ was the least in early summer and ‘uncomfortable’ was the most in late summer. ‘Acceptable’ was most frequently reported in all periods and ‘Acceptable’ was 91.6% in late summer and ‘sometimes not acceptable’ was 39.8% In mid-summer. But there were little statistically significant difference by periods in thermal acceptability (p=.092).

Fig. 5 portrays the ratio of ‘comfortable’ and ‘acceptable’ in each category of thermal sensation in different periods. Relations between thermal sensations and thermal comfort changed with the period. The ratio became higher as the thermal sensation became warmer in early summer. It was unrelated to thermal sensation in mid-summer. It became lower as the thermal sensation became cooler in late summer.



a) 'comfortable'

b) 'acceptable'

Fig.5 Comparisons of ratios of 'comfortable' and 'acceptable' in each category of thermal sensation among periods

Relations between thermal sensation and thermal acceptability changed with the period. The ratio became higher as it became hotter in early summer. It was unrelated to thermal sensations in mid-summer. It became lower as the thermal sensation became cooler or warmer in late summer.

3.1.4 Sleep

Fig. 6 portrays frequency distributions of the degree of sound sleep for periods. The frequency distribution was similar for early and late summer. Actually, 'somewhat good' was the most frequent response for both periods: 47.8% for early summer and 45.7% for late summer. For mid-summer, 'somewhat good' was the most frequent. It was 44.2%, but 'sleep somewhat bad' was 30.0%. The degree of sound sleep was similar in early and late summer (in uniformity test among periods, *p*=.22).

Fig. 7 presents OSA scores compared between mid-summer and late summer in each subject. Each score represents the mean of seven nights. The average score was 45.5 in mid-summer and 48.1 in late summer. The OSA score was lower in mid-summer than in late summer, except for subject no. 3.

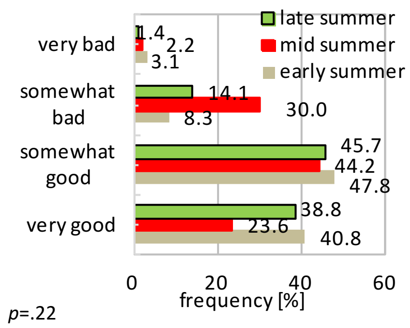


Fig.6 Frequency distribution of degree of sleep for periods

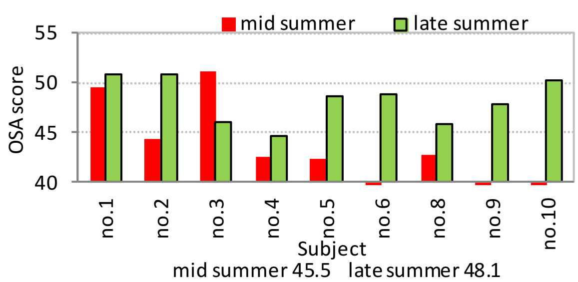


Fig.7 Comparison of mean OSA scores in each subject between periods

Fig. 8 presents a comparison of profiles of the mean vote of each OSA scale between mid-summer and late summer. Scales are ordered in the figure from factor I to V. The lower value shows better sleep. Complete sleep was better in late summer than in mid-summer. Mean votes of Factor I (Drowsiness when waking), Factor IV (Fatigue recovery) and Factor V (Sleeping duration) were higher in late summer than in mid-summer, although few differences were found in Factor II (Falling asleep and maintaining sleep), and no differences in Factor III (Dreaming) between middle and late summer. Differences in liberation in Factor I, languorous in Factor IV and good appetite in Factor V were significant in t-test .

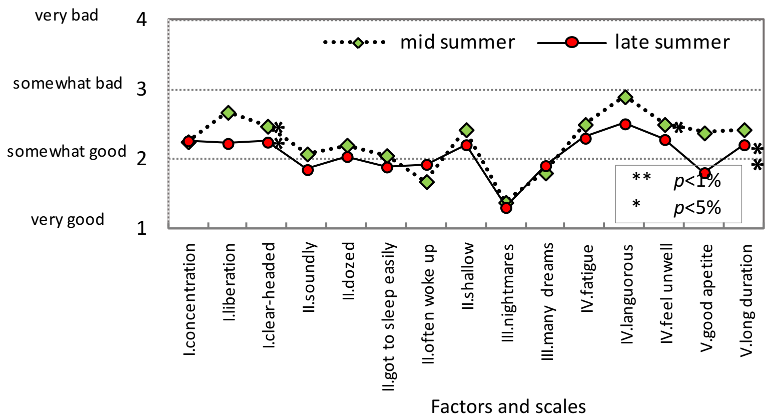


Fig.8 Comparison of profile of OSA scales between periods

Fig. 9 shows the mean OSA scores for respective categories of thermal sensation, comfort, acceptability, and degree of sound sleep for middle and late summer. The OSA score was almost identical for each category of thermal comfort both in middle and late summer (in Kruskal-Wallis test, p=.57 and .61, respectively). The OSA score was higher for 'comfortable' in mid-summer (p=.022), but no difference was apparent in late summer (p=.37). Differences of mean OSA scores were not 3.1 in mid-summer, but 1.6 in late summer between 'acceptable' and 'sometimes not acceptable' (p=.14 and .54, respectively).

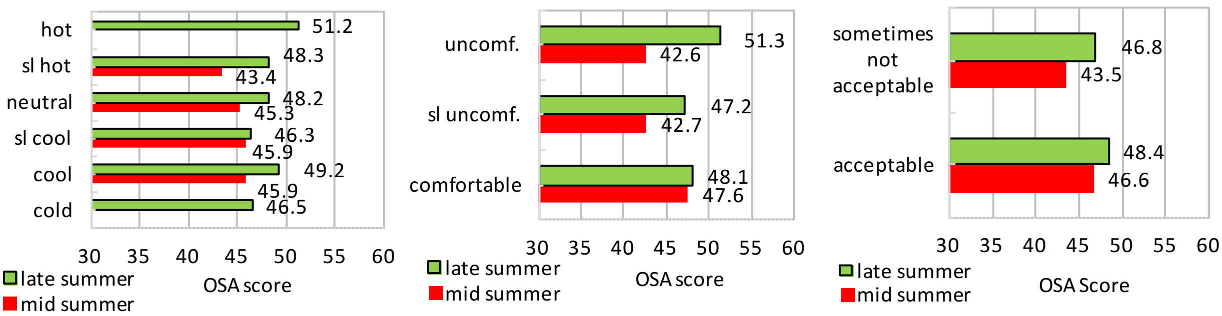


Fig.9 Comparison of mean OSA scores for each category of thermal sensation, comfort and acceptability between periods

Fig. 10 shows the mean bedroom temperature during sleep for each category of degree of sound sleep for periods. The OSA score became lower from 'very good' to 'somewhat bad' in the degree of sound sleep in the middle and late summer (p=.002 and .0006).

Fig. 11 presents the mean bedroom temperature during sleep for each category of degree of sound sleep for early, middle, and late summer. The degree of sound sleep was unrelated to the bedroom temperature in early summer (p=.50). The mean bedroom temperature was 26.1°C for ‘very good’, 27.6°C for ‘somewhat good’, and ‘somewhat bad’ in mid-summer (p=.26). It was 24.2°C for ‘very good’, 25.2°C for ‘somewhat good’, and 25.4°C for ‘somewhat bad’ in late summer (p=.071). Differences of the temperature between ‘very good’ and ‘somewhat good’ were larger than that between ‘somewhat good’ and ‘somewhat bad’. Room temperature was related to the degree of sound sleep in late summer, although the relation was weak in mid-summer.

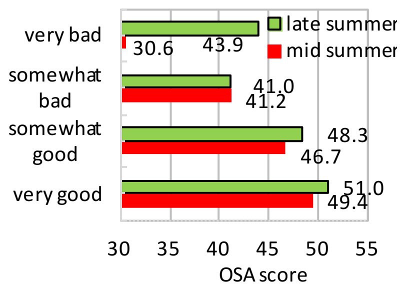


Fig.10 Comparison of mean OSA scores for each category of sound sleep between periods

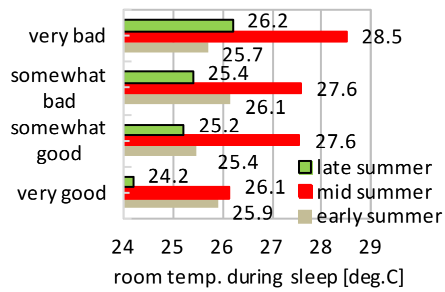


Fig.11 Comparison of mean room temp. for each category of sound sleep between periods

Fig. 12 depicts relations between the mean bedroom temperature during sleep and the OSA score for middle and late summer. The OSA score became slightly higher for the lower bedroom temperature in mid-summer (r=-.22), although little correlation was found between OSA score and room temperature in late summer (r=-.09).

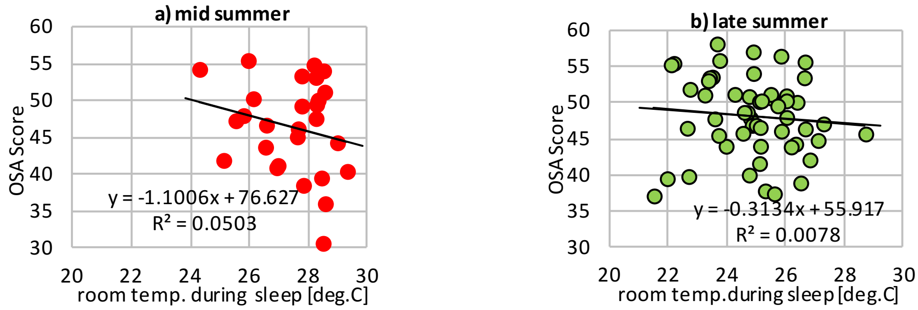


Fig.12 Relations between room temperature during sleep and OSA score for mid-summer and late summer

3.2 Comparison between AC use days and non-use days

The AC non-use day is defined as the day on which respondents did not record AC use in the diary at all during sleep. However, the AC use days include from days of AC use through the night to days of AC use for only 30 min.

3.2.1 Thermal environment

Fig. 13 shows the daily mean outdoor temperature and mean outdoor temperature during sleep for AC use and non-use days. The daily mean outdoor temperatures were 24.6 °C and 23.4 °C for use and non-use days (in t-test, p=.005). Mean outdoor temperatures during sleep were 22.6 °C and 21.4 °C for use and non-use days (p=.002). Differences between use and non-use days were 1.2 K for both daily temperature and temperature during sleep. However, p-values showed that subjects chose to use AC according to the outdoor temperature during sleep.

Fig. 14 presents a comparison of mean bedroom temperature during sleep between use and non-use days for three periods. Differences between use and non-use days were 1.2 K in early summer, 1.1 K in mid-summer and 0.9 K in late summer. Slight differences were apparent in bedroom temperature during sleep between use and non-use days. The mean bedroom temperature during sleep was 26.4°C (25.7°C) and 26.3°C (25.7°C) for use and non-use days for total three periods.

3.2.2 Behaviors

Fig. 15 shows average time ratios of sleep, window opening, and AC use in bedrooms and AC use of the respondents for AC use and non-use days. The time ratio of sleep was not different between use and non-use days. Time ratios of window opening in bedrooms were 24.5% for use days and 47.8% for non-use days. Windows were kept closed for about half of the day even for non-use days. The time ratio of AC use of the respondents was 18.4%. The time ratio of AC use in bedrooms was 4.7% for non-use days. However, the AC use ratio and AC use ratio in bedrooms were similar for use days. Respondents used AC outside the bedrooms for non-use days.

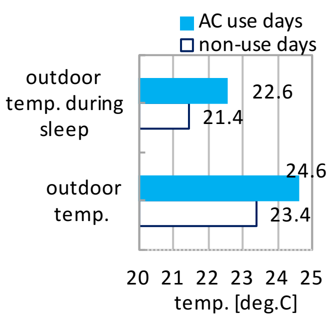


Fig.13 Comparison of mean outdoor temp. between AC use and use and non-use days

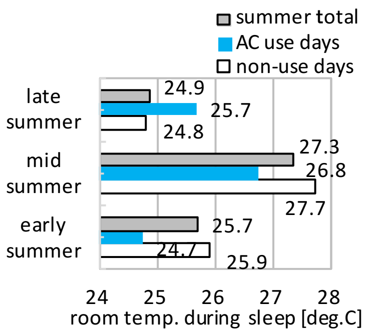


Fig.14 Comparison of mean room temp. between AC use and non-use days

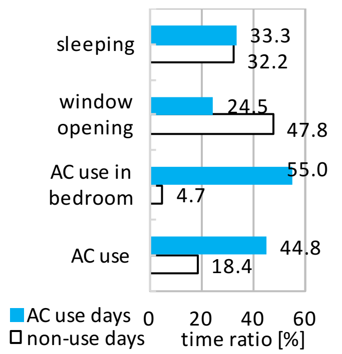


Fig.15 Comparison of time ratio of behaviors between AC non-use days

3.2.3 Thermal sensation

Fig. 16 shows a frequency distribution of thermal sensation, comfort and acceptability for AC use and non-use days. Results show that 'slightly hot' was the most frequent (23.4%) for use days, although 'neutral' was the most frequent (38.3%) for non-use days (in uniformity test between AC use and non-use, p=.19). The mean bedroom temperature during sleep was almost identical for use and non-use days as noted in 3.2.1, but respondents felt hotter for use days, although 'cool' and 'neutral' were the second most frequent.

Actually, 'slightly uncomfortable' was most frequent (43.3%) for use days, although 'comfortable' was the most frequent (51.9%) for non-use days. Little difference was apparent in thermal comfort between use and non-use days (p=.80).

For use days, 'acceptable' was 53.3%; 'sometimes not acceptable' was 43.3%. Actually, 'acceptable' was 75.6% and 'sometimes not' was 22.7% for non-use days. For both use and non-use days, 'acceptable' was the most frequent, but less frequent for use days than for non-use days (*p*=.031).

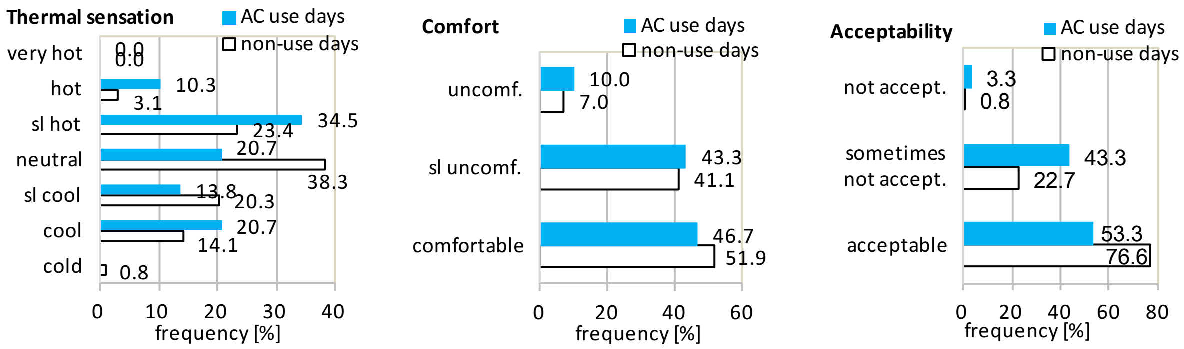
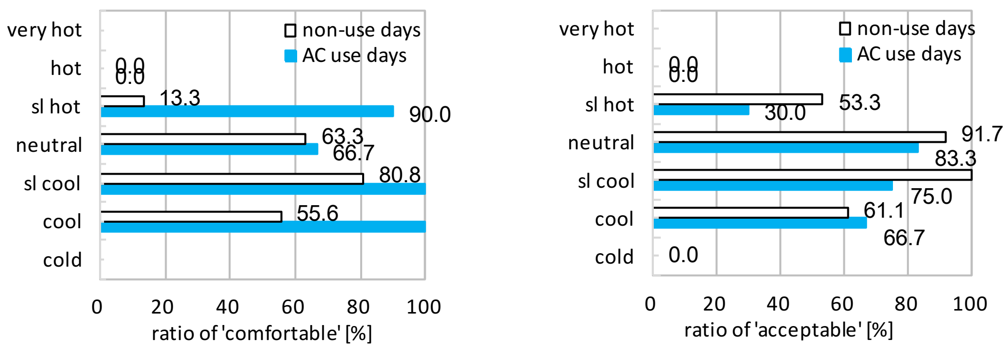


Fig.16 Frequency distribution of thermal sensation, comfort and acceptability for AC use and non-use days

Fig. 17 presents ratios of 'comfortable' and 'acceptable' for each category of thermal sensation for use and non-use days. The ratio of 'comfortable' was higher in 'cool', 'slightly cool', and 'neutral' for use days than for non-use days. The ratio of 'comfortable' was the highest in 'slightly cool' for non-use days, although the ratio in 'neutral' was similar for use and non-use days. The ratio of 'acceptable' was higher in 'slightly cool', 'neutral' and 'slightly hot' for non-use days than use days. Figures show that use days were more comfortable but less acceptable than non-use days, irrespective of thermal sensation.



a) 'comfortable'

b) 'acceptable'

Fig.17 Comparisons of ratios of 'comfortable' and 'acceptable' in each category of thermal sensation

3.2.4 Sleep

Fig. 18 displays the frequency distribution of the degree of sound sleep for AC use days and non-use days. Actually, 'very good' was 50%; 'somewhat good' was 40% for use days. Results show that 'very good' was 32.6% and 'somewhat good' was 46.5% for non-use days. The degree of sound sleep tended to be better for use days than for non-use days (in uniformity test between AC use and non-use, *p*=.238).

Fig. 19 presents OSA scores compared between use days and non-use days in each subject. The OSA score was better for use days than for non-use days in nos. 1, 3, 6 and 9. However, nos. 2 and 6 were the opposite.

Fig. 20 shows mean OSA scores for use and non-use days for mid-summer and late summer. The mean OSA score was 47.9 in mid-summer and 50.2 in late summer for use days. They were 44.1 in mid-summer and 48.0 in late summer for non-use days. Difference of mean scores and *p*-values of *t*-tests between use and non-use days were 3.9 and 0.023 in mid-summer, and 2.3 and 0.39 in late summer. The OSA score was higher for use days than for non-use days in mid-summer. However, little difference was apparent between use and non-use days in late summer.

Fig. 21 presents a comparison of profiles of mean vote of each OSA scale between use and non-use days. Sleep for use days was better than non-use days. Concentration in Factor I, soundly in Factor II, many dreams in Factor III, fatigue in Factor IV and good appetite in Factor V were higher for use days. Little tendency was apparent among factors.

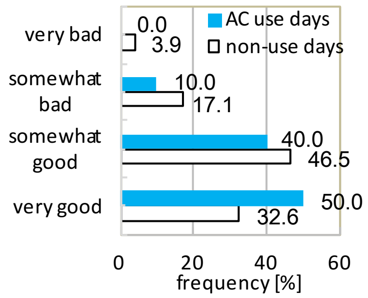


Fig.18 Frequency distribution of degree of sound sleep for AC use and non-use days

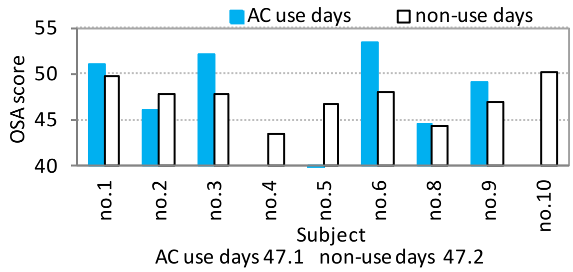


Fig.19 Comparison of mean OSA scores in each subject between AC use and non-use days

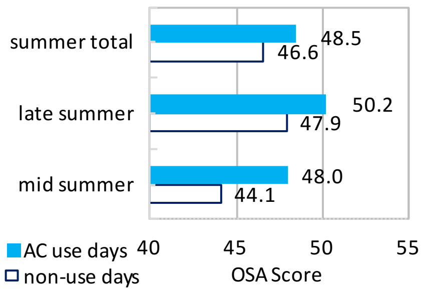


Fig.20 Comparison of mean OSA scores for periods between AC use and non-use days

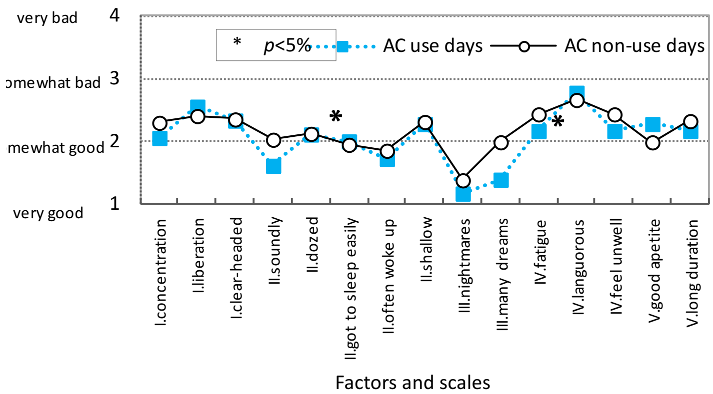


Fig.21 Comparison of profiles of OSA scales between AC use and non-use days

3.2.5 Relation between thermal environment and sleep

Fig. 22 shows a comparison of the mean OSA score of each category of thermal sensation, comfort and acceptability between AC use and non-use days. OSA score slightly correlated to thermal sensation only for use days (p=.0659). OSA score became higher for cooler sensation for use days, but no relation was found between OSA score and thermal sensation. OSA score did not so relate to thermal comfort for both use and non-use days. The mean OSA score for 'acceptable' was 52.0 and 'slightly acceptable' was 45.0 for use days. OSA score was high when thermal acceptability was high for use days (p=.0062). However, little relation existed between OSA score and thermal acceptability for non-use days (p=.18). OSA related to thermal sensation and acceptability, but not to thermal comfort for use days. OSA little related to thermal sensation, comfort and acceptability for non-use days.

Fig. 23 shows the mean OSA scores of respective categories of the degree of sound sleep between use and non-use days. The OSA score was unrelated to the degree of sound sleep for use days (*p*=.058). However, the mean OSA score for ‘sleep soundly’ was 50.4, for ‘sleep somewhat soundly’ was 47.4, for ‘not sleep somewhat soundly’ was 41.7 and for ‘not sleep soundly’ was 37.3 for non-use days. The OSA score was related to the degree of sound sleep for non-use days (*p*=.0001). The degree of sound sleep is one scale of OSA Factor II. Factor II was higher in OSA for non-use days and OSA score was lower when the degree of sound sleep was low for non-use days, although factors other than Factor II became dominant when the degree of sound sleep was high for use days.

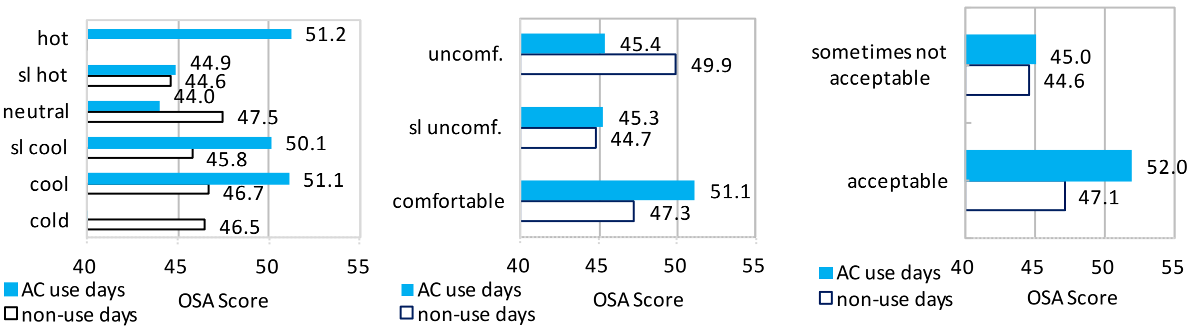


Fig.22 Comparisons of mean OSA scores for each category of thermal sensations, comfort and acceptability between AC use and non-use days

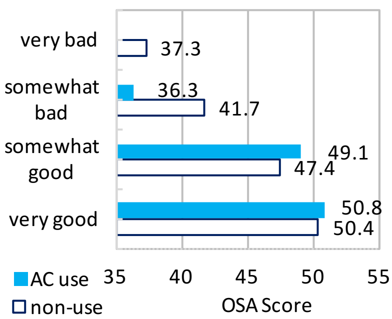


Fig.23 Comparison of mean OSA scores for each category of sound sleep between AC use and non-use days

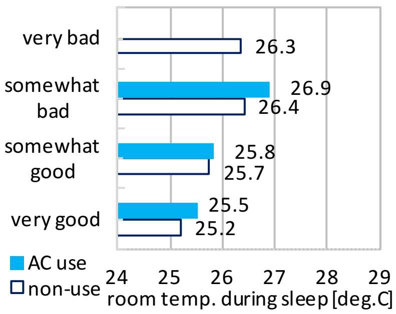


Fig.24 Comparison of mean room temperatures for each category of sound sleep between AC use and non-use days

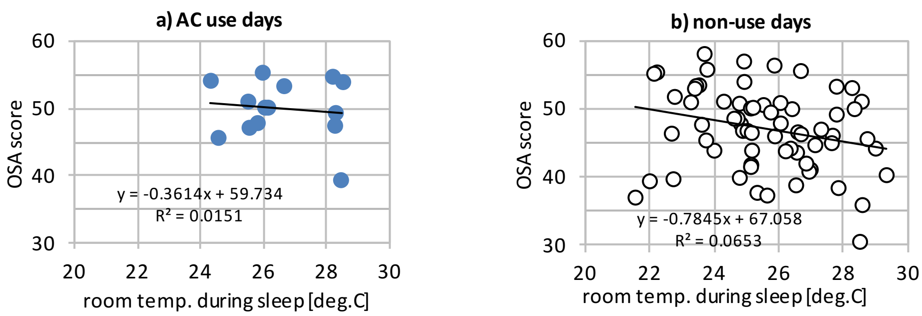


Fig.25 Relations of room temperature during sleep and OSA score for AC use and non-use days

Fig. 24 shows the mean bedroom temperature during sleep for each category of degree of sound sleep for use and non-use days. Degree of sound sleep was unrelated to bedroom temperature for AC use days (p=.68). However, the mean bedroom temperature was 25.2 for 'sleep soundly', 25.7 for 'sleep somewhat soundly', 26.4 for 'not sleep somewhat soundly', and 26.3 for 'not sleep soundly' for non-use days (p=.064). The relation was not significant, but the degree of sound sleep tended to be low when the bedroom temperature was high in non-use days. As Fig. 25 shows, the coefficient of correlation between the mean bedroom temperature during sleep and OSA score was -0.26 for non-use days, where little correlation was found between room temperature and the OSA score for use days. These figures show that room temperatures did not relate to the degree of sound sleep or sleep quality for use days.

4 Discussion

4.1 Comparison among periods

Mean room temperatures were 27.2°C for mid-summer and 25.4°C for late summer. However, 'cool' was most frequent for mid-summer; it felt cooler. The relative frequencies of 'comfortable' responses were around 60% for mid-summer and late summer. However, mid-summer was more uncomfortable because about 20% felt 'uncomfortable' for mid-summer. 'acceptable' responses were about 60% for mid-summer and more than 90% for late summer. It can be said that it was cooler for mid-summer than for late summer, but mid-summer was less comfortable and less acceptable.

The ratios of 'comfortable' and 'acceptable' were not different by thermal sensation for mid-summer. Thermal comfort and acceptability did not depend on thermal sensations in mid-summer.

Regarding the degree of sound sleep 'somewhat good' was reported by 40–50% of respondents for both periods, but the frequency of 'slightly bad' was 30% for mid-summer. The mean OSA score was 45.5 for mid-summer and 48.1 for late summer. Mean OSA scores for respondents were lower for mid-summer than for late summer. It can be said that sleep quality was lower for mid-summer than for late summer. Scores of Factor III (dreaming) and Factor II (maintenance) were similar, but scores of Factor I (waking up), Factor IV (fatigue), and Factor V (duration) were lower for mid-summer. The difference of the OSA scores presumably resulted from differences of Factor I, IV, and V scores.

The OSA scores were higher for 'comfortable' for mid-summer. Thermal comfort was related to OSA score for mid-summer, although OSA scores were not different by thermal comfort for late summer. Thermal acceptability was related to OSA score for mid-summer because the difference in OSA score for 'acceptable' and 'slightly unacceptable' was larger for mid-summer than for late summer. Thermal comfort and acceptability were related to sleep quality for mid-summer.

Room temperature was related to the OSA score or degree of sound sleep for mid-summer, but not related for late summer. The OSA score was related to the degree of sound sleep for both mid-summer and late summer. Relations between OSA scores and thermal sensation were weak for both mid-summer and late summer.

4.2 Comparison between Air-conditioner use days and non-use days

The room temperature during sleep was 25.7°C for both AC use days and non-use days, although outdoor temperatures during sleep were 23.4°C for AC use days and 21.4°C for non-use days. 'slightly hot' was 23.4% and most frequent on use days and 'neutral' was

38.3% and most frequent. Use days were significantly hotter than non-use days. No difference was found in thermal comfort between use and non-use days. ‘acceptable’ was 53.3% on use days and 75.6% on non-use days. Use days were more thermally acceptable than non-use days were. It can be said that thermal comfort was not different between use and non-use days, but non-use days were cooler and more acceptable.

The ratio of ‘comfortable’ was not different by thermal sensation on use days. On the other hand, the ratio of ‘slightly cool’ was the highest and related more to thermal sensation on non-use days than on use days. The ratio of ‘acceptable’ on non-use days was about two times higher than on use days. It was hotter but more comfortable. The range of acceptability was wider on non-use days.

Regarding the degree of sound sleep, ‘very good’ was 50% on use days and 32.6% on non-use days. Mean OSA scores were 48.3 on use days and 46.0 on non-use days. The score on use days was slightly higher than that on non-use days. The difference of mean scores among respondents was not significant. Little difference was found between use and non-use days for late summer, although the mean score on use days was higher than on non-use days for mid-summer. Little difference was found in OSA factor scores between use and non-use days. It can be said that the difference of sleep quality was not so great between use and non-use days.

The OSA score differed by thermal sensation and comfort on use days, although little difference was found in the OSA score by different thermal sensation, comfort and acceptability. The relation between OSA score and thermal sensation, comfort and acceptability was weaker on use days than on non-use days.

OSA score was related to degree of sound sleep tightly on non-use days, but slightly related on use days. Room temperature was not related to OSA scores on use-days, although OSA was lower for higher room temperature on non-use days.

4.3 Air-Conditioner Use Effects on Sleep Quality

AC use days were 15 in mid-summer; non-use days were 27. In late summer, the AC use days were 4; non-use days were 48.

It was cooler in mid-summer than in late summer in spite of higher room temperatures in mid-summer. Air-conditioner use might reduce temperatures, but rooms were slightly cooler on AC non-use days than on use days. AC use did not cause the coolness. It was rather slightly hotter on use days than on non-use days, although room temperatures were almost identical on use days and non-use days. The wide acceptable range on non-use days was rather notable. It was slightly hot, but comfortable on non-use days.

Sleep quality was worse for mid-summer than for late summer, and worse on non-use days than on use days. However, the difference between use days and non-use days was smaller than that between mid-summer and late summer. Not AC use, but higher room temperatures in mid-summer caused lower sleep quality.

The OSA score was related to the degree of sound sleep both for mid-summer and late summer. However, the relation was weak on use days. The relation between the OSA score and thermal acceptability was weak both for mid-summer and for late summer, but the OSA score was related to acceptability on use days. Presumably, AC use caused the weak relation between the OSA score and the degree of sleep quality. Furthermore, AC use caused a strong relation between the OSA score and thermal acceptability.

5 Conclusions

A survey of the thermal environment of bedrooms, sleep quality, and thermal sensations were conducted in summer during seven successive days for three periods for 11 bedrooms. The AC use days and non-use days were compared relative to thermal environment, sleep quality, and thermal sensations considering differences of periods. Number of AC use and non-use days during sleep in early, middle, and late summer were, respectively, 11,15, and 4, and 54, 27, and 48.

1) Outside temperatures were higher on AC use days but room temperatures during sleep were kept almost identical (25.7°C) for AC use days and non-use days.
2) Sleep quality as evaluated by the OSA score was higher on AC use days. However, it was hotter and less acceptable on AC use days than on non-use days, although thermal comfort was not reported as different between AC use and non-use days.
3) On AC use days, the relation between thermal comfort and thermal sensation was weaker. Thermally acceptable ranges were narrower on AC use days.
4) Differences in sleep quality were smaller between AC use days and non-use days than between mid-summer and late summer. Lower sleep quality in mid-summer was caused not by AC, but by higher room temperatures.
5) The OSA score was related to the degree of sound sleep both for mid-summer and late summer. However, the relation was weak on AC use days. Relations between OSA score and thermal acceptability were weak both for mid-summer and late summer, but the OSA score was related to the acceptability on AC use days.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
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Occupant feedback in air conditioned and mixed-mode office buildings in India

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Abstract

India has a largely cooling dominated climate where space cooling accounts for approximately 31% of the energy consumed by commercial buildings. Deeper market penetration of air conditioning systems, higher income levels driving higher comfort expectations, and growing floor space have led to a steep rise in associated carbon emissions. India needs to adopt an energy efficient regime in which governments, businesses and individuals transform the way buildings are designed, built and operated, while still maintaining high levels of occupant satisfaction.

Two diverse approaches are practiced in India to achieve energy efficiency. The first relies on passive design strategies based on traditional wisdom. The second relies on high-performance HVAC building conditioning systems. Most Indian climate zones offer opportunities to design and operate buildings as naturally ventilated or mixed-mode. But such design practices need to be promoted on the basis of scientific studies related to occupant behavior, comfort and associated energy consumption.

This paper evaluates occupant satisfaction in a mix of consciously-designed air conditioned and mixed-mode buildings based on online surveys, and limited physical measurements. The survey includes questions about thermal comfort, indoor air quality, air movement, acoustics and adaptive controls such as windows and fans. The paper offers an understanding about the perception and behavior of occupants in mixed-mode buildings in various climate zones of India to help identify strategies to promote efficient mixed-mode buildings in both India and other regions.

Keywords: Occupant satisfaction, Post-occupancy evaluation, Mixed-mode buildings, Thermal comfort, Indian offices

1 Introduction

India boasts a rich tradition of naturally ventilated buildings with context-specific passive design strategies. Until 10-15 years back, naturally ventilated buildings were the norm for most building types. With better penetration of air conditioning systems in the market, higher incomes resulting in higher comfort expectations and the rapid increase in built-up floor space, air conditioned buildings increased in numbers. Today, many people perceive air conditioning as a requirement, rather than a luxury. Most of the new buildings have air conditioning and many of the old ones are being retrofitted with conditioning systems. This has resulted in a wide array of mixed mode buildings that operate in naturally ventilated mode when the outdoor conditions are favourable and switch over to air conditioning during the extreme conditions. They usually have operable windows and ceiling fans.

Since India has a predominantly warm to hot weather, air conditioning generally refers to cooling and mechanical ventilation. During the mild winter season, the cooling is turned off and the windows are either inoperable or kept shut. Buildings with inoperable windows generally have better air-tightness. That is why new air conditioned buildings with sealed envelopes tend to be more energy-efficient than old buildings that are retrofitted, since the latter are originally designed to operate in naturally ventilated mode.

In India, electricity demand already exceeds supply. The largest and most significant end use of electricity in commercial buildings is air conditioning. The rapid growth in new floor space combined with an increase in thermal comfort expectations and aspirations, will lead to a surge in demand for air conditioning. If permitted unchecked, the growth in building air conditioning will add immense pressure on electricity infrastructure and exacerbate the already extreme peak-demand problem in the country.

In order to prevent an increase in energy use associated with space cooling, the deployment of low energy adaptive strategies in building operation is critical. To this end, an India specific adaptive thermal comfort model (IMAC) was recently published based on extensive field study of Indian offices in five climate zones and three seasons (Manu, Shukla, Rawal, Thomas, & de Dear, 2016). The results from this study prove that the neutralities predicted by the IMAC models for naturally ventilated buildings followed the outdoor temperatures more closely than the existing international adaptive models for free-running buildings. However, the most significant contribution of the IMAC study was to propose a single, valid and robust adaptive model for mixed-mode buildings where the neutral temperatures ride (not surprisingly) lower than the ASHRAE and EN15251 free running models. For mixed-mode buildings, the IMAC study also shows evidence of neutral temperatures of up to 28.4˚C when outdoor conditions ride at 38-40˚C (Manu et al., 2016).

In addition to implementing an India-specific adaptive comfort model, it is important to understand the performance and operation of mixed-mode buildings in more detail from an occupant's perspective since a majority of the building stock is increasingly becoming mixed-mode. Occupant surveys are important tools to measure the performance of buildings.

A paper analysing over 34,000 survey responses to air quality and thermal comfort questions in 215 buildings across US, Canada and Finland (C Huizenga, Abbaszadeh, Zagreus, & Arens, 2006), clearly indicated that only 11% of buildings had 80% or more satisfied occupants. Only 26% of buildings met the (then current) ASHRAE Standard 62.1-2004 standards for acceptable air quality.

In a study of web-based survey responses from 351 US office buildings, the researchers concluded that satisfaction with the amount of space, noise level and visual privacy were the most important parameters for overall workspace satisfaction (Frontczak et al., 2012). Another study based on the same database used Kano's model of satisfaction and identified 'temperature' and 'noise level' as basic IEQ factors (Kim & de Dear, 2011). This means that a building's poor performance in terms of thermal and acoustic performance has a significant negative impact on overall satisfaction levels. Air quality and lighting were assigned to the group of proportional factors exerting negative or positive impacts of comparable intensity on overall occupant satisfaction.

In another study that analysed over 43,000 individual responses to the CBE web-based survey, mixed-mode buildings were found to be performing much better than the overall building stock with regard to thermal comfort and air quality (Brager & Baker, 2009). A post-occupancy evaluation of a building in Australia highlighted the importance of increased fresh air, daylight, glare control, access to views, noise management, low VOC finishes towards improving user experience of indoor environmental quality (Thomas, 2009). A survey on workplace occupant satisfaction in 16 office buildings in Germany revealed that the occupants' control of the indoor climate, and the perceived effect of those interventions, strongly influenced their satisfaction with thermal indoor conditions (Wagner, Gossauer, Moosmann, Gropp, & Leonhart, 2007).

The design and operation of HVAC systems aims for an optimum 'steady-state' temperature setting based on Fanger's PMV-PPD model (Fanger, 1970) to provide acceptable thermal comfort (Drake, de Dear, Alessi, & Deuble, 2010). The studies cited here indicate that this 'static' approach to thermal comfort in air-conditioned buildings may be detrimental to occupant satisfaction and that a 'person-centred' approach to provide variability across time and space is important (Brager & de Dear, 1998). Therefore, it is important to design mixed-mode buildings to operate effectively in both naturally ventilated and air conditioned modes without compromising occupant thermal comfort and indoor air quality. It is also important to operate these buildings to take advantage of their 'dual' character in an optimal way. In order to do this, one must understand the performance of a range of MM buildings in terms of occupant satisfaction and gain an insight into how occupants use these buildings.

2 Methods

2.1 CBE survey

The CBE web-based survey tool (Charlie Huizenga, Laeser, & Arens, 2002) is an efficient way of remotely getting occupant feedback on indoor environmental quality (IEQ) and various other aspects of the building. The survey consists of a core module with eight IEQ categories and additional modules such as window and fan usage. The phrasing of the questions and options were tailored to suit the local culture and parlance to use the surveys effectively in Indian offices. The survey asked occupants to rate their satisfaction with these different aspects on a 7-point scale that ranged from -3 (Very dissatisfied) to 0 (Neutral) to +3 (Very satisfied). The tool also has a unique feature that is helpful for diagnostic purposes; when an occupant votes to be dissatisfied in any category, the tool automatically follows up with branching questions that ask about the reasons for dissatisfaction. Details about the building features such as floor area, number of occupants, LEED compliance and type of HVAC system, envelope and glazing are filled out by the building manager separately. More details about the CBE survey tool can be found in (Zagreus, Huizenga, Arens, & Lehrer, 2004). A list of the most relevant survey questions for this study is illustrated in Table 1.

Table 1 Important categories from the CBE survey analysed in this paper

Category	*Questions asked*
Thermal comfort	Satisfaction with temperature, ability to control temperature, thermal comfort during summer
Indoor air quality	Satisfaction with air quality (i.e. stuffy/stale, cleanliness, odors)
Air movement	Satisfaction with amount of air movement, ability to control amount of air movement
Window usage	Satisfaction with operable windows (summer and winter and monsoon) Importance of having an operable window to the user

Category	Questions asked
	Times adjusted (daily, weekly, monthly) Time of adjustment Reasons to ‘open’ or ‘close’ a window
Fan usage	Satisfaction with ceiling fans, Times adjusted during summer (daily, weekly, monthly), Time of adjustment, Reasons to turn ‘on’ or ‘off ’ a fan

2.2 Building selection

The survey was administered in 9 buildings across three climate zones of India – hot and dry (H&D), warm and humid (W&H) and composite (CT). Table 1 lists the buildings with their locations and availability of operable ceiling fans and windows. The buildings were classified into three categories:

1. Spatial mixed-mode (SMM) where certain zones of the building are air conditioned and others operate in natural ventilation mode across the year. Such buildings have provisions for operable windows and ceilings fans.
2. Temporal mixed-mode (TMM) where the entire building is air conditioned and switched over between AC and NV modes based on the outdoor conditions. Such buildings have provisions for operable windows and ceilings fans.
3. Air conditioned mode (AC) where the buildings are air conditioned for most part of the year. When outdoor conditions are sufficiently favourable for the MAC to be turned off, mechanical ventilation may be used). There is no provision for natural ventilation (or operable windows) in these buildings.

Table 2 Details of the case study buildings

Building Type	*Building code*	*City*	*Climate*	*Operable windows*	*Ceiling fans*	*Survey period*	*No. of responses*
Spatial mixed-mode	SMM-1	Ahmedabad	H&D	Y	Y	Mar, 2014	48
	SMM-2	Delhi	CT	Y	N	Mar-May, 2015	16
Temporal mixed-mode	TMM-1	Ahmedabad	H&D	Y	N	Mar, 2014	31
	TMM-2	Ahmedabad	H&D	Y	Y	Mar, 2014	27
	TMM-3	Ahmedabad	H&D	Y	Y	Mar-Apr, 2014	40
	TMM-4	Delhi	CT	Y	N	May-May, 2015	13
Air Conditioned	AC-1	Baroda	H&D	N	N	Apr-May, 2015	131
	AC-2	Pune	W&H	N	N	Sep-Oct, 2015	54
	AC-3	Pune	W&H	N	N	Sep-Oct, 2015	45

SMM-1 is the office of an architecture firm. It relies on passive design strategies to maintain thermal comfort inside. It was designed to primarily operate in fully naturally ventilated mode, but was later retrofitted with air conditioners, where occupants turn off the air conditioner and open the windows when the outdoor conditions are suitable for natural ventilation. The building has a high vaulted roof structure over the studios that facilities better ventilation. Both the operable windows and pedestal fans are operated by the occupants. It has low openings on the south to reduce direct radiation. At other places, glass brick is sometimes used to provide diffused daylight. The building mass is compact, and the building is partially underground, further reducing the impact of direct radiation. Glazing is approximately 25% of the wall area. The vaulted roofs have an air cavity filled with ceramic fuses (9" long conical pieces mixed with concrete) to provide thermal insulation, and the entire roof is covered with high SRI tiles. The immediate surrounding is heavily landscaped with dense trees and water bodies, generating its own microclimate. The total floor area is spread across four levels, including the mezzanine level.

SMM-2 is located on the outskirts of Delhi in the industrial sector of Greater Noida. The building comprises of several conferences rooms, open plan work spaces and personal cabins. It houses a laboratory for material testing of the products manufactured in the premises. The building has 26-50% of wall area covered with high performance glass and self-operational windows mostly facing north to utilise natural diffused light. Occupancy sensors and efficient indoor lighting balances its lighting requirements. It has individual air conditioning units.

TMM-1 is a building design and consulting firm located on the seventh floor of an 11-story building that is LEED Platinum rated. Other than installing double-glazed windows, TMM-1 did not attempt to optimize the envelope, but instead reduced their energy consumption by addressing the active systems. They have a very efficient HVAC system, demand controlled ventilation, energy-efficient lighting and lighting controls, and occupancy sensors. TMM-1 has operable windows, but they are not often used by the occupants as the air conditioning is used for most part the year. The envelope is heavily glazed (51-75% of the wall area). In spite of the high WWR and lighting controls, the building seems to rely more on artificial lighting than daylighting. The materials used in TMM-1 conform to LEED 2.1 specifications such as low VOC paints, coatings, adhesive, sealants and fabrics, green label carpets and cleaning materials. It has an open-plan layout with individual or shared cabins on the east and west periphery of the building.

TMM-2 is an office of a computer software developer firm in a heavily urbanized area, located on eighth floor of an 11-story building (similar to TMM-1 being on an intermediary floor of a taller building). It is representative of the most energy intensive building with a business-as-usual envelope and air conditioning system and operation. The office has a variable air volume (VAV) type central air conditioning unit that is on throughout the year. The walls are heavily glazed, with the WWR almost identical to that in TMM-1 (51-75% of the wall area). The windows are operable and have a reflective glazing. The building also has interior blinds and exterior shading.

TMM-3 is an office of a building construction and MEP consulting firm in a less dense and more vegetated area, located on ground and first floor of an 8-story building. It has a variable refrigerant flow (VRF) type central air conditioning unit, operable windows and ceiling fans. The glazing area is in between the other examples (30-50% of the wall area). The windows have a clear glass, compared to the reflective glazing of TMM-2. While the air-conditioning in TMM-2 operates almost continuously throughout the year, in TMM-3 occupants have a choice to operate it when indoor becomes uncomfortable.

TMM-4 is a LEED Platinum rated building located in the same complex as SMM-2. The building which sits like a cube consisting of three floors; the top floor is surrounded by a balcony. The roof has solar panels with transparent underneath to allow daylight penetration inside the space along with occupancy sensors for lighting controls. 33% of wall area consists of high performance glass. Each window unit has motorized louvers sandwiched between two glazing panes. Some of these units are operable but are rarely used for natural ventilation. The facade is made of rigid Polyisocyanurate (PIR) foam to insulate against heat and moisture. The building uses primary and secondary chilled water pumping systems, active chilled beams, primary AHU, cooling towers with variable frequency drive (VFD).

AC-1 is a single 9 storey block of a building complex on the outskirts of Baroda and a LEED Gold rated building. Each floor has large open plan office spaces with over 100 people working on each floor. It uses a VAV air distribution system controlled with a BMS operating system running almost throughout the year. 40% of wall surface has high performance glazing complimented by internal blinds.

AC-2 is part of a building complex spread over 10.5 acres. It is a LEED Platinum and a GRIHA 5-star rated building. With 92% of its energy produced on site, it is a ‘near’ zero-energy building. 76-100% of its wall surface has high performance glazing with external louvers. It doesn’t have the provision of operable windows or ceiling fans. VRF and radiant panels are used for cooling. AC-3 in located in the same complex as AC-2 and has the same building characteristics.

3 Results and analysis

Figure 1 shows the percentile ranking compared to the overall CBE dataset, and Figure 2 shows the mean percentage satisfied per survey category in each building (occupants voting +1 and above were counted as satisfied). In both, green colors designate better performance and yellow designates low performance.

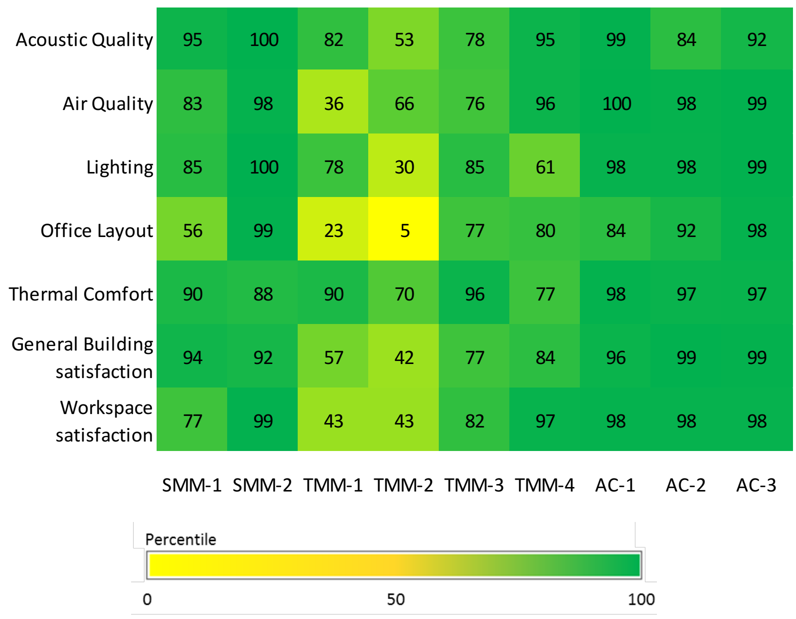


Figure 1 Percentile ranking of case study buildings compared to CBE database

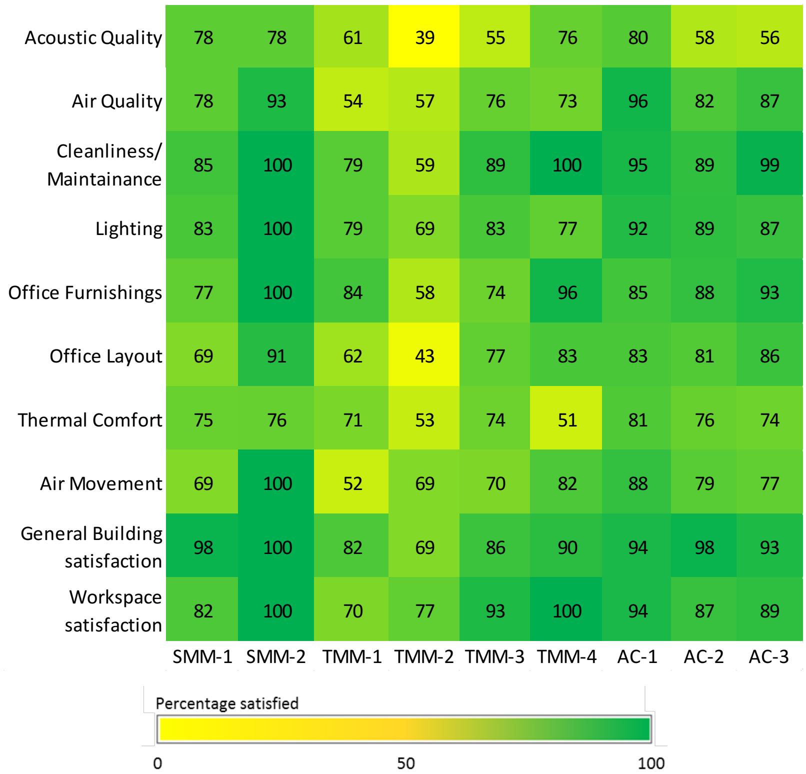


Figure 2 Percentage of occupants satisfied in each case study building

Starting first with the comparison to the CBE database (Figure 1), AC-3 and SMM-2 stand out as the best performers of the nine buildings followed closely by AC-2. TMM-1 and TMM-2 are the lowest performers of the nine buildings across most categories but TMM-1 ranked relatively well in thermal comfort, acoustic quality and lighting. These rankings, however, may not reflect the performance of these buildings in the context that they operate since they are being compared with the CBE database comprising buildings primarily from the US. The cultural, social and economic contexts are different and are likely to affect occupant expectations and how they use buildings. For the rest of this paper, comparisons are made between the Indian case study buildings.

In terms of occupant satisfaction (Figure 2), SMM-2 ranks the highest, with more than 90% satisfaction in all categories except thermal comfort (76% satisfaction) and acoustics (78%). These are also the two categories which typically receive the lowest levels of satisfaction in the overall CBE database (this is why buildings might have low levels of satisfaction in Figure 2, but still rank high in the CBE database in Figure 1).

The three AC buildings had high levels of satisfaction in all categories except acoustic quality where AC-2 and AC-3 had less than 60% of the occupants satisfied.

Looking now at the temporal mixed-mode buildings, thermal comfort satisfaction ranged from 51-74% (which was associated with 70-96th percentile in the CBE database, again a result of thermal issues being a pervasive problem in buildings). In TMM-1, of the IEQ categories, occupants were most satisfied with lighting, but the highest satisfaction ratings had nothing to do with IEQ (i.e., office furnishings, general building satisfaction, and cleanliness/maintenance). The satisfaction percentage in TMM-1 was lowest with acoustics, air quality, office layout and air movement. Lack of sound privacy was the main reason for acoustic dissatisfaction while lack of visual privacy was the basis for dissatisfaction with office layout. The open plan layout may have contributed to this dissatisfaction. A few occupants from TMM-1 opined that the air was stuffy/stale, not clean and had a bad odor; the source for bad odor was mainly from the toilets. However, the complaints were limited to one particular zone. With regards to air movement satisfaction, occupants were mainly dissatisfied with amount of air movement (saying they preferred to have more air movement) and the ability to control the amount of air movement. This is not surprising given that this building does not have fans, and that occupants rarely use the operable windows.

TMM-2 consistently had the lowest levels of satisfaction of all the buildings studied here, with less than 70% satisfied occupants in all the categories except for workspace satisfaction, where it was 77%. This higher satisfaction may, in part, be due to this office having relatively low occupant density (10 sq.m. per person, compared to a more typical 6.5 sq.m. per person for India). Amongst the dissatisfied categories, acoustic quality, office layout and thermal comfort received the lowest satisfaction ratings (39%, 43%, and 53%, respectively). Lack of sound and visual privacy were the main reasons for dissatisfaction with acoustics and office layout respectively. Overall thermal comfort satisfaction was very low in TMM-2 compared to the other buildings. Those who were dissatisfied cited multiple reasons of discomfort such as incoming sun, air movement being too low and the heating/cooling system not responding quickly to the thermostat.

In TMM-3, acoustic quality was the source of dissatisfaction for 45% of the occupants. In TMM-4, 70% or more occupants were satisfied in all categories, except in thermal comfort, where thermal satisfaction was lowest of all the buildings, at only 51%.

3.1 Thermal comfort

Occupants were asked about their opinion on thermal comfort in the building through multiple questions asking about satisfaction with temperature, ability to control temperature, and thermal comfort specifically during the summer. For each question, they answered on a discrete 7-point scale from +3 (very satisfied) to -3 (very dissatisfied). The responses were pooled into three groups of 'satisfied' (+1 to +3), 'dissatisfied' (-1 to -3) and 'neutral' (0). Figure 3 plots the percentage of occupants in each of these groups, for the three thermal comfort questions.

ASHRAE Standard 55-2010 (ASHRAE, 2010) suggests that an acceptable thermal environment is one in which no more than 20% of the occupants are dissatisfied with the temperature. Although one can (and probably should) argue that we should strive for even high levels of acceptability, this is how the standard is currently framed. Using this number, Figure 3a suggests that 7 of the 9 buildings were below this threshold (redline in the graphs), but SMM-2 just barely met it with 20% of the occupants dissatisfied with the temperature in their workspace, and TMM-3 did not meet the threshold, with 22% dissatisfied.

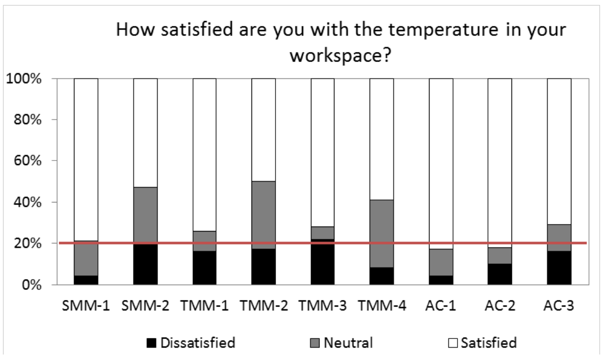
The occupants who express dissatisfaction on the survey are given follow-up questions about the reasons why. In TMM-3, which is located in the hot and dry climate zone, 38% of the dissatisfied occupants reported feeling 'often too hot' and 63% were 'often too cold' in summer, suggesting that the air conditioning was over-cooling more than necessary. This is surprising since in TMM-3 occupants have a choice to operate the air conditioning or not when the indoor becomes uncomfortable. In TMM-3 in winter, 13% were 'often too hot' and 38% were 'often too cold'. 25% cited low air movement as the source of thermal discomfort. 25% felt their workplace was located in a zone that was colder than other areas in the building. 50% of the occupants reported the thermostat being adjusted by other people as the source of discomfort, which could be strongly related to the overcooling problem in summer.

In SMM-2 60% of the dissatisfied occupants reported feeling often too cold and 33% were often too hot in summer. 40% cited high humidity or dampness as the source of thermal discomfort.

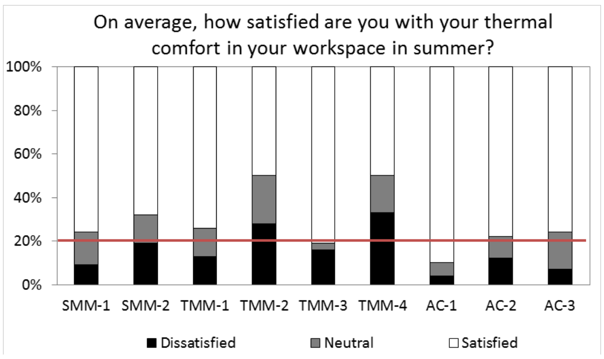
16% of the occupants reported dissatisfaction with the temperature in their workspace in TMM-1, TMM-2 and AC-3. These occupants tended to feel too warm in summer and too cold in winter, suggesting that conditioning wasn't adequate. The main reason for discomfort were low air movement and hot/cold pockets. In TMM-1, physical measurements showed that the temperature variation across the zones was more than 16˚C, which is significant. In TMM-2 and AC-3, occupants also complained about the thermostat being controlled by others as a source of discomfort.

In TMM-4, 33% of the occupants expressed dissatisfaction with the thermal comfort in their workspace in summer (Figure 3b). The primary reasons seem to be poor air distribution since 36% of the occupants reported feeling often too hot and 36% reported feeling often too cold in summer. Dissatisfaction was also high in TMM-2 (28%), SMM-2 (19%) and TMM-3 (16%). These responses align with the dissatisfaction percentages in Figure 3a.

When asked to report their satisfaction with their ability to control temperature in their workspace (Figure 3c), 38% of the respondents in TMM-2 and 25% in TMM-1, TMM-4 expressed dissatisfaction. At least 10% of the occupants across all case studies were dissatisfied with the degree of control they had over the temperature. This number was higher in mixed-mode buildings compared to air conditioned buildings.



(a)



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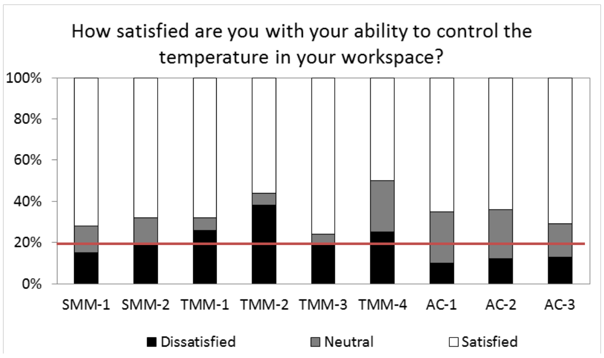

(c)

Figure 3 Occupant satisfaction with thermal comfort

3.2 Air quality

In response to the question related to satisfaction with the air quality (Figure 4), 36% of the occupants in TMM-1 expressed dissatisfaction with the air quality at their workspace (Figure 4a) while 44% were dissatisfied with their ability to control the air quality (Figure 4b). 86% felt that the air being stuffy/stale was big problem and 83% reported air not being clean as a problem. 67% of the occupants felt bad odors from toilets, cafeteria, garbage bins and carpets were a major problem.

20% of the occupants in TMM-2 reported dissatisfaction with the air quality in their workspace (Figure 4a). The reasons for this dissatisfaction are not clear since the follow-up questions were not answered but one of the comments reported air conditioners working at a high temperature setpoint and recirculation of indoor air as a source of odor.

13% of the respondents in TMM-3 reported dissatisfaction with air quality (Figure 4a) as well as their ability to control it in their workspace (Figure 4b). The reasons for dissatisfaction have not been stated but may be related to dissatisfaction with thermal comfort due to low air movement as reported in section 3.1. Most of the occupants in air conditioned buildings expressed satisfaction with the air quality. However, at least 7% of the occupants were dissatisfied with their ability to control air quality in their workspace across all nine buildings.

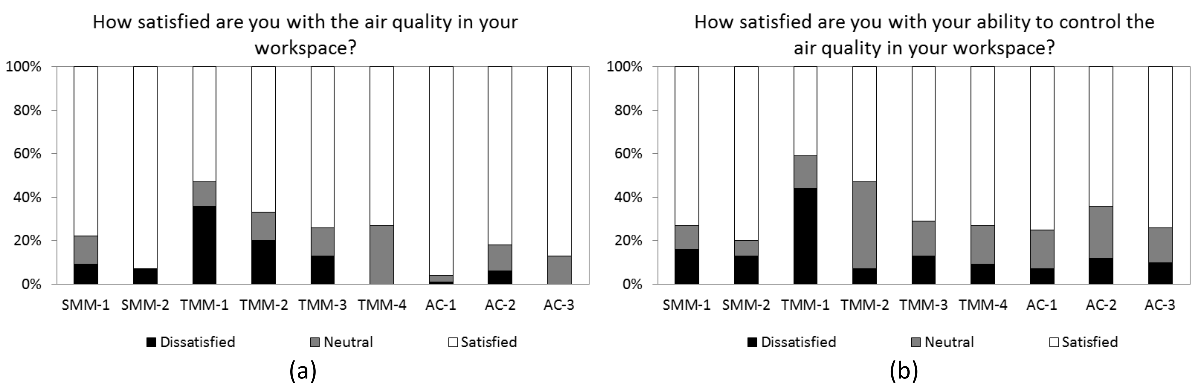

Figure 4 Occupant satisfaction with air quality

3.3 Air movement

Occupants in SMM-2 reported 100% satisfaction with the amount of air movement in their workspace (Figure 5a). This may be explained on the basis of the responses to the window usage questions where a majority of the occupants reported satisfaction with the operable windows and their ability to open or close them (section 3.5).

Dissatisfaction was highest (30%) in TMM-1 where 40% of the occupants also reported dissatisfaction with their ability to control air movement (Figure 5b). Occupants in this building were also dissatisfied with the ceiling fans and windows which may have contributed to their dissatisfaction with the air movement. More than 20% of the occupants were dissatisfied with the amount of air movement and their ability to control it in their workspace in SMM-1.

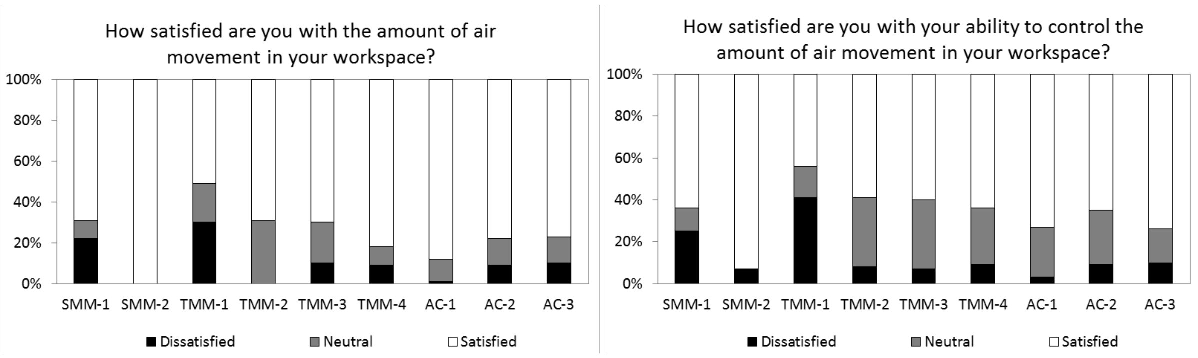

Figure 5 Occupant satisfaction with air movement

3.4 Use of windows and fans

Ceiling fans and windows are the most widely used and cost-effective way of increasing air movement and are widely used as an adaptive measure to alleviate thermal discomfort when the indoor temperatures ride high (Manu et al., 2014). Operable windows were available as a provision in all the mixed-mode buildings. However, in most cases the occupants did not operate the windows for multiple reasons that have been highlighted below. As such, one might characterize them as mixed-mode in design, but not in practice.

TMM-4 stands out as one of the mixed-mode buildings where the operable windows are being used, yet the building got the lowest scores in terms of thermal comfort satisfaction. More than 90% of the occupants reported satisfaction with the operable windows in their workplace in summer (Figure 6a). All the occupants found it easy to operate the windows (Figure 6c) and found them effective in helping them to stay comfortable in summer (Figure 6b).

TMM-1, which is the LEED Platinum building where the focus was on efficient active systems, performed poorly with 48% of the occupants dissatisfied with the operable windows in summer. 44% found it difficult to open or close the windows and 33% said that opening the windows was ineffective in maintaining comfort in summer. The difficulty in operating the windows may have to do with accessibility – 95% of the occupants shared control of the windows with others and 64% never adjusted their windows in summer. Windows were either inaccessible (25%) or were kept closed due to noise, glare and odors (33%). 30% of the occupants reported that the management discouraged the use of operable windows.

In SMM-1, 16% of the occupants reported dissatisfaction with the operable windows and found the windows ineffective in maintaining comfort in summer. 13% found it difficult to open or close the windows in their workspace. 15% of the occupants did not adjust the windows because of complaints from co-workers and 31% said the windows were inaccessible. This was surprising since SMM-1 is the building that paid particular attention to using passive, architectural strategies to achieve low energy use. 9% of the occupants in SMM-1 shared the control of the windows with others in their workspace.

The most frequently cited reasons for opening a window in all the six buildings were, 'to feel cooler', 'to increase air movement' and 'to let in fresh air'. Interestingly, the prevailing reasons to close a window were 'to feel cooler', 'outdoor temperature getting warmer than indoors' (both of these related to having air conditioning on during a hot day), and 'to reduce outdoor noise.' These reasons show that window interaction is driven predominantly by outdoor temperature, air quality and noise levels.

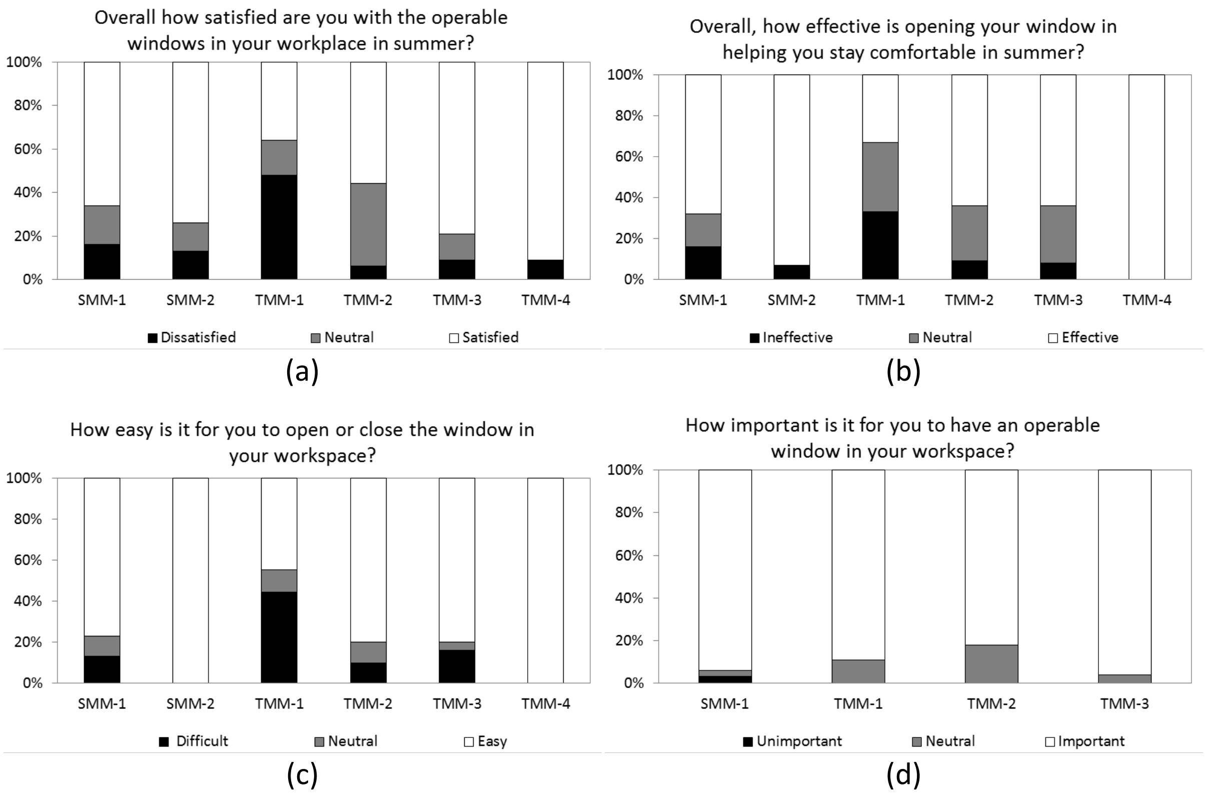

Figure 6 Occupant satisfaction with the use of windows

More than 70% of the occupants reported satisfaction with the ceiling fans in their workplace in the three buildings that had them – SMM-1, TMM-2, TMM-3 (Figure 7). The most cited reasons to turn on a fan in these three buildings were 'to feel cooler' and to 'increase air movement' while the reason to turn off a fan was to 'reduce air movement' and because 'a co-worker requested it.' These are all as one might expect, and the majority of the occupants in these buildings said they were very sure of having the desired effect when they interacted with fans. In TMM-2, 73% of the occupants adjusted the fans daily in summer.

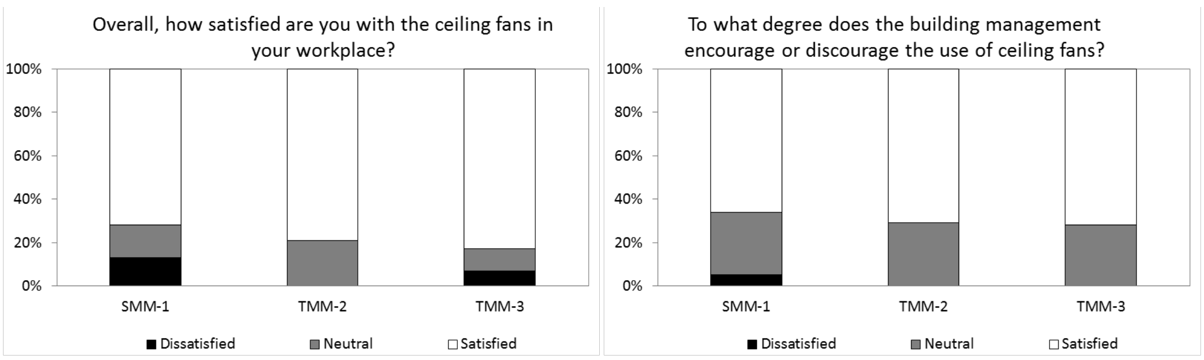

Figure 7 Occupant satisfaction with the use of fans

4 Discussion

The surveys revealed SMM-2 as the only building that had more than 70% satisfaction rate across all categories. All AC buildings scored well in all categories except in the case of AC-2 and AC-3 where a satisfaction percentage of less than 70% was reported in acoustic quality. Overall, occupants seemed to be most dissatisfied with acoustic quality, air movement and office layout.

Lack of adequate air movement was repeatedly cited as a source of thermal discomfort. Occupants were also dissatisfied with the ability to control air movement and opined that they needed more of it. Poor air movement may have resulted in hot/cold air pockets in the building – occupants also reported feeling often too hot or cold in summer.

The most cited reasons to turn on a fan were 'to feel cooler' and to 'increase air movement'. Moreover, when asked about the confidence of having the desired effect on turning on a fan, the majority of the occupants voted that they were confident about this effect. This shows that occupants perceive fans as fast-acting and they rely on it for achieving comfort in a short span of time. However, even in buildings that had ceiling fans, occupants refrained from using them because of complaints from co-workers. It is important to provide ceiling fans to ensure occupants have more control over the air movement but it is equally important to design the space plan and controls to ensure occupants are able to use them.

Windows were opened for fresh air, to feel cooler and increase air movement, and closed when the outdoor got warmer than indoors, and to reduce outdoor noise. The key take-away from this result is that the occupants preferred to have air movement and when there was a combination of windows and fans in use, they worked well in providing it. But, similar to the barriers in using ceiling fans, in most mixed-mode buildings operable windows were provided but since the management did not encourage their use, occupants kept them close. They remain closed for long periods of time without regular maintenance making it difficult to operate them in the rare cases where occupants tried to open them. Noise, glare and odor were also cited as reasons for keeping the windows closed. More interesting, complaints from other occupants also affected window operation indicating conflicts between occupants' preferences.

A result worth noting here is that, for the case studies in this paper the air conditioned buildings provided higher levels of thermal comfort than in the mixed-mode buildings (the only exception was SMM-2). This goes against what might have been expected based on adaptive comfort theory, which suggests that having access to operable windows might produce higher levels of control and satisfaction. This may be explained by two observations – first is that with an exception of SMM-2, all other mixed-mode buildings were not being actively operated in mixed-mode. SMM-1 was designed as a passive building which was later retrofitted with air conditioning. TMM-1 and TMM-2 are located on individual floors of buildings that are typical office buildings with high window-to-wall ratio, designed to be air conditioned throughout the year. On the other hand, all air conditioned case studies are high performance, LEED-rated buildings with optimized envelopes and efficient air conditioning systems. They are better than the 'business-as-usual' air conditioned office buildings in India. TMM-4 is also a high performance, zero- emissions building. It is difficult to explain the low satisfaction in the thermal comfort category since the occupants did not respond to the follow-up questions but lack of controls was cited as a source of discomfort.

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WORKSHOP 1.1

Thermal Comfort with Radiant & Convective Systems

Invited Chairs: Risto Kosonen and Caroline Karmann

WS1.1: Thermal Comfort with Radiant and Convective Systems.
Chairs: Risto Kosonen and Caroline Karmann

Radiant systems are often considered to provide better thermal comfort than air systems due to their active control of the mean radiant temperature. Yet beyond this theoretical explanation, what do we really know about thermal comfort for both systems? This workshop will begin with the results of a critical literature review on thermal comfort for radiant compared to all-air systems. In rooms with high heat loads (high cooling demand) it becomes challenging to achieve the targeted indoor climate without sacrificing occupants' thermal comfort due to the increased convective flows (high volumes of air supplied). Therefore cooling systems based on convective, radiant or combined heat exchange are used. During this workshop, the differences between them will be discussed and also the performance of four systems based on radiant and convective cooling – chilled beam (CB), chilled beam with radiant panel (CBR), chilled ceiling with ceiling installed mixing ventilation (CCMV) and radiant cooling panels with ceiling installed mixing ventilation (MVRC) – compared with regard to the generated thermal environment and human responses.

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Thermal Comfort with Convective and Radiant Cooling Systems

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Abstract
The thermal environment in a two person office room obtained with chilled beam (CB), chilled beam with radiant panel (CBR), chilled ceiling with ceiling installed mixing ventilation (CCMV) and four desk partition mounted local radiant cooling panels with mixing ventilation (MVRC) was compared with laboratory measurements. CB provided convective cooling while the remaining three systems (CBR, CCMV and MVRC) provided combined radiant and convective cooling. Solar radiation, office equipment, lighting and occupants were simulated to obtain different heat load conditions; 38 W/m^2 and 64 W/m^2. Air temperature, operative temperature, radiant asymmetry, air velocity and turbulent intensity were measured and draught rate levels calculated. The results revealed that the differences in thermal conditions achieved with the four systems were not significant. CB and CBR provided slightly higher velocity level in the occupied zone.

Keywords: physical measurements, radiant cooling, convective cooling, thermal comfort

1 Introduction
Present standards (ISO 7730, 2005 and EN 15251, 2007) recommend maximum values for the indoor climate parameters for both winter and summer conditions in order to achieve thermally comfortable environment for occupants. However, in rooms with high cooling demand (> 50 W/m^2-floor area) it becomes challenging to achieve the targeted indoor climate without sacrificing occupants' thermal comfort due to the increased convective flows. Therefore cooling systems based on convective, radiant or combined heat exchange are used.

The differences between radiant and convective systems have been discussed, and in the literature and by system manufacturers, often radiant systems have been recommended for being able to provide favourable difference in the operative temperature for energy efficiency and thermal comfort, and more acceptable draught rate levels when comparing to convective systems.

This study was performed to compare the performance of four systems based on radiant and convective cooling, namely chilled beam (CB), chilled beam with radiant panel (CBR), chilled ceiling with ceiling installed mixing ventilation (CCMV) and four desk partition mounted local radiant cooling panels with ceiling installed mixing ventilation (MVRC). The CB and CCMV systems are often used in modern office buildings.

The study comprised comprehensive physical measurements. This paper compares the physical environment obtained with the systems in two person office room. The results of the human subject experiments performed in the case of office room are presented in a separate paper (Duszyk et al., 2011).

2 Method

Measurements were performed in a climate chamber (4.12 x 4.20 x 2.89 m, L x W x H) under steady state conditions at 26 °C design room air temperature. Office room with two occupants were simulated. Two cooling conditions were simulated: design (maximum) heat load 64 W/m^2 and usual heat load 38 W/m^2. Heat load from occupants, computers, four lighting units and solar radiation was simulated. The heat load for the studied conditions is specified in Table 1.

Surface temperature of simulated windows (water panels) and floor surface temperature (electrically heated foils below part of floor covering near the windows) was controlled to distribute the solar heat gain.

Table 1. Heat balance in measured cases.

Heat balance of test for	Office room			
In cooling conditions with	Maximum heat loads		Usual heat loads	
Occupants (about 78 W/occupant)	2	persons	2	persons
	156	W	156	W
	9	W/m²	9	W/m²
Computers (about 65 W/computer)	2	computers	2	computers
	130	W	130	W
	8	W/m²	8	W/m²
Lighting	160	W	160	W
	9	W/m²	9	W/m²
Solar load - window surface temperature	34	degC	30	degC
with 6.3 m2 window and 26 degC room ~	404	W	202	W
Solar load - direct solar load on the floor	250	W	0	W
Total solar load	38	W	12	W
Total heat loads	1100	W	648	W
	64	W/m²	38	W/m²
Supply air flow rate	26	l/s	26	l/s
Supply air temperature	16	degC	16	degC
Supply air cooling power in 26 degC room	312	W	312	W
	18	W/m²	18	W/m²
Cooling power demand from water	788	W	336	W
	46	W/m²	20	W/m²

The positioning of the heat load in the room is shown in Figure 1. Air temperature, operative temperature, mean velocity and turbulent intensity were measured at 8 heights (0.05 m, 0.1 m, 0.3 m, 0.6 m, 1.1 m, 1.7 m, 2.0 m, 2.4 m from floor), at 25 locations in the room (Figure 1).

At the locations of the desks, the measurements were performed at heights 1.1, 1.7, 2.0 and 2.4 m. Surface temperature (walls, floor, ceiling, window) and radiant temperature asymmetry was measured. Draught rate index (ISO 7730, 2005) was calculated based on the measured parameters.

Radiant asymmetry was measured at 1.1 m height at location 13 (Fig. 1) in CCMV, CB and CBR cases. In MVRC cases, radiant asymmetry was measured at the workstation at 1.1 m height between both occupants and radiant panels, and at 0.6 m and 1.1 m heights between both occupants and side walls. Air temperature and operative temperature sensors were of a thermistor type with accuracy of ±0.2 °C. Air temperature was measured with radiation shielded sensors. Velocity sensors were of an omnidirectional hot-sphere type with accuracy of ±0.2 m/s or ±1% of the reading 0.05-0.5 m/s. Multi-channel wireless low-velocity thermal anemometer with eight velocity sensors was used. All measurement sensors were calibrated prior to the measurements and measurement results were 5 minutes average readings.

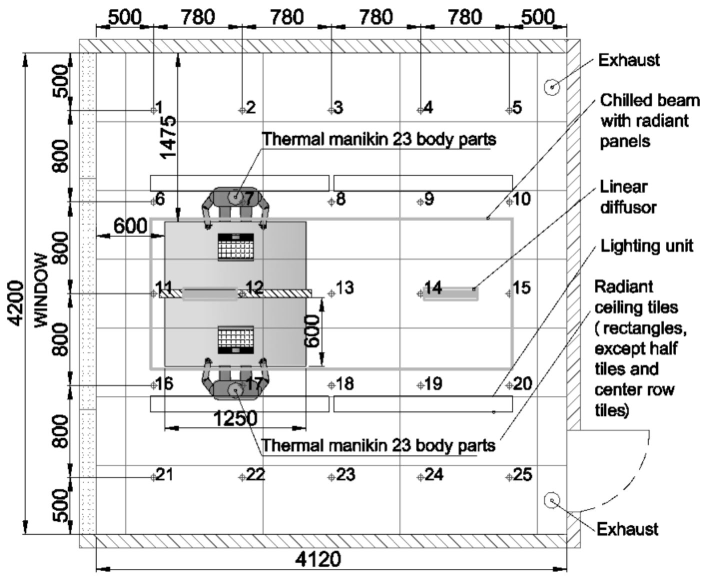

Figure 1. Top view of the test room with measurement pole locations.

The operating principle of the four cooling systems is schematically shown in Figure 2. In the case of CCMV cooling panels were integrated into the false ceiling tiles. The radiant ceiling covered 77% of the total ceiling surface. The top surface of the tiles was not insulated. Supplied air was distributed with two linear diffusers both with two slots size 472 x 20 mm, L x W each (Figure 2). Supply air temperature in all cases was 16 °C and water inlet temperature 15 °C with return water 2-3 °C warmer.

The same chilled beam (coil length 2100 mm) was used in the cases CB and CBR was used (Figure 2). In the case CBR the surface area of the radiant panels was 3.6 m². The chilled beam was removed from ceiling when chilled ceiling cases were measured. Personal radiant panels were installed at the desks as shown in Figure 3. In this case with design heat loads, supplied air volume flow was increased to 44 l/s to compensate the missing cooling power from panel radiators.

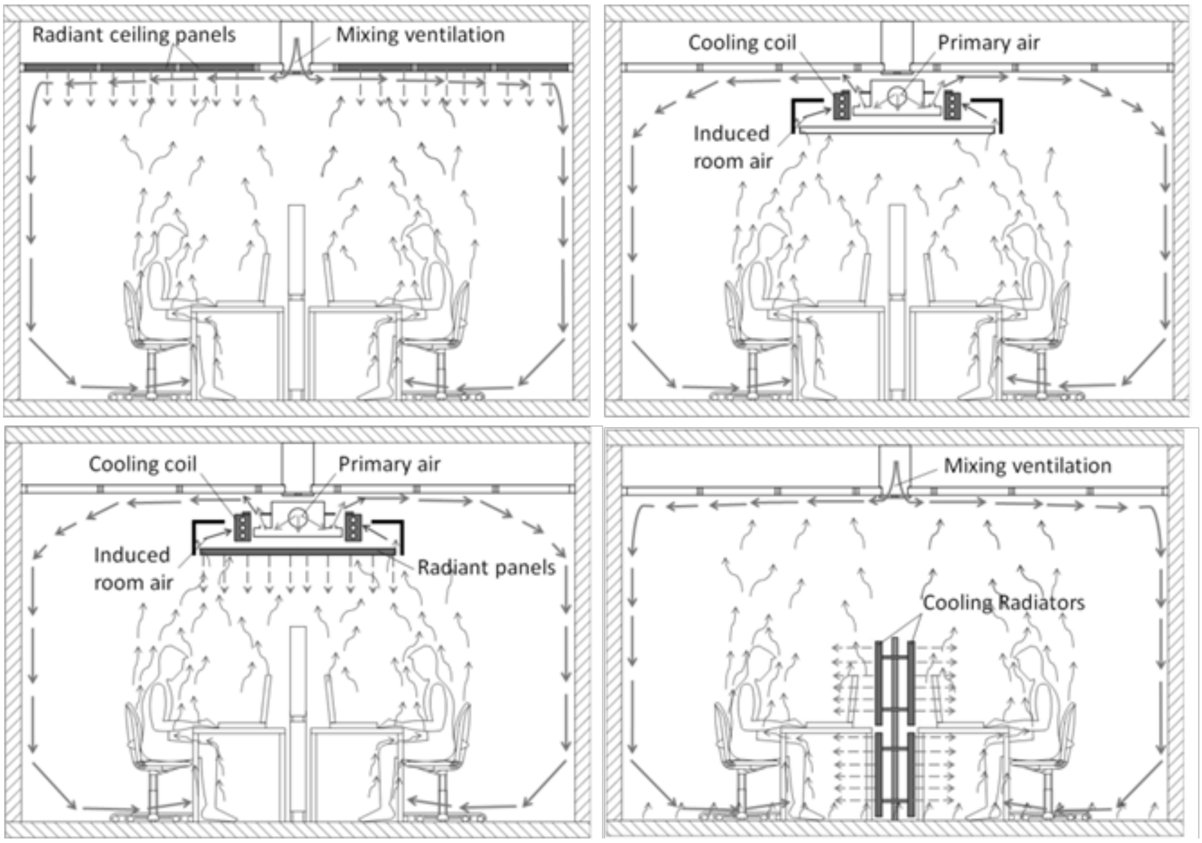

Figure 2. Operating principle of the four cooling systems: A) CCMV, B) CB, C) CBR and D) MVRC

3 Results

Summary of measurements results, including average, minimum, maximum and standard deviation of values, has been presented in Table 2 for overview of the thermal conditions.

Thermal conditions with all studied systems were very similar and similar behavior of the air distribution can be seen in smoke visualizations for all cases with supply air jets turning towards the wall opposite to simulated window.

Average room air temperature and operative temperature were rather similar with all systems; only small difference, on an average 0.2°C, between them can be seen in design conditions. There was significant horizontal operative temperature difference between window side and door side of the room (in design conditions on an average 1.5 °C and in usual conditions 1.0 °C). The maximum horizontal temperature difference in design conditions was about 2.0 °C. It was similar with all cooling systems and was caused by the one-sided locations of the heat loads. Only in MVRC cases this difference was a bit smaller and that was also measured in lower equivalent temperatures of the thermal manikins.

Due to the horizontal temperature difference, the operative temperature level near the window was about 0.4-1.8 °C higher than room design temperature (in the middle) in all cases. Vertical temperature difference in the room in all cases was very small (-0.1 - 0.7 °C). This difference was a bit smaller with radiant systems CCMV and CBR due to the bigger view factor towards floor when comparing to the MVRC case. In the design cooling case the difference can be seen most clearly.

Table 2 Summaries of measurement results in design (64 W/m^2) and usual (38 W/m^2) conditions.

	OFFICE ROOM IN DESIGN CONDITIONS				OFFICE ROOM IN USUAL CONDITIONS			
Measurement results in occupied zone at heights 0.1, 0.6, 1.1 and 1.7 m	CCMV	CB	CBR	MVRC	CCMV	CB	CBR	MVRC
Average air temperature [°C]	26.1	25.8	26.1	25.9	26.0	25.8	25.9	25.8
Min. air temperature [°C]	25.3	24.9	25.3	25.0	25.5	25.0	25.2	24.2
Max. air temperature [°C]	28.0	26.7	27.6	27.2	26.8	26.4	26.7	26.7
Std. dev. of air temperature [°C]	0.6	0.5	0.6	0.4	0.3	0.3	0.3	0.4
Average operative temperature [°C]	26.3	26.1	26.3	26.1	26.1	25.9	26.1	25.9
Min. operative temperature [°C]	25.3	25.1	25.4	25.4	25.5	25.1	25.2	24.5
Max. operative temperature [°C]	28.2	27.2	27.8	27.5	27.1	26.6	26.9	26.8
Std. dev. of operative temperature [°C]	0.7	0.6	0.6	0.5	0.3	0.4	0.4	0.4
Average operative - air temperature [°C]	0.1	0.3	0.2	0.1	0.1	0.1	0.0	0.1
Min. operative - air temperature [°C]	-0.2	-0.1	0.0	0.0	-0.1	-0.1	-0.3	-0.1
Max. operative - air temperature [°C]	0.6	0.7	0.5	0.6	0.5	0.4	0.3	0.3
Std. dev. of operative-air temperature [°C	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
At height 1.1 m:								
Avrg. air temperature of window side [°C]	26.8	26.4	26.9	26.8	26.4	26.2	26.4	26.5
Avrg. air temperature of door side [°C]	25.7	25.4	25.7	25.9	25.7	25.6	25.7	25.9
Avrg. horizontal air temp. diff. [°C]	1.1	1.0	1.2	1.0	0.7	0.7	0.7	0.6
Avrg. oper. temp. of window side [°C]	27.4	27.1	27.4	27.3	26.8	26.6	26.7	26.7
Avrg. oper. temperature of door side [°C]	25.8	25.7	25.9	25.9	25.9	25.7	25.8	26.0
Avrg. horizontal oper. temp. diff. [°C]	1.6	1.4	1.5	1.3	0.8	0.9	0.9	0.8
Avrg. oper. - air temp. of window side [°C	0.6	0.7	0.5	0.4	0.4	0.3	0.3	0.2
Avrg. oper. - air temp. of door side [°C]	0.1	0.2	0.2	0.1	0.2	0.1	0.0	0.0
At heights 0.1 m - 1.7 m:								
Avrg. vertical air temperature diff. [°C]	0.0	0.3	0.2	0.6	0.3	0.4	0.2	0.8
Avrg. vertical oper. temperature diff. [°C]	-0.1	0.5	0.2	0.6	0.3	0.5	0.5	0.7
Max. radiant asymmetry (window-door) [°C]	5.0	4.0	4.2	3.3	2.3	3.2	2.5	2.3
Max. radiant asymmetry (side-side wall, except in MVRC radiator-side wall) [°C]	0.3	0.6	1.5	-3.4	0.7	0.7	0.8	-1.7
Max. radiant asymmetry (floor-ceiling, except in MVRC radiator-manikin) [°C]	4.1	0.8	1.7	-6.5	3.0	-0.8	0.3	-4.3
Average air velocity [m/s]	0.13	0.13	0.12	0.10	0.11	0.12	0.11	0.06
Average of 3 highest velocities [m/s]	0.23	0.27	0.24	0.20	0.21	0.26	0.25	0.13
Highest velocity [m/s]	0.24	0.29	0.25	0.21	0.23	0.27	0.26	0.14
Std. dev. of air velocity [m/s]	0.04	0.05	0.05	0.04	0.04	0.05	0.05	0.03
Average turbulence intensity [%]	39	45	45	47	40	42	48	46
Average of 3 highest turb. intensities [%]	76	74	77	78	71	72	84	100
Std. dev. of turbulence intensity [%]	14	13	12	15	12	15	16	58
Average draught rate [%]	7.9	9.5	8.1	6.1	5.7	7.8	6.9	2.0
Average of 3 highest draught rates [%]	14.7	19.8	18.0	14.1	12.3	18.2	16.6	7.2
Highest draught rate [%]	16.3	20.8	19.5	14.9	13.0	18.4	17.4	8.3
Std. dev. of draught rate [%]	3.3	4.6	4.2	3.7	2.8	4.6	4.2	2.1

The radiant asymmetry was in all cases between window and door wall few degrees Celsius, so quite significant due to the solar heat load and supply air jet cooling the door wall when turning towards it. Also in CCMV case radiant asymmetry between floor and ceiling was at the same level due to the chilled ceiling surface. Radiant asymmetry in MVRC case was measured at different locations than in other cases. The radiant asymmetry in MVRC case was few degrees between all directions it was measured, and it was highest between radiant panel and thermal manikin (6.5 °C).

Average room air velocities were quite similar with all systems. With design heat loads in CCMV, CB and CBR cases relatively high velocities can be found (0.24-0.34 m/s). When usual heat loads are used, the velocity levels were mostly lower in all cases except in MR case where highest velocities were bigger with CB and CBR systems. This difference with CB and CBR in MR case was however smoothed away when average of three highest velocities was compared.

There was quite consistent 0.05 m/s difference in highest room air velocity levels between radiant CCMV system and purely convective CB system. The highest velocities of MVRC were lower in both design and usual heat load cases when compared with other systems.

The average turbulence intensity was rather similar with all systems, between 40% and 50%. Also average of three highest turbulence intensities were at roughly same level. Very high turbulence intensity readings in MVRC case with usual heat loads were caused by very low air velocity level (average 0.06 m/s). The average draught rate difference in measurement pole readings was small, 1-2% higher in purely convective CB cases and the highest readings were about 5% higher in CB cases than in mostly radiant CCMV cases.

The effect of using radiant panels integrated chilled beam can be seen slightly in the draught rate results, in CBR cases of OR, but not in MR cases. With usual heat loads, draught rates got smaller for all systems. This was most pronounced in the CCMV and MVRC cases. Draught rate levels in MVRC cases were lower than with other systems.

4 Conclusions

The results revealed that the differences in thermal conditions between the measured radiant and convective systems were not big. Also with radiant cooling systems, the convective heat transfer was significant and convective flows in the room were similar. The air temperature and operative temperature were near each other and very similar in all studied cases with about 0.2°C difference between operative and room air temperature. This is differs from some design guides of radiant cooling systems where even 2-3°C lower operative temperature is used. Based on this research this might lead to too high room air temperatures in cooling design conditions.

There was significant horizontal operative temperature difference between window side and door side of the room (maximum difference about 2.0 °C) with all systems. The room air velocities and draught rates were slightly higher in the CB and CBR cases (about 0.05 m/s difference in the highest velocities and 5 % in the highest draught rates) when compared with CCMV cases. When comparing thermal conditions with the design and usual heat load levels, with higher heat loads levels, the velocity and draught rate levels got higher in all cases.

Acknowledgement

The study is supported by Technology Agency of Finland (TEKES) in RYM-SHOK research program and the International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark.

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Natural ventilation performance of heritage buildings in the Mediterranean climate. The case of a two-storey urban traditional dwelling in Nicosia Cyprus.

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Abstract
The Mediterranean climate offers ideal conditions for the exploitation of natural ventilation as a cooling strategy. However, its effectiveness is highly dependent upon various parameters concerning architectural layout and occupant behaviour. This study provides insight on the way occupants interact with the buildings' elements in order to achieve comfort, focusing on the occupants' behaviour towards vernacular heritage buildings in Nicosia, Cyprus. A questionnaire based survey confirms that ventilation is a major cooling strategy. Further investigation is conducted on window operation patterns through simulation tools. After a thorough analysis of a large number of urban vernacular dwellings, a representative vernacular dwelling located in the urban core of Nicosia was selected as a case study. Its architectural layout reflects the typical arrangement of a two-storey dwelling with a three-bay interior arrangement and thus ensures a number of passive design strategies related to natural ventilation. The study explores two types of natural airflow; namely, wind effect, in single-sided and cross ventilation mode, and stack effect. The impact of daytime, night-time and all day ventilation is also assessed comparatively. The results indicate that occupant behaviour concerning window operation has significant impact on the overall thermal performance of the building. Finally, the comparative analysis confirms and quantifies the effectiveness of night ventilation as a cooling strategy.

Keywords: natural ventilation, vernacular dwellings, occupant behaviour

1 Introduction

The rising global environmental concern has increased the importance of thermal comfort studies and has highlighted the need for energy retrofit projects. The built vernacular heritage constitutes a large part of the existing building stock and incorporates typical examples of integration of environmental design principles, such as the consideration of climatic conditions, topography, rational use of local resources and construction techniques (Coch, 1998). Vernacular buildings have had a continuous life through time as occupied spaces, acquiring their specific form and layout as a result of an ongoing process of adaptation in response to both environmental and social challenges. While vernacular building envelopes incorporate a series of passive cooling and heating strategies, the effectiveness of several strategies relies on the interaction of the occupants with the integrated environmental design elements.

Natural ventilation requires the active participation of occupants and is acknowledged as a principal passive cooling strategy linked to the Mediterranean way of living. The design of vernacular dwellings offers the possibility of wind-driven ventilation, i.e. single-sided or cross ventilation, which arises from the different pressures created by wind around a building, as well as buoyancy-driven ventilation, i.e. stack ventilation which is driven by density differences between cool and warm air, through a vertical flow path, such as an atrium, stairwell or chimney. The effectiveness of night ventilation is associated with climatic conditions and diurnal temperature fluctuation, as well as with the thermal inertia of buildings (Santamouris 2006, Givoni 1994, Blondeau 2001, Ogoli2013, Shaviv et al. 2001, Martin et. al., 2010). Santamouris (2006) showed that night-time ventilation is suitable for climates with high daily air temperature fluctuations and relatively low night temperatures. Shaviv et al. (2001) examined the influence of thermal mass and night ventilation on the maximum indoor air temperature in a hot humid climate during the cooling period and suggested that daily air temperature fluctuation should be greater than 6°C in order to achieve an effective reduction in daytime peak air temperature of 3°C. Givoni (1994) stated that a daily air temperature fluctuation of about 10°C is required to achieve the cooling effect of night ventilation. Finally, according to Blondeau et al. (2001) night ventilation can decrease diurnal indoor air temperatures from 1.5 to 2°C, even when the average daily air temperature fluctuation is 8.4°C.

The use of massive structural elements and local materials with high thermal mass is quite common (Philokyprou et al., 2014) in the vernacular architecture of Cyprus. Kalogirou et al. (2002) argued on the potential of cooling load reduction when thermal mass is applied, as the temperature variations in Cyprus are ideal for the implementation of such a strategy. *In situ* measurements on ventilation strategies, conducted in traditional adobe buildings in Cyprus, confirm the effectiveness of night ventilation when the diurnal temperature fluctuation is 8-9°C (Demosthenous et. al., 2015).

This paper provides insight on the cooling strategies applied by the occupants of vernacular dwellings in the urban core of Nicosia. The occupant thermal comfort assessment, and the occupant behaviour concerning window operation modes, is explored on an annual basis, based on a questionnaire survey of an extended sample of urban vernacular dwellings. *In situ* measurements and simulation tools are used in order to quantify the contribution of ventilation driven by wind or buoyancy forces according to multiple operational modes, potentially applied by the occupants, i.e. all day, daytime and night-time ventilation, during the hot summer period. For this purpose, after a comprehensive study of a large number of dwellings in the urban area of Nicosia, a representative case study building was selected; whose building envelope design offers multiple ventilation options.

2 Occupants’ behaviour and thermal comfort assessment

An overview of the vernacular architecture of Cyprus, and more specifically of the urban historic centre of Nicosia, reveals several architectural features and passive design techniques which cool or warm indoor spaces through the exploitation of local climate conditions. Such strategies involve the materials and construction techniques, orientation of the building, the existence of semi-open spaces, the proper location and size of openings, the existence of shading devices such as window shutters etc. (Philokyprou et al., 2013). However, some of the possibilities offered by the design of traditional dwellings require the active participation of the occupants. The question addressed here is: which of these strategies are used by contemporary occupants and to what extent?

In order to answer the above research question, a questionnaire-based survey was carried out, involving a large number of occupants of traditional dwellings in the urban core of Nicosia (n=60). For the purposes of this paper, the results presented are related to the overall comfort assessment of the occupants and their behaviour, focusing on the cooling strategies and window operation patterns applied.

2.1 Occupants' assessment on the overall thermal comfort

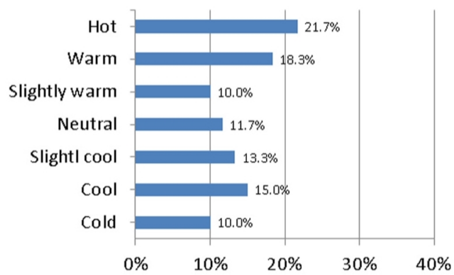
The overall thermal sensation (TS) of occupants was evaluated for the four seasons, based on the responses to the question: "*How do you find the thermal environment inside your traditional house during winter / summer / spring / autumn?"*. The ASHRAE thermal sensation scale was used ranging between *hot / warm, slightly warm / neutral / slightly cool / cool / cold*. The results reported correspond to a percentage of the total sample (n= 60).

The majority of respondents claimed to have a *neutral* feeling during the intermediate seasons and discarded the need of auxiliary heating or cooling systems. Specifically, 96.7% of the respondents expressed a *neutral* thermal sensation for spring, and 98.3% for autumn. As far as the thermal sensation during winter is concerned, opinions varied; 40% of the respondents evaluated the building as *warm* / *hot*, 35% as *neutral*, while, the remaining 25% appraised it as *cool/cold* (Figure 1).

Concerning the description of the dwelling during the summer, 45% of the respondents opted for *cool*, while 35% of them for *slightly cool, neutral* and *slightly warm* (Figure 1). It is worth noting that, the respondents' choice to characterise the dwelling as *cool* intended to emphasize the relative temperature difference between the external and internal environment, pointing out the comfort conditions provided within traditional dwellings. Although it seems difficult for field study respondents to balance and express their thermal preferences with accuracy (Cena and de Dear, 1999), it can be safely said that the thermal comfort of vernacular buildings is deemed by the occupants to be within the range of 80% acceptability during the summer period.

2.2 Occupant behaviour

The answers of respondents to the question "*What do you do in order to cool down or prevent overheating within the indoor spaces during the summer?*" confirm the fundamental assumption of ACS that people take actions in order to restore their thermal comfort (Nicol and Humphreys, 1973). Specifically, 83.1% of respondents apply shading by closing the external venetian blinds, 61% by wetting or watering the yard and, thus, providing evaporative cooling and 95% operate the windows in such a way that increases airflow through cross ventilation. Despite the passive means available for cooling, the vast majority of the sample (97% of respondents) resorts to occasional use of technical means, i.e. fans and air conditioning, in order to achieve thermal comfort.



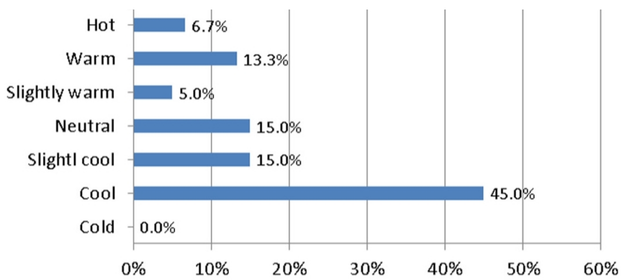


Figure 1: Thermal Sensation of vernacular dwellings occupants in winter (left) and summer (right) period.

Focusing further on the ventilation strategy applied by the occupants -as this constitutes the more widely used cooling strategy-, Philokyprou et al. (2013) pointed out the importance of the size and location of the windows in the vernacular architecture of Cyprus. The presence of small-sized openings, called *arseres*, at a considerable height, mainly on the street façades, contributes to stack-driven ventilation and enhances the extraction of hot air from the building, due to the difference in temperature and density of the incoming air. However, according to the findings of the survey, only 41.9% of the users, with *arseres* in their buildings, take advantage of their existence. This can be attributed to either lack of awareness regarding the role of these openings, or to difficulty in accessing the particular openings due to their high level location, or due to interventions that render these windows inaccessible.

Regarding the window operation pattern, as shown in figure 2, three main operation modes are applied concerning the time and duration of ventilation within the day: all day ventilation (24-hours), daytime ventilation and night-time ventilation. Two additional modes of effective window opening are applied: wide and partial opening of windows, corresponding to a different airflow rate. During the periods of winter, autumn and spring, the findings show that the wide opening of windows is preferred in the morning. During the summer period, windows are preferred wide open during the morning, afternoon and night and less frequently at noon. As made evident, night ventilation is used mainly during the summer rather than in the other seasons, revealing that occupants acknowledge its effectiveness as a cooling strategy. Yet, another interesting observation is the apparent preference towards all day ventilation. Given that the temperatures of the external environment during noon and the afternoon are higher than the ones of the indoor environment in the summer, it can be deduced that the above behaviour might not be beneficial in terms of heat exchange and might be associated with the preference of increased air movement. Nonetheless, as highlighted by other researchers, thermal comfort alone may not suffice to predict adequately human behaviour in the interior of buildings (Borgerson and Brager, 2002). Indeed, Fabi et al. (2012) provided an extended literature review on the drivers of window opening behaviour; mentioning a series of driving forces for energy related behaviour in residential buildings, i.e. physiological, psychological, social, environmental and contextual.

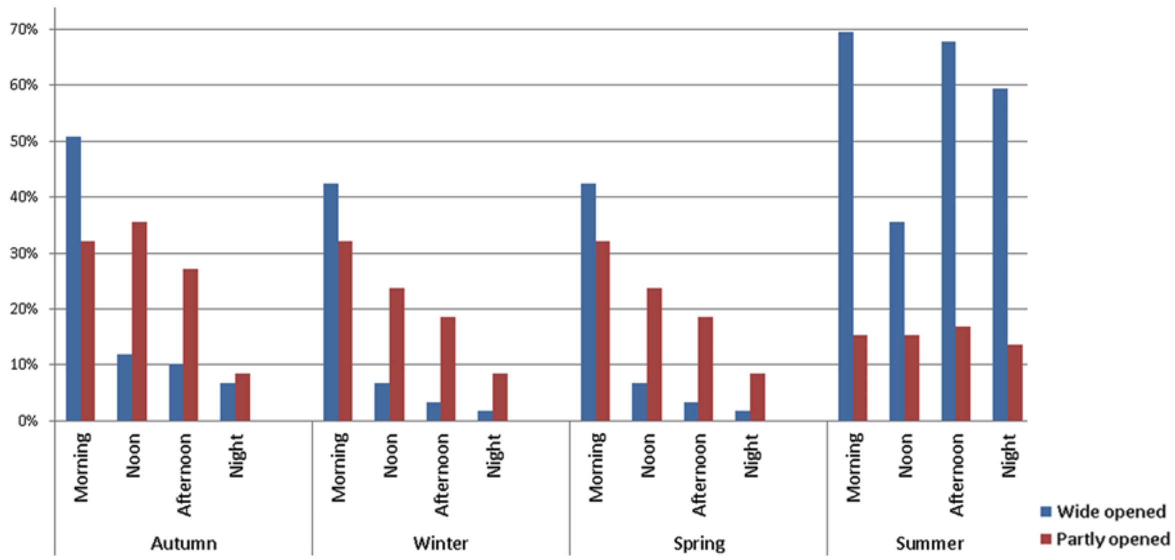


Figure 2: Window operation pattern of vernacular dwellings in the urban core of Nicosia.

3 The cooling effectiveness of ventilation

3.1 The case study building

Following an extended survey on the vernacular heritage of the historic core of Nicosia, more than 100 buildings were examined in terms of typology and environmental design principles. Several vernacular buildings, located within the area that is enclosed by the Venetian walls, were selected for detailed investigation and monitoring of the interior thermal conditions. The study made evident that, even though various typological and morphological elements of the original building types changed over time so as to adapt to the urban context, a number of environmental design features, especially those concerning ventilation, remained prevalent in the urban vernacular architecture of Nicosia. The study showed that the most common building typology was the tripartite arrangement of the main part of the building. This arrangement offers ventilation possibilities of wind driven ventilation, (through the windows), as well as buoyancy-driven ventilation (through the stairwell). The position of the case study building within the urban tissue, and the location of the courtyard, favourite cooling ventilation driven by wind, as wind direction during the summer period is north and/or northwest. It is a typical two-storey urban dwelling with a rectangle-shaped typology and a triple-bay arrangement. The entrance of the house is achieved through the central bay, called *portico* (Figure 3, 4). The *portico* mainly refers to an intermediate semi-open space through which the access from the street to the courtyard was achieved and sometimes it refers to a through space with large openings towards the yard (Demi, 1997). A typical morphological element of this building type is the projection of part of the central room, with extended window surfaces on the upper floor, called *sachnisi* (Figure 3, 4). The specific morphological element became widespread, in various forms, in the 19th and in the beginning of the 20th century in the wider Balkan Peninsula and shares common characteristics with traditional buildings encountered in the Eastern Mediterranean (Oikonomou and Bougiatioti, 2011, Umar et al., 2013).

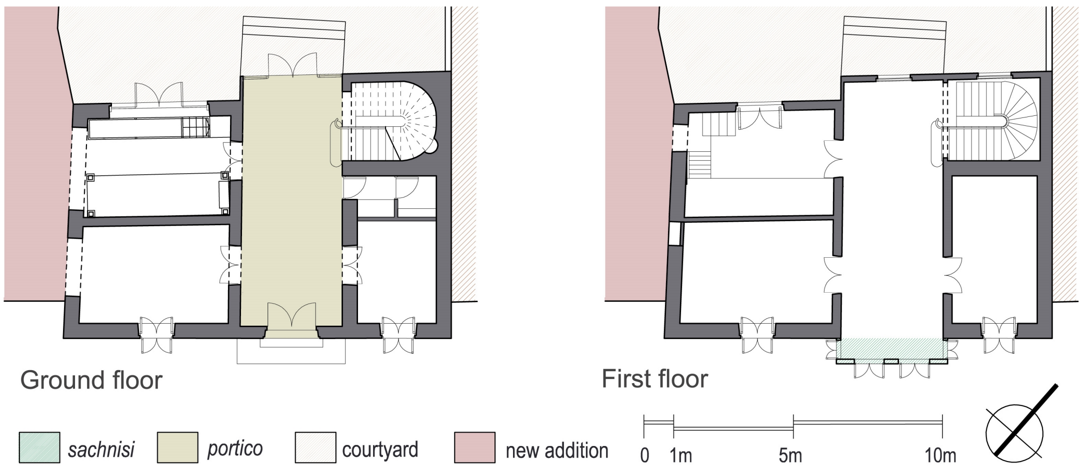


Figure 3: The case study building

The structural system of the building comprises of load-bearing mud brick walls of 50 cm width, resting on a stone foundation and a timber double-inclined roof. The projecting volume of the main façade *(sachnisi)*, is a lightweight construction formed by timber frames 20 cm wide, originally filled with adobe or stones. This building has been renovated and the traditional filling material was replaced by autoclaved aerated concrete blocks for insulation purposes. The original roof structure has also been modified and insulation foam-boards were added to improve thermal performance.

Figure 4: External and internal views of the case study building

3.2 The simulation tool

This study employs the building energy analysis simulation tool EnergyPlus v8.3. The graphic interface of Design Builder v4.6 software is used for modelling the building's geometry and for inputting other data. In order to accurately predict the thermal performance of selected zones of the building (*portico, central room of upper floor*), data regarding the geometry, activity, internal gains, as well as infiltration and ventilation, were integrated into the model. Natural ventilation and infiltration measurements are calculated based on window openings, cracks, buoyancy and wind-driven pressure differences. The ventilation control mode is set to constant, enabling windows to open for fresh air-supply, regardless of inside and outside temperature and enthalpy. The airtightness of the building is deemed poor. Simulations employ full interior and exterior solar distribution, calculating the amount of solar radiation falling on each surface of the building zone including the floor, walls and windows, taking into account factors such as direct solar and light transmission through internal windows. The thermal properties of the construction materials were identified by the use of non-destructive experimental methods.

Measurements of indoor temperature and relative humidity levels (USB-2-LCD data loggers), as well as external weather data (Davis Vantage Pro-2), were monitored on site in order to confirm the digital model. For the verification of the model, the inequality coefficient (IC) was calculated according to equation 1 (Williamson, 1995):

$$IC = \frac{\sqrt{\frac{1}{n}\sum_{t=0}^{n}\left(D_{sim,t}-D_{exp,t}\right)^2}}{\sqrt{\frac{1}{n}\sum_{t=0}^{n}\left(D_{sim,t}\right)^2}+\sqrt{\frac{1}{n}\sum_{t=0}^{n}\left(D_{exp,t}\right)^2}} \qquad (1)$$

where $D_{sim,t} = \left(T_{int,t} - T_{ext,t}\right)_{sim}$ is the simulated and $\mathrm{D}_{\mathrm{exp,t}} = \left(\mathrm{T}_{\mathrm{int,t}}\text{-}\mathrm{T}_{\mathrm{ext,t}}\right)_{\mathrm{exp}}$ the recorded temperature differences. IC presents the degree of agreement between measured and simulated data, ranging in value between 0 and 1, with 0 indicating a strong correlation. The IC was calculated to be 0.16 for ground floor and 0.29 for the first floor. This indicates a fair level of accuracy of the simulation tool and credibility in terms of the research findings on the thermal performance of the building under study.

3.3 Thermal comfort assessment background

The case study building is supported by technical means for heating and cooling. However, since vernacular heritage buildings are mainly naturally ventilated, for the purposes of this paper, the case study is considered as a free-running building. Therefore, the adaptive approach introduced by de Dear and Brager (1998) is adopted, integrated within ASHRAE Standard 55 (ASHRAE, 2004). According to the Adaptive Comfort Standard (ACS), the acceptable indoor operative temperature, T_{comf}, is expressed as a function of the mean monthly outdoor air temperature, $T_{a\ (mean)}$. A mean comfort zone band of 5°C is estimated for 90% acceptability and 7°C for 80% acceptability, around the optimum indoor comfort temperature, calculated as in equation 2 below:

$$T_{comf} = 0.31 * T_{a(mean)} + 17.8 \qquad (2)$$

Given that the focus is on the summer conditions, the present paper examines only the months with the highest temperature levels, i.e. July and August. The correspondent thermal comfort zone for 80% acceptability ranges for July from 23.7 ^{o}C to 28.7 ^{o}C, and for August from 23.9 ^{o}C to 28.9^{o}C.

3.4 Case study scenarios

In order to estimate the impact of ventilation on the thermal comfort of the vernacular building under study, multiple scenarios of window operation patterns are comparatively examined. Specifically, two parameters are considered: a) the type of ventilation offered by the building's elements, i.e. single-sided and cross ventilation and b) the period of time within the day when ventilation is applied according to the findings of the occupant behaviour survey, i.e. daytime, night-time and all-day ventilation. The space under study on the ground floor is the central part of the building that corresponds to the entrance of the building, i.e. *portico*. Respectively, on the first floor, the space under study is the central part that includes the *sachnisi* and is connected to the *portico* through the interior staircase.

On the ground floor, only single-sided ventilation was examined (opening of windows towards the courtyard) as security and privacy reasons do not allow the prolonged opening of doors or windows toward the street. The single-sided ventilation mode on the first floor refers to the operation of the windows toward the courtyard, while cross ventilation refers to the opening of the street front façade windows and particularly, opening of the windows of *sachnisi*. The effective opening surface of windows is considered to be 30% in all cases, which corresponds to partially open windows. Table 1 presents the case study scenarios. The reference scenario is considered to be the operation mode that the occupants usually apply during the summer (derived from their questionnaire answers).

Table 1. Case study scenarios

		REF.	S 1	S 2	S 3	S 4	S 5
First floor	**Ventilation Type**	SV	CV	SV	SV	SV	CV
	Day (07:00-19:00)			X			
	Night (19:00-07:00)	X	X	X	X	X	X
Ground floor *portico*	**Ventilation Type**				SV	SV	SV
	Day (07:00-19:00)					X	
	Night (19:00-07:00)				X	X	X

SV stands for single sided ventilation, CV stands for cross ventilation

3.5 Results and discussion

This section addresses the thermal performance of the aforementioned window operation patterns under the influence of the examined ventilation modes, i.e. single-sided ventilation, cross ventilation and displacement ventilation due to buoyancy forces, i.e. stack effect. Moreover, additional factors such as time and duration of ventilation within the day, i.e. all day ventilation (24-hours), daytime ventilation and night-time ventilation were also considered. The results of the hourly simulation on the first and ground floor are presented in tables 2 and 3 respectively.

According to the findings, when applying the actual window operation mode used by the occupants, i.e. reference scenario, the ground floor meets the comfort conditions of 80% acceptability almost throughout the examined period (96.8% of the time), while the first floor only for 38.8% of the time. The mean operative temperature on the first floor, which is exposed to solar heat gains from the roof, is 1.5 °C higher than the respective temperature in *portico,* reaching 29.8 °C. The thermal stability recorded in the interior environment (less than 2°C diurnal indoor temperature fluctuation compared to the outdoor fluctuation of 8.7 °C) (Figure 5) is attributed to the building's high thermal mass and is in line with other studies concerning the thermal behaviour of heavyweight vernacular dwellings (Oikonomou and Bougiatioti, 2011, Martin et.al., 2010).

Table 2: Operative temperature (°C) levels and fluctuation in the central part of the ground floor *(portico)*

		REF.	S1	S2	S3	S 4	S5	External environment*
July	Mean T (max)	29.2	29.1	29.2	28.6	28.9	28.4	31.4*
	Mean T (min)	27.3	27.1	27.3	26.2	26.3	25.8	22.8*
	Mean Daily Fluctuation	1.9	2.0	1.9	2.4	2.6	2.6	8.7*
August	Mean T (max)	29.6	29.5	29.6	29.1	29.3	28.9	32.0*
	Mean T (min)	27.9	27.7	27.8	26.8	26.9	26.4	23.3*
	Mean Daily Fluctuation	1.7	1.8	1.7	2.2	2.4	2.4	8.7*
Percentage of time within the comfort zone for 80% acceptability		**96.8**	**97.6**	**96.8**	**99.1**	**97.6**	**99.9**	

*refers to dry bulb temperature

Table 3: Operative temperature (°C) levels and fluctuation in the central part of first floor *(sachnisi)*

		REF.	S 1	S 2	S 3	S 4	S 5	External environment*
July	Mean T (max)	30.8	30.7	30.8	30.2	30.4	30.0	31.4*
	Mean T (min)	28.8	28.5	28.7	27.9	28.0	27.5	22.8*
	Mean Daily Fluctuation	2.1	2.2	2.1	2.3	2.4	2.5	8.7*
August	Mean T (max)	31.4	31.3	31.4	30.8	31.0	30.6	32.0*
	Mean T (min)	29.4	29.2	29.4	28.6	28.7	28.3	23.3*
	Mean Daily Fluctuation	1.9	2.1	2.0	2.2	2.2	2.4	8.7*
Percentage of time within the comfort zone for 80% acceptability		**38.8**	**46.2**	**40.2**	**64.0**	**59.3**	**71.6**	

*refers to dry bulb temperature

In a temperate climate such as the one of Cyprus, daytime natural ventilation can be efficient provided that the solar and internal gains are low and/or the thermal inertia is high (Santamouris, 2006). Daytime ventilation can be used in the morning to cool down the indoor air and the thermal mass of the building so long as the outdoor temperature is below the indoor temperature. Indeed, according to the findings, the application of all-day ventilation, in *portico,* in comparison to reference scenario is found to have a beneficial effect. Specifically, the application of all-day ventilation in *portico,* i.e. S4, results in a slight improvement of the thermal comfort of *portico* (reaching 97.6 % of the time within the comfort zone) and in a notable improvement of the thermal comfort on the first floor, raising the percentage of time within the comfort zone from 38.8%, in reference scenario, to 59.3%. The respective mean daily fluctuation of the operative temperature in *portico* is recorded to rise from 1.7°C to 2.4°C, revealing greater heat exchange rate. However, all-day ventilation is less effective than night-time ventilation. Specifically, when applying night-time ventilation in *portico,* i.e. S3, the percentage of time within the comfort zone rises to 99.1% for *portico* and 64% for the first floor.

As mentioned above, the central part of the ground floor, *portico*, is connected to the central part of the first floor through the interior staircase. In this way, the temperature difference between the indoor space and the outdoor environment causes a density difference whereby the upper opening drives outflow and the lower opening at the ground floor drives inflow. However, this buoyancy-driven flow, i.e. stack effect, occurs simultaneously with the wind effect and the two phenomena counteract each other (Gładyszewska-Fiedoruk, & Gajewski, 2012). Therefore, the improvement on the thermal performance of S4 with respect to the reference scenario is attributed to the simultaneous effect of these phenomena.

Cross ventilation ensures higher air-change rate than single-sided ventilation; thus, if applied at night when the heat exchange with the external environment is beneficial, better results are expected. Indeed, the opening of windows in *sachnisi* on the first floor, i.e. S1, improves the thermal conditions with respect to single-sided ventilation applied to reference scenario, raising the percentage of time when the first floor lays within the comfort zone from 38.8% to 46.2%.

Similar effect is recorded in the case S5 in comparison to case S3. Specifically, S5 combines the beneficial effect of cross ventilation and night-time ventilation and presents the most efficient performance; *portico accounts* for 99.9% of the time within the extended comfort zone and the first floor for 71.6% of the time. As observed in figure 5, night-time ventilation succeeds in reducing peak operative temperature in *portico* to the level of 90% acceptability. An overall reduction of 1.5°C in the mean operative temperature in *portico* is recorded (with respect to reference scenario) and of 1.2°C on the first floor. The results are in line with other studies concerning the effectiveness of cross ventilation in respect to single-sided ventilation (Stabat, 2012) and the effectiveness of night ventilation in the climatic conditions of Cyprus (Kalogirou et. al. 2010, Demosthenous et. al., 2015).

Finally, it is noted that in all the examined scenarios, where ventilation is applied at ground level (S3-S5) or not (reference scenario, S1 and S2), the *portico* offers very high levels of comfort, with 96,8% of time within the comfort zone for 80% acceptability for the reference scenario and 99.9% for scenario S5. The above demonstrates that the application of the examined ventilation strategies has less impact on the thermal performance on the ground floor compared to the first floor. This is attributed to the limited effectiveness of single-sided ventilation, the introverted character of the ground floor that has less glazed surfaces and limited wall surfaces exposed to the external environment, as well as to the fact that the first floor has elevated solar heat gains deriving from the roof.

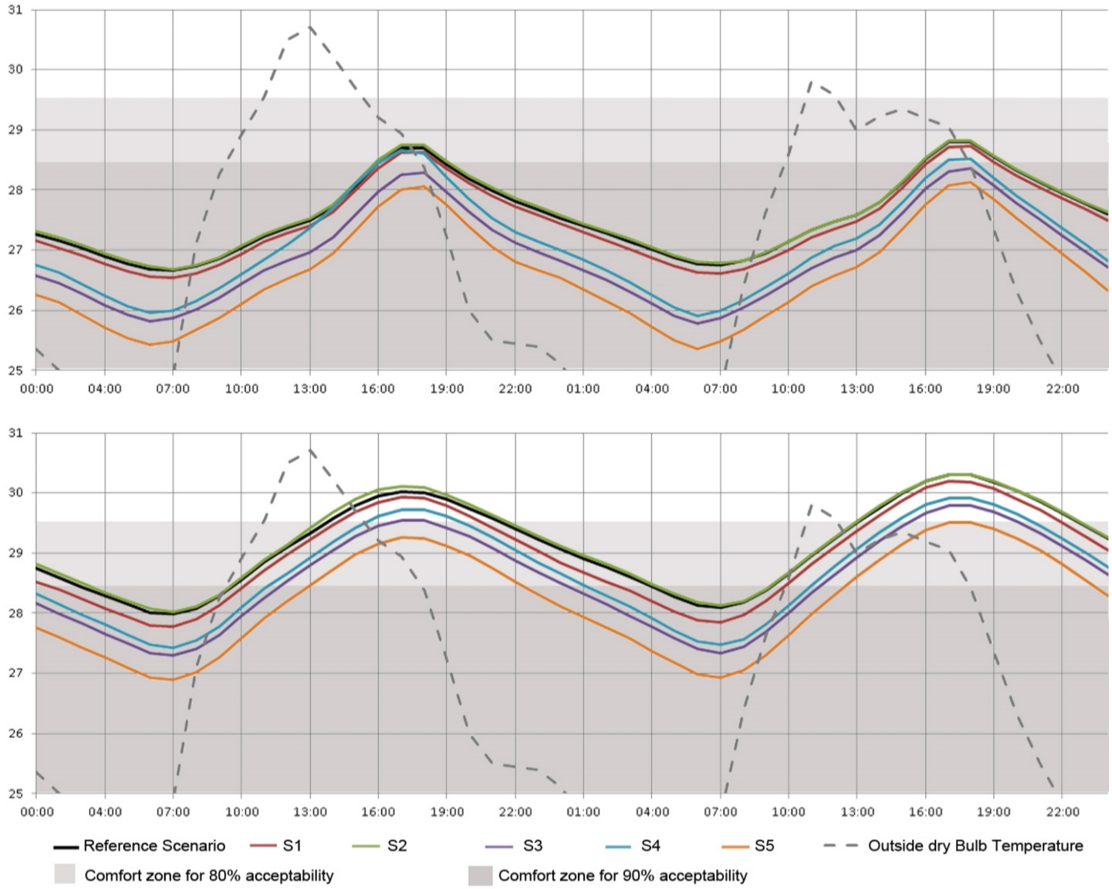


Figure 5: Operative temperature (°C) levels in *portico* on the ground floor (above) and *sachnisi* area of the first floor (below), on the 1st and 2nd of July.

4 Conclusions

Natural ventilation relies on natural driving forces i.e. wind and buoyancy, which are highly variable. However, the ability to predict thermal comfort conditions attributed to certain airflow characteristics is essential for designing and implementing passive environmental strategies. In this study, ventilation is approached as the main cooling strategy applied by occupants of heritage buildings in the urban core of Nicosia. The extended questionnaire-based survey confirms the interaction of the occupants with the building elements in order to apply ventilation strategies for the improvement of indoor thermal conditions during the hot summer period. The results on the operation of windows reveal that although thermal comfort is not the prime driving force for occupant behaviour, proper ventilation strategies are positively exploited for cooling purposes during the summer period. According to the respondents' answers concerning thermal sensation, 80% of occupants declare that the indoor thermal conditions of traditional dwellings are in satisfactory levels during the summer period without the use of any technical cooling systems.

The ventilation performance was recorded and evaluated by *in situ* measurements and software simulation, in a representative case study building that bears the typical layout of a two-storey building with a three-bay arrangement and the morphological element of *sachnisi* on the first floor. The study explores two types of natural airflow; i.e. wind effect, through the operation of windows in single-sided and cross ventilation mode, and stack effect through the stairwell. An additional parameter investigated was the period during which windows were operated within the day, focusing on daytime, night-time and all day ventilation.

The results reveal that cross ventilation presents higher cooling efficiency compared to single-sided ventilation due to a higher air change rate. Additionally, night ventilation is found to be more effective than daytime and all-day ventilation, as opening the windows during the night results to greater diurnal indoor temperature fluctuation and higher air change rate, which consequently enhances convective heat loss from mass elements and dissipates the heat outdoors. Specifically, the overall reduction of the mean operative temperature in the case of night-time ventilation (S5) compared to the *reference* scenario is 1.5°C on the first floor and 1.2°C on the ground floor. The aforementioned performance is attributed to the simultaneous effect of wind and stack effect. Further improvement of ventilation effectiveness can be achieved through the incorporation of ceiling or floor fans that can increase air speed within the indoor spaces and thus, significantly increase comfort levels.

The present study underlines that the Mediterranean climate offers ideal conditions for the exploitation of natural ventilation as a cooling strategy during hot summer period. The effectiveness of natural ventilation is highly dependent upon various parameters including the ventilation type, the period during the day applied, building architectural layout and the occupants' behaviour. Further investigation on the aforementioned parameters will provide a thorough understanding of the role of natural ventilation in the thermal comfort of vernacular buildings.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Temperature distribution and ventilation in large industrial halls

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Abstract

In this study vertical temperature gradient was measured and ventilation need was analyzed in two hall buildings with room height close to 10 m. One building was industrial assembly hall (without process) and another heated and ventilated warehouse. Both buildings had high ventilation rate of about 2 l/(s m^2) and well insulated building fabric according to the Finnish building code values. One objective was to measure differences in the temperature distribution as one building had air heating and another one radiant ceiling panel heating. This was quantified by vertical temperature gradient measurements in winter. Another objective was to assess minimum ventilation need in such halls. For that purpose available literature on indoor sources and ventilation needs was reviewed. The results showed about 0.2 K/m vertical temperature gradients in both halls which is by factor 5 smaller for air heating than the guidebook value likely because of ventilated and well insulated building. Temperature gradients kept reasonably constant at all measured outdoor temperatures. The differences caused by air heating and ceiling panel heating were very small, however, in the case of air heating, room temperature control was less accurate and the setpoint was not always achieved. Ventilation need analyses showed that studied buildings were over ventilated by about factor 2 and 1 l/(s m^2) would be relevant design value for general ventilation in such halls with low occupancy and low polluting materials.

Keywords: Temperature gradient, stratification, industrial halls, ventilation need

1 Introduction

Modern industrial halls are often assembly halls without significant process generating neither pollutants nor heat gains. Such buildings in Finland are well insulated, heated and ventilated that applies also for many warehouses. In a cold climate, heating dominates in energy use and space heating solutions combined or not combined with ventilation may have significant effect on energy performance. For air heating and ceiling panel heating, studied in this paper, handbooks provide quite different vertical temperature gradient values due to stratification, 1.0 K/m vs. 0.2 K/m respectively (Kabele 2011). This indicates that ceiling panel heating can save energy not only because of avoiding some fan energy but also due to lower heat losses from upper part of a building. However, it is not known how valid an old handbook values are in well insulated halls with mechanical supply and extract air ventilation which is mixing indoor air and could reduce stratification.

Another debated issue in halls is evidence based ventilation need. In Finland a default code value of 2 l/s per floor m^2 (D2:2012) has been widely used, but in practice it is often noticed that the occupancy is low and halls are over ventilated which is indicated by extremely low CO_2 concentrations.

The objective of this study was to quantify energy saving potential of ceiling panel heating due to smaller vertical temperature gradient relative to air heating system. For that purpose vertical temperature stratification was measured in two modern halls with described heating systems. Measured temperature gradient results could be applied in energy simulations which are possible to run with actual ventilation rates and with lower ventilation rates suggested by scientific literature. In this study we were however limited on thermal comfort and ventilation aspects, i.e. on temperature gradient and general ventilation need, parametric energy simulations based on these results are planned to be conducted in future study.

2 Methods

Measurements were conducted in Assembly hall with air heating in Hämeenlinna, construction year 2006, and in Warehouse with ceiling panel heating in Vantaa, construction year 2008. Both buildings are heated, ventilated and well insulated hall buildings, Figure 1. Heating and ventilation solutions are shown in Figure 2. Regarding thermal insulation and ventilation both of these halls follow Finnish building code U-value reference values (C3:2003) and ventilation recommendations (D2:2003):

- External walls U = 0.25 W/(m^2 K)
- Roof U = 0.16 W/(m^2 K)
- Slab on the ground U = 0.25 W/(m^2 K)
- Ventilation rate 2 l/(s m^2)
- Building leakage rate at 50 Pa 4.0 1/h (measured value at the assembly hall 0.9 1/h)

Figure 1 Photo of Assembly hall with air heating in Hämeenlinna, construction year 2006 (left) and Warehouse in with ceiling panel heating in Vantaa, construction year 2008 (right).

Figure 2 Ventilation and air heating in Assembly hall (left), temperature measurement from ceiling and supply air duct can be seen. Warehouse with ceiling panel heating and similar ventilation (right).

In the measurements the pressure difference from outdoor to indoor air was measured by KIMO CP101 pressure transmitter. The measuring range of pressure transmitter was -500 to +1000 Pa with 1Pa resolution and output was displayed in 0-10V or 4-20mA. After that, indoor air temperature was measured by Pt100 temperature sensor. It could measure temperature in between -40°C to +60°C with resolution of 0.1°C and temperature output range was 0-10V. 23 sensors were calibrated in laboratory during 1 hour and 12 sensors were selected which gave similar data. USB temperature loggers were used to measure the outdoor temperature. The measuring range was -40°C to +70°C with resolution of 0.1°C. The USB data loggers also well calibrated in laboratory before onsite measurement.

In this study, KIMO CP101 pressure transmitter integrated with data logger and pressure differences were recorded with 10 second interval in Warehouse and Assembly hall. Temperature sensors in Assembly hall were placed along height with distance of 0.10, 1.86, 3.86, 5.86, 7.06 (supply air point) and 8.66m respectively from floor surface, Figure 3, and measurements were taken from 10.12.2014 to 22.02.2015. In warehouse temperature sensors were placed with distance of .10, 1.86, 4.11, 6.11, 9.13 (supply air point) and 9.83m respectively from floor surface and measurement period was 19.12.2014 to 11.3.2015. Those Pt100 sensors were connected with data logger which recorded temperature in 10 minutes interval. Measurement period of outdoor temperature followed the same measurement duration for both buildings. Two USB temperature data loggers were placed in northern and southern direction in both sites and recoded in 10 minutes interval.

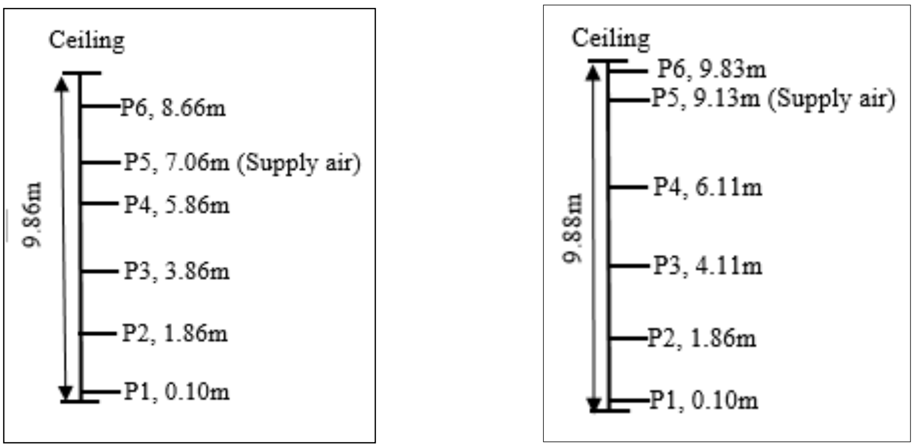

Figure 3 Location of temperature sensors in Assembly hall with air heating system (left) and in Warehouse with ceiling panel heating (right).

3 Results and discussion

3.1 Ventilation need in assembly halls, retail buildings and warehouses

Ventilation need was assessed based on existing standards, scientific literature and building code values. Most of scientific literature was found for retail buildings which are also adequately described in EN 15251:2007 and ASHRAE 62.1-2013 standards as well as in Finnish building code part D2:2012. Industrial halls (neither assembly halls nor warehouses) are not specifically mentioned in EN 15251, but the occupancy and building material emission based method may be applied for them for general ventilation need assessment if specific pollutants are not handled or produced by processes in such halls. In addition to general ventilation, evidently source control (local exhausts) are needed to control polluting processes.

EN 15251 method calculates the total ventilation rate for the breathing zone by combining the ventilation for people and building:

$$q_{tot} = n \cdot q_p + A_R \cdot q_B \tag{1}$$

where

q_{tot} = total ventilation rate for the breathing zone, l/s

n = design value for the number of the persons in the room,

q_p = ventilation rate for occupancy per person, l/(s* person)

A_R = floor area, m^2

q_B = ventilation rate for emissions from building, l/(s,m^2)

With EN 15251 indoor climate category II and low polluting material values in the case of one person per 25 m^2 floor area in industrial halls it results in (1 pers*7 l/(s pers) + 25 m^2* 0.7 l/(s m^2))/25 m^2= 0.98 l/(s m^2). In supermarkets and shopping malls the reported occupancy densities are higher. Karjalainen (2015) ended up with 20 m^2 per person in a weekend rush hour (duration about 6 hours) and for weekday rush hour about 30 m^2 per person (duration 3 hours) in Finnish supermarkets. Stensson (2014) measured occupancy in 11 Swedish shopping malls where maximum occupant densities were 40 m^2 and 14 m^2 per occupant during weekdays and weekends respectively, however in most of shopping malls occupant densities were much lower. 14 m^2 per occupant results in 1.2 l/(s m^2) ventilation rate with EN 15251 equation (with category II and low polluting values) which is the same ventilation rate ASHRAE 62.1-2013 prescribes assuming 11 m^2 per person occupant density.

California's building energy efficiency standards (Title-24) require retail stores to provide adequate ventilation to satisfy both 7 l/s per person and 1.0 l/(s m^2), where the per floor area value is often used for design purposes. At default occupant density, these minimum ventilation rates are similar to the specifications in ASHRAE 62.1-2013. Finnish building code has no minimum ventilation rate requirements but provides recommended default values which may be used in order to comply with general healthy and comfortable ventilation requirement. For industrial halls and retail buildings 2 l/(s m^2) and for warehouses 0.5 l/(s m^2) are recommended. There is no scientific references behind these values, however the high occupant density provides some justification for retail buildings. A common design practice of all air (air heating and cooling with ventilation system) supports higher airflow rates.

Chan et al. (2014) measured ventilation rates and pollutants concentrations in 21 retail stores in California. One naturally ventilated store was clearly below the requirement of 1 l/(s m^2) being 0.4 l/(s m^2), two stores were close to the requirement (0.8 and 0.9 1 l/(s m^2)), 10 in between 1 and 2 l/(s m^2) and 8 had higher ventilation rate than 2 l/(s m^2). Formaldehyde concentrations measured in furniture/hardware stores tended to be higher than in the other two store types and often exceeded California's OEHHA guideline (2014) of 9 μg/m3. Merchandise containing composite wood products was likely a key indoor source of formaldehyde in furniture/hardware stores. The source strengths of acetaldehyde in grocery stores, likely from baking, were much higher than in the other stores. Besides formaldehyde and acetaldehyde, few VOCs with established health guidelines had measured concentrations that were near the levels of concern. The source strength analysis from this study indicated that even if stores were to ventilate at twice the minimum ventilation requirement, formaldehyde concentrations in retail stores would still exceed California health guideline. Therefore, to maintain the formaldehyde levels in retail stores below the guideline value the study concluded that source control instead of increasing ventilation rate is a viable strategy.

In another study Chan et al (2015) measured in grocery stores having adequate ventilation according to ASHRAE 62.1-2013 significantly higher concentrations of acrolein, fine and ultrafine PM, compared to other retail stores, likely attributable to cooking. To lower acrolein concentration a substantial increase in outdoor air ventilation rate by a factor of three from current level would be needed. Alternatively, it was recommended to reduce acrolein emission to indoors by 70% by better capturing of cooking exhaust.

Dutton et al. (2015) measured ventilation rates and concentrations of of volatile organic compounds (VOCs) in 13 stores. Mass balance models were used to estimate ventilation rate that would maintain concentrations of all VOCs below health- or odor-based reference concentration limits. These ventilation rates ranged in between 1 and 10 ach in 11 stores and were even higher in two last stores indicating the importance of the source control.

Ng et al. (2015) modeled in big box retail buildings two ventilation strategies: (1) 1.2 l/(s m^2) of outdoor air during occupied hours, which is the ventilation rate prescribed in ASHRAE 62.1-2013 for retail buildings assuming approximately 9 occupants per 100 m^2, and (2) 0.4 l/(s m^2) 24 h a day based on the IAQP analysis performed by Bridges et al. (2013). In Bridges et al. (2013), the concentration of formaldehyde, selected VOCs, and carbon monoxide (CO) were measured over 48-h periods in retail buildings. The 0.4 l/(s m^2) ventilation rate was based on the minimum calculated ventilation rate required to maintain formaldehyde below 100 $\mu g/m^3$, TVOC below 1000 $\mu g/m^3$, and CO below 10 mg/m^3 assuming steady state conditions. This study demonstrated that ventilating at a lower rate (0.4 l/(s m^2)) for 24 h a day saved energy compared with ventilating at the higher rate (1.2 l/(s m^2)) and that the simulated indoor contaminant concentrations did not exceed common benchmarks or health guidelines, however the higher rate led to somewhat lower concentrations.

The importance of adequate ventilation was shown in the survey by Zhao et al. (2015). This study including 611 employees in 14 retail stores concluded that the air exchange rate is the most influential parameter on the employee perception of the overall environmental quality and self-reported health outcome. Measured air change rates were in between 0.2 – 1.5 1/h and it was found that when the air change rates increased from 0.6 ach to 1.2 1/h, the probability of common cold infection frequency decreased by 43%. It should be noted that in the case of 4 m room height 1.2 1/h corresponds to 1.3 l/(s m^2).

Available evidence in these studies shows that general ventilation only cannot remove pollutants in all cases such as merchandise containing composite wood products or poor capturing of cooking exhaust. If source control (i.e. local exhausts) will be applied for such cases the values in EN 15251 and ASHRAE 62.1 standards, i.e. about 1.0 l/(s m^2) for industrial halls with lower occupancy and about 1.2 l/(s m^2) for retail stores with high occupancy are likely to be reasonable approach for general ventilation. In the case of all air systems (heating and cooling via ventilation), required air flow rates are to be checked based on heating and cooling needs and if necessary air flows may be boosted by recirculation.

3.2 Vertical temperature gradient measurement results

In this section the temperature gradient measurement results over a 3 month period are reported in Warehouse with ceiling panel heating and Assembly hall with air heating system.

The operational strategy of both systems was not similar during office and non-office hour. Results are presented for Office Hour (OH) and Non Office Hour (NOH) so that OH were considered from 8-18 hours during weekdays and rest of hours in a week were considered as NOH. Heat was distributed in Assembly hall by ceiling supply air valves and supply air temperature was found in between of 18.5 to 20.5°C which compensated with outdoor air temperature. In Warehouse heating was provided by ceiling panels and partly also by supply air valves. The supply temperature from ceiling valves was in between of 18.0 to 19.5°C based on outdoor temperature. Air temperature at different height from floor level during OH is shown in Figure 4.

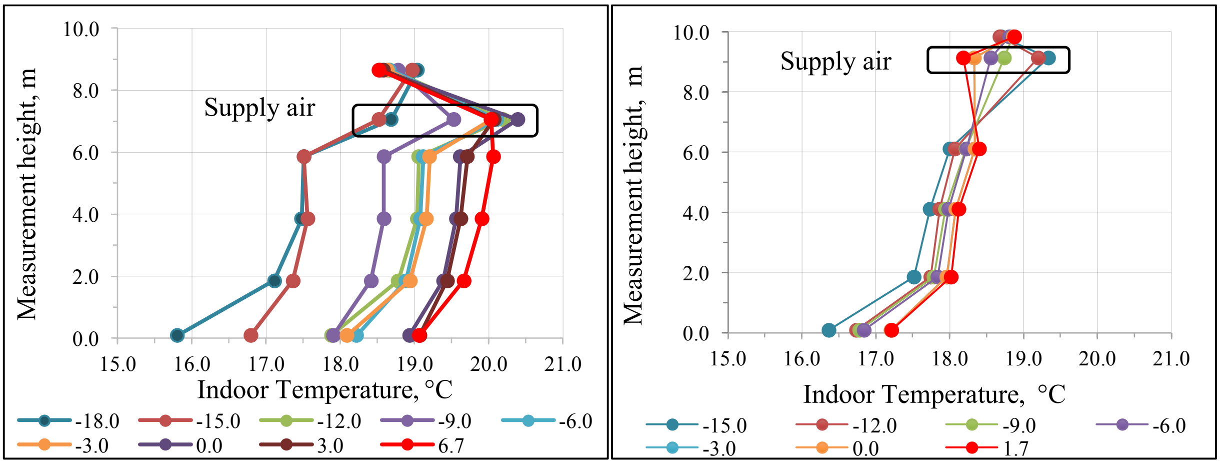

Figure 4. Temperature at different height during OH in Assembly hall with air heating system (left) and in Warehouse with ceiling panel heating (right). Indoor temperature curves at different outdoor temperatures are marked with colour codes.

Figure 4 shows the indoor temperature behavior along height at different outdoor temperatures. Outdoor air temperature has stronger impact on indoor air temperature in air heating system compared to ceiling panel heating. The average temperature at point P1 and P2 were 18.9 and 17.6 °C for Assembly hall and Warehouse respectively during measured OH period (see locations from Figure 3). In NOH supply air temperature was decreased in Assembly hall and in Warehouse the ventilation was switched off. The results from NOH are shown in Figure 5.

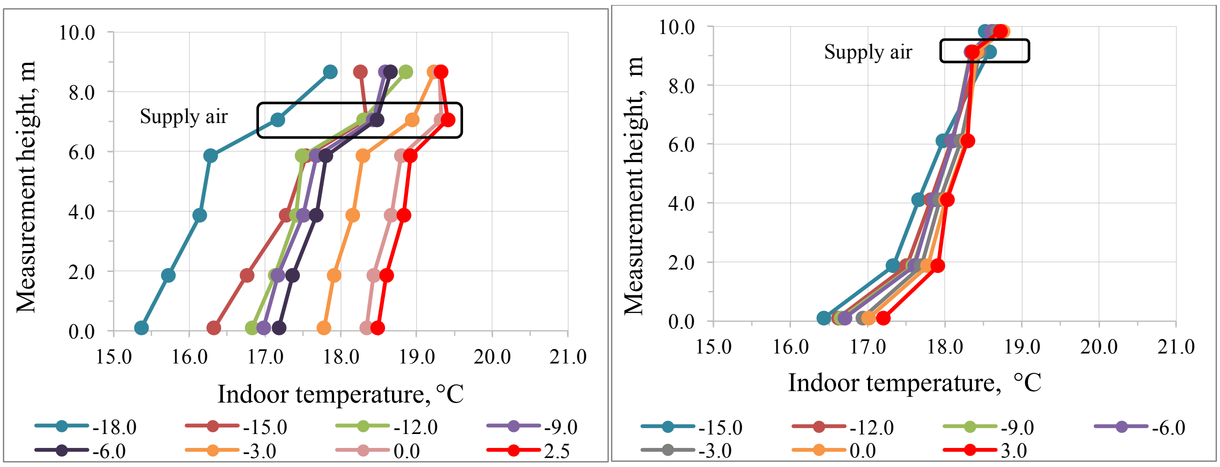

Figure 5. Temperature at different height during NOH in Assembly hall with air heating system (left) and in Warehouse with ceiling panel heating (right). Indoor temperature curves at different outdoor temperatures are marked with colour codes.

During NOH the average temperature at point P1 and P2 in Assembly hall and Warehouse were recorded of 17.9 and 17.3°C respectively. With lower supply air temperature indoor temperature dropped in Assembly hall. The supply air temperature difference during OH and NOH is shown in Figure 6 where indoor temperature is calculated as an average value of P1 and P2 measurement points. In the case of NOH in Warehouse, supply air temperature (ventilation switched off) corresponds to indoor temperature at supply air valve height.

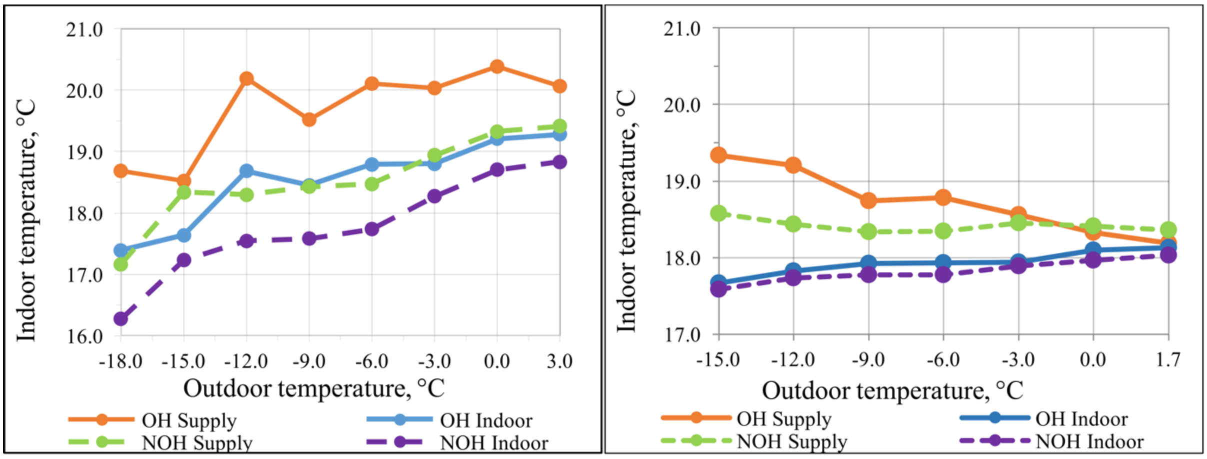

Figure 6. Supply and indoor temperature during Office hour (OH) and Non office hour (NOH) in Assembly hall with air heating system (left) and in Warehouse with ceiling panel heating (right).

Figure 6 illustrates air heating performance in Assembly hall, however at low outdoor temperatures there seems to be a lack of supply air heating capacity. Results are unexpected in Warehouse where ceiling panel heating is a main heating source, but supply air is also heated. Ceiling heating has likely been an additional installation and supply temperature curve has not been corrected afterwards to a constant setpoint which could be expected as a common operation mode for ceiling heating.

Heating source location had an effect on temperature gradient along building height. In Assembly hall supply air valve was located 7.06 m from ground floor and visible difference of gradient was observed from measured points P1-P4 and P4-P6. In Warehouse ceiling panel was the primary source of heating and the supply air at 9.13m from ground floor had smaller effect on temperature gradient. Temperature gradient from ground floor to below supply air valve (P1-P4 point) and over supply air valve to ceiling (P4-P6 point) is shown in Figure 7.

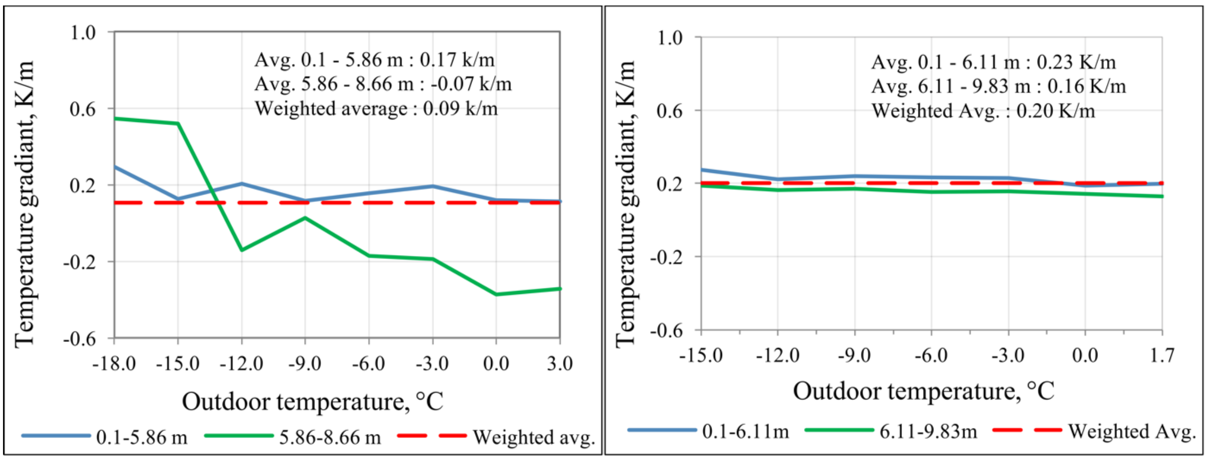

Figure 7. Average value of gradient during OH in Assembly hall with air heating system (left) and in Warehouse with ceiling panel heating (right).

The negative temperature gradient in Assembly hall indicated that nearby ceiling air temperature was colder compare to the supply air temperature for air heating system. The temperature gradient from point P1-P4 was steady compared to point P4-P6 in Assembly hall. In Warehouse, temperature gradient was quite steady and outdoor temperature had less effect on it. The weighted average temperature gradient during OH were 0.09 and 0.2 K/m for Assembly hall with air heating system and Warehouse with ceiling panel heating respectively. During NOH the scenario of temperature gradient had changed because of lower supply air temperature/switched off ventilation, Figure 8.

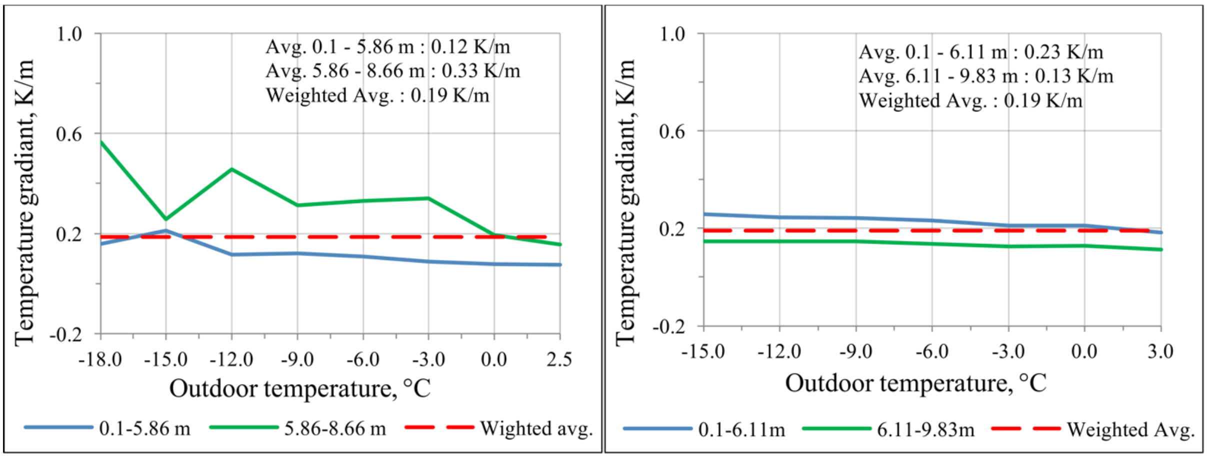

Figure 8. Average value of gradient during NOH in Assembly hall with air heating system (left) and in Warehouse with ceiling panel heating (right).

During NOH the supply air temperature was low compared to OH and its effect was clearly visible at weighted average and average temperature gradient in Assembly hall. In Warehouse almost similar results were found during OH and NOH. In addition, outdoor temperature had less significant effect on temperature gradient compared to Assembly hall. The difference of weighted average temperature gradient during OH and NOH was 0.1 K/m in Assembly hall whereas in Warehouse it was very small i.e. 0.01 K/m.

4 Conclusions

This study conducted vertical temperature gradient measurements and ventilation need review on thermal comfort, general ventilation and energy assessment purposes in large hall buildings. The results serve as an input data for energy analyses which will be conducted in future study.

Ventilation need review indicates that ventilation in Finnish industrial hall buildings is commonly oversized by about factor 2 based on the default values of the Finnish building code. Available evidence suggests that about 1.0 l/(s m^2) general ventilation is needed in industrial halls with lower occupancy and about 1.2 l/(s m^2) in retail stores with high occupancy up to 11 m^2 per person occupant density. There is reported evidence that general ventilation only cannot remove pollutants in all cases such as merchandise containing composite wood products or poor capturing of cooking exhaust. In such cases source control (local exhausts) is needed to remove effectively pollutants and this has been more effective measure than increasing general ventilation rate.

Measured results showed about 0.2 K/m vertical temperature gradients in both halls which was expected result for the ceiling panel heating, but by factor 5 smaller for air heating than the guidebook value. Ventilation with high airflow rate, well insulated building and significant lighting power during operating hours are possible reasons explaining very small temperature gradient in the air heating case. Temperature gradients kept reasonably constant at all measured outdoor temperatures and there was no difference between air heating and ceiling panel heating. The only difference observed was the higher fluctuation of room temperature in the case of air heating indicating some limitations in the temperature control of air heating.

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WINDSOR CONFERENCE 2016

MAKING COMFORT RELEVANT

WORKSHOP 1.2

Putting People in to Building Comfort Models

Invited Chairs: Boris Kingma and Paul Tuohy

WS1.2: Putting People into Building Comfort Models.
Chairs: Boris Kingma and Paul Tuohy

This workshop deals with modelling thermal comfort and aims to harvest ideas and allow space for discussions around the challenges of representing the wide variability of people into building comfort and energy models. This includes the identification of sub-populations that can be stratified by age, gender and body composition (e.g. lean vs. obese). The workshop will focus on 1) physiological differences between these sub-populations, and the consequences on thermal demand & health, 2) commonly used software packages of building comfort and energy models, and how they should be adjusted to better represent all occupants, their comfort demands, and impacts on energy use etc. so that comfortable low energy buildings can be achieved.

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Pervasive and real-time Indoor Environmental Quality (IEQ) monitors

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Abstract

The green buildings sector in Australia has, to date, focused primarily on energy efficiency. Other dimensions of building sustainability such as Indoor Environmental Quality (IEQ) are less well developed and certainly less well understood by the industry. With concern for occupant productivity burgeoning in recent years the green building spotlight is shifting onto IEQ as a key performance indicator. This paper describes a radically new approach to IEQ monitoring based on low-cost desk-based devices (SAMBA) that include sensors for thermal comfort (air and radiant temperatures, air speed and humidity), acoustics (SPL), lighting (lux) and air quality (CO_2, CO, TVOC, Formaldehyde and PM10). Relatively modest unit-cost makes it feasible for SAMBAs to be installed in each HVAC zone of large office buildings. The SAMBA network architecture is a self-forming mesh that does not require access to the host organisation's ICT infrastructure. Observational data are relayed wirelessly to a gateway placed centrally within the building that transmits data through the public cellular network to the IEQ Laboratory's server every 15 minutes. Various IEQ indices and compliance metrics are calculated in real-time and presented on a web-based IEQ dashboard to which the building operator and any other interested parties (e.g. owner, tenant, occupants, public) have access. This new approach to pervasive and continuous performance monitoring ushers built environmental quality into the "Internet of Things" and opens up completely new IEQ field research opportunities.

Keywords: Indoor environmental quality; acoustics; indoor air quality; thermal comfort, lighting.

1. Introduction

In the past couple of years Australia's commercial building sector has been paying increasing attention to Indoor Environmental Quality (IEQ), mainly in response to concerns about IEQ impacts on the performance of office-based workers which are compounded by steady increases in personnel costs. Even though scientific quantification of this link remains contentious (e.g. de Dear et al, 2013) there seems little doubt that more satisfied building occupants with higher levels of comfort generally translate into better outcomes for the organizations leasing the building (e.g. Newsham et al.,2008).

Building sustainability rating tools such as Green Buildings Council Australia's "Green Star - Performance" (GBCA, 2015) and the National Australian Built Environment Rating System "Indoor Environment" (NABERS, 2015) specifically assess indoor environmental quality of buildings using two broad strategies; occupant questionnaires called Post-Occupancy Evaluations (POE), and instrumental measurements of physical conditions inside the building. Despite the inconvenience of collecting instrumental data they remain an important part of the IEQ rating process simply because of the lingering suspicions that non-building issues such as industrial relations and staff morale may "contaminate" ratings of their workplace environment on a POE questionnaire. Instrumental measurements are seen as an objective check on the validity of subjective evaluations captured by POE questionnaires. Clearly there will always be a role for instrumental measurements when assessing building IEQ performance (Heinzerling, 2013).

Measurement of IEQ inside a building reduces to a spatio-temporal sampling problem. Many of the key IEQ parameters are characterised by significant variability in spatial and temporal dimensions, and to accurately capture that variability with a sample of instrumental IEQ measurements inside a building poses several technical and logistical challenges. The **spatial variability** of IEQ variations can be at the scale of HVAC zone (perimeter versus core zones, east versus west zones in morning and afternoon, north versus south zones in summer versus winter). Some IEQ parameters demonstrate variances on an even smaller spatial scale, for example, in terms of metres in the case of air speed, which is directly related to location of air-supply vents and the often-complex flow patterns within a room filled with air. Specific IAQ parameters such as Total Volatile Organic Compounds (TVOC) can also demonstrate sharp spatial gradients and variations, depending on proximity to individual emission sources such as cleaning detergents, particular furniture items, or even particular fit-out materials such as drapes. Mean radiant temperature within a space also exhibits significant spatial heterogeneity, depending on proximity to heat-emitting appliances such as computer terminals or photocopiers, or complex and changing patterns of direct solar penetration onto the building floor-plate through the large expanses of un-shaded perimeter glazing that is so popular in contemporary office building architecture. Indeed, it was this inherent spatial heterogeneity of mean radiant temperature that was successfully used to argue for the exclusion of that parameter from the NABERs Indoor Environment rating scheme (2015), despite the fact that mean radiant temperature is as important as air temperature in determining human thermal comfort sensations (ASHRAE, 2015).

As with spatial scales, the **temporal dimension** of IEQ parameters within buildings is characterised by considerable variability, including cycles and random variations across multiple timescales ranging from second-to-second turbulence, through diurnal cycles, up to synoptic-scale changes in the daily weather conditions outside the building, up to seasonal-scale variations in solar position, deciduous tree shading, and general outdoor meteorological environment. Air temperature time-series within office buildings demonstrate complex ebbs and flows as HVAC systems start-up and shut-down at either end of the working day. Likewise with indoor air quality, bellwether parameters such as CO_2 concentrations that reflects the tidal flows of building occupants at the start, middle and end of the working day. The mix of daylight to artificial lighting inside a building responds to the sun path arc from one side of a building to the other, through the course of a day, and the background noise level inside a contemporary sealed-facade office building is overwhelmingly dominated by occupant density that fluctuates dramatically several times in a working day.

2. Previous instrument solutions to the IEQ sampling problem

In view of the inherent spatial and temporal heterogeneity of IEQ parameters within a building it is perhaps surprising that some IEQ rating tools have deemed a one-day sampling strategy to be sufficient to characterise the indoor environmental quality of a building. For example, Australia's NABERS IE (2015) allows a consultant to do a one-day walk-through sample of the key IEQ parameters on a random selection of floors in morning and afternoon periods. Apart from missing most of the spatio-temporal variability described above, a one-day on-site measurement campaign encourages the unscrupulous building owner/operator to "game the system" i.e. temporarily optimise the building management system settings for the duration of the measurement campaign and then revert to less-than-ideal settings once the IEQ rating has been made, in order to minimise energy consumption.

The ASHRAE/USGBC/CIBSE Performance Measurement Protocols (PMP) (2010) prescribes three levels of measurement detail: Basic, Intermediate and Advanced. Instrumental measurements prescribed in the Basic protocol include spot measurements with a hand-held temperature, humidity, air speed, illuminance and sound pressure level meters. The intermediate PMP protocol requires time-series (datalogger) observations of air and mean radiant temperatures, relative humidity, occupied zone air speed, CO_2, and vertical plus horizontal surface light-level measurements. The required acoustic measurements include sound pressure level using a meter with parallel octave band filters and a noise source for calculation of background noise and reverberation time respectively (Kim, 2012). To test at the ASHRAE/USGBC/CIBSE Advanced PMP level (ASHRAE, 2010) requires air and radiant temperatures, humidity, air speed, CO_2, PM2.5, and TVOC sensors to be logged continuously for a defined sample period, while the requisite lighting measurements include a High Dynamic Range (HDR) camera and software that can create an HDR image. Advanced PMP level acoustics requires measurements with a sound pressure level meter equipped with a parallel one-third octave band filters and a noise source such as loudspeakers for evaluations of speech privacy, speech communication and sound and vibration isolation respectively (Kim, 2012).

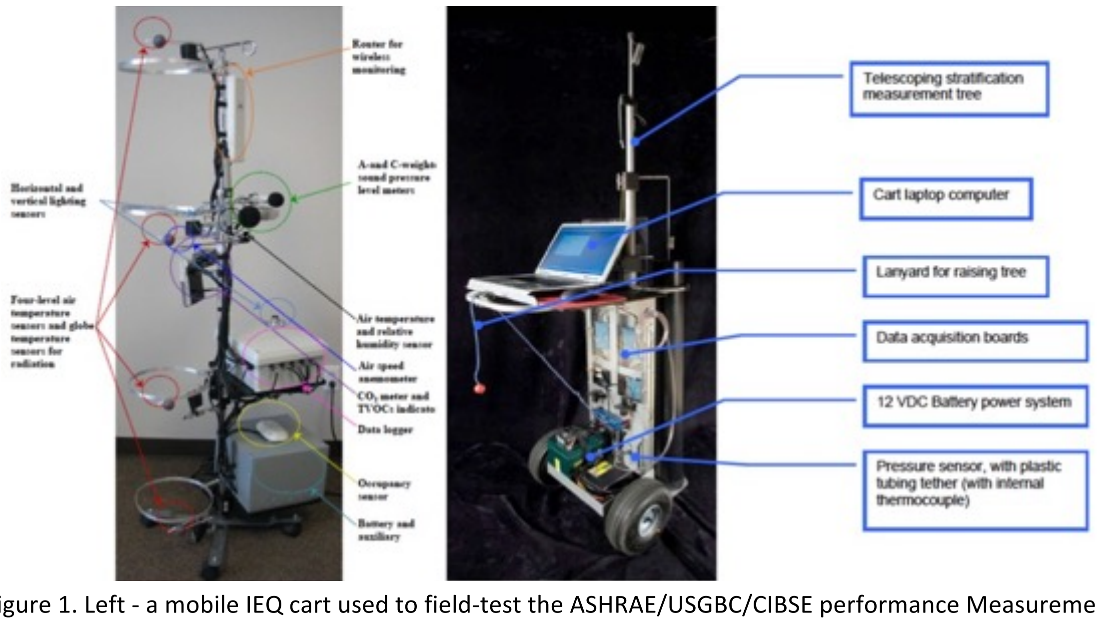

Figure 1. Left - a mobile IEQ cart used to field-test the ASHRAE/USGBC/CIBSE performance Measurement Protocols (Kim, 2012); Right - a mobile IEQ cart with telescopic mast of temperature sensors designed to specifically commission underfloor air distribution systems (Webster et al, 2007).

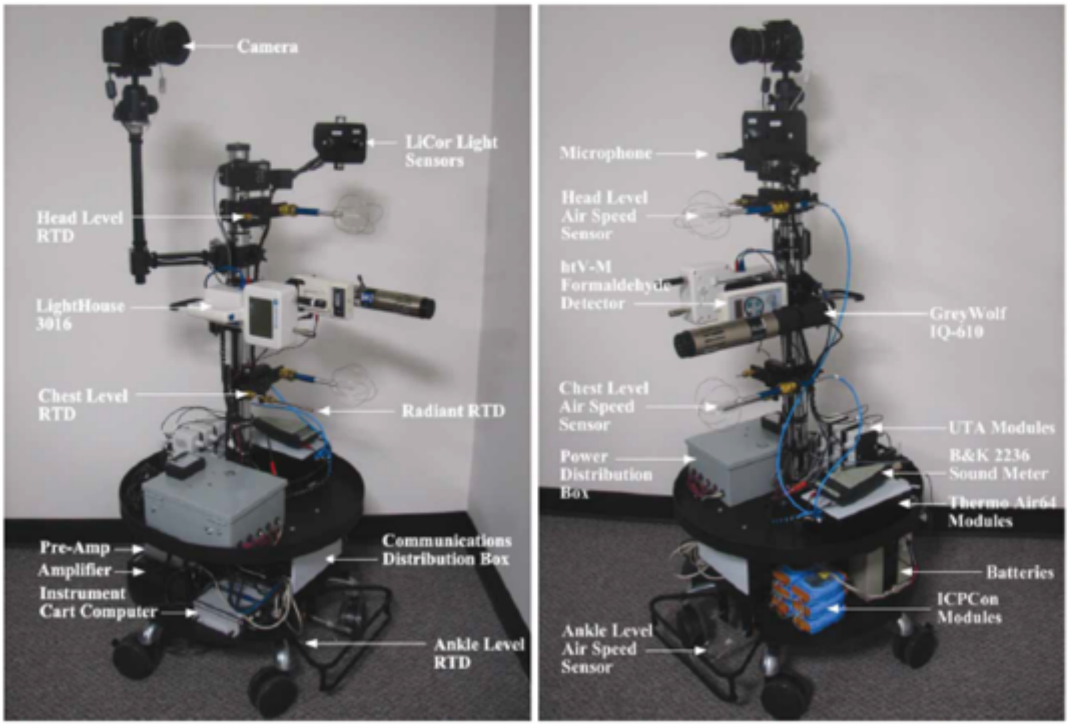

Figure 2: Perhaps the most sophisticated mobile IEQ cart to date includes most transducers required by the ASHRAE/USGBC/CIBSE PMP Advanced Level protocol (Newsham et al, 2013).

IEQ researchers have developed a variety of solutions to the problem of registering spot measurements inside buildings. Typically they have involved a mobile cart of some sort with an on-board data-logger into which the various transducers have been wired. The cart is typically wheeled around inside the building and the data-logger is randomly triggered to perform a sweep of all transducers. Figures 1 and 2 depict some examples of various carts from the recent research literature.

In all these mobile cart examples (Figures 1 and 2) the design strategy has simply been to select off-the-shelf, laboratory-grade instruments for each one of the individual IEQ parameters of interest, and then hard-wire them into a centralised datalogger. The end result, without exception, has been a prohibitively expensive apparatus that requires a human operator to wheel through the space and to periodically trigger the datalogger to poll all transducers, time-stamp their data, and store them all in memory for safe retrieval after a day "on the job." The prohibitive expense of this IEQ measurement solution arises from three main causes;

- The individual off-the-shelf instruments themselves are exorbitantly priced because of the relatively small "scientific" market, even if the actual transducer component being used is abundantly available and modestly priced (e.g. a turnkey hand-held CO_2 instrument can easily cost two orders of magnitude more than the actual non-dispersive infra-red sensor component sitting at its centre).
- Mobile IEQ measurement carts require a human operator to steer them along their "random sampling trajectory" within a building. The labour cost, including associated on-costs such as worker insurance and payroll tax, for a technically skilled engineer or research assistant conspire to make the on-site day an expensive proposition.

- Logistical complexities (inter-city air freight or even just intra-city road transport) and the associated insurance costs of placing an elaborate and extremely delicate scientific apparatus (e.g. Figures 1 and 2) on-site, all add significantly to the overall costs of a day of IEQ sampling inside a building.

As a result of these factors, measurement of a building's IEQ is exorbitantly expensive and beyond the reach of most building owners in the Australian commercial buildings sector. There are only a handful of IEQ consultants operating in the Australian market and the mainstay of their business is collection of the requisite data for NABERS IE ratings. But the demand for NABERS IE ratings has been very low since the rating scheme's inception inception, prompting the NABERS organisation to fundamentally redesign the IE rating protocol in 2014/15 (NABERS, 2015). The stated aim of that review was to reduce the costs of collecting the IEQ data and applying for the IE rating.

3. Introducing SAMBA IEQ monitoring stations

The basic aim of the SAMBA project (**S**entient **A**mbient **M**onitoring of **B**uildings in **A**ustralia) was to design a small, low-cost, autonomous IEQ monitoring device that could be placed permanently at multiple sampling points across the occupied zone of a building floor-plate (spatial sampling) and on multiple levels of a multi-storey building (vertical sampling). Permanent placement of such devices could allow longitudinal measurements through time (i.e. all occupied hours for weeks, months, seasons or even years). In this way it would be possible to capture a truly representative picture of a building's IEQ performance – not just on "a good day."

The expected Australian end-users of such a system for IEQ performance monitoring and improvement include, but will not be limited to;

- IEQ researchers.
- Building owners seeking market advantage in the highly competitive commercial property sector (includes portfolio and individual building owners).
- Commercial building tenants seeking to ensure that the building they are leasing is providing an indoor environment at a quality level specified in their lease.
- Building services engineering firms.
- Architectural and interior design firms.
- Office fit-out firms.
- The Property Council of Australia.
- Green Building Council of Australia (Green Star-Performance).
- National Australian Built Environment Rating System (NABERS Indoor Environment).
- Facilities Management firms and consultants.
- Building services and FM accredited assessors for NABERS IEQ and Green Star-Performance.

1.1 SAMBA's sensors

Decisions about which sensors to include in SAMBA were made largely on the basis of the specifications in Australia's NABERS Indoor Environment (IE) rating tool (2015), but also on component costings. The list of IEQ parameters can be found in Table 1 and cover the four key IEQ areas of thermal comfort, indoor air quality, lighting and acoustics. The SAMBA hardware design integrates a low-cost suite of sensors into a small monitoring station intended to be placed on the desk surface (i.e. occupied zone) in a random selection of workstations throughout the building. Rather than focusing on laboratory-grade measurement practices which are appropriate for detailed workplace health audits and perhaps forensic investigations (see Figures 1 and 2 above), SAMBA's sensing capabilities have been scaled to the application at hand – 'good-enough' real-time data – thus allowing very substantial reductions in both hardware costs and also on-site technical personnel costs.

Figure 3: The SAMBA desktop IEQ monitoring system. Heat sensitive sensors are in the small satellite unit while heat generating components and other heat-insensitive sensors reside in the larger unit. A flat Ethernet cable connects the two units while a mains power cable exits the base of the main unit.

1.2 Calibration of SAMBA's sensors

SAMBA comes with the caveat that it is not intended to be a laboratory-grade or forensic-grade IEQ data acquisition system. Referring to the ASHRAE/USGBC/CIBSE nomenclature for performance measurement protocols SAMBA would qualify at the BASIC measurement protocol, with parts of the INTERMEDIATE protocol covered as well. SAMBA definitely would not withstand legal scrutiny in a forensic context. Nevertheless we have conducted a series of in-house calibration of the SAMBA sensors against laboratory-grade reference instruments across the range of parameters reasonably expected inside office buildings (Kim, 2012). On the basis of explained variance (R^2) of the relationship between SAMBA sensor and the relevant calibrated laboratory-grade reference instrument listed in Table 1, the suite of sensors selected for SAMBA are consistent with the performance specifications of ASHRAE/USGBC/CIBSE Basic Level (ASHRAE, 2010). To safeguard against calibration drift, the SAMBA device is swapped over, new for old, at the end of every 12 months in service. Each new SAMBA device is laboratory-calibrated using the reference equipment described in Table 1 before being sent out into the field.

Table 1: The suite of transducers selected for SAMBA and their calibration performance against relevant laboratory-grade reference instruments.

Parameter	SAMBA Transducer Type	Measure-ment Range	Resolution	Accuracy	Calibration Reference Instrument	Calibration R^2
Air temperature	NTC thermistor	-40 to 125°C	0.04°C	±0.3°C	Innova 1221 Comfort Logger w/ MM0034 air temperature transducer	0.99
Relative humidity	Capacitive humidity sensor	0 to 100%	0.1%	±2%	Innova 1221 Comfort Logger w/ MM0037 air humidity transducer	0.98
Globe temperature	NTC thermistor	-40 to 125°C	0.04°C	±0.2°C	Innova 1221 Comfort Logger w/ MM0034 air temperature transducer	0.99
Air speed	Hot-wire anemometer	0 to 2m/s	0.01m/s	±5%	Dantec 54T21 omni-directional anemometer	0.98
Carbon dioxide	Non-dispersive infrared	0 to 5000ppm	1ppm	±30ppm ±3%	CET AST-IS infrared CO_2 sensor	0.97
Particulate Matter	Photodiode	0.001 to 1 mg/m3	0.001mg/ m3	-	TSI DustTrak II Aerosol Monitor 8532	0.99
TVOC	Photo-Ionisation Detector	0.001 to 50ppm	0.01ppm	-	N/A	-
Carbon Monoxide	Electrochemical	0 to 500ppm	1ppm	-	N/A	-
Formal-dehyde	Electro-chemical	0 to 5ppm	0.01ppm	-	N/A	-
Sound Pressure Level	Electret condenser microphone	-	-	-	N/A	-
Illuminance	Broadband photodiode	01 to 40,000 lx	0.1 lx	±3 lx	Konica T10A Minan Meter	0.99

1.3 SAMBA gateways

SAMBA's autonomous IEQ performance data acquisition and transmission does not require access to or cause disruption to any of the host building's existing services or information/communication networks. Data network autonomy was a design priority because of the extremely sensitive nature of many of the host buildings' data operations. As depicted in Figure 4, SAMBA's IEQ data stream is periodically transferred, using our own *ad hoc* wireless mesh network, back to a gateway that is centrally located within a building. A single hub is configured to service all SAMBA monitoring stations within each building if none of the SAMBAs are more than one or two storeys distant from the rest of the units in the SAMBA mesh network. The gateway collates time-series data from all nearby SAMBAs and transmits them through the public cellular telephone network to a remote server for quality assurance and subsequent assimilation into the IEQ Lab's cumulative database.

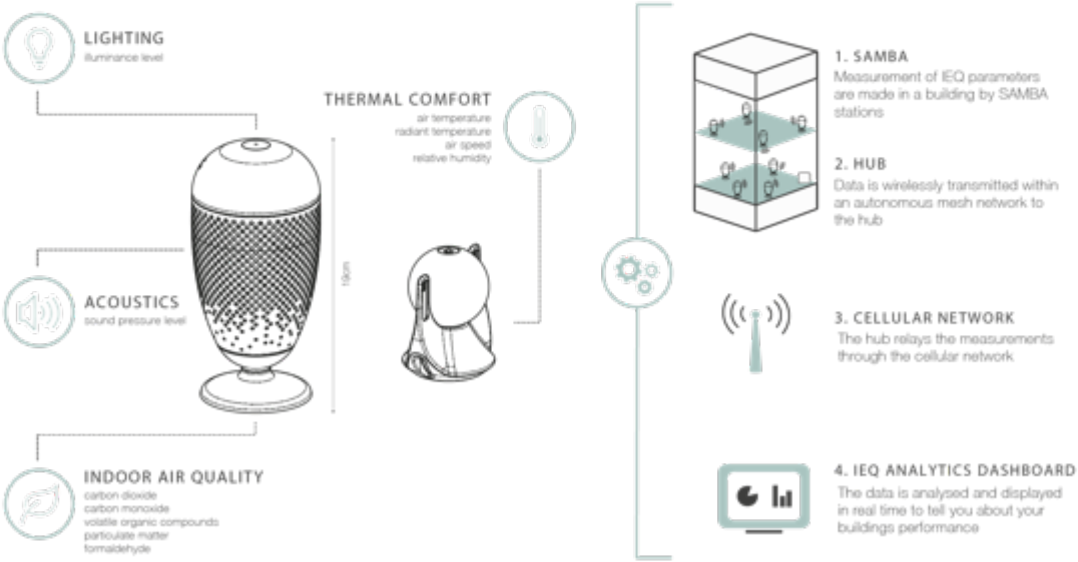

Figure 4. The SAMBA and IEQ Analytics concept diagram

1.4 IEQ analytics dashboard

Once they have been assimilated into the IEQ lab server SAMBA's data undergo some automated statistical analyses and visualization scripts for on-line reporting procedures. The online portal, shown in Figure 5, has been specifically designed for interpretation by building facility managers (often non-technical personnel in Australia's commercial buildings sector), and it delivers a timely and concise visualization of all measured IEQ parameters. All data are compared alongside the relevant IEQ standards and rating criteria (e.g. GreenStar "Performance" and NABERS "IE") to give building operators, owners and their tenants concise and accessible reports on their building's IEQ performance. The IEQ Analytics portal was designed after extensive consultation and with a large sample (over two dozen) of industry stakeholders during three months of pilot testing in Sydney and Melbourne commercial office buildings early 2015.

Figure 5. The IEQ Analytics dashboard is a website that displays a building's real-time IEQ performance data (SAMBA data) in a format that is intelligible to, and useful for a building facility manager.

Apart from displaying measured parameters the dashboard also displays some derived comfort indices. For example, in the thermal comfort section of the dashboard is a real-time stream of PMV/PPD calculations (ASHRAE, 2013). SAMBA collects all the requisite environmental parameters for these industry-standard comfort indices (air temperature, globe temperature, air speed and relative humidity) and once the data have been transmitted to the server, the first three parameters are used to calculate a mean radiant temperature. Apart from four environmental parameters PMV/PPD requires estimates of two so-called personal parameters, namely building occupants' metabolic rate and the intrinsic insulation value of the clothing ensembles being worn indoors. On the basis of extensive surveys in office buildings across Australia that have been collated together in the ASHRAE Global Thermal Comfort Database (de Dear, 1998) an estimate of 1.2 met units has been adopted in SAMBA's PMV/PPD calculations. Building occupant clothing insulation is estimated in real-time using ASHRAE Standard 55's (2013) statistical clothing model that is based on a running mean of outdoor air temperature, the latter being supplied by the closest automatic weather station and scraped from the internet by our servers on an hourly basis.

4. Research opportunities created by SAMBA

SAMBA provides a method for the efficient data acquisition of IEQ parameters *en masse*. Apart from providing timely and actionable IEQ performance data to building operators and facility managers, it opens up rich new possibilities for building science research. First and foremost SAMBA will feed the world's largest commercial building IEQ performance database. Such an extensive database of IEQ measurements will allow for a range of scientific investigations through data-mining, particularly when combined with subjective IEQ measurements from building occupants. For example, the database could be used to identify trends such as the recently discussed "indoor climate change" – the observation that indoor summertime air conditioning temperatures have been drifting lower in Australia and North America, in contrast to upward trends across parts of East Asia (de Dear, 2012).

Exploration of the multimodal interaction effects of different IEQ vectors in commercial buildings would also be possible with SAMBA. This research topic is underdeveloped partly due to the methodological difficulties in collecting the appropriate data from the field. SAMBA combined with smartphone questionnaire affords the researchers the opportunity of polling survey respondents with a right-here-right-now questionnaire precisely whenever the indoor environmental conditions meet specific values, or combinations of values of interest to the research question (e.g. dBA and ^{o}C). Traditional thermal comfort field studies have always had to make do with whatever data are "caught in the net" of their survey campaign, often resulting in independent variable ranges that are too small for some of the most useful statistical procedures such as regression to be applicable. And this problem has not always been remedied by enlarging the sample size because the new data is most likely to fall in the same bins that already have enough. But SAMBA can help researchers populate bin in their research design matrix with just the right quantity of responses, bringing a level of data efficiency and statistical power to field studies that is normally reserved for controlled laboratory experiments.

The research potential of SAMBA is not limited to commercial office buildings either – these low-cost IEQ monitors afford the possibility of conducting investigations of IEQ in residential settings, health-care facilities, retail facilities, or educational institutions. Pervasive and continuous monitoring of indoor environmental quality with these devices opens up completely new field research opportunities that have not previously been feasible.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
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Utilising Calibration to Quality Assure CFD Models for Predicting Thermal Comfort in Naturally Ventilated Buildings Designed for High Occupancies

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Abstract

This paper discusses application of Computational Fluid Dynamics (CFD) software to predict occupant comfort in large auditoria. CFD simulates three-dimensional airflow within a space. The modelling process is documented for a case study of Wellington's Opera House, New Zealand. Constructed in 1913, the Opera House was designed to ventilate without mechanical assistance while seating 2,000 people. Original plans show a sliding roof and sliding ceiling system above the main seating. This system is no longer in use and, despite comfort complaints, no mechanical system has been added. An upgrade to the non-existent ventilation system in the Opera House is imminent. To calibrate the CFD simulation of the existing situation temperature sensors were located throughout the auditorium. Recordings from a warm evening when the Building was empty and real time external data from the Wellington Weather Station provide the calibration data. The ability of a CFD model to reproduce the stratified airflow within the space has been assessed by comparing predicted to measured temperatures.The goal of this exercise is to quality assure the CFD simulation to build a reliable model, and therefore enable a degree of trust for upcoming iterations with measured data from the forthcoming Arts Festival when the auditorium is in regular use. The goal is to provide a tool with which to explore occupancy comfort if natural ventilation is reintroduced to the Opera House.

Keywords: CFD, Natural Ventilation, Simulation, Calibration, Wellington Opera House

1 Introduction

Large, institutional, unreinforced masonry buildings designed in the early 1900s are prevalent throughout New Zealand's towns and cities. With risk of seismic activity, many of these high occupancy buildings are scheduled for strengthening renovations. The seismic strengthening process creates an opportunity to improve other aspects of these buildings simultaneously, such as internal environment quality and therefore occupancy comfort. Many of these buildings are from an era when natural ventilation was a part of their design, but that has since been compromised or replaced with mechanical systems. Understanding the intended airflow of these original systems may enable their restoration. A second incentive for developing this understanding is the potential that a better understanding of these traditional solutions may enable more effective design of natural ventilation systems for new buildings with a similar purpose and scale.

Computational Fluid Dynamics (CFD) software has the potential to predict airflow within a space, allowing a simulated analysis of an existing building's airflow. In order to utilise CFD simulation in the early stages of design, a degree of trust is needed regarding the results produced by the software. Before design iterations can be tested, in order to alter and ultimately improve the airflow within a building, the existing situation must be simulated and calibrated against reality.

This paper documents the process of calibration for the existing situation of one case study, Wellington's Opera House. While this study is based on CFD analysis, ultimately the measure of success for subsequent design alterations is the comfort of people within the auditorium. Accordingly, calibrating the CFD modelling by using temperature readings from within this space relates directly with the purpose of the CFD modelling process, and allows calibration utilising a measure that is more feasible to assess than air movement.

1.1 The Case Study – Wellington's Opera House

Located in New Zealand's capital city, Wellington's Opera House was constructed in 1913. Originally designed with a capacity of 2,141 people, the Opera House boasted an innovative sliding roof and ceiling system designed by Australian architect William Pitt (Sawyer, 2009).

The Opera House is a challenging case study, due to its high occupancy, complex design, and heritage value. The fresh air design was similar to other buildings in Australia, Europe, and North America around this time. Original plans of the Opera House show the sliding roof and ceiling system above the main seating area, as can be seen in figure 1. This void was the Building's main opening to fresh air.

Within 15 years of the building's construction this system was no longer in use; the sliding roof was rumoured to have only ever opened once (Adnett, 1927). The reason for this innovative system's lack of use is not documented, and therefore it is unknown whether it was a successful ventilation system.

Since construction, several renovations have been undertaken, including three stages of major seismic strengthening between 1977 and 1982. Existing penetrations in the auditorium were covered in or reduced to improve the structural integrity (Christianson, 1983). The hatching in figure 2 below shows the penetrations in the original construction of the Opera House that were blocked during the 1977-85 upgrades. These renovations have masked the natural ventilation systems expected to be included in a Pitt design of this era.

The existing Opera House has a capacity of 1,381 people, and is on the Wellington City Council's list of earthquake damage prone buildings (PWV, 2015). There are three levels of seating; the stalls, dress circle, and grand circle. The Building is currently in use for performances. The Opera House has an impending seismic renovation, easy accessibility, and a history of an innovative natural ventilation system. Therefore, a trustworthy calibrated CFD simulation of the existing Opera House is potentially useful.

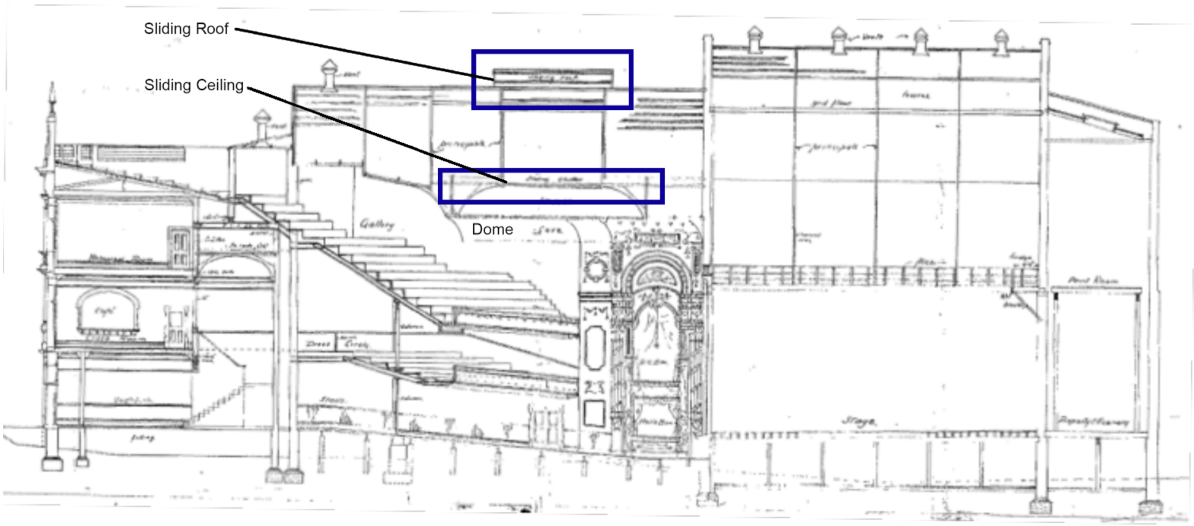

Figure 1. Longitudinal Section of the original plans for the Opera House, showing the sliding roof and ceiling system (Pitt, 1913)

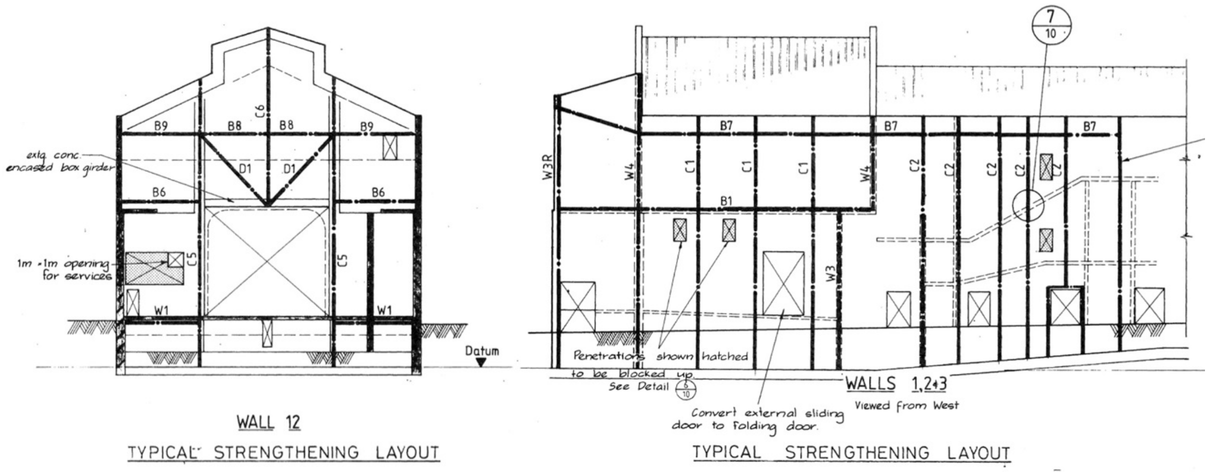

Figure 2. Strengthening layouts of the 1977-85 seismic renovations of the Wellington Opera House (Christianson, 1983)

2 Methodology

The tolerance allowance for calibrating simulated models with reality has been explored, and the process of pre simulation calibration selected. Temperatures were then recorded at various locations in the Opera House building, and a subsequent simulation model was created using boundary conditions from the recording process.

Throughout this investigation, CFD analysis was undertaken using the selected software of Autodesk's Simulation CFD. Initial simulations of the original design of the Opera House, including the external opening in the ceiling and roof, showed air movement downwards into the space through the roof opening (figure 3). The direction of air flow in these initial exercises raised questions regarding the potential performance of this ventilation system, and accuracy of the simulation modelling. Clearly, a calibration process was needed.

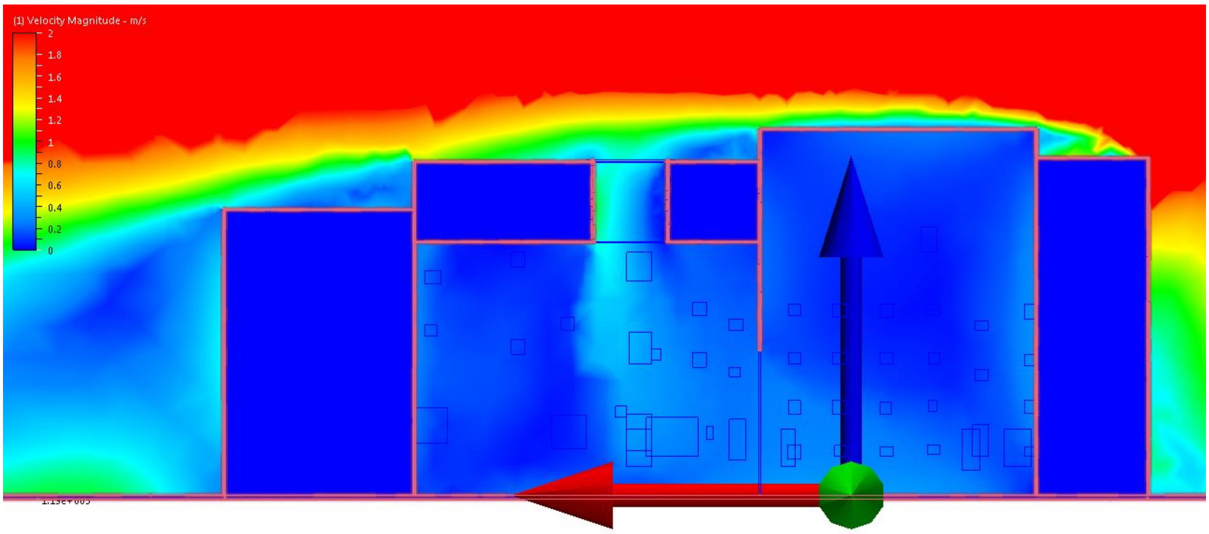

Figure 3. Initial CFD simulation of the original design of the Opera House, showing air movement entering through the roof and ceiling void

2.1 Calibration Tolerances

In order to compare modelled data with measured data for long term hour-by-hour simulations, statistical comparison techniques are often used to determine whether the modelled outputs are within acceptable calibration tolerances (ASHRAE, 2002).

The Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Squared Error (CV(RMSE) are the two statistical indices used to determine compliance with calibration tolerances. According to ASHRAE Guideline 14 (2002), a model is declared to be calibrated when it will produce:

- MBE within ± 10%, and CV(RMSE) within ± 30%, when using hourly data,
- MBE within ± 5%, and CV(RMSE) within ± 15%, when using monthly data.

The MBE measures how closely modelled energy consumption aligns with reality. However, if some hours of modelled data exceed the measured data and other hours are less than the measured data, the errors can become offset. Consequently, the CV(RMSE) is needed to determine the proportion of variation that occurs between the modelled and measured data (ASHRAE, 2002).

The 'Measurement and Verification Guidelines' of the U.S. Department of Energy state calibration tolerances can be set on an individual project basis, dependent on the appropriate level of effort required to align an energy model with reality (Nexant, Inc., 2008). Minimum acceptable calibration tolerances however, given in ASHRAE Guideline 14, are also referred to by the U.S. Department of Energy (ASHRAE, 2002).

The issue for this project is that CFD models represent a dynamic airflow as a single mass balance within a space. Calibration requires some knowledge of the 'boundary conditions'. In this case, knowledge of how much air is coming in from outside, and going out elsewhere through the fabric; how much heat gain there is in the auditorium (if there is an audience and the lighting is on for example); and what are the temperatures of the surfaces in the space. Choosing first, measurements in an empty building from a calm day so the pressures driving the air flow in and out of the building are merely temperature differences, enables a simple model calibration. Choosing next a windy day, when external wind speeds can be measured (from wind tunnel tests and from other CFD analyses) enables a second, more complex model to be calibrated. Choosing then to add complexity of internal heat gains from people and lights, and to examine the time based match of changes as the auditorium moves from empty to full, is the final stage of calibration.

As the whole process is a series of single case studies, the ASHRAE Guideline 14 does not outline a particularly suitable process as it focuses on simulations where hundreds, if not thousands of hours of data for a year are available. What is proposed, in the absence of other independently verified guidelines is that initially the calibration goal should be that the average deviation of all temperature sensors together is less than 10%, and that no individual sensor should be more than 30% 'out'.

2.2 Temperature Recording Methodology

The model of the Opera House had not previously been simulated; therefore a process of pre-simulation calibration was undertaken. Pre-simulation calibration involves updating an existing model or creating a new model informed by measured data (Raftery, Keane, & Costa, 2009). The modelling takes into consideration wind driven ventilation due to external wind speeds and temperatures, as well as buoyancy driven ventilation from the heat gain of occupants. Therefore, the following factors need to be considered during the recording of measurements, so they can be replicated for subsequent simulations:

- External weather conditions:
    - Wind speed,
    - Wind direction,
    - Temperature.
- Occupancy numbers,
- Location of measurement points.

CFD modelling is a tool used to assess airflow within a space, however the movement of air and quantity incoming from the external environment also dictate temperature within an unconditioned internal environment. While measuring airflow directly is possible with laser Doppler anemometry, the cost of and lack of accessibility to this equipment is a major limitation. As an alternative, temperature-measuring devices were available with the ability to record information in different locations throughout the space simultaneously and over a long period, allowing for a more comprehensive and three-dimensional picture of the space to be analysed.

The temperature sensors used were Testo Loggers 175-H2. Fifteen of these units were located throughout the auditorium space of the Opera House, as seen in figure 4 below. The locations of the sensors were selected due to the anticipated airflows in the space and relevance to occupancy comfort: in the roof space, in the stage area, and at the front and back of each of the three layers of seating, and beside a representative selection of the major openings to the foyer, which in turn opens to the outdoors.

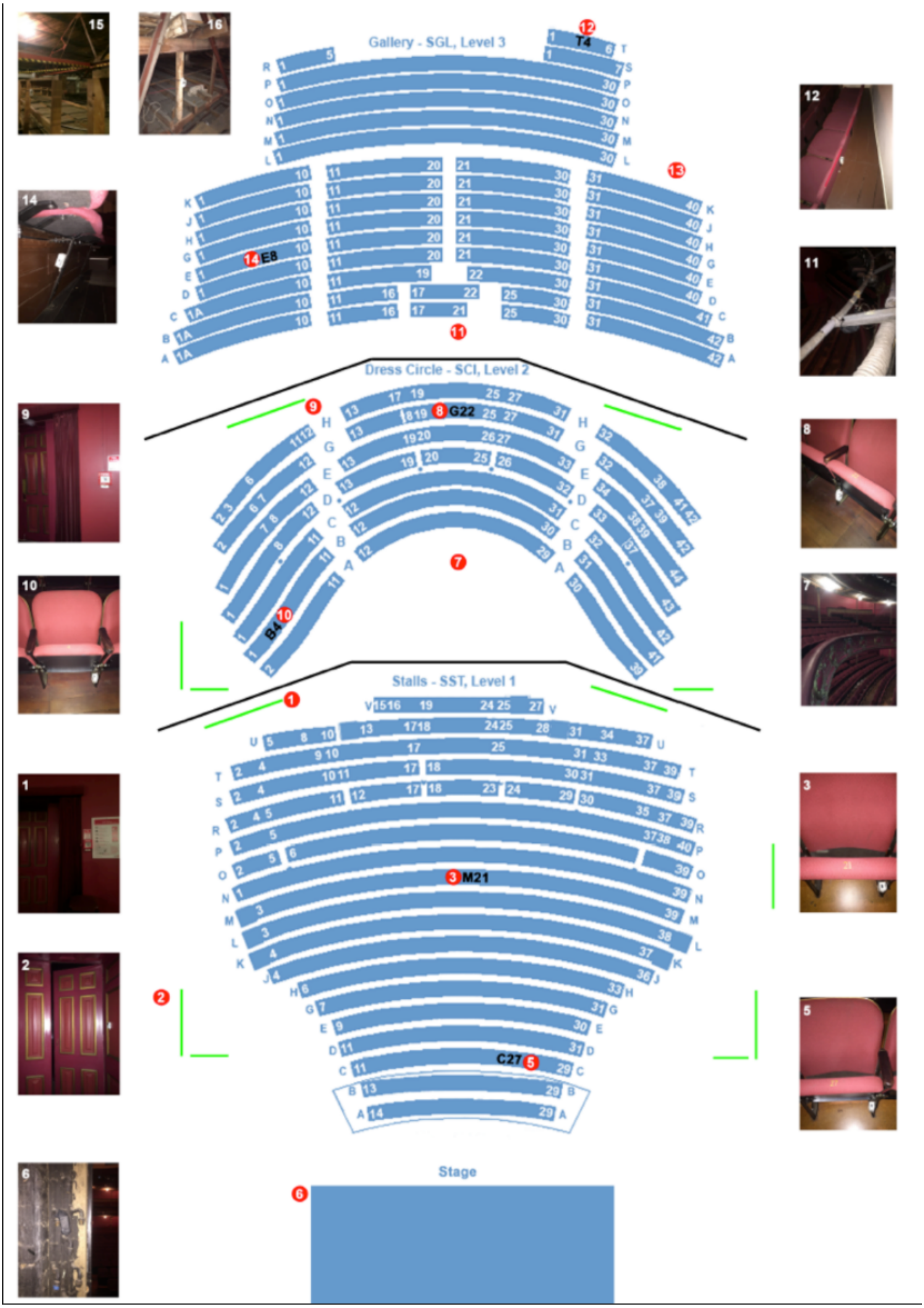

Figure 4. The locations of the temperature recording devices within the Opera House

For the purpose of this initial calibration feasibility test, the devices remained in the building for 4 days, and the data used for analysis were selected during the unoccupied state of the building.

2.3 Modelling Methodology – Revit Geometry

The base model for CFD analysis was created using Autodesk Revit software. As seen in figure 5, the geometry of the space has been simplified and internal elements were not included.

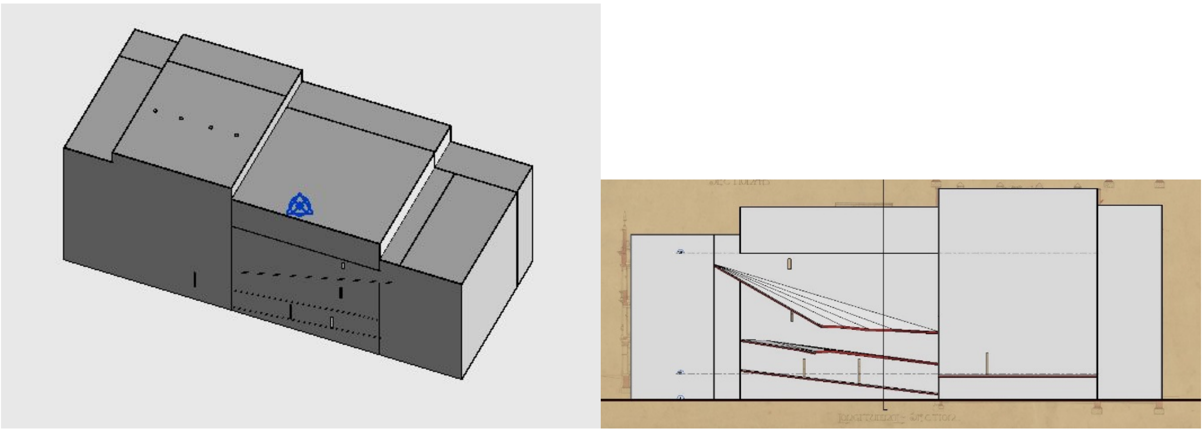

Figure 5. Axonometric and longitudinal section views of the Revit Model of the Opera House used as the base for the CFD Simulation analysis

The model is a simplified abstraction of reality, reflecting elements including the thickness of the walls, location of openings, angle of seating levels, and construction type. This allows the process of calibration to be undertaken more efficiently. Increasing complexity within a model not only extends simulation time but, also makes it difficult to attribute inconsistencies between reality and simulation results to specific elements. The aim of the Revit geometry is to create a representative model, which will produce believable results in a CFD analysis, minimising modelling time as well as simulation time. This modelling process also allows new elements such as seating to be added as they are required, should it become necessary to add elements to evaluate whether these elements help align the results more closely with reality.

2.4 Modelling Methodology – simulated in Autodesk Simulation CFD

Autodesk's Simulation CFD has been selected, as it is accessible to industry and is able to model wind-driven, and buoyancy-driven internal natural ventilation. This software can import from external geometry modelling programmes such as Revit, is comparatively reasonably priced, and has minimal learning time with learning support available (Autodesk, 2015).

2.4.1 Boundary Conditions

In order to model the boundary conditions closely with real weather conditions during the time the measurements were undertaken, information has been used from the Wellington Weather Station (Windfinder, 2016). The external wind speed and air temperature are needed to inform the modelling. The temperature from the weather station has been directly applied as the ambient temperature of the CFD simulation.

2.4.2 Wind

In order to predict the average wind speed on site at the time of the recordings, the ratio between the average wind speed at the location of the Opera House and the airport has been interpreted from a 2004 wind tunnel study completed by Opus International Consultants. This study is the most recent to have been undertaken in the vicinity of the Opera House, an area of Wellington where very little development has occurred in the last 12 years that would affect the air flow.

For the hour of the 31st January at 6pm, the wind speed recorded at Wellington Airport was 7.2m/s at 190 degrees (south). The point on the southern side of the Opera House building from the 2004 wind tunnel test report shows 3.0m/s average wind speed recorded at the location for a 21m/s speed wind blowing from 185 degrees at the Airport; and a 5.2m/s average wind speed recorded for a 22m/s speed wind from 200 degrees at the Airport. In order to estimate the wind from 190 degrees, the assumption of 3.73m/s at site for a 21.33m/s wind at the Airport has been made. Thus, the wind at the site is predicted as 17.5% of the wind at the airport.

Accordingly, 7.2m/s at 190 degrees at the Wellington Airport equates to 1.26m/s at 190 degrees on site. This value has been used in the Simulation CFD modelling process.

3 Results – Temperature Recording Devices

The temperature logging devices remained in the Opera House for four days for this initial trial. As seen in figure 6 below due to the thermal mass of the building the temperatures within the main auditorium space, excluding the roof space, do not change dramatically are delayed compared with the external conditions.

Figure 7 shows the trend of the difference between the external temperature and internal temperatures logged at each location. The two sensors located in the roof space had the greatest difference with the external temperature during the late afternoon.

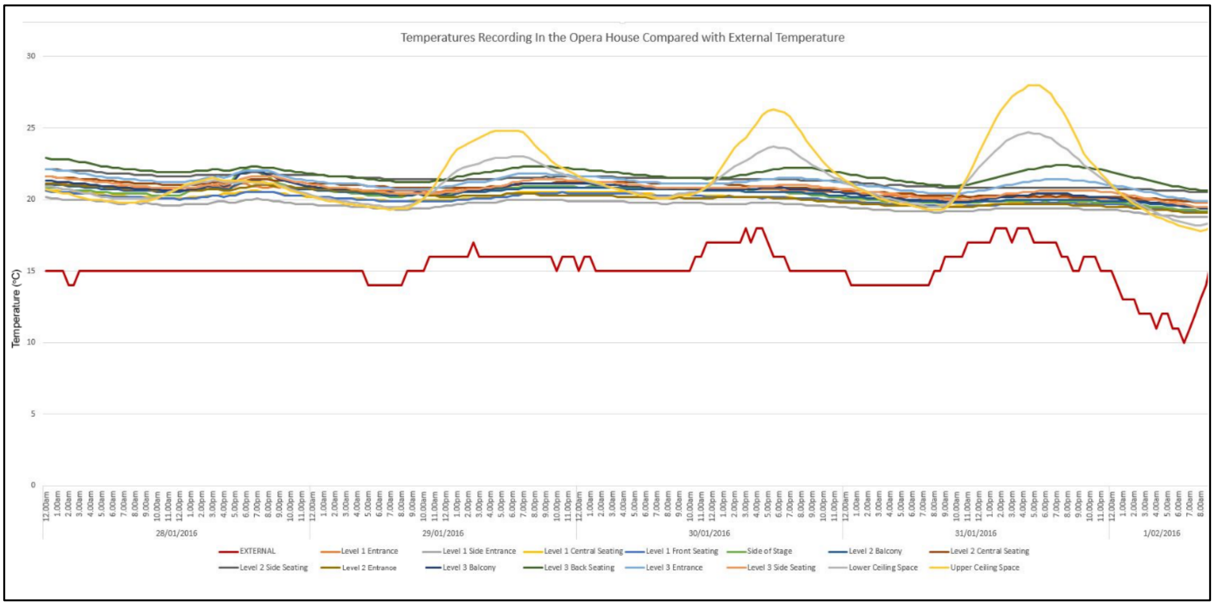

Figure 6. Overview of the four and a half days of temperature recordings in the space of the Opera House in comparison with simultaneous external temperatures

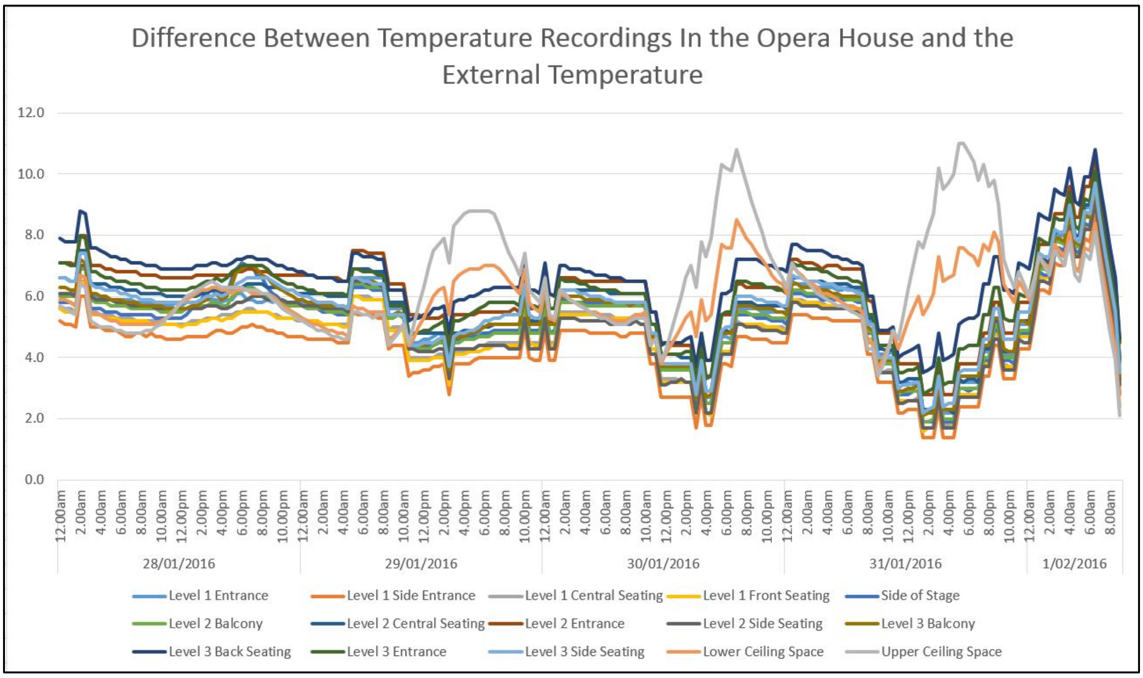

Figure 7. The trend of the temperature difference between the external conditions, and the internal temperature recordings

Due to the steady state of CFD simulation, in order to utilise the data one specific time needed to be selected. To calibrate the simple model and review its alignment with reality an unoccupied time was selected for this analysis. There were no people in the space to create heat gain, and the state of the auditorium space remained constant for three hours either side of the selected data time point.

Table 1. Results from the Testo Loggers for 6pm Sunday the 31st January 2016, with external weather conditions of 17^{o}C and 7.2m/s wind at 190 degrees (south) at Wellington Airport Weather Station

Location (refer figure 4)	Device Number	Temperature [ºC]
Level 1	ONE	20.20
Level 1	TWO	19.40
Level 1	THREE	19.80
Level 1	FIVE	19.80
Stage	SIX	19.90
Level 2	SEVEN	20.00
Level 2	EIGHT	20.30
Level 2	NINE	20.80
Level 2	TEN	19.70
Level 3	ELEVEN	20.40
Level 3	TWELVE	22.30
Level 3	THIRTEEN	21.40
Level 3	FOURTEEN	20.60
Roof	FIFTEEN	24.40
Roof	SIXTEEN	27.70

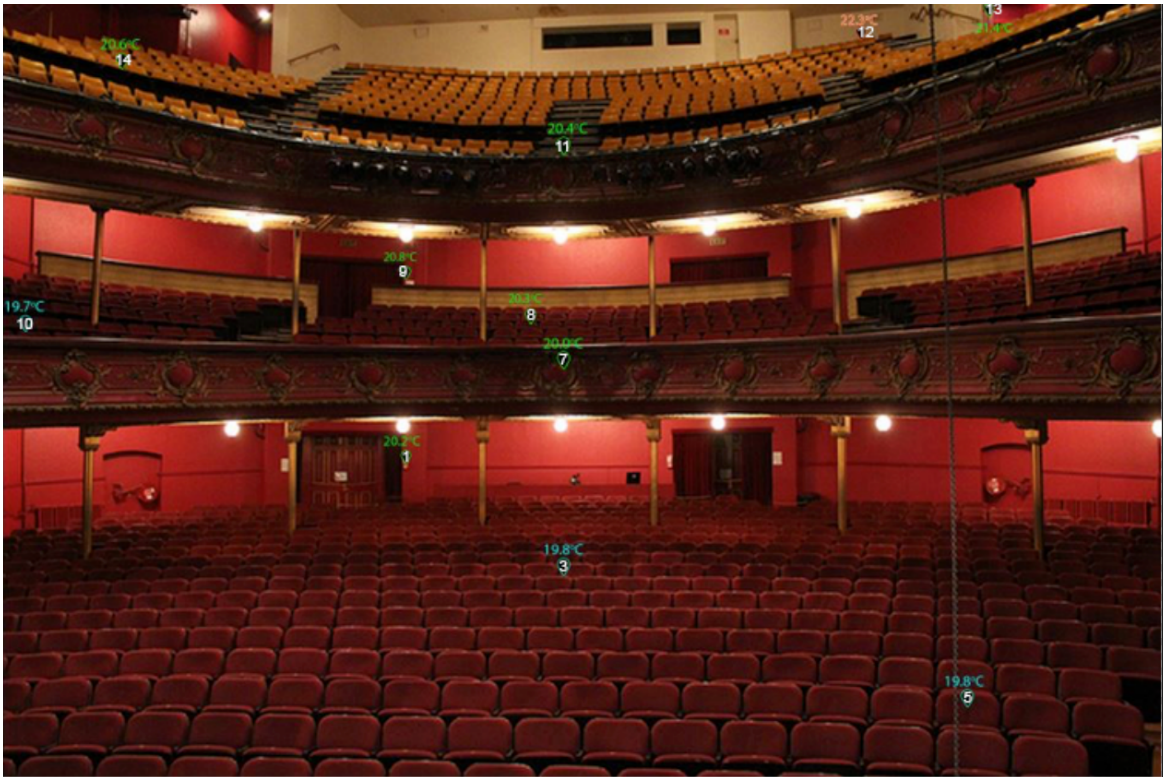

Figure 8. The temperatures at various points recorded by the Testo Loggers during an external temperature of 17°C

The stratification of air temperatures recorded within the space while unoccupied can be seen in figure 8. As was expected from the analysis, lower temperatures were observed in level 1 of the space, and at the side of level 2 nearest the opening. The back of the space in level 3 experienced the highest recorded temperature inside the seated area of the auditorium during this scenario.

4 Results – Simulation CFD Analysis

The Simulation CFD analysis of the Opera House has resulted in an evaluation of the space that aligns with the trend shown by the Testo Logger measurements. As seen in figure 10 below, stratification of air in the space can be seen, at similar rates and locations to the Testo Logger results seen in figure 8.

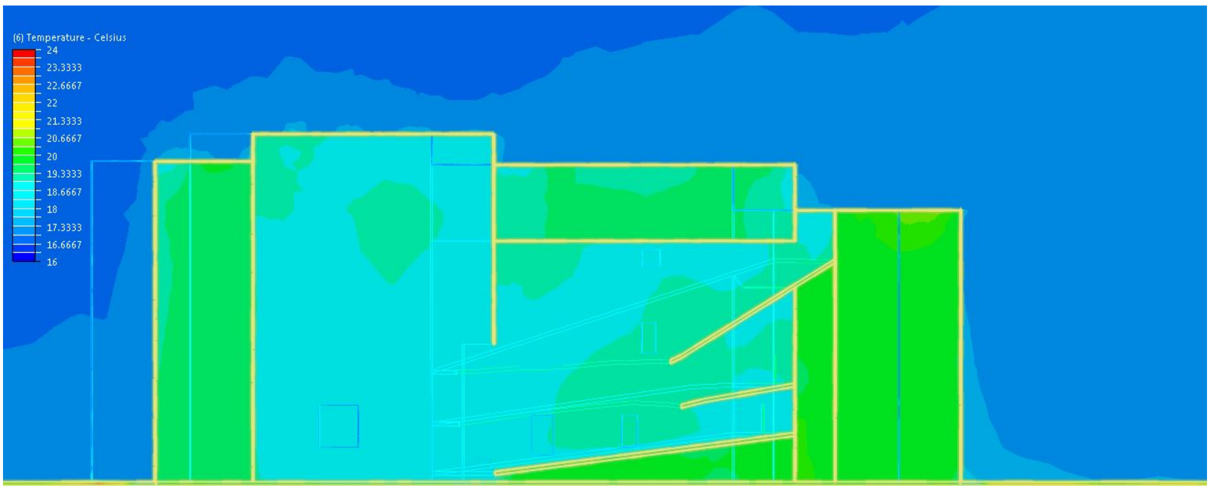

Figure 9. Longitudinal Section from the CFD Simulation analysis of the temperatures within the whole building space showing stratification between the layers of seating.

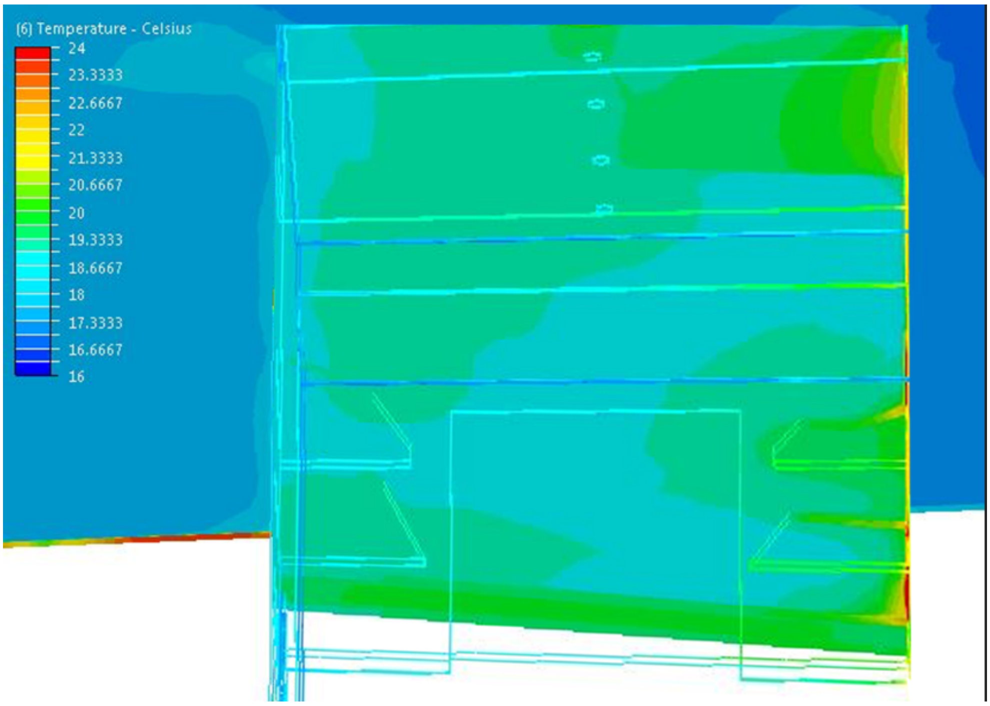

Figure 10. Perspective from the CFD Simulation analysis of the temperatures within the auditorium seating space, showing stratification between the layers of seating with comparative results to Testo Logger measurements shown in Figure 8

5 Conclusion

The ability of a CFD model to reproduce stratified airflow within the space has been assessed by comparing simulation results to measured temperatures.

The process for calibrating CFD simulation of the existing situation of the Opera House for one scenario has been undertaken. The next step in the calibration process to ensure quality assurance will include specific analysis of individual measurement locations, as well as further real time measuring and simulation modelling for different weather conditions and occupancy scenarios. Further analysis of the space at difference occupancies, wind and temperature situations is required in order to fully trust the modelling and understand the sensitivity of the different elements. However, the feasibility of the process has been proven in order to produce a simple model which displays believable results.

The value of the calibrated CFD models is their potential for future application, examining the feasibility of reintroducing natural ventilation to modern buildings. By following this calibration process, the results of the CFD simulations can be quality assured and therefore enable a degree of trust for upcoming iterations. These models can also be used to predict occupancy comfort for any proposed reintroduction of a natural ventilation system to the Opera House. A further outcome of this process is to enable investigation of whether the original sliding roof/ceiling natural ventilation system might have been successful.

Acknowledgments

Positively Wellington Venues, for permission to place devices in the Wellington Opera House.

Opus International Consultants Ltd, Wellington, for providing a wind tunnel study of the case study area.

Multi-Media Systems Ltd for access to the Wellington Opera House.

BRANZ, for assisting with funding this research.

Victoria University, Wellington, for providing temperature-recording devices for the study.

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Task-Based Approach to Define Occupant Behaviour in Agent-Based Modelling

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Abstract

This paper presents a development approach and design of a task-centered agent-based model (ABM) to represent the interactions of occupants with a commercial office building. The model is built with the understanding that occupant behaviour is driven by tasks the occupant performs. A contextual task analysis questionnaire explored occupant perspectives on the interactions between their tasks, their individual behaviour and comfort, and the physical characteristics of their workspace. This task-based information defines five ABM elements that represent occupants, task and workspace environment, task list, occupant actions, and the impact of the occupant-workspace interaction on tasks. An example of an occupant, performing a task, and conducting an action in response to an environmental mismatch demonstrates the ABM design. The example discusses the generation of possible actions as well as the result from those actions in terms of task performance and occupant satisfaction. As the ABM design evolves, it will aid in the understanding of occupant behaviour in buildings, and ultimately standardize the approach to occupant behaviours affecting building energy demand.

Keywords: Agent-based modelling, Occupant-building interaction, task performance, occupant satisfaction

1 Introduction

Building occupants play a critical role in affecting building operation. Occupant behaviour is multi-disciplinary, complex, and stochastic. Occupant behaviour affects building energy demand and indoor environmental quality (Ole Fanger, 2001; Hoes et al., 2009). The resulting environment may affect future occupant decisions and behaviour (An, 2012). For example, occupants who open a window shade for daylight also allow solar radiation to penetrate the building, adding to the building's cooling load. The increased solar radiation may cause the occupant to feel warmer, causing the occupant to turn down the temperature, further increasing the building's cooling load.

In traditional building simulations, schedules represent occupant-environment interactions. Schedules define building occupancy and occupant actions as a set of static events that occur regardless of environmental influences (Klein et al., 2012). For example, an office building's equipment schedule dictates equipment is "on" 6 am to 6 pm and "off" 6 pm to 6 am Monday through Friday, and is "off" Saturday, Sunday, and holidays. Schedules ignore individual-occupant level actions (e.g. occupant leaving mid-day), do not account for complexities in their actions (e.g. occupant opening a window shade might also turn off lights) , and fail to integrate cross-discipline data (e.g. equipment usage is not integrated with an occupant schedule)(An et al., 2005). For example, the "on" equipment from 6 am to 6 pm is actually turned on and off throughout. This affects internal heat gains, leading to improper calculation of occupant thermal comfort and space cooling demands. Additionally, failing to include periods of “off” misrepresents the equipment’s actual energy demand.

Agent-based modelling (ABM) has been particularly useful to understand and manage multi-disciplinary systems with many interacting elements (Axelrod, 1997; Bonabeau, 2002). ABM is a computer simulation technique that replicates the behaviour of individuals (agents), and their interactions with the environment and other agents (Axtell et al., 2002). In commercial office buildings, individual agents are building occupants, and the occupant’s environment is their workspace. ABM simulates the unique decision-making behaviour of individual occupants and then shows how the overall, complex building behaviour emerges as a result of those behaviours (Klein et al., 2012). The decision-making process of individual occupants explains behaviour intentions and actions in response to environmental stimuli (Gaudiano, 2013). Behavioural intentions are the occupants’ goals of eliminating undesired environmental conditions. Occupant actions initiate changes in the environment.

Behaviour intentions define an ABM structure to evaluate impact of various occupant actions in response to a number of different physical environment stimuli factors. Coupled with building energy simulation, a majority of ABM efforts thus far focus on evaluating building energy demand in a variety of different building types (Azar and Menassa, 2012; Chen et al., 2013) and building occupancy (Azar and Menassa, 2015) in response to occupant thermal comfort behaviours (Langevin et al., 2014; Lee and Malkawi, 2014) and, less commonly, visual comfort behaviours (Andrews et al., 2011). For example, using thermal comfort, an occupant takes action with the intention to eliminate discomfort. The behaviour, or action, of the occupant is evaluated for its impact on building energy demand and the resulting occupant satisfaction or dissatisfaction with their thermal environment (Langevin et al., 2015).

While ABM has been successful in representing occupants in building simulation, using comfort as the behaviour intention has caused several issues. First, this limits the model to only what the occupant would and could interact with, and leaves out components that potentially could affect simulation results. For example, evaluating thermal comfort leaves out actions related to visual comfort, such as turning lights on/off, that would affect space heat gains and overall building energy use. Second, the lack of consistency between models makes it difficult to compare models and incorporate multiple behaviour intentions for evaluation. To address these issues, the key is to select the proper intention.

To select a proper intention, one must understand the overall purpose of the building. In a commercial office building, the building’s purpose is to support business goals. The goal of the business is to make a profit (Von Paumgartten, 2003). While profit is related to building energy performance, employee salaries account for 80% of operating costs (Von Paumgartten, 2003) signifying the major determinant of business profit is employee task performance. If task performance is the basis of success in an office building, an ABM structured on occupant tasks to define behaviour intentions should provide the link between task performance and building energy demand.

In order to develop an ABM using behaviour intentions as the structure, one must understand the need behind the intention. When an occupant is uncomfortable, they seek comfort, but what is the original need for the occupant to seek comfort? Because discomfort is the result of a mismatch between the environment and task requirements, tasks, in which the occupant is engaged, drives the need and type of comfort. The need, therefore, is to remove discomfort to improve task performance.

This paper proposes a novel ABM structure to represent occupant behaviours that affect building operation. The realization that tasks are integral drivers of occupant behaviour in a commercial office building provides the basis for the ABM approach. Based on occupancy task data collected in the fall of 2015, this paper builds towards two main objectives: 1) define an ABM structure that uses tasks to define behaviour intentions, and 2) integrate task performance with occupant satisfaction to evaluate occupant behaviour. While this ABM is in early stages of development, the goal is to couple the ABM with a building simulation, such as EnergyPlus, to evaluate the impact of the task-based occupant behaviour on building energy usage.

While there is research available relating occupant behaviour to their environment and the environment to task performance, there are significant gaps in current research regarding the link between occupant behavior and task performance. Further, research tends to define these connections in generic terms such as “the occupant is working”, which lacks the specificity to distinguish between different types of work that have different environmental requirements. Thus, further task-specific data are needed to define the ABM model. The next section of this paper describes the data collection and the modelling approach to collect task-specific data. A contextual task analysis (CTA) questionnaire was designed to collect the basic data required to establish the ABM: occupants, the environment, and their relations to tasks. The task-based information defines the five ABM elements. Two elements are initialization definitions that represent occupants and task and workspace environment. Two elements are inputs representing task list and occupant actions. The fifth element is a process model that evaluates the impact of the occupant-workspace interaction on tasks in terms of task performance, occupant satisfaction, and building energy. The subsequent section describes an example that demonstrates the ABM design: an occupant, performing a task, and acting in response to an environmental mismatch. Finally, the paper concludes with a discussion, future work, and recommendations.

2 Methods

2.1 Data Collection

The contextual task analysis (CTA) questionnaire explored occupant perspectives on the interactions between their tasks, their individual behaviour, comfort, and the physical characteristics of their workspace. 35-questions, derived from a variety of survey instruments for building performance and post-occupancy evaluation (Ornstein et al., 2005; Vos and Dewulf, 1999; IBPE Consortium, 1995), were grouped into five parts in the questionnaire. The first part asked basic demographic questions along with individual characteristics, such as mode of transportation and length of time with company and current job. The second part asked participants to identify their daily work schedule. From this schedule, participants were to select five tasks that are critical, performed most frequently, and most important for their job. The third part, participants listed and sketched furniture and equipment within their workspace. Participants associated each item in their workspace to the selected tasks as well as identified any equipment required for their job that is located outside their workspace, such as a copier located in the copy room. The fourth part asked how aspects of the participant’s workspace affected their task performance. The fifth part asked about participant values and overall perception of their workspace. These include identifying objects the participant is allowed to change, current clothing level, and overall satisfaction with their workspace. While the participant took the survey, physical measurements of the occupant's workspace were documented. The measurements included the interior air temperature, relative humidity, air speed, work surface light levels, and dimensions. Additionally, the workspace location within the overall building, office type, building systems, and any available controls with the workspace were recorded. Exterior conditions were taken prior to administering the questionnaire at the business, which included air temperature, relative humidity, air speed, and other conditions, such as cloud cover and rain.

Participants were included in the survey if the occupant worked in a typical commercial office setting and performed at least 50% of their tasks in their workspace. A typical office setting is defined as business group B, per the International Building Code, where the use of a building is for professional or office-type services (IBC, 2011). The questionnaire took no longer than 30 minutes to complete, and was conducted in the participant's workspace during the fall of 2015. Follow-up interviews were used to clarify any of the questionnaire responses, and to allow the occupant to demonstrate and expand on any comments.

CTA responses were recorded from 37 participants (22 male and 15 female) with a mean age of 34 years (range: 22-56). Participants were from three different businesses located in five buildings. Follow-up interviews were conducted with nine participants.

CTA analysis was conducted by part. Therefore, if a participant did not complete a part of the questionnaire, the responses from the other parts were still included. The detailed analyses and results for each CTA part are not included in this paper. Rather, the information from each part of the CTA is discussed on how it is used to develop the ABM elements in next section.

2.2 ABM Elements

The CTA and sources from literature develop and refine the structure, dynamics, and data for five ABM elements. Table 1 outlines the CTA part(s) and source(s) from literature associated with each ABM element. The ABM includes five elements: occupant, task and workspace environment, task list, occupant actions, and workspace environment impact. Occupant and task and workspace environment are initialization definitions that representing building occupants and the space in which they perform their tasks. Task list and occupant actions are ABM inputs. Task list represents a daily list of the tasks the occupants perform, the order performed, and for how long. Actions are the events an occupant may take to change their environment. The workspace environment impact is a process that evaluates the occupant-workspace interaction on tasks in terms of task performance and occupant satisfaction.

Table 1. Data sources referencing the part of the Contextual Task Analysis (CTA) and the research literature used to develop each ABM element.

ABM Element	CTA Part	Sources from Literature
Occupant	1,5	Disability (BLS, 2015) Workspace type (IFMA, 2010)
Task and Workspace Environment	2,3,4	Comfort Standards and Environment Ranges (see section for references)
Task List	1	
Occupant Actions	5	Decision order (An, 2012)
Workspace Environment Impact	4	Environment impacts on productivity (see section for references)

2.2.1 Occupant

Occupant agents are an element generated during the initialization of the ABM. Occupant attributes define occupant characteristics and influence their actions and perception of the environment. Characteristics, values, and attributes define each individual occupant, which allows for individual evaluation and preferences. For instance, if an occupant has a disability, the environment might need to be changed to enable the occupant to complete his or her tasks. Static variables define occupants' attributes and values, and do not change. Static variables include the occupant's gender, employee type, workspace, preferences (e.g. tendency to be hot or cold, preference of brighter/darker illumination levels, preference of daylight to electric light, and tolerance of louder/quieter sound levels), and disability (e.g. vision impairment). Dynamic variables are those that may change per model time step as influenced by other environmental or occupant static attributes. For example, an occupant may modify their clothing throughout the day in response to their environment. Dynamic variables include clothing and activity levels.

2.2.2 Task and Workspace Environment

The task and workspace environment is an element generated in ABM initialization. Occupants perform tasks in the workspace environment. Tasks were identified and defined (Kalvelage et al., 2016b) by outlining the physical and mental processes, furniture and equipment, and physical movement required to perform the task. Tasks were grouped in five categories: 1) create and analyse information, 2) search for information, 3) process information, 4) communicate information, and 5) manage information. Communicate information was divided into three sub-categories representing phone call, small meeting, and large meeting.

The workspace and task requirements generated a specific task definition for each task category. Workspace requirements define the physical workspace, and building operating schedules link the requirements to the building model. Workspace requirements include the furniture, equipment, and number of occupants required. Schedules represent when equipment is on/off, when an occupant is present/absent, and the furniture internal mass.

The task requirements define the processing resources and environment parameters. Processing resources are the capabilities and resources an occupant has to bear on a task (Wickens and Hollands, 1999; Clements-Croome and Baizhan, 2000). Four components typically describe processing resources: visual, auditory, cognitive, and psychomotor (commonly referred to as VACP). Visual (V) and auditory (A) refer to the external stimuli that must be attended to; cognitive (C) refers to the level of information processing required; and psychomotor (P) refers to physical actions. Rating scales developed by McCracken and Aldrich (1984) for each VACP component provide a relative rating of the use each resource component in tasks. The rating interval scales range from 0.0 or no activity, to 7.0 or a high degree of activity.

Each task places a specific workload demand on an occupant (Keller, 2002). For example, resources required for a large meeting (communicating information) include the visual component of looking at the speaker, the auditory component of hearing the speaker, the cognitive component of processing speech, and the psychomotor component of taking notes. The base VACP for values for a task are determined when the environment is at optimal task performing conditions. The environment parameters define the task's optimal environment. Parameters for thermal, visual, acoustical, and air quality were developed by using design reference standards to define a reference range. References include: ASHRAE standards 90.1

(2013b), 62.1 (2013a), 189.1 (2014), EN standard 15251 (2007), and ISO standards 9241 (2006) and 7730 (2005). Next, these ranges were fine-tuned using other research: temperature (Wong et al., 2008), (Jakubiec and Reinhart, 2012) glare, (Boyce, 2014) illumination levels (Ayr et al., 2002; Kjellberg et al., 1996), sound levels, and air quality (Niemela et al., 2006). Information from the CTA questionnaire correlated parameter ranges to specific tasks.

2.2.3 Task List

The task list is the first ABM input, and dictates time on task and the order of tasks. Figure 1 outlines the process to generate an occupant's daily task list. First, task list constraints define the workday start and end times as well as any lunch or break times (Kalvelage et al., 2016a). Next, occupant characteristics modify the task list; for example, assign a time-slot for a 15-minute smoke break. The occupant's employee type selects the task list type. Previous work (Kalvelage et al., 2016a) identified four task list types: active meeting, semi-active meeting, inactive meeting, and stationary. The task list types represent the time spent performing the five different tasks as a percentage of the available work time. Using these percentages, the tasks are distributed throughout the remaining time-slots in the workday to create the occupant's specific task list. Task lists are automatically generated, daily, during the simulation for an entire reference year, which includes holidays and weekends.

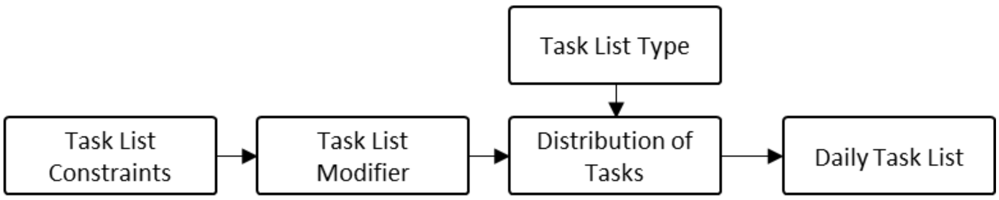

Figure 1. Task list definition combines task list constraints with occupant-defined task list type and task list modifiers to generate a daily task list.

2.2.4 Occupant Actions

The occupant action is an input element in the ABM, and defines the available actions for an occupant and organizes them into the appropriate order for the occupant to choose. Occupant actions are those in response to an environment mismatch, such as distractors, interruptions, or stressors that negatively affect task performance. For example, a workspace may be too dark to read text in a book. The actions available to the occupants are gathered from object actions (e.g. adjustable furniture and occupant clothing layers) and workspace actions (e.g. turn on/off lights) (Kalvelage et al., 2016b).

When an individual has to choose from among two or more mutually exclusive actions, the action that generates the "best" environment for task performance determines the decision order. These actions would be determined based on balancing minimal task workload impact, energy efficiency, and effectiveness at producing the desired conditions. For instance, an occupant could open the window shade to increase illumination, but this adds additional workload by requiring the occupant to stop working, walk over to the window, raise the blind, walk back to their chair, refocus on task, and resume working. Further, while it is the most energy efficient, there is no guarantee adequate illumination levels and introduces the potential for glare. Alternatively, turning on a task lamp guarantees adequate illumination and adds minimal workload by only requiring the occupant to reach up and turn on the lamp – only stopping work for a fraction of the time it would take to open the blinds.

2.2.5 Workspace Environment Impact

The workspace environment impact is the runtime ABM process, and consists of three submodels to evaluate the impact of the workspace environment on task performance and occupant satisfaction. The three submodels compare environment parameters, evaluate comfort, and evaluate processing resources (Figure 2).

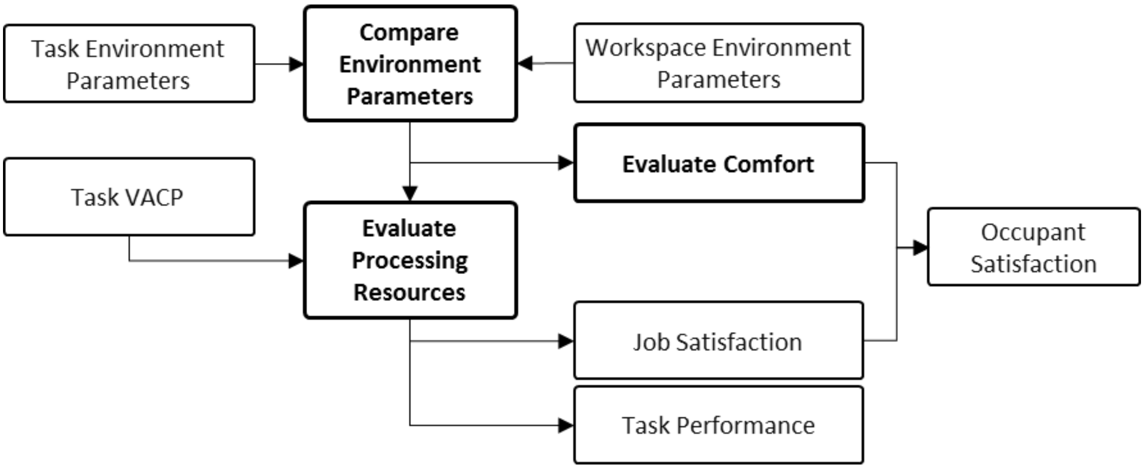

Figure 2. Environment impact process, consisting of three submodels (bold boxes), evaluates task performance and occupant satisfaction as a result of the occupant-workspace interaction.

Compare environmental parameters retrieves the workspace environment parameters (as a result of previous action and component interaction) from the building model and compares to the task environment parameter ranges. The ABM compares effective temperature (thermal), illumination level (visual), decibel level (acoustic), and CO_2 concentrations (air quality). Any environmental mismatch affects both occupant comfort and processing resources.

Evaluate comfort submodel corresponds an environment mismatch to a comfort category (i.e. thermal, visual, acoustical, air quality). Evaluating each comfort category individually then combining, generates a single comfort rating. For this reason, one comfort rating cannot determine the occupant's overall comfort. For example, a beeping printer generates noise. The noise would negatively affect the occupant's acoustical comfort. However, if thermal, visual, and air quality comforts are deemed acceptable, the occupant could report they are comfortable.

Evaluate processing resources examines the additional workload on the occupant caused by the environment mismatch. For instance, if the beeping printer causes an acoustical annoyance to an occupant creating and analysing information, the increased noise adds to the cognitive component by causing concentration difficulties for the occupant (Kjellberg and Skoldstrom, 1991). Further, prolonged exposure may reduce the occupant's motivation to work (Evans and Johnson, 2000), and cause negative long term effects on occupant health, such as sleep disturbance and physiological stress (Job, 1996). Numerous studies have examined the effect of various environmental factors on occupant processing resources; for example: thermal factors (e.g. temperature) (Kosonen and Tan, 2004a; Wyon, 2013; Lan et al., 2010; Niemelä et al., 2002; Seppanen et al., 2006), visual factors (e.g. type of light system) (Fostervold and Nersveen, 2008), acoustical factors (e.g. sound levels)(Maxwell, 2000; Smith-Jackson and Klein, 2009), and air quality factors (e.g. CO2 levels) (Kosonen and Tan, 2004b; Singh, 1996; Apte et al., 2000; Wargocki et al., 2000; Niemela et al., 2006).

The environment's impact on processing resources is added to the task's processing resources to generate task performance and job satisfaction. Task performance can be viewed as both quantitatively (e.g. amount of work completed and accuracy) and qualitatively (e.g. quality of work). Job satisfaction is the perceived satisfaction the occupant has with their task performance. Job satisfaction is influenced by comfort (Clements-Croome and Baizhan, 2000), and therefore, is combined with comfort to produce the overall occupant satisfaction. Occupant satisfaction is used to determine the occupant's health. Low satisfaction for an extended period of time could result in the occupant being sick or quitting.

2.3 ABM Structure

Figure 3 outlines the interactions and relationships between the ABM elements in the overall ABM structure. While not included in this paper, the external building model simulation (grey box) was included in the diagram to suggest its relationship in the ABM. (The building model simulation will be used to evaluate overall building energy usage as a result of the ABM element interactions.) The ABM starts by generating the occupant and the task and workspace environment. These elements remain unchanged throughout simulation run. These two elements are used to generate the occupant's daily task list. The task list is generated automatically accounting for monthly and yearly activities variations, and contains the information regarding the optimal task and workspace environment and occupant characteristics required to evaluate the actual workspace environment. The workspace environment impact compares the environment parameters required for the task and the actual environment parameters from the building model simulation. Using the comparison, comfort and processing resources are evaluated and output task performance and occupant satisfaction. Should the two workspace environment parameters not align, the occupant has the option of taking action to change the environment. Any change made in the environment is sent to the external building model simulation for recalculation of environment parameters then re-evaluated.

The ABM is conducted for each occupant in the building, performing their specific task(s), in their specific workspace(s). Because of this, individual satisfaction and task performance can be examined in addition to calculating building-wide occupant satisfaction and task performance.

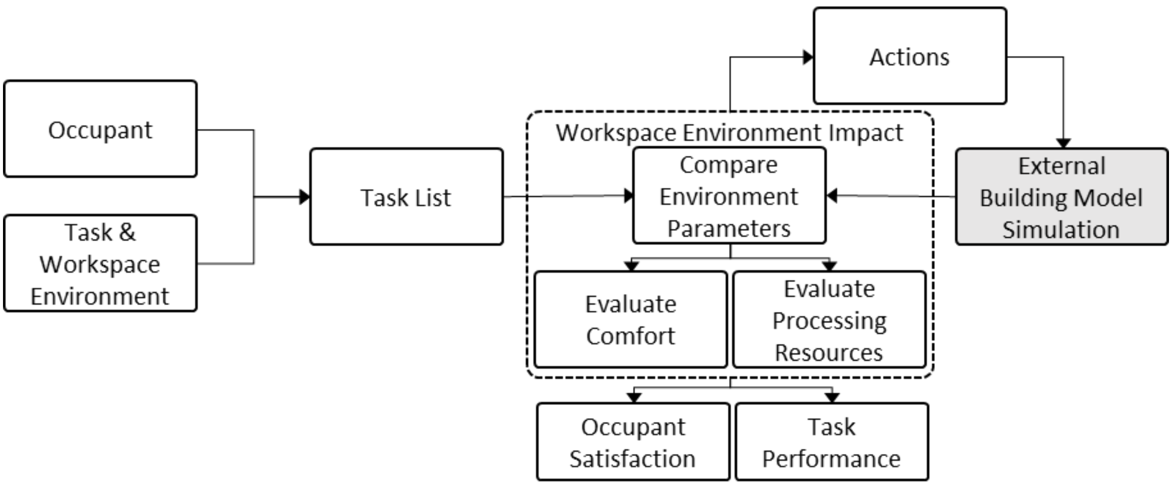

Figure 3. ABM used to evaluate the occupant-workspace interaction impact on tasks. The external building model (grey box) was included in the diagram to suggest its relationship in the ABM.

3 Demonstrative Example and Discussion

Discussion of the ABM uses a demonstrative example. Figure 4 outlines the parameters generated for one day, for a single occupant performing a process information task, and turning on a task light in response to illumination levels too low to perform the task. The output results are task performance and occupant satisfaction.

The ABM first generates the occupant profile shown in box 1 of Figure 4. The occupant profile includes the following variables: non-smoking male (no smoking break needed in the task list), non-management employee (determines task list type), works in a private office (determines available actions), has no disabilities (no additional workload on processing resources), and prefers the standard environment parameters as defined by the task (no modification to the environment parameter comparison to account for occupant comfort preferences). Additionally, occupant clothing (box 3) is generated daily. Today the occupant is wearing the base level of clothing for a male: socks, shoes, briefs, light trousers, a t-shirt under a long-sleeved shirt. The combined clothing insulation value is 0.70 clo. A common range in an office environment is 0.5 to 1.2 clo. The building simulation uses this value to calculate the effective temperature.

The non-management employee type is assigned the inactive meeting task list type for today (box 2), which has 30%-40% meetings (most of which take place in his workspace), 40%-50% create/analyse, < 10% search, < 10% process, 5%-10% manage, <10% email, and <5% break distributed into a schedule. The occupant begins his day at 8:00 am and ends at 4:30 pm with a 30-minute lunch and a 15-minute break in the afternoon. After defining the occupant and task list, the ABM operates at a 15-minute time step, and uses the occupant's task list to determine which task the occupant is performing during that time step. The time step for this example is 8:30 am, and the occupant is performing the process information task (box 2).

The processing information task is performed in the occupant's workspace (box 5), and defines the equipment (box 8), furniture (box 9), and affordances (box 10). These items introduce possible environment factors as well as define the possible actions the occupant can take to change his environment. The activity level for this task is low at 1.2 because the occupant is seated with low physical exertion (only typing is required) (box 4). The building simulation uses the activity level to calculate the effective temperature. The task also defines the two set of parameters used for evaluation. The environment parameters (box 6) and task processing resources (box 7) as shown in Figure 4 and Table 2, which indicate the processing information task is a visual- and motor-related intensive task.

The *Compare environmental parameters* ABM submodel compares the task environment parameters (box 6) to the workspace environment parameters (box 15) retrieved from a building simulation. The reported values indicate the illumination levels are 300 lux below the task requirements (box 11). During the *evaluate comfort* submodel, the occupant's visual comfort drops (box 16), and in the *evaluate processing resources* submodel, the lack of illumination increases the processing resources of the task (box 12). The environment and task processing resources are combined (box 13). The resulting VACP values determine task performance (box 19) and job satisfaction (box 17). High values correspond to low task performance and low job satisfaction, and vice versa for low values. In the example, both task performance and job satisfaction decrease due to the high visual demand of the task. Combining Job satisfaction with comfort produces the overall occupant satisfaction of eight (box 18).

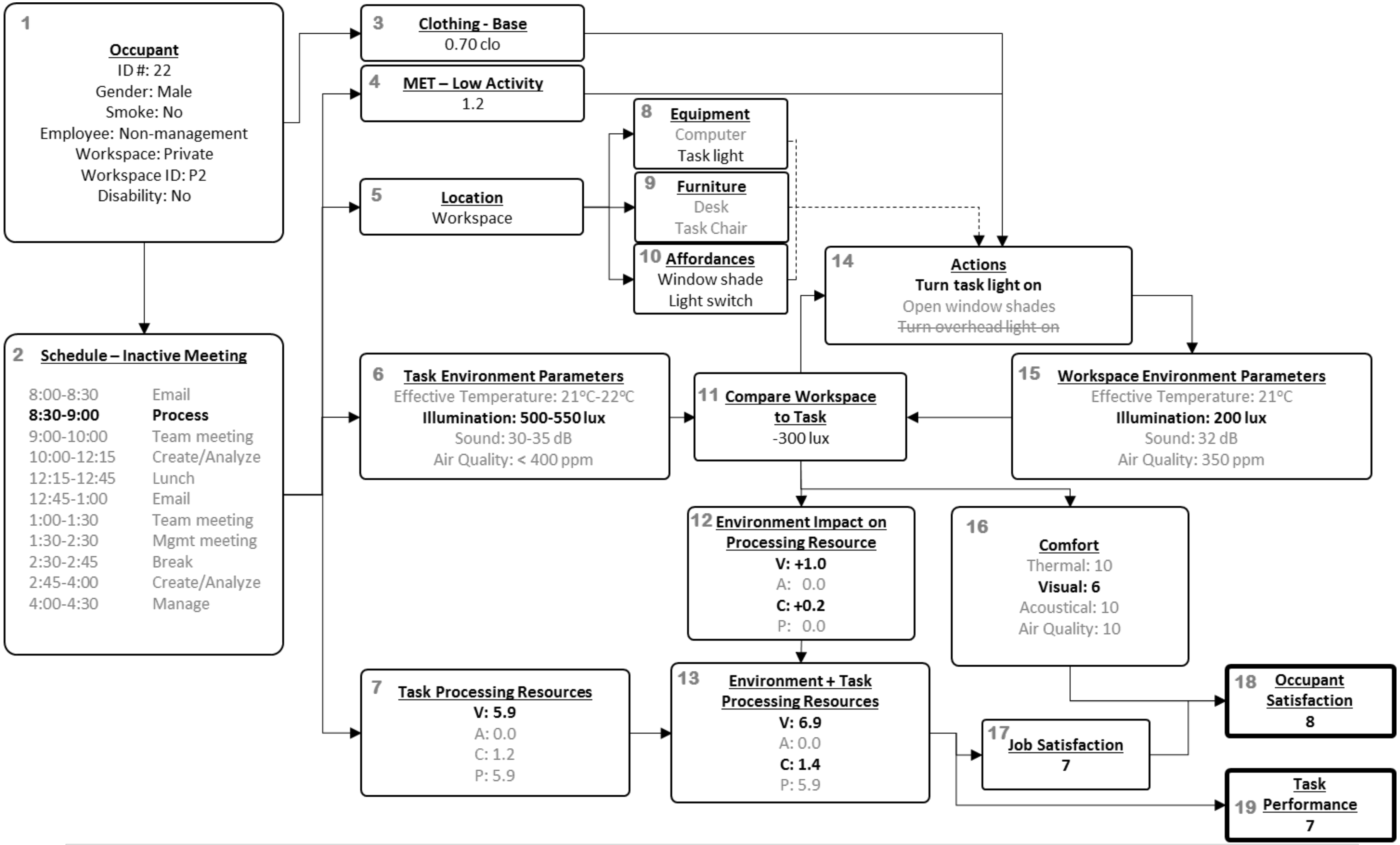

Figure 4. Example ABM. Each box lists the title and corresponding ABM variables. Grey text represent the information in the model that does not apply to the example, and the crossed out text represents an item removed from the available actions. The bold boxes are ABM output results.

Table 2. Processing information task variable values for processing resources and environment parameters.

Task Processing Resource	Value	Environment Parameter	Value
Visual	5.9	Effective Temperature	21^{o}C-22^{o}C
Acoustical	0.0	Illumination Level	500-550 lux
Cognitive	1.2	Sound level	30-35 decibels
Psychomotor	5.9	CO2 level	< 400 parts per million

The occupant could continue working without modifying the environment. The effects would compound, eventually causing significant occupant dissatisfaction and very low task performance until the occupant left or took action to change his environment. In this case, the occupant has several options available to improve his workspace environment. The actions available to the occupant are those that provide additional illumination. Actions presented to the occupant are in order as to the "best" option for the task rather than by allowing the occupant to choose based on their own experience – what they think is the "best" option. The available actions are turn on task light, open window shades, or turn on overhead lights (box 14). The overhead lights have already been turned on, and therefore, are removed from the available actions (crossed out). Turning on the task light is the first action because it results in less energy than the overhead lights, and it is convenient for the task (less workload and time away from task). While the occupant could open the window shades, glare on the computer screen is a potential source of discomfort. The model completes the time step by sending the selected action of turning on the task light to the building simulation to recalculate the environment parameters. The new environment parameters are compared to the task environment parameters to output an updated satisfaction and task performance rating.

4 Conclusion

This paper presents an approach to representing occupant behaviours using the understanding that occupant tasks are the driver of behaviour intentions. Defining occupant behaviour as an intention to satisfy tasks defines a clear boundary to work within to identify model input parameters. Using a contextual task analysis questionnaire, the model input parameters are represented as five ABM elements in the task-based ABM structure. By using tasks to define the ABM structure, behaviour actions consider task performance when determining occupant actions. While the ABM is still in its early stages, the data collection enabled the development of the overall ABM structure on which we will continue to build. As this ABM evolves, further ABM development should build a strong understanding of how task-related occupant behaviours affect office buildings.

This ABM approach goes farther than previous approaches in that it includes task performance and occupant satisfaction metrics that can translate to cost-savings. An additional benefit is the ability to expand on the elements enabling the integration of new building systems and occupant behaviours. The next steps in this research include expanding on data collection and model development. Continued data collection using the CTA questionnaire as well as additional studies to collect task-specific data relating to the optimal task environment, specific environment factors that affect task performance, and occupant preferred actions. In addition to informing the current identified inputs, future work includes expanding evaluation criteria to include additional comforts such as ergonomics, and incorporating transient occupants, such as stakeholders and guests, into building operation.

Finally, validation of the model will require sensitivity analyses to ensure a reasonable simulation of office occupant behaviour as well as comparisons to conventional, standalone building simulations. Comparisons can be made related to building energy demand and overall thermal comfort, but comparisons of occupant satisfaction and task performance will require alternate means, such as a cost-benefit analysis, because these metrics are not available in the conventional building simulations.

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Capturing Uncertainty in Operation, Behavior and Weather in Building Performance Assessment: An Egyptian Case Study

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Abstract
New building energy standards have recently been proposed for Egypt. There is however insufficient data on the performance of existing buildings to provide a baseline for assessment of the impact of these new standards or other possible upgrade measures. In common with the rest of the world, there is also no standard design assessment method which takes account of the inherent uncertainty in operation, behavior, and weather. This paper first explores the current energy and environmental performance of offices in Egypt through a simple energy survey of multiple offices and more detailed investigation of an individual office building. The observed indoor thermal environment is compared against adaptive and non-adaptive thermal comfort standards. A method is then proposed for assessment of building performance which takes account of uncertainties in operation, behavior and weather through the definition and use of representative input parameter sets. The application of the method is illustrated for energy and thermal comfort performance of a typical Egyptian office building. The more general applicability of the method in design and policy, and potential for further developments, are discussed.

1 Introduction

To help reduce energy use in buildings, we need accurate modelling methods for energy demand that take into account building characteristics, operation and user behavior. User behavior influences the energy demand of a building both passively and actively. On the one hand, the presence of people in a building will lead to effects due to metabolic processes which change heating, cooling and dehumidification loads depending on the prevalent hydrothermal conditions. On the other hand, active effects include the operation of control devices (e.g. window opening, lighting controls, thermostat settings), the presence and use of electrical appliances (e.g. computers, printers, unitary cooling and heating devices) or the consumption of hot water (e.g. cooking or personal hygiene related). Robustness or resilience of buildings against variations in operation, behavior and weather has been put forward as desirable and various methods proposed for how this might be evaluated (Aerts et al. 2014), (Fabi et al. 2011), (Mahdavi 2011), (Morishita et al. 2015), (Wang et al. 2005) but no standard method for this has yet evolved.

The incorporation of occupant behavior and the impact on comfort and energy use in building performance models can be represented through a bottom up modeling approach where each control action is explicitly represented in a stochastic algorithm, agent based, with physical triggers such as visual, thermal or olfactory environment and the history and pre-condition of the agents e.g. window opening (Yun et al. 2009), window and blind use

(Tuohy 2007), lighting use and occupancy (Reinhart 2004), (Mahdavi et al. 2009). There are problems with this approach with both a lack of a comprehensive set of algorithms with sufficiently detailed and validated parameters appropriate to specific contexts and the computational power that would be required to incorporate these within the required multi-domain building performance assessment modeling tools. While this bottom up approach has the potential to provide a virtual reality to designers in future there are significant challenges to be overcome before this is available for building practitioners.

An alternate approach proposed and explored in this paper is to capture variations and uncertainties in building operations, user behaviors and weather within higher level parameter sets representing realistic distributions, and then to evaluate the energy and comfort performance of buildings across these ranges. This approach is developed and illustrated here using Egyptian office buildings as an example. First, the baseline energy and comfort performance is explored for existing offices and a typical model created. Next, parameter sets are developed representing variations in operation, behavior and weather. Finally, the energy and comfort performance of the typical office and the impact of possible upgrades are evaluated across these ranges. The general applicability of the approach in building design is then discussed.

Insights into the energy and comfort performance of Egyptian office buildings are also generated by this work which may be useful in characterizing the Egyptian building stock.

2 Energy and Comfort Performance of Existing Egyptian Office Buildings

The current energy and comfort performance of offices in Egypt is explored through a simple energy survey of multiple offices and a more detailed investigation of an individual office building. The observed indoor environment is compared against adaptive and non-adaptive thermal comfort standards.

2.1 Energy Survey of Multiple Offices

Historical surveys such as ECON19 0in the UK have underpinned energy performance calculation methods however no historical survey data is available for Egyptian offices. ECON19 categorizes buildings by their HVAC strategy and type. As a first step in the exploration of the energy performance of Egyptian offices, electricity bill data was gathered for 59 offices in Alexandria. The energy performance was then analyzed for 3 HVAC types: 1. Natural Ventilation and no cooling (11 offices); 2. Natural Ventilation and local unitary AC systems (41 offices); 3. Central HVAC with mechanical ventilation.

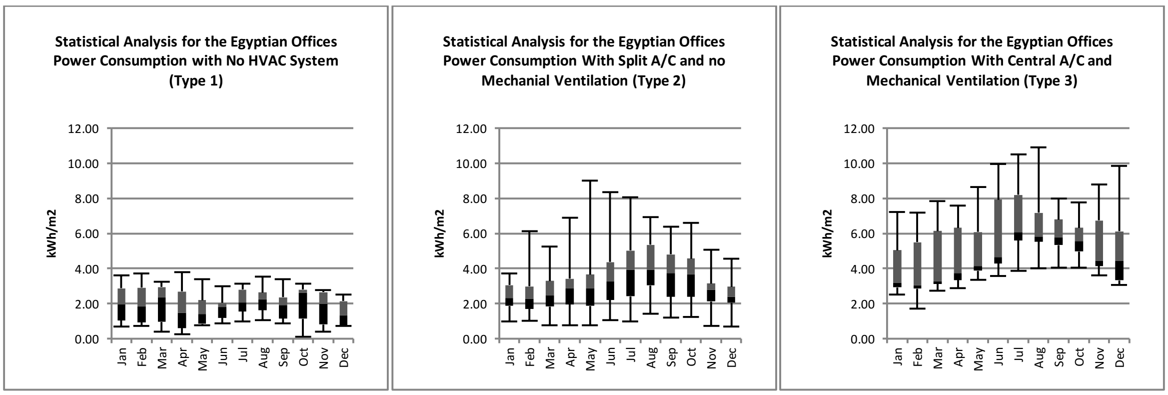

Figure 1 Monthly power consumption for Egyptian office Buildings According to HVAC system

Figure 1 shows the summary results, the central grey/black box shows the 25th, 50th, and 75th percentiles and the whiskers show the max and min for each month. This high level data provides only some high level insight, more detailed information is required to better understand Egyptian building performance. The same trend is seen as for the ECON19 study such that more highly serviced buildings consume more energy.

2.2 Energy and Indoor Environment for an Office, comparison to Comfort Standards.

Type 2 (Natural ventilation and local cooling) was found to be the most prevalent category. A more detailed investigation of an individual Type 2 office building was then carried out. The office was chosen as it is a common building type found in Egypt. In addition to the measurements the occupancy and patterns of use were recorded including window and blind use, local cooling system setpoints, and the clothing being worn by the occupants. Local weather station data was also available. The investigation involved energy and environmental monitoring during 2014. Measurements were made of space resultant temperature, humidity, carbon dioxide and electrical power. The monitoring instruments were moved around to various locations to facilitate gathering of useful data and also to capture variations. The survey was designed to allow a calibration of a dynamic simulation model as well as provide further data on current building performance. The building configuration and external views are shown in figure 2, internal views in figure 3. The external and internal views highlight the variation in use of windows and blinds.

Figure 2. The type 2 case study building - example floor plan and external views.

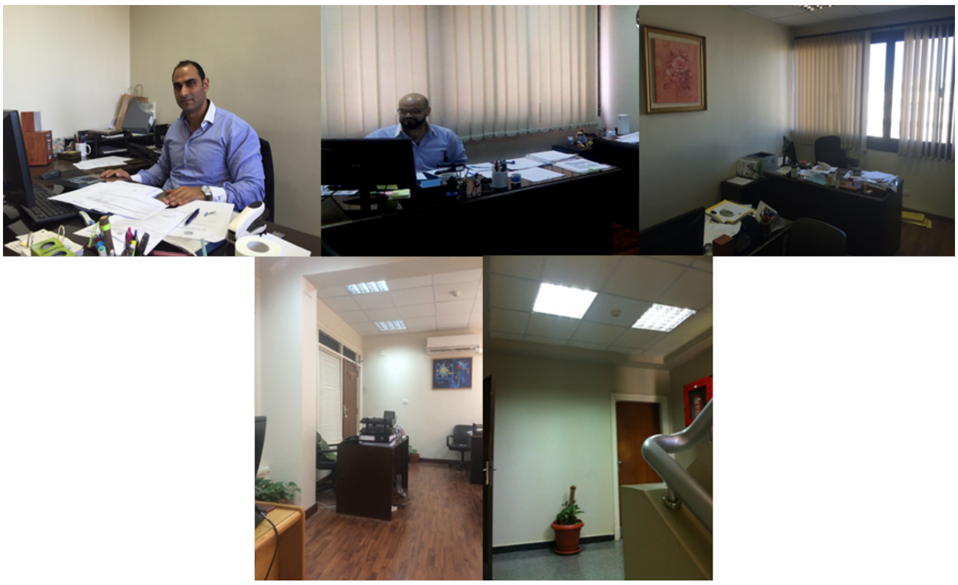

Figure 3. The case study building – example internal views.

The monitoring data highlighted high variability in internal conditions during working hours. Some spaces were observed to have the local cooling setpoint set to 16C and the system running throughout the working day, others had setpoints of 22 or 24C, while others ran the local cooling set at 22C for an initial period and then switched it off. Behaviours in offices varied based on time of year and also day to day. The behaviour shown in figure 5 for office S08 where the cooling setpoint is set at 22C and the room operative temp achieved was around 23.5C was the most typical and representative of the summer conditions across the majority of the space.

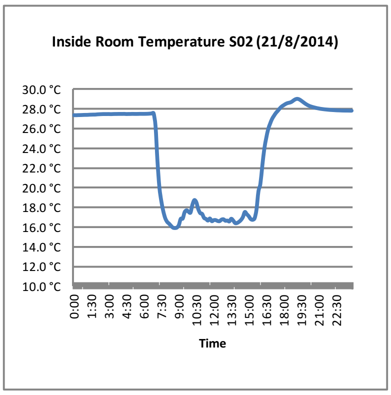

Figure 4. Actual inside room temperature during the day for one of the colder offices

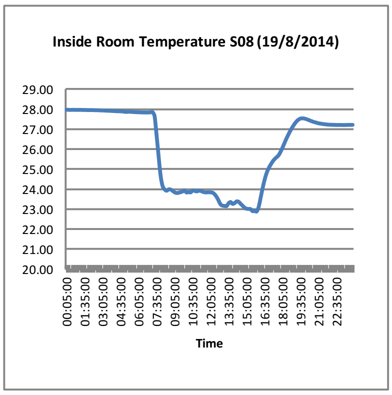

Figure 5. Actual inside room temperature during the day for one of the typical offices

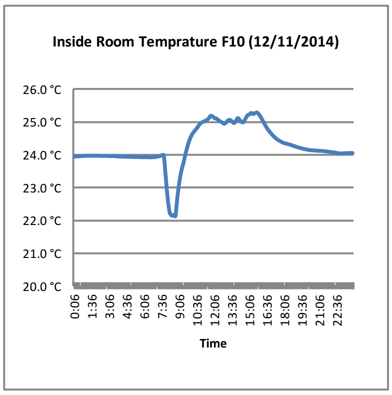

Figure 6. Actual inside room temperature during the day for one of the hotter offices

The internal conditions for the typical office S08 are shown plotted against the various comfort criteria from international standards in figure 7 (ASHRAE Standard 55-2004), (Cen, E. N. "15251" 2007). The measured internal temperatures for this type 2 office with available cooling appear to most closely follow the comfort temperature predicted by the PMV method.

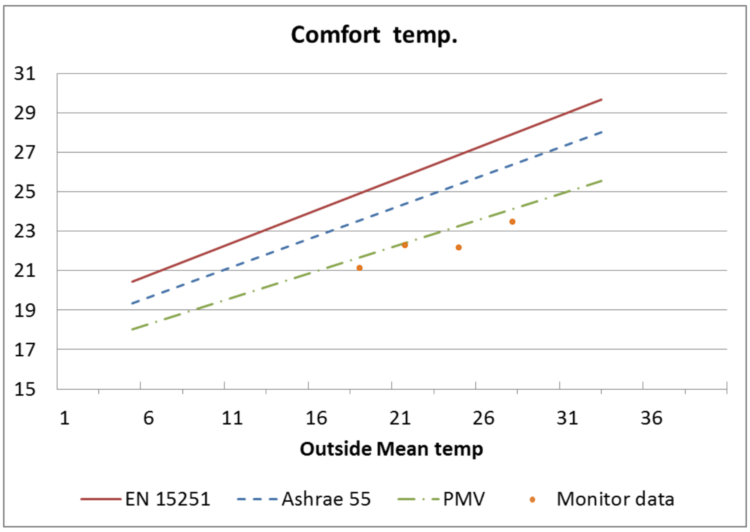

Figure 7. Internal conditions and predicted comfort temperature v. outdoor mean temperature.

3 Energy and Comfort Assessment Methodology for Upgrades

A methodology is proposed for assessing energy and comfort impacts of retrofit or new build measures. The methodology involves creation of: a typical model; input parameter sets representing variation and uncertainties in operating conditions and behaviors; and, inputs representing variation in weather. The typical model is then used as the base and changes evaluated against this base performance across the range in operations, behaviors and weather. The output is then a performance map allowing energy and thermal comfort performance to be assessed.

3.1 Creation of the typical model

A double calibration process is used to create the typical model: first a calibrated model is created for the case study building for which detailed information is available, and then the calibrated model is adjusted to be more representative of typical performance determined from the multi-building survey. The case study building used to create the calibrated model is situated in Alexandria on the Mediterranean coast.

Figure 8. Location of the detailed monitoring building.

3.1.1 Calibrated model from detailed monitoring study

Standard methods (Raftery et al. 2009), (Tahmasebi et al. 2013), (Royapoor et al. 2015), (Westphal et al. 2005) were used to create a calibrated model of the case study building. The creation of the calibrated model has been reported in detail elsewhere (Elharidi et al. 2013) and is only briefly summarized here. First a best guess model was created from construction and monitored data; next a parametric study was carried out to identify the uncertain parameters with the greatest influence on building performance; then a sequential calibration process in order of decreasing influence was carried out to set parameters for minimum root square mean variance (RSMV).

The base building is typical Egyptian un-insulated solid wall and single glazed construction. The calibration process was partitioned to allow parameters to be independently calibrated i.e. calibration of electric power use was first done in the winter period to establish lighting and equipment performance, then summer calibration carried out to establish cooling performance, air infiltration rate was calibrated using occupancy and carbon dioxide measurements etc. The results of the model calibration process are illustrated in figure 9.

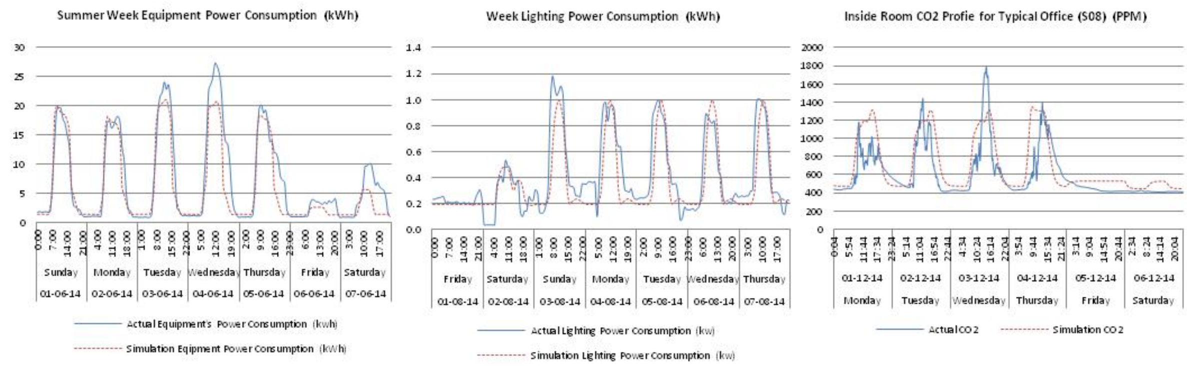

Figure 9. Calibrated model energy and carbon dioxide performance.

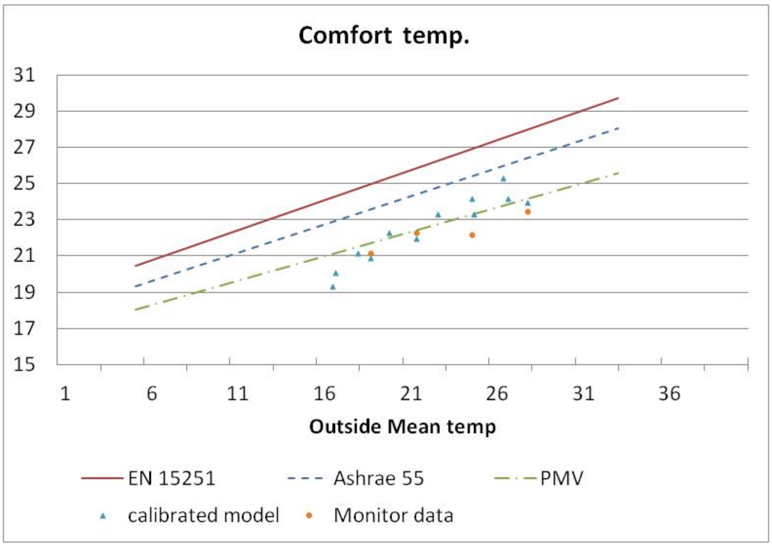

Figure 10. Internal temperature (real and model), predicted comfort v. outdoor mean temperature.

3.1.2 Adjusted Calibrated Model to Represent Typical Performance

The calibrated model while giving good agreement with the measured data has a different monthly energy use profile from that seen in the multi-building survey as shown in figure 11. The case study building is the administration building for the University and had very high occupancy and energy use in June and August associated with the University calendar, either side of Ramadan which was in July and had low occupancy and activity levels, to create a more typical profile these months were adjusted in the model to have a more consistent occupancy pattern similar to non-academic buildings. The winter occupancy and associated equipment and lighting use was adjusted up to represent a more typical occupancy pattern, with these adjustments the model gave results close to the 50th percentile of the survey data. The model then is tuned to represent performance of a typical type 2 office, figure 11 however highlights the variability in performance seen in the energy survey, and it would appear to be important to also represent this variability in assessing energy performance.

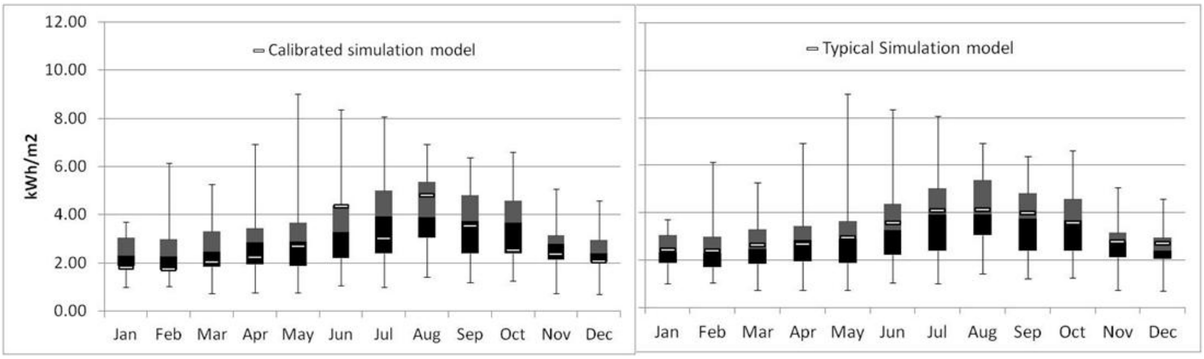

Figure 11. Monthly power consumption for type 2 offices from the survey and simulation results from the calibrated model of the single office and the 'typical' model.

3.2 Realistic worst case parameter sets for operations and behavior.

From the parametric screening study and literature (Lam et al. 1996), (Tian 2013) the primary input parameters which affect energy use and their likely ranges were determined. The ranges are tabulated in table 1, the max and min extremes have been labeled as + and - 3 standard deviations, this superimposes a notional normal distribution on each parameter for which the standard deviations have been determined.

Table 1: Primary input parameters and ranges (D.F. = Diversity Factor)

Parameter		Max (+3 σ)	Min (-3 σ)	σ	Mean
Equipment load	W/m2	30	10	3.33	20
Equipment D.F		1	0.2	0.13	0.6
Lighting Load	W/m2	18.8	7.8	1.83	13.3
Lighting D.F		1	0.2	0.13	0.6
Occupancy Load	m2 / person	16	4	2.00	10
Occupancy D.F		1	0.2	0.13	0.6
A/C Set point	°C	26	18	1.33	22
Infiltration Rate	l/s.m2	1.3	0.3	0.17	0.8

The impact of these parameters on the energy performance of the building are either positive or negative e.g. increasing equipment loads will positively increase power consumption (equipment plus cooling), while increasing the cooling setpoint will reduce power consumption (less cooling).

The infiltration rate as described in table 1 is the daytime sum of infiltration due to window and door openings, extract fans, and unintended fabric air leakage. In the model the daytime and nighttime infiltration due to the use of openings and fans are separately specified from the unintended fabric leakage so that each can be separately specified, for simplicity this was not shown here.

Variations in these parameters will depend on how the building is operated and equipped, over the life of a building it is reasonable to expect that these parameters will be varied over time. In order to capture this likely variation it would seem reasonable to combine these uncertain parameters into best case and worst case parameter sets to represent likely variations and uncertainties. The offices were assumed to have occupancy based around an 8 hour work day as this was found to be the case in the survey. Combining the extremes (max, min) of each parameter would give a possible but very unlikely worst case range, rather by applying adjustment of 1 standard deviation to each parameter and combining settings based on positive or negative effect a more realistic set of worst case parameters was established (table 2 and figure 12). It was then proposed that this best case, worst case and typical parameter sets be considered in assessment of likely building performance.

Table 2: Best case, worst case and typical model input parameters

Parameter	contribution to power Consumption	Best Case ('light ')	Worst Case ('heavy')	Typical
Equipment load (IT)	positive	12.2	18.8	15.5
Miscell		4.5	4.5	4.5
Equipment D.F	positive	0.5	0.7	0.6
Miscell D.F				0.6
Lighting Load	positive	11.5	15.1	13.3
Lighting D.F	positive	0.5	0.7	0.6
Occupancy Load	nigative	12.0	8.0	10
Occupancy D.F	positive	0.5	0.7	0.6
A/C Set point	negative	23.3	20.7	22
Infiltration Rate	positive	0.6	1.0	0.8

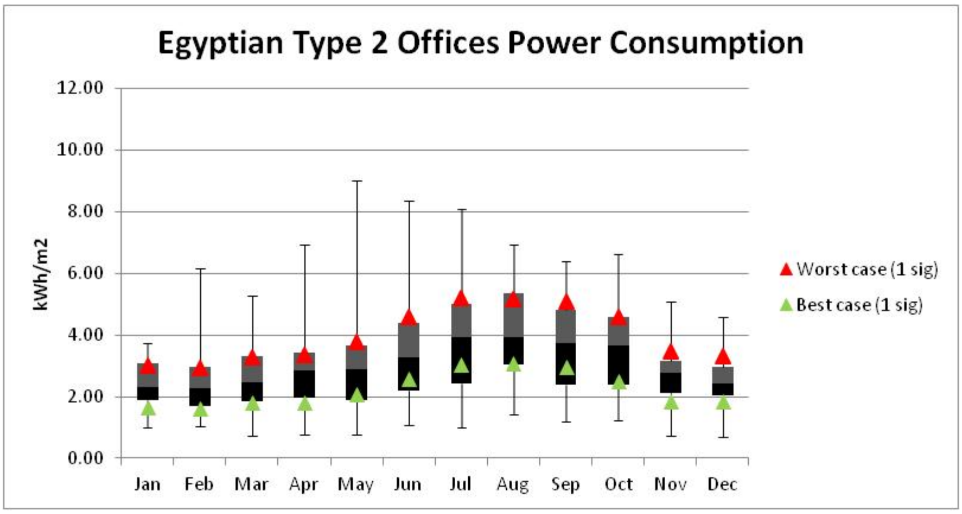

Figure 12. Realistic worst case parameter sets superimposed on monthly power consumption.

3.3 Realistic worst case weather datasets.

The weather was measured during the monitoring period and used in the modeling described above however the variation in weather also should be considered in assessing likely building performance. To address this point the statistical analysis as proposed by Crawley (Crawley 2007, 2015) was used to create weather files representing realistic spreads in weather. First cooling degree days were analyzed for recent years and the highest and lowest degree day's climate files identified for use as extremes, 2006 as a 'cool' year, and 2010 as a 'warm' year. These years are shown in figure 13, it can be seen that the difference is largely due to extension of the warmer summer period into the autumn. The difference in degree days and peak temperatures between the cool and warm years for Alexandria is relatively small (20%) compared to other regions, possibly due to its coastal location.

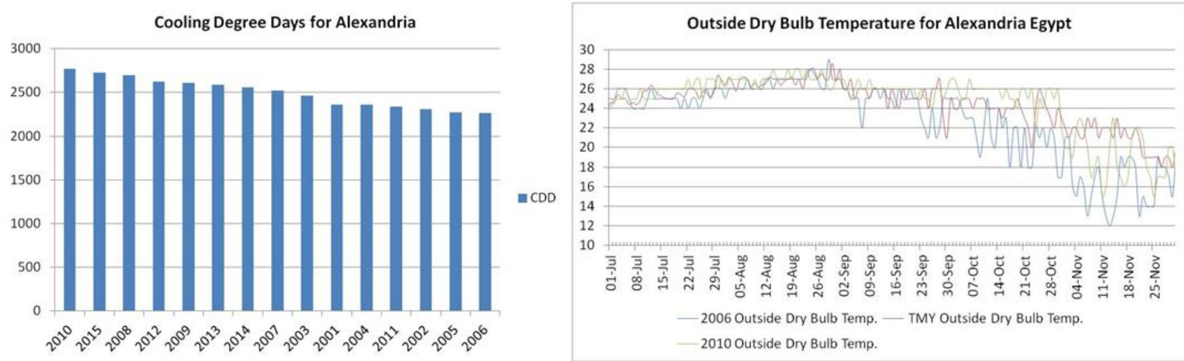

Figure 13. Weather files for Alexandria: cooling degree days and dry bulb temperatures.

3.4 Application of the Methodology

Now with a typical model and parameter sets representing uncertainties in operations and behavior and weather it is possible to include these likely variations and uncertainties in evaluating typical building performance and the impact of potential upgrades.

The modeling results (Total Annual Energy Use and Summer PPD) for the typical office are illustrated in figure 14 for each combination of weather and occupancy behavior pattern. The occupancy and behavior related variation in energy consumption is very large while the impact of weather is relatively small. Similarly the impact of the cooling setpoint is apparent with the light and typical with higher cooling setpoints having accordingly higher calculated PPDs.

Total Energy (MWh/year)

Occupancy + Behavior	cool	average	warm
heavy	50.5	51.8	52.9
typical	38.5	39.5	40.4
light	28.3	29.0	29.7

Weather

Summer PPD

Occupancy + Behavior	cool	average	warm
heavy	20.1	20.3	20.9
typical	26.4	26.5	27.3
light	34.2	34.3	35.2

Weather

Figure 14. Performance for typical office building.

An upgrade scenario is illustrated in figure 15, in this scenario the lighting and IT equipment is replaced with the most energy efficient available, 7.8 and 10 W/m2 respectively see table 1. The variations in lighting and IT equipment use patterns of use as represented by the diversity factors of table 1 are the same as for the typical building evaluation. In this scenario the reduction in energy consumption is very apparent compared to the typical case; there is a small but consistent improvement in PPD.

Total Energy (MWh/year)

Occupancy + Behavior	cool	average	warm
heavy	29.7	30.1	32.0
typical	25.1	25.3	26.9
light	20.8	20.9	22.2

Weather

Summer PPD

Occupancy + Behavior	cool	average	warm
heavy	19.3	18.7	20.1
typical	25.8	25.2	26.7
light	33.8	33.1	34.8

Weather

Figure 15. Performance for typical office building with low energy lighting and IT equipment.

A further scenario is illustrated in figure 16, where in addition to the lighting and IT upgrade the lower cooling system setpoint temperature is applied in all cases. Here the calculated PPD shows a corresponding improvement but the energy penalty associated with this is made clear.

Total Energy (MWh/year)

Occupancy + Behavior	cool	average	warm
heavy	29.7	30.1	32.0
typical	26.5	26.8	28.5
light	23.3	23.5	25.1

Weather

Summer PPD

Occupancy + Behavior	cool	average	warm
heavy	19.3	18.7	20.1
typical	19.1	18.5	19.9
light	18.9	18.4	19.7

Weather

Figure 16. Typical office with low energy lighting and IT equipment and lower cooling setpoint (20.7^{o}C).

These scenarios are used to illustrate the potential use of the methodology, there are of course many other possible upgrades. The performance views are intended to capture energy and comfort performance across the range of conditions likely to be experienced over building lifetime. The performance information is intended to usefully inform design and operational decision making. The scenarios here are for type 2 offices with a single main occupancy period of 8 hours with reduced occupancy outside these times (security and cleaning etc), separate performance scenarios would be generated for type 2 offices with 16 or 24 hour occupancy periods.

4 Discussion

The general principle that buildings should work across likely patterns of use and ranges in weather would appear to be obvious, however how this should be assessed is rarely addressed, and there is no standard approach commonly used. The method proposed and then explored here is an attempt to move discussion forward.

The illustration of the method for the Egyptian context is purely circumstantial, the method is intended to be applicable elsewhere, in other countries there may be more established datasets. Starting from scratch in the Egyptian context has however provided some useful insights.

The simple performance views illustrated here may be easily augmented to give a more comprehensive performance dashboard with individual energy uses and more complex or alternative performance metrics e.g. indoor air quality etc. or alternative time periods.

The performance views containing energy and comfort performance across the different operation and weather scenarios may be useful in design stage but can also serve as a communication vehicle to the operations team and could in future be linked into a real time feedback system. Any perceived performance gap may in part be explained by the different operating conditions or weather from that used to show compliance to specifications.

The choice of the notional best and worst case datasets made here, and the selection of PPD as the comfort criteria were choices made by the authors and different choices may be made by others. The PPD criteria for these type 2 offices with available cooling would not necessarily apply in the naturally ventilated offices with no cooling systems where the adaptive standards may apply.

The survey of the Egyptian office buildings is not extensive but shows the same trend in increasing energy use in the more highly serviced buildings as found in other situations such as in the ECON19 UK survey. There is scope for further survey to be carried out to give a more comprehensive picture.

The focus of the work presented in this paper was to develop a method for assessing building performance including variation in operation, behavior and weather, the next steps are to develop the method further (alternative office types / comfort criteria, performance view extension etc), and investigate the use of the method in support of design and policy.

5 Conclusions

Building operating conditions, weather and the behavior of occupants are inherently variable and uncertain.

This paper proposes a simple method for including the impact of these variations and uncertainties in building performance assessment for use in design or policy.

The current energy and environmental performance of offices in Egypt is characterized through a simple energy survey of multiple offices.

A more detailed investigation of an individual office building with natural ventilation and independently controlled local cooling systems is carried out.

The method demonstrated includes the creation of a calibrated model, a typical model, and parameter sets representing likely variations in operations, behavior and weather.

The observed indoor environment is compared against adaptive and non-adaptive thermal comfort standards.

The application of the proposed method is demonstrated for a typical Egyptian office and the same office with changes applied.

The more general use and applicability of the method in design and policy is highlighted, and potential usefulness in operation phase discussed.

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WINDSOR CONFERENCE 2016

MAKING COMFORT RELEVANT

WORKSHOP 1.3

The Role of Clothing in Comfort

Invited Chairs: George Havenith and Roberto Lamberts

WS1.3: The Role of Clothing in Comfort.
Chairs: George Havenith and Roberto Lamberts

Today in cold climates we often see very high set point temperatures during winter and very low ones during summer, but both energy savings and enhanced comfort can be achieved simply through the use of appropriate and effective clothing behaviours. The CoolBiz and Setsuden programmes in Japan provide new field data that demonstrate that in the summer higher temperature set points can be comfortably adopted in conjunction with changes in clothing behaviours, so avoiding, in some climates the need for heating systems completely. New clothing technologies also require new measurement approaches and protocols. What are the differences in insulation values provided to men and women by clothing? What parts of the body should be covered? Are current tables of clothing thermal resistance adequate? How can the seasonal impacts of different traditional clothing assemblages be accounted for? The workshop provides a forum for discussion of research advances in the field and explores new directions of investigation to fill in knowledge gaps.

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Clothing insulation as a behavioural adaptation for thermal comfort in Indian office buildings

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Abstract
Regulating clothing is one of the most obvious behavioural responses to changing thermal conditions. The extent of clothing, in turn, affects thermal sensation and acceptability. A lack of extensive thermal comfort field studies in India has meant that there has been very limited data on clothing related occupant behaviour in Indian offices until now. This paper aims to understand clothing norms and practices in Indian offices using data gathered via an extensive field study of thermal comfort in India. It uses the office occupants' response to thermal sensation, acceptability and preference questions as experienced "right here, right now" from more than 6000 surveys together with simultaneous measurement of environmental conditions, clothing and metabolic activity. These surveys are administered in five climate zones across three seasons in air-conditioned, naturally ventilated and mixed mode buildings. The paper analyses clothing insulation as a behavioural response to changes in the environment. The variation in clothing insulation with observed indoor and outdoor temperature is analysed for different seasons, building types and cities. The study also examines the extent of behavioural regulation in clothing between the male and female office workers. The results suggest that women tend to wear lower clothing insulation on an average in summer compared to men. In naturally ventilated and mixed mode buildings, variability in clothing insulation was higher compared to air conditioned buildings, emphasizing the role of clothing as an adaptive measure.

Keywords: Clothing, Behavioural adaptation, Thermal comfort, Indian offices, Office users

1 Introduction

India's electricity demand is expected to rise from 775 TWh in 2012 to 2499 TWh by 2030. This along with pledge by India to reduce emission intensity of India's GDP by 33-35% by 2030 from the 2005 level India's as part of Intended Nationally Determined Contributions (INDC) building energy efficiency becomes important mitigation tool to achieve intended goals (Government of India 2015). Estimates by National Institution for Transforming India (NITI Aayog) indicates that the mitigation activities for moderate low carbon development would cost India around USD 834 billion till 2030 at 2011 prices.

An adaptive model of thermal comfort recognises that thermal comfort requirements of people depend on their past and present context and that these vary with the outdoor environmental conditions of their location. This concept can play a major role in reducing energy use whilst maintaining the comfort, productivity and well-being of occupants. Thermal neutrality can be achieved for a wide range of outdoor conditions by harnessing measures such as change in clothing insulation level (clo) and activity, operation of fans and windows (de Dear & Brager 1998). Amongst the various adaptive actions performed by building occupants, adjustment in clothing is one of the most practiced action to achieve thermal comfort (Feriadi & Hien 2004).

There are multiple field studies from different geographical regions suggesting that indoor and outdoor temperatures are important determinants of clothing behaviour. In a meta-analysis of more than 21,000 from four continents covering a wide range of climate zones, 66% of the variance in clothing insulation worn indoors could be accounted for by the regression model where the independent variable was mean indoor operative temperature (de Dear & Brager 1998). In the same study, 40% of the variance in clo values was explained by variations in outdoor effective temperature in an exponential decay curve while a straight regression model accounted for 44% of variance in naturally ventilated buildings. A field study in Australia provides evidence that outdoor temperatures significantly influence clothing levels (Morgan et al. 2002). A study done in Libya found a correlation between clothing insulation and both the outdoor temperature (R^2=0.492) and the indoor globe temperature (R^2=0.519), with average clo values ranging from 0.55-0.62 across the three locations (Akair & Bánhidi 2007). A field study in Tunisia documented a large scatter of clothing insulation ranging from 0.7 clo in summer to 1.8 clo in winter and reported a more robust correlation between clothing insulation and indoor temperature (R^2=0.52) as compared to outdoor temperature (R^2=0.5) (Bouden & Ghrab 2005).

Clothing insulation values of male and female respondents was found to be similar in a field study in Seoul, Korea, but the clo value of female respondents was slightly higher than that of male respondents in winter. Female respondents also seemed to change their clo value gradually with the seasonal changes, unlike make respondents. The study also reported a decrease in clo value in both summer and winter from 1980 to 2009 (Bae & Chun 2009). A field experiment in Taiwanese classrooms reported that students adjusted their clothing according to the indoor temperature. AC classrooms, which also had cooler conditions, had higher clothing levels than NV classrooms. More importantly, it showed that female students adjusted their clothing levels more swiftly in response to the indoor temperature (Hwang et al. 2006).

Another field study reported that occupants would accept the thermal environment by adjusting clothing insulation value for an operative temperature up to 29˚C in residential apartments Hong Kong (Lai et al. 2009). A field study done in 25 office buildings in a warm-humid and a composite climatic zone location reported overall clothing insulation values ranging from 0.49 to 0.97 clo units. The study was conducted in summer and south-west monsoon seasons. Clothing insulation correlated rather poorly with temperature in both the cities (Indraganti et al. 2013).

Recognising importance of clothing in providing insulation to human body, thermal comfort guidelines and standards documents such as ANSI/ASHRAE 55-2013, TM52 by CIBSE, ISO 7730: 2005, ISO 9920:2007 and BS EN 15251-2007 have regarded clothing insulation values to determine appropriate thermal conditions.

Indians wear a wide range of clothing attire that stems for the country’s cultural, socio-economic and climatic diversity as well as from the variety of clothing material and degree of customization on offer. Over the years, international clothing styles and norms have been seamlessly assimilated in the day-to-day life, both at home and work. An extensive project with multiple field studies in Indian offices was undertaken by the authors of this paper which resulted in an India-specific adaptive thermal comfort model (Manu et al. 2016) for naturally ventilated and mixed mode buildings and demonstrated that Fanger's static PMV model consistently over-predicts the sensation on the warmer side of the 7-point sensation scale even in AC buildings.

In order to implement these models, it is important to understand the clothing practices in Indian work spaces and variation in clothing insulation with season and building type. It is also important to understand how clothing behaviour changes with indoor and outdoor environmental conditions. This paper focuses on these aspects of adaption in Indian office buildings.

2 Methods

This study is based on the data collected for the larger IMAC (India Model for Adaptive Comfort) field study conducted from 2011-2014 across India to develop an India specific model for adaptive thermal comfort (Manu et al. 2016). More than 6000 'Right here, right now' surveys were administered along with concurrent indoor environmental measurements in 16 office buildings in India. These buildings were located across five Indian cities that were selected as representative locations within five distinct climate zones of India (Bansal & Minke 1995; Bureau of Indian Standards 2005). The surveys were repeated in three seasons – summer, monsoon and winter in each building.

2.1 Surveys

The 'right here, right now' surveys were administered to gather a respondent's assessment of her/his immediate thermal environment at work space at the time of the survey in three office building types – naturally ventilated (NV), mixed-mode (MM) and air conditioned (AC) buildings. The survey questionnaire included the ASHRAE 7-point thermal sensation scale of warmth ranging from cold (-3) to hot (+3) with neutral (0) in the middle. This was a continuous scale allowing non-integer ratings, however very few respondents used that option. The other questions were related to thermal acceptability, preference and general comfort.

Clothing and activity of each subject was also recorded on the questionnaire. The survey was administered in an interview format where the field researcher read the questions to the subject and noted the responses on the form manually. The respondents were observed unobtrusively and the clothing garment checklist was filled-in on the questionnaire by the researchers. The interview and physical measurements were completed in about 5-10 minutes per subject. The respondents were interviewed on the questionnaire at the same time as their workstation environment was being measured using the hand-held instruments.

2.2 Measurements

Indoor climate measurements were recorded using hand-held equipment at each subject's workstation while the survey response was taken. That meant that each set of measurements was spatially and temporally coincident with the occupant location.

Based on the categorization of field studies by Brager & de Dear (Brager & de Dear 1998), IMAC study was a Class II investigation.

Extech HT30 Heat Stress WBGT Meter was used to measure three indoor environmental parameters - air and globe temperature and relative humidity. It is a hand-held instrument that can measure (black) globe temperature in the range of 0 to 80˚C with an accuracy of ±2˚C using a black globe of 40mm diameter. It measures air temperature in the range of 0 to 50˚C with an accuracy of ±1˚C and relative humidity in the range of 0 to 100% with an accuracy of ±3%. For globe temperature measurements, the globe was give 5~10 minutes to reach equilibrium.

TSI VELOCICALC Air Velocity Meter 9525 was used to measure indoor air velocity. It is a hand-held instrument and uses a telescopic probe to measure air velocity in the range of 0 to 50 m/s with an accuracy of ±3% of the reading. Two measurements were taken at each position, the first one parallel to the ceiling (sensor was horizontal) and second parallel to wall (vertical) according to wind source.

U12-012data loggers were used to measure and store outdoor air temperature and humidity data for each location. In each city, a safe location, an office or a residence was identified to install the loggers. Periodic checks were performed either by the field researchers or the owners of the property. The positioning of the loggers was chosen based on the daily activities so it won't be disturbed by the owners. They were installed in semi-open spaces shielded from direct solar radiation.

2.3 Clothing insulation

An extensive clothing garment checklist was prepared for the survey questionnaire. It included Indian garments for women and men, such as sari, kurta, pajama, etc. For each garment, the field researchers also indicated if it was light weight, medium weight or heavy weight, on the questionnaire. Clothing insulation (clo) values were assigned to each garment based on the lists published in ASHRAE Standard 55-2010 (ASHRAE 2010). For garments not listed in the standard, clo values were interpolated from those of the existing garments. The total clo for each respondent was calculated by adding the clo values of individual garments and undergarments (Table 2). To account for insulation provided by a cushioned chair, a clo value of 0.15 was added to the total clo from the garments. Table 3 lists the classification of all chair types documented during the field surveys and the corresponding insulation values assigned to each type. It is important to note here that the IMAC estimates of sari ensemble insulation range from 0.61-0.77 clo (lightweight – heavyweight). This range is very similar to the results from the manikin experiments done by Havenith (Havenith et al. 2015) where the sari ensemble insulation was 0.74 clo and those conducted by Indraganti where she proposed ensemble values of 0.65 (pleated pallu) and 0.74 (unpleated pallu) (Indraganti et al. 2015).

Table 1 Clothing garments checklist and insulation (clo) values

Clothing	Light weight	Medium weight	Heavy weight	Description from ASHRAE Standard 55-2010
Petticoat	0.15	0.15	0.15	
Baniyan/undershirt	0.06	0.06	0.06	
Short sleeved shirt/kurta	0.19	0.24	*0.28*	Short-sleeve dress shirt
Long sleeved shirt/kurta	0.25	0.3	0.34	Long-sleeve dress shirt and Long-sleeve flannel shirt
Pants	0.15	0.2	0.24	Straight trousers (thin and thick); 3 for jeans
Pajama	0.12	0.16	0.21	
Pajama/salwar/churidar	0.13	0.18	0.22	
Scarf/dupatta	0.04	0.08	0.13	
Hijab	0.06	0.1	0.15	

Clothing	Light weight	Medium weight	Heavy weight	Description from ASHRAE Standard 55-2010
Blouse (for sari)	0.12	0.16	0.19	Sleeveless/scoop-neck blouse and Short-sleeve dress shirt
Sari	0.3	0.35	0.39	
Dress	0.33	0.4	0.47	Long-sleeve shirtdress (thin and thick)
Skirt	0.14	0.19	0.23	Skirt (thin and thick)
Long sleeved sweater	0.25	0.3	0.36	Long-sleeve (thin and thick)
Vest/waistcoat/sleeveless sweater	0.13	0.18	0.22	Sleeveless vest (thin and thick)
Jacket	0.36	0.4	0.44	Single-breasted (thin and thick)
Shawl	0.27	0.3	0.35	
Shorts	0.08	0.13	0.17	Walking shorts
Dhoti	0.15	0.15	0.15	
Turban	0.08	0.12	0.17	
Tie	0.01	0.03	0.05	
Thermal underwear - upper	0.2	0.2	0.2	
Thermal underwear - lower	0.15	0.15	0.15	
Socks	0.03	*0.05*	0.06	Calf-length socks, Knee socks (thick)
Stockings	0.02	0.04	0.06	Pantyhose/stockings
Shoes	0.02	0.06	0.1	Shoes and Boots
Chappals/sandals	0.02	0.02	0.02	Sandals

Clo values in highlighted cells have been interpolated from ASHRAE 55-2010 values. Others have been taken as they were in ASHRAE 55-2010.

Table 2 Undergarment Clo values

Clothing	clo
Bra	0.01
Panties	0.03
Men's briefs	0.04

Clo values have been taken from ASHRAE 55-2010

Table 3 Chair insulation

Code	Chair Description	Chair insulation *(clo)*
P1	Plastic moulded chair	0
P2	Plastic moulded chair used with a cushion for seat	0.15
W1	Wooden framed chair with open mesh weave for seat and back rest	0

Code	Chair Description	Chair insulation *(clo)*
W2	Wooden framed chair with open mesh weave for seat and back rest used with a cushion for seat/back rest and hand rest	0.15
M1	Metal framed chair with open mesh weave for seat and back rest	0
M2	Metal framed chair with open mesh weave for seat and back rest	0.15
O1	Revolving chair	0
O2	Revolving chair used with a cushion for seat/back rest and arm rest	0.15

3 Results

Table 4 presents a statistical summary of the clothing ensemble insulation (including chair insulation) for the three seasons. Clo value ranged from 0.38 to 2.24, with an average of 0.79 clo units. Mean clo in summer and monsoon was 0.64 and 0.69 which is higher than the ASHRAE 55-2010 assumed summer value of 0.5 clo. The winter season's average was 1.05 clo. The standard deviation (SD) in clo was higher in winter (0.42 clo), almost thrice the SD in summer and monsoon (0.1-0.12 clo), indicating greater variability in clothing ensemble in winter as increased number of layers lead to more freedom in clothing adjustments.

Female respondents wore lower clothing insulation on an average in summer when compared to male respondents. Similar trends were evident in monsoon and winter. Lower insulation in response to warmer temperatures indicates fewer layers of clothing resulting in diminished opportunity to adjust clothing further. In spite of wearing lower insulation than male respondents, the variability in clo was slightly higher among female respondents in summer and monsoon. In winter, however, clothing insulation among female respondents showed less variability as compared to the male respondents.

Table 4 Clothing insulation statistical summary by season and gender

	Summer			Winter			Monsoon		
	Male	Female	Combined	Male	Female	Combined	Male	Female	Combined
N	1467	636	2103	1434	633	2067	1452	708	2160
Avg.	0.66	0.57	0.64	1.08	0.97	1.05	0.70	0.65	0.69
Max.	1.02	1.00	1.02	2.24	2.07	2.24	1.29	1.35	1.35
Min.	0.40	0.38	0.38	0.43	0.38	0.38	0.40	0.38	0.38
SD	0.09	0.10	0.10	0.42	0.40	0.42	0.11	0.14	0.12

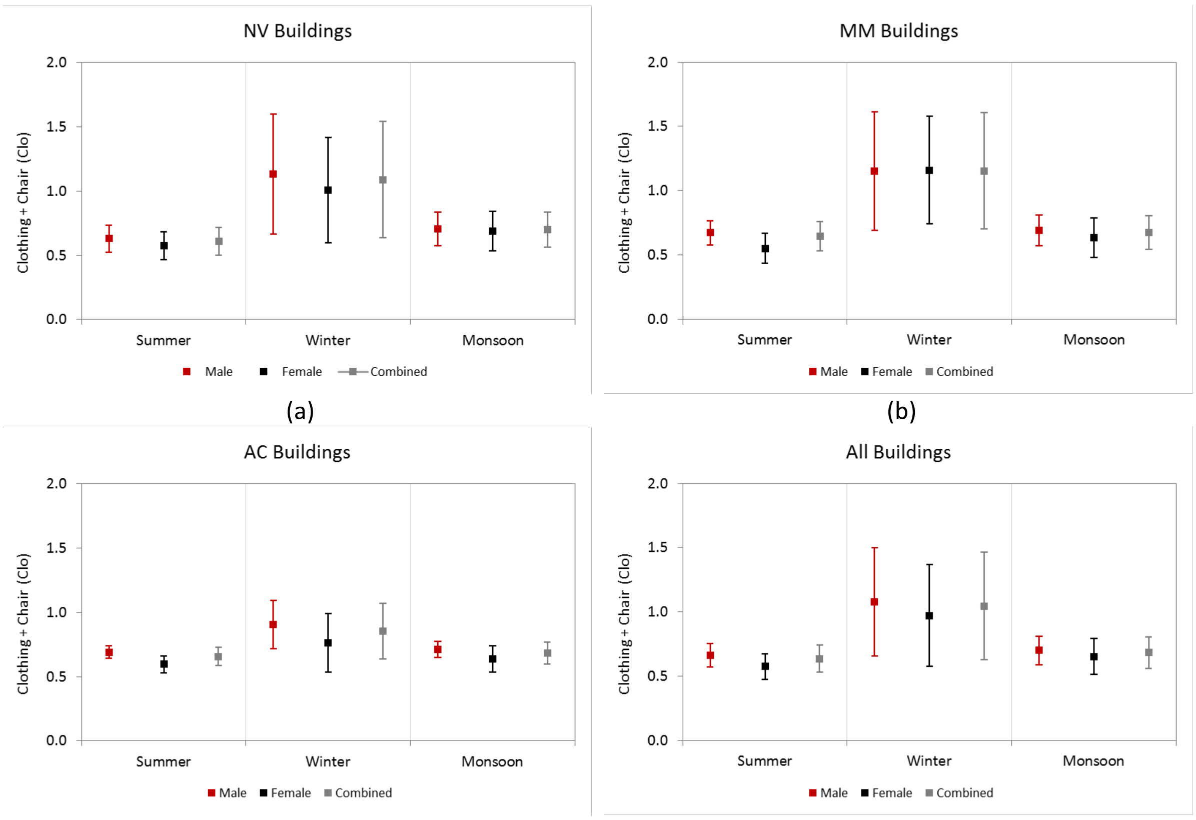
The IMAC dataset was disaggregated into building operation types – NV, MM and AC in Table 5 to present a statistical summary of the clothing ensemble insulation. Average Clo in AC buildings was lower than in NV and MM buildings. The variability (SD) in clo was much higher in NV and MM buildings as compared to AC buildings, for both male and female respondents. This indicates that the respondents changed clothing frequently to adapt to the varying indoor and outdoor conditions in NV and MM buildings. Respondents in AC buildings experienced similar indoor temperatures across the year which may have resulted in low variability in clo. All AC buildings in the dataset were corporate offices with a business attire dress code resulting in restricted opportunities for adaptive clothing behaviour. These buildings also maintained the indoor temperatures with a narrow range conditioning the occupants to similar thermal environment throughout the year, therefore, making personal adaptive measures, such as changing clothing insulation, redundant.

Table 5 Clothing insulation statistical summary by building operation type and gender

	NV Buildings			MM Buildings			AC Buildings		
	Male	Female	Combined	Male	Female	Combined	Male	Female	Combined
N	1312	693	2005	1875	601	2476	1166	683	1849
Avg.	0.82	0.75	0.80	0.83	0.78	0.82	0.77	0.66	0.73
Max.	2.16	2.06	2.16	2.24	2.07	2.24	1.66	1.93	1.93
Min.	0.40	0.38	0.38	0.40	0.38	0.38	0.55	0.53	0.53
SD	0.36	0.32	0.35	0.35	0.38	0.36	0.15	0.16	0.16

Seasonal clothing insulation trends are similar between NV and MM buildings as shown in Figure 1. Winter clo values in AC buildings are lower than NV and mm. 'All buildings' dataset has pooled survey responses from NV, MM and AC buildings. Average clo for male respondents was always higher compared to female respondents across all building operation types and seasons, except in winter in MM buildings. In addition, the variation in average clo values between seasons was least in AC buildings. For instance while there was a reduction of 0.21 clo from winter to summer for males and 0.16 clo for females in AC buildings, the corresponding change in NV buildings was 0.5 for males and 0.43 for females, and 0.48 for males and 0.61 for females in MM buildings.

Average clo was highest in winter in MM buildings – 1.15 for male and 1.16 for female respondents. While the average clo values were not too dissimilar in NV buildings (1.13 and 1.01 for male and female respectively), these values dropped to 0.09 and 0.76 for male and female in AC buildings. Standard deviation in clo insulation, was the highest for male respondents in NV buildings in winter (SD=0.47) and lowest for male respondents in AC buildings in summer (SD=0.05).



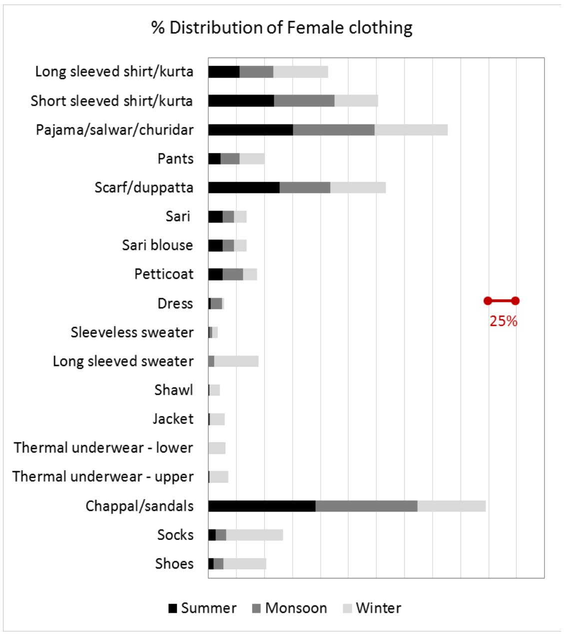
(a) (b) (c) (d)

Figure 1 Clothing insulation mean and standard deviation for NV, MM and AC buildings by season and gender

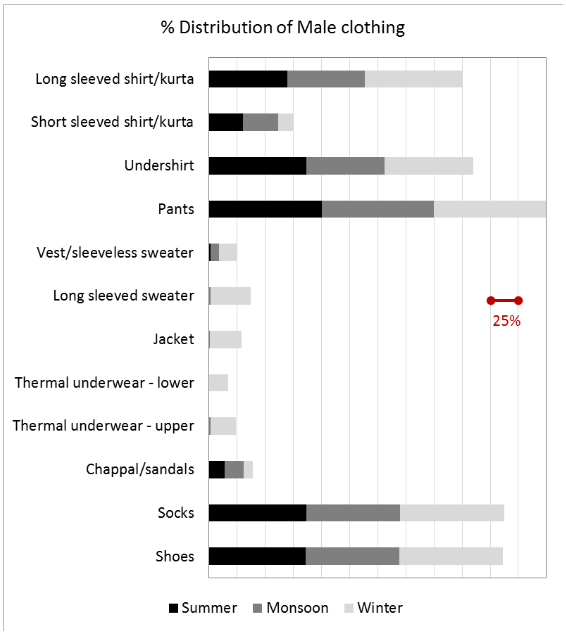
3.1 Distribution of clothing garments

Figure 2 plots the percentage distribution of selected clothing garments for female and male respondents for the three seasons. This distribution presents an interesting view into the clothing patterns and behaviour of office workers in India. From Figure 2a shows that less than 15% of the total female respondents (n=1977) were wearing a sari at the time of the survey. This percentage did not vary significantly from one season to another. Salwar/chudidar was the most widely worn garment, worn with short or long sleeved kurta/shirt to form a complete ensemble. 75% were wearing salwar/chudidar in summer, 73% in monsoon and 65% in winter. Reduced numbers of respondents wearing salwar/chudidar in winter may be explained by an increase in those wearing pants in that season (27%). Another important garment seems to be the scarf or the dupatta, worn by more than 60% of the female respondents in summer and around 45% in monsoon and winter. Sandals seem to be the footwear of choice with more than 90% respondents wearing them in summer and monsoon. This percentage was understandably lower in winter (61%) where 39% were reported wearing shoes.

All male respondents were wearing pants at the time of the survey (Figure 2b). 70% of them were wearing long sleeved shirt with pants in summer and monsoon. This percentage increased to 87% in winter. More than 80% of the total male respondents (n=4353) were wearing shoes in summer and monsoon and 93% in winter.



(a)



(b)

Figure 2 Percentage distribution of female and male clothing garments

3.2 Clothing insulation adjustments with change in indoor temperature

Figure 3 presents weighted linear and exponential trend lines plotted between the mean level of clothing insulation worn for a 'building + season' aggregate and its mean indoor temperatures for male and female respondents. This aggregate has data points from a specific seasonal campaign within a building, leading to a total of 48 aggregates from 16 buildings and 3 seasons. The trend lines were plotted for NV, MM, AC and All buildings datasets.

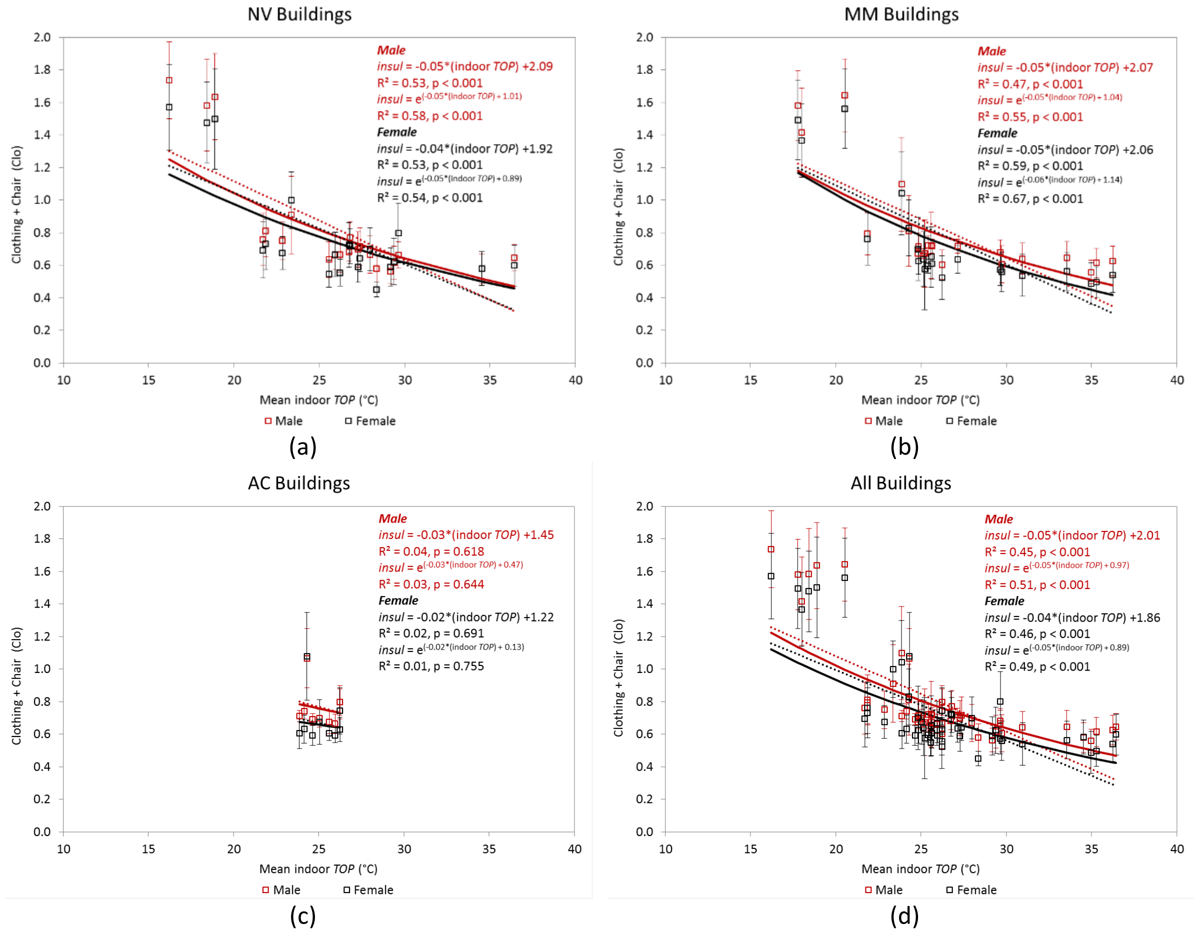


Figure 3 Male and Female clothing insulation inside buildings (mean ±stdev) as a function of mean indoor operative temperatures

The graphs indicate a statistically significant relationship between clothing insulation and mean indoor operative temperature (*TOP)* for NV and MM buildings indicating a gradual decrease in clo values with increase in indoor *TOP*. For these building types, the exponential model provided a better fit than linear regression. The model for AC buildings failed to achieve significance possibly due to the narrow range of indoor temperatures encountered in these buildings as compared to the NV and MM building aggregates.

The error bars on either side of the plotted points in the figure represent ±1 standard deviation around the within-aggregate mean. The standard deviation bars indicate the variability of clothing insulation which decreased as the indoor temperature increased. This probably shows the diminished freedom to adjust clothing as the number of garments in the ensemble reduced to the socially acceptable minimum dress standards.

The regression models indicate that across all building types, male respondents wore higher clothing insulation as compared to the female respondents, irrespective of the prevalent indoor temperatures.

In NV buildings, the linear regression models were significant and explained 53% variance in clothing insulation of male and female respondents with change in indoor operative temperatures. Mean clothing insulation decreased, on average, by 0.05 clo units for male respondents and 0.04 clo units for female respondents for every 1K increase in the mean indoor temperature, very similar to the de Dear's regression model for NV buildings from the RP-884 meta-analysis of global database (de Dear et al. 1997).

The regression models for MM buildings were less robust for male respondents and more robust for female respondents compared to NV buildings. Linear models accounted for about 47% variance in clothing insulation of male respondents and 59% for female respondents with change in indoor operative temperatures. There was no discernable relationship between clothing insulation and indoor temperature in AC buildings.

The slope of the regression models was marginally lower for female respondents compared to their male counterparts in NV buildings, while in MM buildings it was similar. With the increase in indoor temperature there was steeper decline in male clothing insulation indicating more layered clothing as well as a faster adjustment of clothing insulation to address the change in indoor temperatures as compared to the female respondents. At the same time, however, there was lower variability in the male clothing insulation at higher indoor temperatures in NV and MM buildings. The reason might be because the male respondents may be wearing the lowest clothing insulation that social convention may allow and any further reduction may not be possible in a work environment.

3.3 Clothing insulation adjustments with change in outdoor temperature

Since the clothing insulation has a strong relationship with the indoor temperatures, clothing decisions and behaviour may also be expected to be influenced by outdoor weather conditions. Figure 4 presents weighted linear and exponential trend lines plotted between the mean levels of thermal insulation for each 'building + season' aggregate against 30-day outdoor running mean air temperatures. The trend lines were plotted for NV, MM, AC and All buildings datasets.

The graph for NV buildings indicates a statistically significant relationship between clothing insulation and outdoor temperature. The linear regression model accounts for 71% variance in the dependent variable for male respondents and 65% variance for female respondents. Exponential models provide a better fit than the straight line for male respondents explaining 76% of the variance in clo values. The regression models are very similar for male and female respondents. The linear regression models indicated a decrease of 0.04 clo units in mean clothing insulation for every 1K increase in the mean outdoor temperature.

Regression models for MM buildings suggest that outdoor temperature is an important determinant of clothing insulation but the relationship is not as strong as in the case of NV buildings. In MM buildings, the linear regression models explained 60% of the variance in clothing insulation of male respondents and 65% of the variance in female respondents with change in mean outdoor temperatures. Mean clothing insulation decreased, on average, by 0.03 clo units for male and female respondents for every 1K increase in the mean outdoor temperature. Exponential models yielded better regression coefficients. Regression models for female group were stronger than the male group

The linear regression models for AC buildings explained 60% of the variance clothing insulation worn by male and female respondents. The linear regression models predicted a reduction of 0.01 clo in mean clothing insulation for male and 0.02 clo for female respondents for every 1K increase in the mean outdoor temperature.

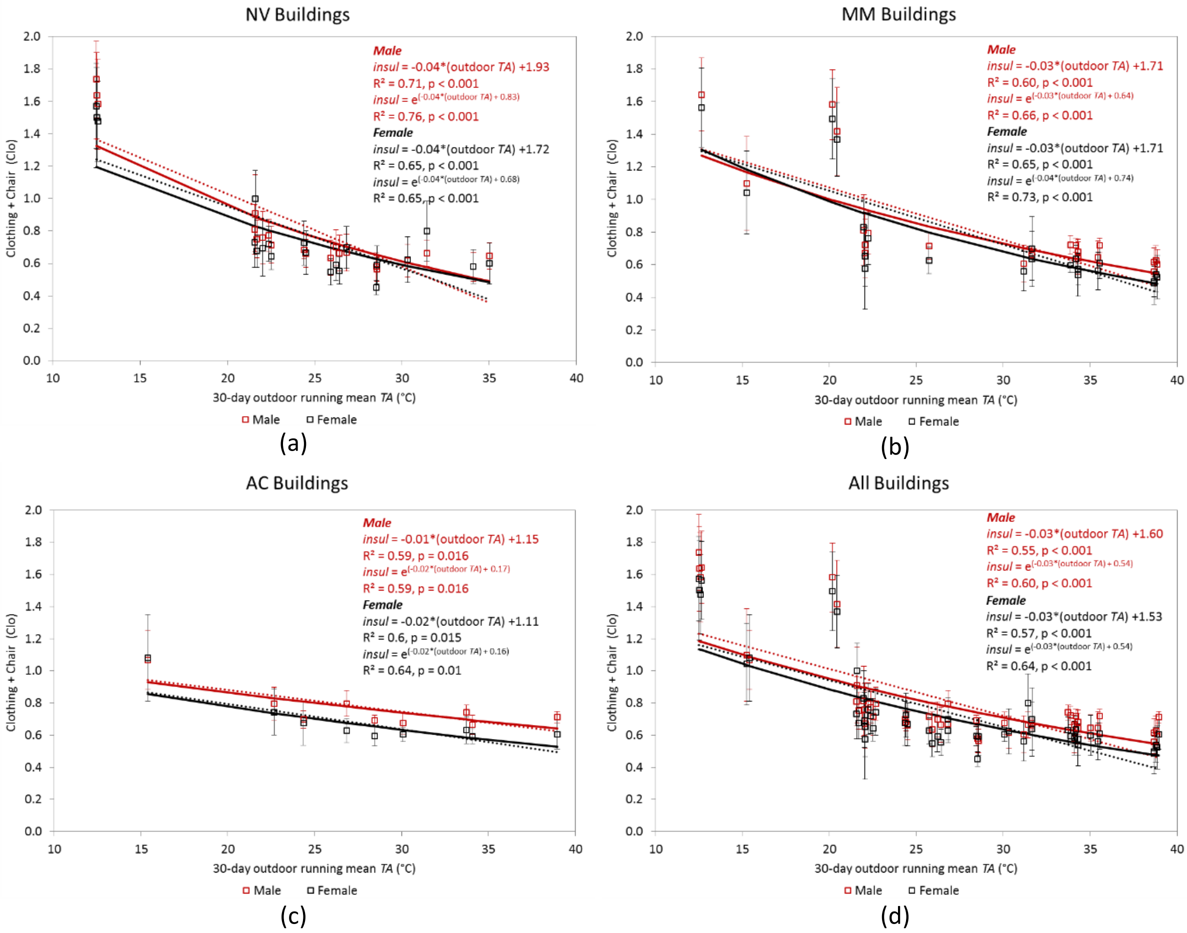


Figure 4 Male and Female clothing insulation inside buildings (mean ±stdev) as a function of outdoor temperature

4 Discussion

This paper offers a number of insights towards a better understanding of clothing insulation as a behavioural response to changes in the environment that are summarised below:

- The findings show that clo value of the IMAC database ranged from 0.38 to 2.24, with an average of 0.79.
- There was a greater variance in the clothing ensemble in winter owing to more clothing layers offering a greater possibility of adjusting clothing as a mechanism for thermal adaption.
- Female respondents wore lower clothing insulation on an average across the year as compared to male respondents. In summer and monsoon, clothing insulation among female respondents showed more variability (SD) as compared to the male respondents.
- Although the annual average clothing insulation did not vary significantly from one building type to another, the variability (SD) in clo was much higher in NV and MM buildings as compared to AC buildings, for both male and female respondents. On the other hand, the change in clothing insulation across seasons was more pronounced in NV and MM buildings than in AC buildings.
- Average clo for male respondents was always higher compared to female respondents across all building operation types and seasons except in winter in MM buildings. But

the difference between the two genders was more pronounced in winter season and in AC buildings.

- The graphs indicate a statistically significant relationship between clothing insulation and mean indoor operative temperature (*TOP)* for NV and MM buildings indicating a gradual decrease in clo values with increase in indoor *TOP*.
- For NV and MM buildings, an exponential decay curve explained the relationship between clothing insulation and indoor temperature better than a straight-line model.
- With the increase in indoor temperature the decline in clothing insulation (slope of the regression model) was similar for male and female respondents.
- In NV buildings, the relationship between clo and outdoor temperature was stronger than the relationship between clo and indoor temperature, for both male and female respondents. This indicates that outdoor conditions play a very important role in clothing behaviour in NV buildings.
- Across all buildings types, the gradient of linear models between clo and outdoor temperature was similar for female and male respondents.

As previously noted (Manu et al, 2016) fan and window operation and change in clothing are significant adaptive measures seen in office buildings in the dataset where Indian respondents were shown to tolerate a wider range of temperatures than would be predicted by Fanger's static PMV model in all building types. Nevertheless, the study has shown adaptive clothing behaviour to be the least evident in AC buildings. The impact of regulating clothing via business dress code coupled with a regulated and narrow range of indoor temperatures across the year as seen in the AC buildings, serves to restrict adaptive behaviour and opportunity. If AC buildings continue to be designed and operated along western standards, they have the potential to create a vicious circle of dependence on energy intensive means for regulating temperatures to achieve thermal comfort in these buildings.

On the other hand, the results presented in this paper demonstrate the critical role clothing can play as an adaptive response. The ability to vary their clothing is an important factor in occupants' ability to adapt to changing outdoor climate and indoor temperatures. As seen here, this is particularly relevant to deliver comfort in the case of NV and MM buildings where thermal conditions vary to a greater extent. Along with other aspects such as fan and window operation, it will be critical that contemporary workplaces offer the ability for adaptation through clothing to suit personal preferences and the Indian climatic and cultural context in contrast to a standardised business dress code. Such a user and climate responsive approach to building design and operation would go a long way in ensuring a sustainable future for the subcontinent.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Why is the Indian Sari an all-weather gear? Clothing insulation of Sari, Salwar-Kurti, Pancha, Lungi, and Dhoti

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Abstract

Barring a few reports on the clothing insulation of sari and salwar-Kurti, little is known about the other traditional ensembles men use in South Asia and beyond. To accurately account for the thermal insulation on the human body, simulation studies necessitate insulation on various body parts. This study reports the segmental level insulation of 52 traditional ensembles of both genders recorded in a climate chamber.

Indian garments are worn as ensembles. We focused on the drape, as traditional ensembles offer great opportunities for thermal adaptation through changing drape. We researched on 41 sari ensembles, four salwar-kurti and seven men's' ensembles, such as *dhoti, pancha* and *lungi*. More than the material, drape has a significant effect on the clothing insulation. For the same pieces of garments, the clo value of the ensemble varied by as much as 3.1 to 32 %, through changing drape in saris, the lower values being associated with lighter saris. A similar trend but somewhat lower variation was noticed in men's' ensembles. This makes the sari an all weather ensemble. Interestingly in the *pancha* ensemble, men can achieve 47% reduction in the clo value with minor variations. The adaptation possibility in traditional ensembles is enormous.

Keywords: India; Sari; Clothing Insulation; Thermal Comfort standards; Thermal Manikin

1 Introduction

Sari is a single piece of unstitched strip of cloth. Only women wear saris mostly in South Asia and in other places across the globe. It is used since millennia, circa 3000 BC. Indian women mostly used traditional ensembles at work ((Indraganti, Ooka, et al. 2014). Unlike western wear the sari is worn as an ensemble and not as different pieces of garments assembled together.

HVAC system design necessitates the insulation offered by many varieties of clothing to estimate the thermal comfort of occupants in buildings. Data on Indian traditional ensembles is not fully represented in the present building standards (ASHRAE 2010, BIS 2005, ISO:9920 2004). More over detailed comfort analysis requires segmental level information on clothing insulation to understand local discomfort of occupants (Huizenga, Zhang and Arens 2001, Zhang, et al. 2010, Zhang, et al. 2010). Being a 'one-size-fits –all' ensemble, it lends itself to a high degree of customisation and acclimatization at wearer's level. However, the present codes and published information on sari and similar ensembles do not address the importance of drapes on clothing insulation (Mitsuzawa and Tanabe 2001, Al-ajmi, et al. 2008).

We have reported earlier on the versatility of the sari in climate adaptation using different drapes. (Indraganti, Lee, et al. 2015). This report presented nine ensembles used in summer and winter/ monsoon seasons. Extending this work, we report the segmental level and whole body insulation of 41 different sari ensembles in this paper. In addition, we also present these values for eleven different traditional ensembles for both the genders. These are women's Salwar-Kurti, and men's Lungi and Pancha used by men.

2 Methods

2.1 The sari ensemble

The sari ensemble has three pieces of garments essentially: a sari, a short blouse or bodice and a petticoat. Sari measures 5.0 – 8.1 m in length and 1.15 to 1.25 m in width. The length usually depends on the draping style. The most common type of sari measures 5.0 - 6.0 m, width being the same, used in this study. A strip of underlining (2 -2.5 m long and 75 – 100 mm wide) is usually attached at the bottom boarder of the sari to improve the drape and durability of the sari.

India has rich and varied textile tradition and saris can be found in very diverse fabrics, designs and embellishments. In this study we used saris in silk, silk chiffon, handloom and milled cotton and polyester and nylon fabrics, common to the normal sari stock.

A bodice or blouse as is referred to in India is a stitched tight fitting garment few inches above the navel. It is usually made in fine cotton or in the same fabric as that of the sari. Some bodices have cotton underlining. The necklines and shoulder lengths are a matter of fashion and user's choice. In this study we tested the blouses with deep and medium depth necklines and short and medium shoulder lengths. The blouse fabrics are cotton, silk, polyester in this study, with the non-cotton blouses being provided with thin cotton interlining.

A petticoat is a conical shaped, drawstring ankle length skirt worn under the sari. Stitched in cotton, polyester or satin, it holds the sari in place, provides fullness and mobility to the wearer. We used cotton, polyester and satin petticoats in this study. Indraganti et al. (2015) described the articles used in the typical sari ensemble in greater detail.

2.2 The sari drape

The sari can be draped in over a hundred different ways, the most common one being the '*nivi*' style of draping. In this study we used the *nivi* style of draping for all the ensembles. This essentially has the sari wrapped around the petticoat in two layers. The second layer has frills or folds at the centre front, which gives the attire fullness. The second layer also covers the belly and the chest in a diagonal manner, the other end of which is the *pullu*. A detailed pictorial description of draping of sari can be found in Boulanger (1997).

2.3 The Salwar- Kurti

The salwar is a loose fitting baggy style trouser that tightens at the ankles. Historical evidence points to its use since Mauryan Period (322–185 BCE) (Vishnu 1993). A stitched garment, it is worn generally as part of a three-piece ensemble, which consists of salwar, *kameez*, *kurta* or *kurti* (stitched top) and *dupptta* (thin shawl). It is traditionally worn in northern parts of India and all over Pakistan and in some parts of Afghanistan. For the last few decades a majority of women across India have been using *salwar-Kurta/ Kurtis* as their everyday attire.

A kurti is a loose fitting short top up to hip length or slightly below worn traditionally along with the salwar. The shoulder length varies and some women also wear it with the trousers. A dupatta is a rectangular piece of cloth (2.25 - 2.5m in length and 0.9 – 1.14 m win width). In this test we used a fine cotton full-sleeved kurti along with a cotton loose fitting salwar and a cotton *dupatta*.

2.4 The Dhoti

Bas-reliefs dating back to 1st century AD point to the use of Dhotis by men (Ganguly n.d.). Traditionally worn predominantly in South Asia, the dhoti is a single piece of rectangular unstitched fabric, synonymous to the women's sari (Ghurye 1995). It measures around 4 m x 1.5 m. Similar to Sari, it is knotted around the waist and is wrapped around the waist and legs. There is a major difference between a sari and a dhoti. The former covers both the upper and lower bodies and worn over a petticoat, while the latter covers only the lower body and is worn on the naked body directly.

Figure 1 Front, rear and side view of a dhoti ensemble on a human subject

A dhoti is usually passed through legs, tucked at the back and covers the legs loosely, and then it flows into long pleats at front of the legs. Historically its draping method hasn't changed much over time. Dhotis nowadays are usually in white, beige or light colours in plain handloom cotton, silk, or poly-cotton fabrics with or without gold thread boarders in contrasting colours. Men wear either full-sleeved or half-sleeved kurtis along with the dhotis to cover the upper body. This is the traditional outdoor and indoor attire for several men in rural and sub-urban parts of India and home-wear garment in cities as well. In this test we studied a dhoti as the nether garment with a half sleeved handloom cotton men's kurti.

2.5 The Lungi

Similar to the sari and dhoti, the Lungi or sarong is a single piece unstitched piece of cloth draped around the waist as a nether garment. It is a traditional garment worn in South Asian regions and beyond, stretching as far as Southeast Asia, Northern Arabian Peninsula and Somali Peninsula. It is everyday attire for men especially in warmer parts of Asia where the climate is unsuitable for western trousers. In some areas the shorter ends or the fabric are sewn together to form a tube like structure. A lungi usually measures 2 m x 1.15 m. Most common fabrics are handloom cotton, silk, and poly-cotton. In certain socio-political sections of the society, men in South India wear lungis as their everyday formal attire. On the other hand, in modern offices men in India usually wear western trousers and shirts (Indraganti 2010). In some parts of Kerala, India even women use lungis as a nether garment.

The lungi is tied around the waist forming a double layer in the front in a double twist knot. This layering provides fullness to the wearer. It is worn over the naked body, unlike the sari. The draping style and length of body coverage are region and activity/ occasion specific. We tested a handloom cotton lungi with a cotton kurti in two ensembles of two different drapes.

2.6 The Pancha

In some parts of India, a very fine cotton dhoti (4m X 1.50 m) is folded into two layers and is draped as a lungi. This type of ensembles is traditionally referred to as 'pancha.' In this experiment we tested four ensembles with a Pancha and two of these with Kurti. In two of the drapes we folded the pancha up to a few inches above the knees, as is usually done by men at work or in summer. All the garments tested along with their weights are listed in Table 1.

Table 1. Weights, dimensions and the material characteristics of the garments tested

SNo	Code	Clothing	Weight (g)	Length (mm)	Width (mm)	Material
1	UG01	Bra	40			Shell: 100% Cotton: Trims: 100% Elastin
2	UG02	Panty	34.99			100% Cotton
3	UG03	Vest	50			100% Cotton
4	SA01	White and Indigo Sari	180	5817	1168	100% Polyester (without the fall attached)
5	SA02	Light Printed Kashmiri Sari	220	5131	1092	Sari: 100% Silk, Sari boarder underlining: 100% nylon
6	SA03	Orange Chanderi Sari	230	5400	1200	Sari: 100% Silk, Boarder: 50% silk, 25% copper -polyester blended wire, 25%: polyester; Sari boarder underlining: 100% cotton
7	SA04	Blue green Khadi Sari	240	5500	1150	Sari 100% Silk, Sari boarder underlining: 100% cotton
8	SA05	Kota supernet Sari	300	5258	1130	50% Rajasthani Cotton, 50% silk; Sari boarder underlining: 100% cotton
9	SA06	Brown printed voile Sari	300	5283	1054	100 % Cotton
10	SA07	Guntur Jari Sari	330	5029	1092	Sari: 100% Hand loom cotton; Sari boarder: 75% copper -polyester blended wire
11	SA08	White	430	5800	1200	Sari: 100 % Silk Chiffon,

		embroidered Sari				Embroidery: 100% rayon and plastic crystals
12	SA10	Pochampalli blue Sari	460	5359	1130	Sari: 100% Mercirised cotton, Boarder underlining: 100% Polyester
13	SA11	Mauve KSIC Crepe Sari	490	5410	1168	Sari: 100% silk, Boarder: 50% silk, 50% gold-silver -polyester blended wire; Boarder underlining: 100% polyester
14	SA12	Red embellished Sari	500	5258	1092	Sari: 100% Polyester; Sari boarder under lining:100% cotton; Embellishment: 100% White-metal foil and plastic beads
15	SA13	Ochere Kanchi Sari	500	4851	1168	Sari: 100% Kanchi Silk; Boarder: 70% silk, 25% gold-silver -polyester blended yarn; Sari boarder underlining: 100% Polyester
16	SA15	Benaras Yellow Golden Sari	800	5588	1118	Sari: 100 % Silk satin; underlining on boarder and pallu: 100% polyester
17	DH01	Dhoti	310	3277	1295	100% hand loom Cotton
18	DH02	Pancha	240	3353	1270	100% hand loom Cotton
19	LU01	Lungi	210	1930	1168	100% hand loom Cotton
20	B1	Blue bodice	20			100% Polyester
21	B2	Orange Rubia bodice	40			100% Cotton
22	B3	Orange Pochampalli bodice	55			100% hand loom Cotton
23	B4	Cream Yellow Gurjari bodice	60			100% hand loom Cotton
24	B5	Mauve bodice	78			100% Cotton
25	B6	Yellow bodice	78			Shell: 100% Silk, Lining: 100% cotton
26	B7	Banaras Satin blouse	98			Shell: 100% Satin silk: Underlining: 100% cotton
27	P1	Orange Petticoat	120			100% hand loom Cotton
28	P2	White Petticoat	196			100% Polyester satin
29	P3	Green petticoat	200			100% Cotton
30	P4	Pink Petticoat	205			100% Cotton
31	SK01	White patiyala Salwar	155			100% Cotton
32	K2	Black short kurti	120			100% Cotton
33	K3	Khadi Pink Kurti	140			100% Khadi (hand spun) Cotton
34	C1	White Dupatta	160	2250	1120	Dupatta: 100% cotton, embellishment: glass beads

2.7 The experimental setup

Table 2. Experimental test conditions

Ambient temp. (ºC)	Manikin skin temp. (ºC)	RH (%)	Air velocity (m/s)	Posture	Chair
20.09 ±0.29	34	51.18	0.1	Seated on a chair	Mesh arm Chair

Table 2 shows the environmental conditions of the climate chamber used for the experiment. We used the 5.5m x 5.5m x 2.5 m climate chamber facility at the University of California, Berkeley for this testing. It has windows on the southern and western sides, which are shaded by fixed external shading devices.

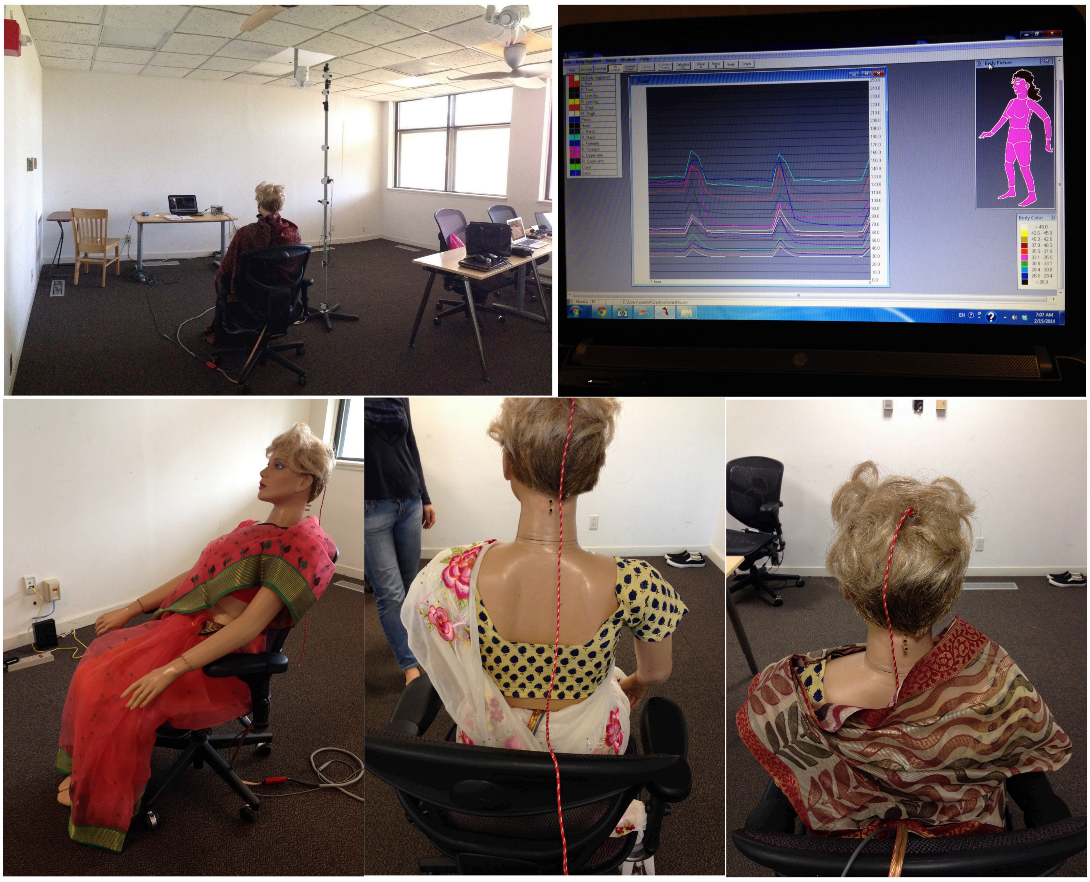


Figure 2 The experimental setup, manikin control, and the sample features of some of the drapes tested

A separate system controlled the temperature of the exterior openings. The chamber has eight floor grill diffusers to precisely control the temperature, humidity, and ventilate the space while the air is exhausted through a ceiling return grill. Even the lighting can be controlled. It has accuracies of 0.5 °C and 3% for temperature and humidity respectively. Table 2 features the experimental conditions. We set the air temperature to be at 20 ºC. The data loggers (HOBO- U12-03) measured the wall temperature and ambient temperatures at 0.1 m, 0.6 m and 1.1 m heights and the relative humidity at the center of the chamber. The data logger has the measurement accuracy of ± 0.35 K at 0 ~ 50 °C range of temperatures and ±2.5 % relative humidity (RH) at 10- 90% range of RH. The ambient temperature was also measured using a high precision mercury thermometer (Fig 2).

We used the same 16 segments Dansih female manikin in this experiment also, that was conducted during February 2014. It has temperature control to maneuverer different body segments. Its surface areas of various body segments are shown in Table 3.

Table 3. Body segments and their respective areas of the manikin

SNo.	Name of Part	Area (m^2)
1	Left Foot	0.043
2	Right Foot	0.041
3	Left Leg	0.089
4	Right Leg	0.089
5	Left Thigh	0.160
6	Right Thigh	0.165
7	Pelvis	0.182
8	Head	0.100
9	Left Hand	0.038
10	Right Hand	0.037
11	Left Arm	0.052
12	Right Arm	0.052
13	Left Shoulder	0.073
14	Right Shoulder	0.073
15	Chest	0.144
16	Back	0.133
Total		**1.471**

The skin temperature setting of the manikin was 34 ºC following the protocols of ASTM (ASTM-F1291-10 n.d.), and ISO (ISO:9920 2004) for testing with the manikin. The ISO uses individual pieces of garments for testing and the clothing insulation of the ensemble is obtained through the summation of individual pieces of the ensemble. However, we tested the sari, dhoti, lungi, pancha and chudidar as a whole ensemble, as the individual pieces of garments are seldom used separately (Fig. 2).

With a manikin draped in the designated ensemble seated on a mesh chair, we had run the experiment for nearly two hours till its heat exchange with the chamber got stabilized. When stable, we noted down the last 10 minute readings and averaged them. The insulation of the mesh chair and the nude body manikin were also estimated separately. We then subtracted the insulation of the chair and nude manikin from the total insulation obtained with a particular ensemble for all the body parts, thus eliminating the effect of the chair and nude insulations. The experiment was repeated for all the ensembles one after the other.

3 Data analysis

Given the manikin skin temperatures ($T_{s,i}$) and heat fluxes ($Q_{t,i}$), we calculated the total insulation using the Eq (1),

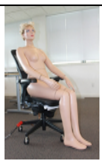
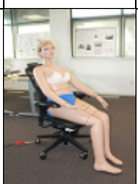
$$I_{t,i} = (T_{s,i} - T_a) / (0.155 * Q_{t,i}) \qquad [1]$$

Where, T_a is the ambient air temperature, I_{cl} = Clothing Insulation (clo) and,

1 clo = 0.155 m^2 ℃/W. The intrinsic insulation of the clothing itself was calculated by Equation (2):

$$I_{cl,i} = I_{t,i} - I_a / f_{cl} = I_{t,i} - I_a/(1+0.3\ I_{cl,i}) \qquad [2]$$

Table 4. Clothing Insulation of mesh chair, nude and with undergarments for whole body and sixteen segments

SNo.	Clothing ensemble	Codes of Ensemble sari, bodice, petticoat and details of drape	BSAC (%)	Whole-body	Head	Chest	Back	Shoulder_L	Shoulder_R	Lower arm_L	Lower arm_R	Hand	Pelvis	Thigh	Lower leg	Foot
1		Mesh Chair		0.02	0.00	0.01	0.02	0.01	0.01	0.01	0.02	0.02	0.01	0.03	0.02	0.00
2		Nude		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3		Panty		0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.05	0.00	0.05	0.03	0.00
4		Panty Bra	20	0.05	0.00	0.22	0.00	0.00	0.00	0.00	0.18	0.03	0.03	0.08	0.05	0.00

The nude body recorded a thermal resistance of 0.78 clo in this experiment (Table 4). We measured the insulation values of the 41 sari ensembles as shown in Table 5. In addition we tested four salwar-kurti ensembles for women, four Pancha ensembles, two lungi ensembles and one Dhoti ensemble for men (Table 6). These show thedescription of an ensemble along with the body surface area covered (BSAC) and insulation values. The insulation values for the right and left extremities are averaged and combined.

Table 5. Clothing Insulation of saris for whole body and sixteen segments

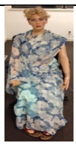
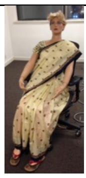
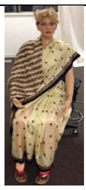
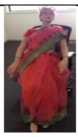
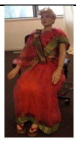
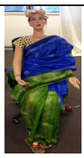
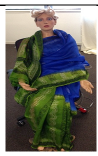
SNo.	Clothing ensemble	Codes of Ensemble sari, bodice, petticoat and details of drape	BSAC (%)	Whole-body	Head	Chest	Back	Shoulder_L	Shoulder_R	Lower arm_L	Lower arm_R	Hand	Pelvis	Thigh	Lower leg	Foot
1		E 201 (SA01, B1, P3) Polyester Georgette, both arms uncovered	65	0.76	0.28	1.57	0.71	0.65	0.21	0.04	0.03	0.03	1.79	2.01	0.80	0.20
2		E202, (SA01,B1,P3) Polyester Georgette, Right arm covered, pleated pallu	73	0.82	0.27	2.04	0.99	0.52	0.55	0.03	0.19	0.04	1.78	2.32	0.85	0.12
3		E203 (SA02,B4,P1) Light Printed Kashmir, both arms uncovered	65	0.77	0.36	1.51	0.48	0.83	0.24	0.01	0.04	0.04	2.33	2.45	0.84	0.16
4		E204 (SA02, B4, P1) Light Printed Kashmir, Right arm covered, pleated pallu	73	0.88	0.30	2.41	1.06	0.87	1.06	0.01	0.37	0.02	2.24	2.35	0.85	0.16
5		E205 (SA03, B2,P1) Orange Chanderi silk, both arms uncovered	65	0.71	0.28	1.44	0.83	0.51	0.18	0.02	0.01	0.06	1.75	1.53	0.65	0.06
6		E206 (SA03, B2, P1) Orange Chanderi silk, Sari Right arm covered, pleated pallu	73	0.77	0.16	2.06	0.84	0.42	0.66	0.03	0.19	0.06	1.86	1.59	0.55	0.18
7		E207 (SA04, B4, P1) Light Khadi Silk, both arms uncovered	65	0.78	0.29	1.37	0.89	0.79	0.30	0.08	0.03	0.02	2.12	1.87	0.64	0.22
8		E208 (SA04, B4, P1) Light Khadi Silk, Left arm covered unpleated pallu	73	0.83	0.25	1.25	0.77	0.93	0.17	0.64	0.03	0.07	2.69	2.38	0.71	0.23
9		E209 (SA04, B4, P1) Light Khadi Silk, Right arm covered, Pleated pallu	73	0.86	0.23	2.15	1.27	0.40	1.18	0.06	0.49	0.01	2.19	1.94	0.63	0.24
10		E210 (SA04, B4, P1) Light Khadi Silk, both arms covered	81	0.92	0.13	1.86	1.35	0.82	0.96	0.48	0.52	0.07	2.39	2.10	0.67	0.23

Table 5. (Contd) Clothing Insulation of saris for whole body and sixteen segments

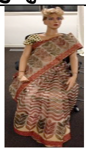
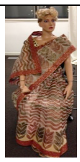
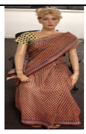
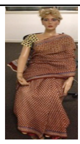
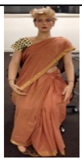
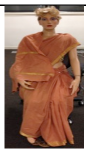
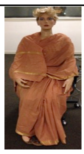
SNo.	*Clothing ensemble*	*Codes of Ensemble sari, bodice, petticoat and details of drape*	*BSAC (%)*	*Whole-body*	*Head*	*Chest*	*Back*	*Shoulder_L*	*Shoulder_R*	*Lower arm_L*	*Lower arm_R*	*Hand*	*Pelvis*	*Thigh*	*Lower leg*	*Foot*
11		E211S (A05, B4, P4) Kota Supernet, both arms uncovered	65	0.75	0.31	1.52	0.65	0.70	0.30	0.05	0.06	0.02	1.78	2.30	0.66	0.11
12		E212 (SA05, B4, P4) Kota Supernet, Right arm covered, pleated pallu	73	0.79	0.29	1.87	0.96	0.60	0.74	0.04	0.16	0.11	1.87	2.08	0.64	0.13
13		E213(SA06, B4, P4) Printed Cotton Voile, both arms uncovered	65	0.77	0.33	1.71	0.59	0.71	0.31	0.01	0.09	0.11	1.87	1.74	0.74	0.16
14		E214 (SA06, B4, P4) Printed Cotton Voile, Left arm covered unpleated pallu	73	0.78	0.29	1.24	0.44	0.77	0.34	0.43	0.06	0.11	2.08	1.81	0.77	0.07
15		E215 (SA06, B4, P4) Printed Cotton Voile, Right arm covered, pleated pallu	73	0.79	0.19	2.05	0.64	0.57	0.73	0.00	0.09	0.12	1.82	1.66	0.73	0.15
16		E216 (SA07, B4, P1) Handloom Guntur Zari both arms uncovered	65	0.74	0.33	1.54	0.41	0.65	0.22	0.03	0.05	0.05	1.53	2.27	0.79	0.19
17		E217 (SA07, B4, P1) Handloom Guntur Zari, Right arm covered, pleated pallu	73	0.85	0.33	2.15	1.00	0.63	0.98	0.02	0.37	0.06	1.58	2.26	0.81	0.19
18		E218 (SA07, B4, P1) Handloom Guntur Zari, both arms covered	81	0.91	0.31	1.85	1.25	1.17	0.96	0.43	0.32	0.07	1.84	2.44	0.83	0.19
19		E219 (SA08, B4, P2) White Silk Chiffon, both arms uncovered	65	0.74	0.32	1.44	0.47	0.75	0.18	0.05	0.06	0.02	2.15	1.83	0.79	0.18
20		E220 (SA08, B4, P2) White Silk Chiffon, right arm covered, pleated pallu	73	0.81	0.35	1.61	1.02	0.63	0.72	0.04	0.29	0.02	2.12	1.85	0.82	0.19

Table 5. (Contd) Clothing Insulation of saris for whole body and sixteen segments

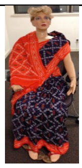
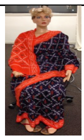
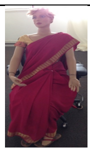
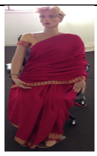
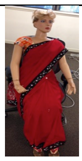
SNo.	Clothing ensemble	Codes of Ensemble sari, bodice, petticoat and details of drape	BSAC (%)	Whole-body	Head	Chest	Back	Shoulder_L	Shoulder_R	Lower arm_L	Lower arm_R	Hand	Pelvis	Thigh	Lower leg	Foot
21		E221 (SA10, B3, P4) Pochampalli Handloom cotton, both arms uncovered, pleated pallu	65	0.78	0.31	1.29	0.68	0.83	0.18	0.04	0.01	0.02	1.99	2.13	1.13	0.08
22		E222 (SA10, B3, P4) Pochampalli handloom cotton Left arm covered unpleated pallu	73	0.81	0.28	1.13	0.38	0.89	0.18	0.72	0.04	0.10	2.40	2.21	1.12	0.18
23		E223 (SA10, B3, P4) Pochampalli Handloom Cotton, Right arm covered, pleated pallu	73	0.89	0.26	1.77	0.86	0.68	1.21	0.04	0.74	0.03	1.93	2.26	1.13	0.19
24		E224 (SA10, B3, P4) Pochampalli Handloom cotton, both arms covered	81	0.96	0.30	1.61	1.42	1.03	1.09	0.71	0.49	0.07	2.35	2.14	1.19	0.20
25		E225 (SA11, B7,P3) Heavy Crepe Silk, both arms uncovered	65	0.72	0.27	1.32	0.56	0.86	0.22	0.03	0.05	0.03	1.01	1.45	1.18	0.25
26		E226 (SA11, B7, P3) Heavy Crepe Silk, Left arm covered, unpleated pallu	73	0.81	0.28	1.06	0.33	0.81	0.22	0.65	0.04	0.03	2.05	2.09	1.32	0.29
27		E227 (SA11, B7, P3) Heavy Crepe Silk, Right arm covered, Pleated pallu	73	0.82	0.33	2.02	0.98	0.56	1.06	0.02	0.44	0.02	1.31	1.40	1.14	0.24
28		E228 (SA11, B7, P3) Heavy Crepe Silk, both arms covered	81	0.95	0.21	2.24	1.18	0.87	1.20	0.61	0.45	0.12	1.93	1.99	1.21	0.26
29		E229 (SA12, B3,P3) Red Polyester Nylex, both arms uncovered	65	0.78	0.28	1.39	0.65	0.67	0.13	0.04	0.02	0.01	1.75	2.13	1.01	0.28
30		E230 (SA12, B3, P3) Red Polyester Nylex, Left arm covered unpleated pallu	73	0.81	0.26	1.16	0.64	0.86	0.11	0.51	0.05	0.05	1.96	2.43	0.93	0.25

Table 5. (Contd) Clothing Insulation of saris for whole body and sixteen segments

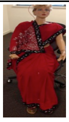
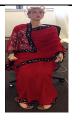
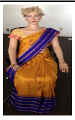
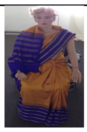
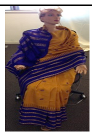
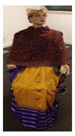
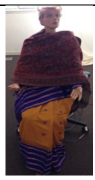
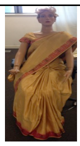
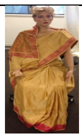
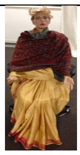
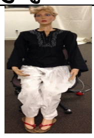
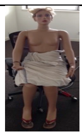
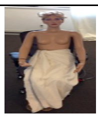
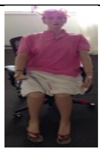
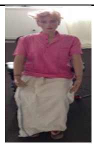
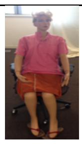
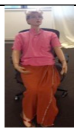
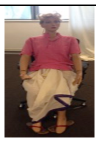
SNo.	Clothing ensemble	Codes of Ensemble sari, bodice, petticoat and details of drape	BSAC (%)	Whole-body	Head	Chest	Back	Shoulder_L	Shoulder_R	Lower arm_L	Lower arm_R	Hand	Pelvis	Thigh	Lower leg	Foot
31		E231 (SA12, B3, P3) Red Polyester Nylex, Right arm covered, pleated pallu	73	0.86	0.27	1.95	1.11	0.75	0.73	0.05	0.38	0.02	1.83	2.12	0.96	0.18
32		E232 (SA12, B3, P3) Red Polyester Nylex, both arms covered	81	0.91	0.27	1.47	1.15	1.09	0.60	0.49	0.36	0.09	2.10	2.29	0.90	0.26
33		E233 (SA13, B7, P4) Ochere Kanchi Silk Gold Zari, both arms uncovered	65	0.79	0.25	1.38	0.33	0.65	0.19	0.04	0.05	0.02	1.93	2.38	1.41	0.48
34		E234 (SA13, B7, P4) Ochere Kanchi Silk Gold Zari, Left arm covered, unpleated pallu	73	0.88	0.17	1.22	0.54	0.87	0.19	0.87	0.04	0.13	2.23	2.71	1.41	0.43
35		E235 (SA13, B7, P4) Ochere Kanchi Silk Gold Zari, Right arm covered pleated pallu	73	0.91	0.25	2.15	1.06	0.43	1.28	0.03	0.55	0.03	1.99	1.95	1.44	0.43
36		E236 (SA13, B7, P4) Ochere Kanchi Silk Gold Zari, both arms covered	81	1.03	0.16	1.86	1.31	0.98	1.18	0.84	0.53	0.09	1.98	2.69	1.69	0.44
37		E237 (SA13, B7, P4) Ochere Kanchi Silk Gold Zari, right arm covered Pleated pallu with Shawl	81	0.90	0.39	1.98	1.01	1.55	1.18	1.28	0.68	0.11	0.82	1.50	1.29	0.43
38		E238 (SA13, B7, P4) Ochere Kanchi Silk Gold Zari, both arms covered with Shawl	81	1.17	0.10	3.32	2.07	2.31	1.51	1.96	0.67	0.20	2.18	2.60	1.56	0.49
39		E239 (SA15, B7, P4) Benaras satin silk both arms uncovered	65	0.86	0.31	1.52	1.00	1.18	0.22	0.04	0.01	0.02	2.25	2.54	1.42	0.37
40		E240 (SA15, B7, P4) Benaras satin silk Right arm covered, pleated pallu	73	0.94	0.29	1.99	1.30	1.22	1.20	0.02	0.50	0.06	2.13	2.21	1.43	0.28
41		E241 (SA15, B7, P4) Banaras Silk Right arm covered Pleated pallu with Shawl	81	1.20	0.09	5.24	2.32	3.40	1.66	1.07	0.84	0.06	2.63	2.85	1.38	0.27

Table 6. Clothing Insulation of Salwar-kurti, Pancha, Lungi and Dhoti for whole body and sixteen segments

SNo.	Clothing ensemble	Codes of Ensemble sari, bodice, petticoat and details of drape	BSAC (%)	Whole-body	Head	Chest	Back	Shoulder_L	Shoulder_R	Lower arm_L	Lower arm_R	Hand	Pelvis	Thigh	Lower leg	Foot
1		E301 (SK01, K2) Light Cotton Loose fit Salwar, full sleeve kurti	81	0.76	0.27	1.17	0.87	0.64	0.69	0.47	0.45	0.07	1.40	1.22	0.58	0.20
2		E302 (SK01, K2, C1) Light Cotton Loose fit Salwar, kurti, Voile Dupatta multi folded into V shape	81	0.80	0.29	1.90	1.32	0.76	0.90	0.56	0.43	0.05	1.60	1.28	0.44	0.17
3		E303 (SK01, K2, C1) Light Cotton Loose fit Salwar, Kurti, half folded Voile Dupatta covering chest, arms	81	0.86	0.21	2.41	1.09	1.55	1.68	0.72	0.63	0.07	1.65	1.25	0.50	0.17
4		E303 (SK01, K2, C1) Light Cotton Loose fit Salwar, Kurti, single layered Voile Dupatta fully covering arms	81	0.91	0.29	2.42	1.30	1.39	1.22	1.04	1.09	0.15	1.95	1.54	0.60	0.16
5		E401 (DH 02) Handloom Pancha, Panty, Folded up		0.53	0.22	0.03	0.05	0.03	0.04	0.04	0.03	0.02	1.52	1.72	0.07	0.10
6		E402 (DH02) Handloom Pancha, Panty, Ankle length		0.58	0.24	0.06	0.04	0.02	0.02	0.01	0.00	0.05	1.07	1.40	0.92	0.32
7		E403 (DH02, K3, UG3) Handloom Pancha, Vest, Kurti, Panty, Folded up		0.70	0.27	1.46	1.35	0.67	0.73	0.05	0.07	0.02	1.87	1.71	0.10	0.11
8		E404 (DH02, K3, UG3) Handloom Pancha, Vest, Kurti, Panty, Ankle length		0.78	0.28	1.32	1.10	0.73	0.72	0.04	0.04	0.02	1.82	1.42	0.93	0.35
9		E405 (LU102, K3, UG3) Handloom Lungi, Vest, Kurti panty, Ankle length		0.75	0.24	1.37	1.06	0.67	0.54	0.03	0.05	0.01	1.52	1.70	0.64	0.23
10		E406 (LU102, K3, UG3) Handloom Lungi, Vest, Kurti panty, Folded up		0.69	0.27	1.52	1.11	0.68	0.64	0.06	0.05	0.01	1.52	1.46	0.13	0.13
11		E407 (DH01, K3, UG3) Handloom Dhoti, Vest, Kurti, Panty,		0.73	0.33	1.35	1.07	0.75	0.72	0.06	0.04	0.00	1.88	1.68	0.45	0.14

4 Discussion

We tested the saris in four weight categories: Super light (180 – 240 g), light (300 – 330 g), medium (430 -500 g) and heavy (500 -800 g). As can be noted in the above tables each sari ensemble is tested for two to four different variations of drape in the upper body keeping the nether garment ensemble unaltered. These drapes are: Pleated pallu with both hands exposed, unpleated pallu with left arm exposed, pleated pallu with right arm covered and left arm exposed, unpleated pallu with both arms covered. For a heavy sari generally used in winter we also tested with an acrylic shawl.

4.1 Effect of drape

Heavy weight saris generally had higher insulation, for a given drape. For example, in a drape with pleated pallu having both arms exposed, the clo value variation was as much as 21% between super lightweight and heavy category saris (E205 and E239). Similarly when both the arms are covered, the clo value varied a bit lesser: by 13% between lightweight and medium weight saris tested in this experiment.

However, for a given sari, blouse, petticoat ensemble drape in the upper body alone had a substantial effect on the clothing insulation value of the total ensemble. The variation due to drape in a given garment combination was noted to be varying from 7.7% to 40.1%. Understandable, the lower variation was in lightweight saris, generally used in summer.

Similar variations in clo value due to the drape are noted in other three attires tested: Salwar-kurti, Pancha and Lungi.

4.2 Comparison with other's results

The clothing insulation offered by an ensemble directly relates to the surface area of the body enveloped by the garments. This area is referred to as body surface area covered (BSAC) (McCullough and Jones 1983). The BSAC varied from 65% to 81% while the clo value varied between 0.71 clo to 1.20 clo.

For example, the clo value varied between 0.71 clo and 0.91 clo for summer ensembles (very light and lightweight saris, (i.e., weight within 180 – 330 g range) giving 28% variation. With winter ensembles, we recorded an increase in clo value from 0.72 clo to 1.26 clo (67 % variation). These are typically medium to heavy weight saris (weight range: 430 – 800 g), and lightweight shawls.

The wearers can achieve this variation without adding any new pieces of garments to the ensembles, just by changing the drape. Indraganti (2010) noted in a residential building study in India that the subjects have modified BSAC by raising the sari pleats up to the calves, while at heavy work in warm environments. This adaptability of the sari could have further reduced the clo value, for the same pieces of garments. However, due to logistic constraints we could not test the variations with the sari ensemble in the lower portion of the body.

These values matched closely with the values obtained in our previous experiment and others (Indraganti, Lee, et al. 2015, Mitsuzawa and Tanabe 2001, Havenith, et al. 2014). Mitsuzawa and Tanabe reported the basic clothing insulation for cotton sari with cotton petticoat and bodice as 0.65 clo. Havenith et al. reported a basic clothing insulation of 0.74 clo for polyester sari with cotton bodice and cotton petticoat and 0.96 clo for the same ensemble worn along with an acetate shirt and a cotton towel worn as a head cover.

Interestingly the summer clothing of the Middle Eastern women wearing summer *daraa* (a full-sleeved loose fitting long gown), *shiala* (fully covering long head scarf), bra, panty and sandals with a clothing insulation of 1.20 clo (Al-ajmi, et al. 2008) was noted to be a near equivalent to the winter ensembles tested in this study. Lee et al. noted Western summer ensembles (e.g.: bra, panty, turtleneck blouse, skirt and socks with formal shoes) offering similar clothing insulation (0.65 clo) (Lee, Zhang and Arens 2013), to that of the light Indian summer ensembles as found in this study. The Middle eastern ensembles offered higher clothing insulation, perhaps as the *daraa* covered the arms and legs fully while, the *shiala* covered the neck and head completely, leaving only the face exposed.

5 Conclusions

In a climate chamber study using a Danish manikin we measured the traditional ensembles both women and men use in the South Asia and elsewhere. This paper presented these results. We measured 41 sari ensembles in nivi style of draping using very light weight, lightweight medium weight and heavy weight saris. These saris were in typical fabrics that women wear typically to work, such as: light cotton, voile, georgette, handloom fine cotton, Khadi silk, crepe silk, polyester, nylon, Kota Super-net and Kanchi silk (heavy mulberry silk). We testing using four types of drapes commonly noted in offices: pleated pally with both arms exposed, pleated pallu with right arm exposed, unpleated pallu with left arm exposed, both arms covered.

Clothing insulation of lighter weight saris used in summer varied between 0.71 clo and 0.91 clo and medium to heavy weight saris generally used in monsoon and winter varied from 0.72 – 1.20 clo, with the higher insulation being achieved by additional acrylic shawl. It means that the sari ensemble can effortlessly offer 28 – 67% change in insulation by draping differently and by simple addition of a light shawl. Similar improvement of 14 -20 % is possible in the other traditional ensemble, Salwar-kurti by draping the dupatta, a thin accouterment worn on the upper body.

The possibility of clothing insulation adaptation in the Pancha was found to be much higher, from 0.53 clo to 0.78 clo among the four drapes tested. It means that men can alter their clothing insulation by as much as 47% in this traditional ensemble. By folding the lungi up to the knee length, we noted the clo value reducing by 9%. The Dohti, another traditional ensemble was found to have a clo value of 0.73, similar to a light sari ensemble.

The values obtained in this study are a valuable addition to the clothing insulation databases, as these are frequently used simulation studies for HVAC systems design. Accommodating appropriate clothing insulation values in the design ensures higher acceptability of the thermal environments and reduced energy use. Therefore, the fundamental data provided in study assumes great significance.

Acknowledgements

For the manikin testing and analysis, we used the climate chamber facilities at the Centre for the Built Environment, University of California Berkeley. The test facility is made available through the Fulbright Grant and the support of HAE, R&D Center, LG Electronics, South Korea. The authors appreciate their financial and logistic support. Padma Indraganti of Los Angeles, USA, Gayatri Ullat, and Balagopal Menon, Prasad Indraganti of Riyadh, Saudi Arabia, Rajyalakshmi Indraganti of Hyderabad, and CEPT, Ahmadabad, India USA provided us the garments. A part of the analysis was done at the Qatar University through NPRP-7- 143-2-070. We thank them for their support.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Impact of local clothing values on local skin temperature simulation

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Abstract

Current human thermophysiological models calculate skin temperatures to predict human thermal comfort. To identify local influences on overall thermal comfort, local skin temperatures should be computed with high accuracy. This necessity depends on reliable input data of local clothing properties. However, only few data sets on local clothing insulation are published, and these values can be inconsistent. This paper analyses the effect of different sets of local clothing values on simulated skin temperatures using the thermophysiological model ThermoSEM. The skin temperatures are computed for a seated (1met), average man wearing a light clothing combination (0.5clo). Four sets of local clothing values are taken from the literature. This data is used to simulate local skin temperatures for uniform operative temperatures between 18°C and 34°C. Furthermore, the comparison to measured data is included. The results show that local skin temperatures are sensitive to the local clothing properties, and deviations might be up to 4K. These findings emphasize that local clothing parameters have to be chosen carefully. Additionally, current local clothing databases scarcely reflect the wide variety of clothing ensembles worn in practice. Therefore, this study underlines the need for further measurements of local clothing properties with detailed documentation of experimental set up.

Keywords: thermal modelling, local clothing, thermophysiology

1 Introduction

Current human thermophysiological models calculate skin temperatures in uniform and non-uniform environmental conditions to predict human thermal comfort. In non-uniform environments, local thermal dissatisfaction can negatively influence overall thermal comfort. To identify this effect, local skin temperatures should be calculated with high accuracy, which depends, among others, on reliable input data of local clothing properties. These properties include the clothing insulation or thermal resistance, the moisture permeability index or clothing evaporative resistance and the clothing area factors. These values are mostly published for whole-body applications in the literature. In case of local applications, only few studies are available concerning typical every day and office clothing ensembles. Moreover, the values can differ for the same prescribed outfit. The impact of these differences has not been analyzed in recent literature. To fill this gap, this paper gives an overview of recently published studies on local clothing properties and analyzes the impact of deviations in local clothing values on the prediction of local skin temperatures using the thermophysiological model ThermoSEM (Kingma, 2012).

2 Methods

This study compares the simulation outcome of different sets of clothing properties to each other and to one set of measured skin temperatures of a study case with four subjects. Therefore, this section will present the main simulation properties, the local clothing data sets, the environmental conditions of the study cases and the strategy of the data analysis.

2.1 Simulation model and general input data

All simulations in this study are done with the thermophysiological model ThermoSEM as described by Kingma (2012). This model uses 18 concentric cylinders and one concentric semi-sphere to characterize the human body (Figure 1). Every part has multiple tissue layers with defined attributes, e.g. basal metabolic heat, specific density and conductivity. Moreover, the elements are divided into anterior, posterior and inferior sectors, to account for differences due to the orientation. In the default model, these specifications represent an average adult man with a weight of 73.5kg, a body surface area of 1.86m² and a body fat percentage of 14%. Additionally, the basal metabolic heat production is set to 87.1 W. These values are not changed for the simulations in this study.

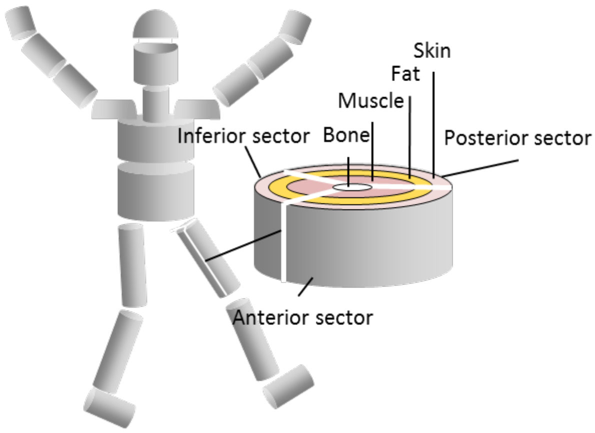


Figure 1 Representation of the human body by the ThermoSEM model (Kingma, 2012)

In addition to the basic input data, ThermoSEM requires the activity level, the data on the surrounding environment, and the properties of the worn clothing ensemble of the simulated person. In this paper, the activity level is set to 1 met, which represents a seated person performing light office activity (ANSI/ASHRAE, 2004). The low activity level is chosen, on one hand, to minimize influences on the local skin temperatures by heat production due to higher activity. On the other hand, it still provides the opportunity to compare the computed results to measurements in an office environment. The environment of the simulations is assumed to be uniform and steady state. To analyse the effect of different environmental temperatures on the results, five scenarios are designed with constant air and wall temperatures of 18°C, 22°C, 26°C, 30°C and 34°C. The relative humidity is kept constant at 40%. In all cases, the simulation time is 90 minutes, allowing the simulation to also reach steady state. The five environmental temperature scenarios are each combined with all clothing data sets representing a light clothing combination (overall insulation of 0.5 clo), which are described in detail in section 2.2.

2.2 Local clothing properties

In ThermoSEM and other multi-segment thermophysiological models, clothing properties have to be defined at every body part. These local clothing parameters usually include values for the local clothing insulation, the local moisture permeability and the local clothing area factor. For this study a clothing combination consisting of underwear, t-shirt, trousers, socks and shoes is chosen, because the highest number of data sets were available in this case. The clothing properties used in the simulation are obtained from the papers by Curlee (2004) and Nelsen et al. (2005), Havenith et al. (2012), Lee et al. (2013) as well as Lu et al.(2015), which are referred to as “Curlee”, “Havenith”, “Lee” and “Lu” as scenario names. All local clothing properties are summarized in Table 1.

The data by Curlee (2004) and Nelsen et al. (2005) are based on the whole-body data published by McCullough (1985, 1989), and then recalculated into local values. Hence, these papers provide local clothing insulation, evaporative resistance and area factor values for a variety of clothing items, which then can be combined into clothing ensembles. However, in contrast to whole-body values, the calculation of multi-layer clothing is not investigated. Therefore, two assumptions have to be made in case of multiple layers of clothing: 1) the clothing insulation values of separate clothing items are added up and 2) the largest values of the area factor and moisture permeability index is close to the combined value. The specific clothing items used in this study are listed in the second column of Table 1. Since the other studies do not provide local clothing area factors, the ones mentioned in Curlee (2004) and Nelsen et al. (2005) are adopted in the other scenarios (third column in Table 1).

Table 1 Comparison of local clothing insulation for a clothing ensemble consisting of underwear, t-shirt, trousers, socks and shoes

			Local clothing insulation (clo)				**Moisture permeability index**	
Body part	**Clothing items**	**Local area factor****	**Curlee**	**Havenith (18-34°C)**	**Lee (No. 8)**	**Lu (EN 9)**	**Curlee**	**Havenith, Lee, Lu**
Whole body	--	--	0.57*	0.52	0.52	/	/	
Head/ Neck	None	--	0.00	0.00	0.00	/	0.00	0.00
Chest	Bra, t-shirt	1.22	1.12	1.04 - 0.43	1.14	1.09	0.67	0.34
Back		1.22	1.12	1.04 - 0.43	0.84	0.79	0.67	0.34
Abdomen/ Pelvis	Panty + t-shirt + trousers	1.17	2.07	1.04 - 0.43	1.04	1.44	0.67	0.34
Upper arm	T-shirt	1.23	0.75	1.04 - 0.43	0.42	0.44	0.67	0.34
Lower arm	None	(1.23)	0.00	0.00 #	0.00	0.02	0.00	0.00
Hand	None	--	0.00	0.00	0.00	/	0.00	0.00
Thigh	Trousers (fitted)	1.20	0.93	0.97 - 0.67	0.58	0.55	0.53	0.34
Lower leg	Trousers (loose)	1.44	1.27	0.97 - 0.67##	0.62	0.49	0.38	0.34
Foot	Socks + shoes	1.25	1.85	0.61 - 0.34	0.82	/***	0.10	0.34

* Men’s Summer Casual from (McCullough et al., 1989)
** taken from (Curlee, 2004; Nelson et al., 2005)
*** for the simulations a value of 0.82 is assumed
# assumed to be zero, since the ensemble is known (values corresponding to long-sleeved shirts are calculated otherwise)
assumed to be same as thighs, since long trousers are set (values corresponding to shorts are calculated otherwise)

In Havenith et al. (2012), the local clothing insulation values are given as a function of the environmental temperature based on clothing typically worn in these conditions. Because of this method, also a clothing insulation at the lower arm is computed in environmental temperatures below 28°C. These values are set to zero, since this study prescribes a t-shirt for upper body clothing. Similarly, the clothing insulation values for the lower leg are very low in warmer conditions (representing shorts). This issue is solved by assigning the value of the upper leg also to the lower leg. Keeping these assumptions in mind, Table 1 presents the values at 18°C and 34°C operative temperature.

The local clothing insulation values in Lee et al. (2013) and Lu et al.(2015) are derived from measurements on a thermal manikin. Lee et al. (2013) provide these values for a large variety of typical office and outdoor clothing ensembles. In this study, the 8th outfit was chosen. A smaller number of clothing combinations are measured in Lu et al.(2015). For the analysis in this paper, the outfit with the case number EN9 is used. Unfortunately, no values for the head and the feet are available. To maintain a complete data set, the value for the foot insulation is taken from Lee et al. (2013).

Havenith et al. (2012), Lee et al. (2013) and Lu et al.(2015) do not calculate or measure values for the moisture permeability index. According to Havenith et al. (2012) and EN-ISO 9920 (ISO, 2009), a value of 0.34 is chosen for all clothed body parts.

2.3 Measured data

The measurements were done in the climate chambers by the department of the Built Environment, Eindhoven, The Netherlands and are part a of comfort study investigating cooling strategies in office spaces. The subjects were seated at an office desk performing light activities (1 met). For this study, four male subjects were electable, since they wore a light clothing combination (0.5 clo) and their body composition (Table 2) was not too different from the default values of ThermoSEM.

Table 2 Subject characteristics

	Male 1	*Male 2*	*Male 3*	*Male 4*	*Average*
Body mass [kg]	70	85	100	67	80.5
Height [m]	1.60	1.98	1.85	1.77	1.8

The experiments were performed in uniform conditions with a set point air temperature of 28°C. The actual air temperature and humidity were recorded during all experiments. Moreover, the skin temperature of the human subjects was measured at the 14 sites as suggested in ISO (2004) using iButtons (Thermochrom iButton DS1922L, Maxim Integrated, USA). Each experiment had a duration of 90 minutes.

For the comparison between measured and simulated data, the measured skin temperatures were averaged for the human subjects, and the standard deviation was calculated. Furthermore, simulations based on the measured environmental conditions are performed for each clothing combination of section 2.2. The comparison is then done for the last 45 minutes of the measured and simulated data allowing time for steady state conditions during the experiments.

2.4 Data analysis

In this paper, the results for the mean skin temperature and four local body sites are presented. Both the simulated and measured mean skin temperature is the average over the 14 local skin temperatures as suggested in EN-ISO 9886 (ISO, 2004). For representing local body parts, the skin temperatures of the upper arm, lower back, hand and foot were chosen.

For better comparison of the simulated scenarios with each other, the mean and local skin temperatures for each set of clothing data was averaged over the last 45 minutes. These calculations result in four comparable temperatures for each body part in every environmental temperature. For further analysis, the average and maximum difference is computed out of the four values for every body part at each operative temperature. For this, firstly, each difference in skin temperature is calculated per pair (Curlee/ Havenith, Curlee/ Lee, Curlee/Lu, Havenith/ Lee, Havenith/ Lu, Lee/ Lu) separately and then, the average and maximum is taken from these six values. The same is done for comparing the local clothing data.

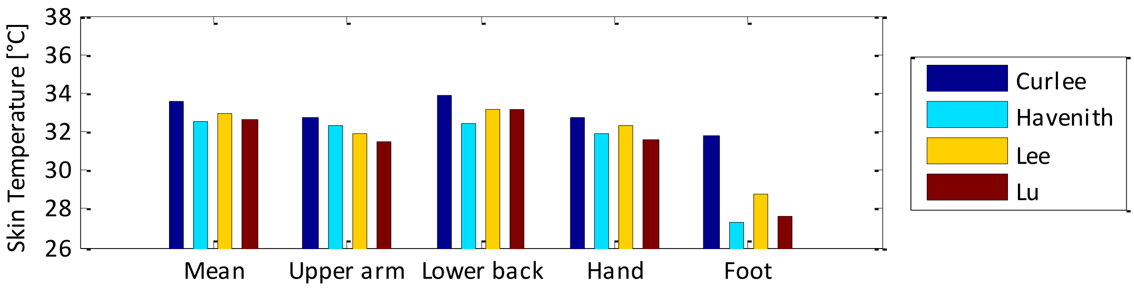
3 Results

In this section the simulated skin temperature for the cases described in the previous section are compared. Firstly, this comparison is done within the four clothing scenarios. Secondly, measurements are compared to the simulated outcomes in the measured conditions.

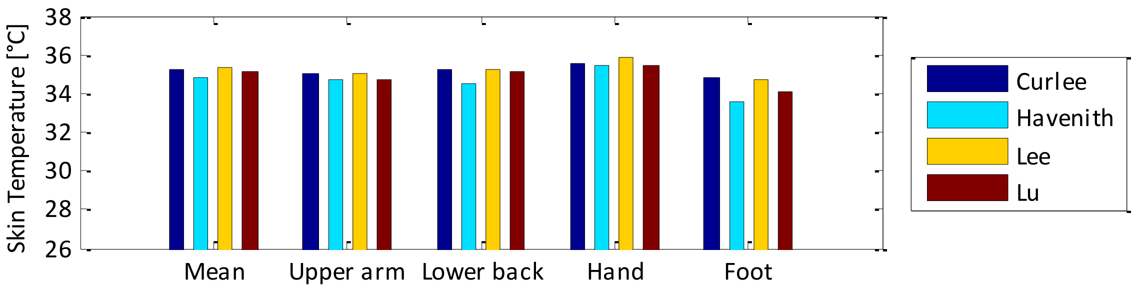
3.1 Comparison of computed skin temperature in between simulation scenarios

The simulated mean and four local skin temperatures for all four sets of clothing values are compared for two environmental temperatures in Figure 2. The graphs show that differences in skin temperature between the four clothing data sets exist and that these deviations vary for different body parts as well as different environmental temperatures. For both illustrated uniform environmental temperatures of 22°C and 30°C, the highest deviations are found for the foot with a maximum difference in skin temperature of 4.5 K and 1.2 K, respectively. Furthermore, temperature differences also occur at non-clothed body parts, e.g. hands. Additionally, when comparing the order of the computed skin temperature from highest to lowest, it is notable that this order might change for different operative temperatures. For example, sorting the clothing data sets for the upper arm skin temperature from highest to lowest leads to Curlee > Havenith > Lee > Lu for an environmental temperature of 22°C and to Lee > Curlee > Havenith > Lu for an environmental temperature of 30°C.

To further investigate the variation of the computed skin temperature over different environmental temperatures, Figure 3 presents the maximum and average skin temperature difference (ΔT_{max} and ΔT_{avg}, respectively) of the mean and the four body parts for five uniform environmental temperatures. In the graph, two patterns can be found: 1) for upper arm and hand, ΔT_{max} and ΔT_{avg} drop with increasing operative temperature, and 2) for mean, lower back and foot, ΔT_{max} and ΔT_{avg} have a maximum at around 22°C and then decrease. Again, the highest deviations in skin temperature are found for the foot ranging from 0.8 K up to 4.5 K.



a) $T_o = 22°C$



b) $T_o = 30°C$

Figure 2 Simulation results for mean and local skin temperatures at a) 22 °C and b) 30 °C uniform operative temperature (T_o) for all four clothing input data sets derived from Curlee (2004), Haventih et al. (2012), Lee et al. (2013) and Lu et al. (2015)

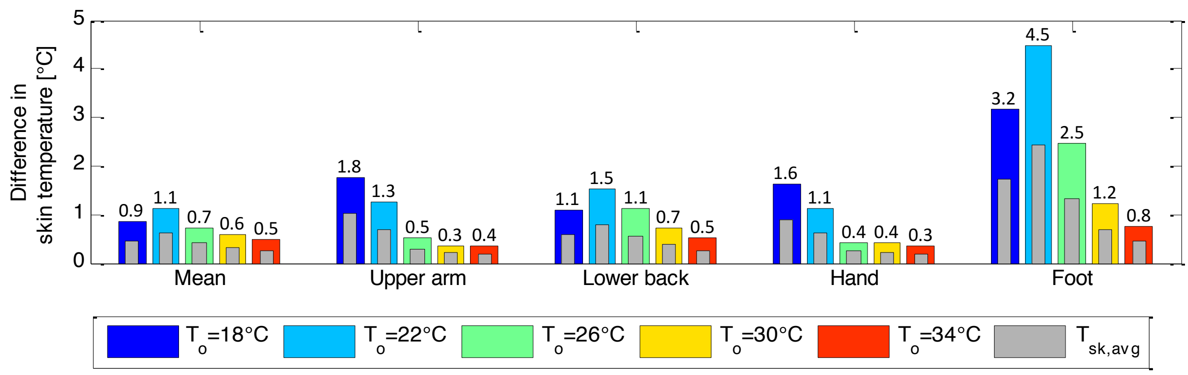


Figure 3 Maximum and average difference in skin temperature for the mean and four local skin temperatures

The relation between the differences in skin temperature and in clothing insulation is examined with the help of Table 3. The most striking observation is that even though no insulation is provided at the hand, the skin temperature can differ up to 1.1 K. Furthermore, the differences in clothing insulation of the foot and the lower back are very similar, but the skin temperature deviation is higher for the foot. Comparing the upper arm and lower back, the situation is switched. In this case, the differences in skin temperature are similar and the difference in clothing insulation of the lower back is higher. All in all, these observations indicate that the skin temperature of the body parts do not only depend on the clothing values provided for itself, but also on the clothing values of the other body parts.

Table 3 Average and maximum differences in temperature and clothing insulation for two uniform environmental temperatures

		Body part			
	Operative temperature	Upper arm	Lower back	Hand	Foot
Average difference in skin temperature [°C]	22	0.7	0.8	0.6	2.4
	30	0.2	0.4	0.2	0.7
Maximum difference in skin temperature [°C]	22	1.3	1.5	1.1	4.5
	30	0.3	0.7	0.4	1.2
Average difference in clothing insulation [clo]	22	0.2	0.7	0	0.7
	30	0.2	0.9	0	0.7
Maximum difference in clothing insulation [clo]	22	0.3	1.3	0	1.3
	30	0.3	1.6	0	1.5

3.2 Comparison of simulated and measured skin temperatures

For the comparison of simulated and measured skin temperatures, this paper uses the measured data set as described in section 2.3. The measured environmental data is used in all simulations as input data for the environment. In this case, the environmental temperature was uniformly around 28 °C. Figure 4 shows the simulated skin temperatures of all four clothing sets, the measured skin temperature averaged for all human subjects, and the standard deviation of the measurements. Again, graphs are presented for the mean and four body parts. It must be noted that the standard deviations of the measurements differ largely for the five shown graphs between ≈0.2 K (mean) and ≈1.2 K (upper arm). However, in this case this does not interfere with the main outcomes. For the skin temperature of the mean, upper arm, lower back and hand, most results are close to the averaged measured skin temperatures and fall within the standard deviation of the measurements. Also, the skin temperature deviations within the simulated results are smaller than 1 K as can be expected from the results in the previous section. However, larger differences are found for the foot skin temperature. In this case, all simulated results are below the measured ones and differ up to 2.5 K. Moreover, the deviation in skin temperature in between the simulations is also up to 1.8 K. The highest foot skin temperature (Curlee) corresponds with the largest clothing insulation value at the foot (Table 1). This finding suggests that the insulation values of the feet might need to be revised.

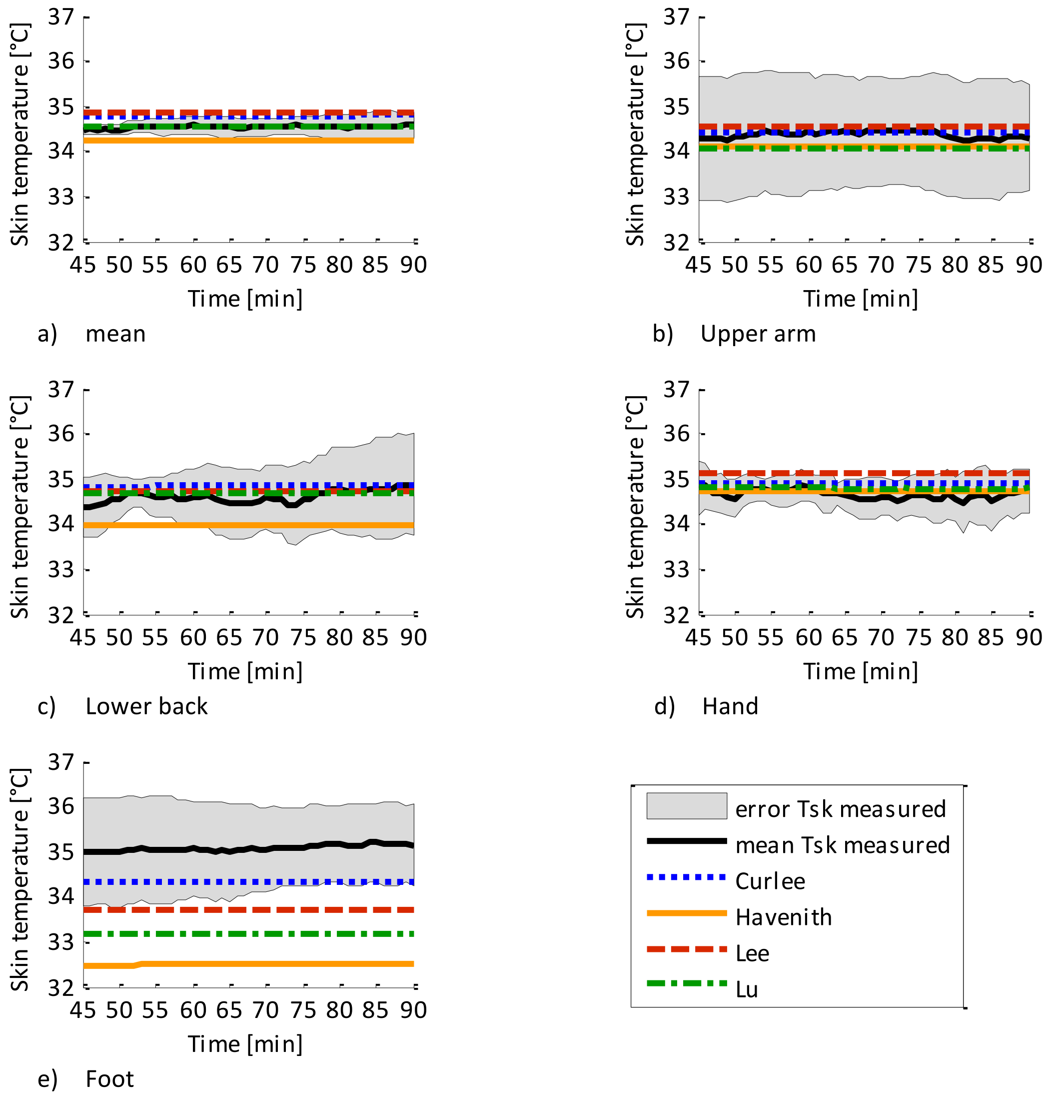


Figure 4 Comparison of measured and simulated results at an environmental temperature of ~28°C for the last 45 minutes of the measurements and simulations.

4 Discussion

The aim of the study was to identify the impact of variations in local clothing properties on simulated local skin temperatures. To achieve this goal, the recent literature was searched for data on local clothing properties. All in all, four studies were found providing data on office clothing options. However, to include the data of all four papers in this study, the clothing ensemble had to be limited to the light clothing ensemble as described in the methods (section 2.2). Moreover, three out of four studies only provided information on the local clothing insulation. The values for the local moisture permeability index and local area factor had to be assumed using standards or the fourth paper. However, the influence of the moisture permeability index was probably small, since sweating was limited in most cases due to low activity and moderate temperatures. Another issue of obtaining comparable data is that for measured values the conditions of measurements are not always stated clearly. Hence, differences in local clothing properties might be also due to this uncertainty. In summary, this study identifies a need for traceable and complete data sets for local clothing properties for a variety of office clothing ensembles.

The results of this study show that the simulation of local skin temperatures is influenced by the local clothing properties used for describing a specific clothing ensemble. The magnitude of this effect, however, can vary largely for different body sites and different environmental conditions. In this study, variations from 0.3 K up to 4.5 K were found. The highest values for all skin sites were reached at environmental temperatures of 18°C and 22°C. In lower environmental temperatures, the heat losses to the environment contribute a higher amount to the local and overall energy balances of the human than in warmer conditions. Therefore, variations in heat losses due to the differences in clothing resistance, might also be higher in colder conditions. This possibility might be overlapped by the fact that vasoconstriction is likely to occur at lower environmental temperatures. This effect limits the amount of heat contributed by the blood flow and hence, the variation in heat loss is more visible in the skin temperature calculation. This explanation might also clarify why the deviation in foot skin temperature exceeds the other body parts. At distal locations the blood flow is generally lower than for proximal body sites and vasoconstriction is more likely to occur.

The data analysis also identified that local clothing values not only influence the skin temperature of the applied body part, but also at other body locations. This effect can be seen in unclothed body parts and clothed ones. The reason most likely lies in the internal heat exchange via blood flows of each body part with the central blood pool. In the thermophysiological model used, the heat fluxes of the blood flows coming from each body part are mixed, and the resulting temperature is used for the returning blood flows in the next simulation step. Additionally, these values are corrected in some body parts, where counter current heat exchange occurs due to the close location of arteries and veins. In any case, this fact emphasizes the importance for accurate local clothing input values at each body location.

The comparison to measurements revealed that for some body parts, all simulated skin temperatures are located within the error of measurement. However, at other body parts (here foot), some or all simulations can under- or overestimate the measured skin temperature. In the present case, the foot skin temperature was underestimated by all simulations. However, the values of the temperatures do relate to the amount of clothing insulation as presented in Table 1. Therefore, a possibility is that the local clothing insulation at the foot is generally too low in the presented papers. Other causes might be the discussed dependence of one body part on all local clothing values or the thermal history of the human subjects.

In all presented and discussed cases of this paper, the environmental conditions were kept uniform and steady state. This was done to focus on the effect of local clothing properties on local skin temperatures. However, in thermal comfort research the prediction of local skin temperatures and the resulting local sensation as well as local comfort votes are of special interest in non-uniform conditions, e.g. local heating of hands or face cooling. These situations could be included in future research to give a complete picture of the discussed issue in this paper.

The graphs comparing simulated and measured data also show that the thermophysiological model predicts the mean skin temperature fairly accurate, while larger deviations can be found at local skin sites. The skin temperature of these locations is included in the calculation of the mean. In the case of a 14-point mean, differences are reduced because over- and underestimated numbers cancel each other out and because of the amount of points. In case of a lower number average calculation, the influence of each body part is larger, which might change the result. Therefore, this option has to be considered carefully. In addition, the discrepancy between mean and local skin temperatures are relevant when validating a thermophysiological model.

5 Conclusions

In this study, the impact of local clothing values on local skin temperature simulation is investigated. This analysis was done by comparing the simulation outcome of four sets of clothing properties representing one clothing ensemble to each other and to measured data. The main conclusions of this paper are that:

- only few studies are published providing local clothing properties for typical office clothing ensembles,
- variations in thermal and moisture resistance are found in these papers,
- different sets of local clothing properties affect computed local skin temperatures also for the uncovered body parts such as hands,
- the magnitude of the deviations depends on the environmental temperature and skin site.

For future research, this study underlines the need for further measurements of local clothing properties, which include clothing insulation, moisture permeability and area factor values, and contain a detailed documentation of the experimental set up.

Furthermore, the skin temperatures are typically translated into local thermal sensation or thermal comfort in thermal modelling. Therefore, the effect of the variation in skin temperature is very important for predicting (local) thermal comfort and needs to be investigated further in upcoming research.

Acknowledgements

We would like to thank Jacob Verhaart of the research group by Professor W. Zeiler at Eindhoven University of Technology, the Department of Built Environment, The Netherlands, for sharing his measured data with us for our study.

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Elizabeth Shove

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SESSION 4

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Neutral, comfort or preferred: what is a relevant model for acceptable thermal environmental conditions for low energy dwellings in Australia?

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Abstract
Thermal performance assessment is an important means in understanding the future performance of a building design. Existing assessment methods employed to demonstrate compliance with minimum Energy Efficiency performance requirements for residential buildings in Australia use static thermostat settings to determine heating and/or cooling loads by which performance is judged. This approach has been shown to be inappropriate in cases where the dwelling is designed to use little or no heating or cooling during actual operation. The research in this paper suggests that, in the assessment of these types of 'low energy' house designs, the use of comfort criteria would be a more appropriate measure of performance. Over 6000 thermal comfort vote surveys were collected from a longitudinal thermal comfort study of 40 Australian households comprising of 20 earth buildings in Melbourne, Victoria and 20 naturally ventilated dwellings in Darwin, the Northern Territory. The results demonstrate that existing models of thermal comfort do not adequately encompass the extent of conditions that these occupants find acceptable. Based on the collected data, this paper offers a model of thermal preference that can be used in the performance assessment of the two types of dwellings studied. Such an approach would assist in recognising the diversity of comfort related expectations, behaviours and preferences that contribute to the thermal performance of low energy dwellings.

Keywords: Thermal comfort; residential; mavericks; performance assessment

1 Introduction

In Australia, the 2015 National Construction Code (NCC) Energy Efficiency provisions outline mandatory minimum performance requirements for all new residential buildings. These provisions are aimed at reducing greenhouse gas emissions through the efficient use of energy during the operational phase of the dwelling. One of the main methods by which the compliance of a design can be demonstrated is via an Energy Rating. The protocols for the Energy Rating assessment method are governed by the Nationwide House Energy Rating Scheme (NatHERS) and utilises the Australian Government Endorsed calculation engine, *AccuRate*, to predict heating and cooling loads expressed in MJ/m^2 per annum. Necessary to the simulation of heating and/or cooling are assumptions regarding the operation of the dwelling, e.g. hours of occupancy, thermostat settings, rooms conditioned. These assumptions, specified by NatHERS, are based on a standardised user profile and cannot be modified in the regulation mode of the software. Previous research has demonstrated that these assumptions cause considerable over estimation of the operational energy load requirements of dwellings designed to use little or no heating or cooling to maintain comfort conditions i.e. free running houses (Williamson et al, 2010; Kordjamshidi, 2011;

Daniel et al, 2015a). This has presented a barrier in the compliance certification of some forms of this type of housing.

This research is focused on two specific examples of such housing: dwellings incorporating earth construction elements in a cool temperate climate (Melbourne) and naturally ventilated dwellings in a hot humid climate (Darwin). It has been demonstrated that these households operate their dwellings differently to the assumptions used in the Energy Rating simulations (Daniel et al, 2015a; 2015b) which means these two forms of housing have lower energy use than typical homes in the same locations. Whilst the motivation for these occupants' behaviour is unlikely to be explicitly linked to the NCC Energy Efficiency objective per se (reducing greenhouse gas emissions), their actions (of not relying on heating and/or cooling) naturally achieve this outcome. The aims of the research presented in this paper are (1) to demonstrate that the existing models of thermal comfort cannot adequately describe the thermal preferences of occupants of these two forms of housing; and (2) to propose a more relevant model which will better support thermal performance assessment of these forms of housing.

1.1 Thermal comfort in residential building performance assessment

Building on the approach taken by several recent studies (e.g. Peeters, 2009; Kordjamshidi, 2011; Candido et al 2011; Scalco et al, 2012) this paper suggests that the use of comfort criteria in the assessment of free running buildings may provide a more appropriate indicator of building thermal performance. In 2009, Peeters et al proposed a set of comfort values and scales for use in the Building Energy Simulation (BES) of dwellings. The comfort criteria were based on an extension of the ASHRAE 55 (2004) Standard adaptive model with modifications to account for variation in thermal comfort in bathrooms and bedrooms. Whilst not specifically aimed at free running houses, the authors argue that the adaptive model more accurately represents the less predictable activities and increased access to adaptive opportunities available to occupants in residential buildings (Peeters et al, 2009). Specific to the Australian context, Kordjamshidi (2011) proposed a method to assess free running house designs using Degree Discomfort Hours (DDH), also based on the ASHRAE 55 (2004) Standard adaptive equation. Kordjamshidi proposed that the final indicator of performance was a weighted aggregation of both the proposed comfort metric and the existing energy load metric in order to account for the performance of the dwelling design in both free running and conditioned modes. This pathway would still be problematic for houses that are not designed to be conditioned at all. For example, the NatHERS simulation is unable to provide a sensible result for the award winning Rozac House located in the Northern Territory because the walls are primarily flyscreens (Williamson et al, 2010, p525). In Brazil, a voluntary assessment method, the Brazilian Energy Labeling Schemes for Residential Buildings (RTQ-R), using a comfort criteria performance indicator has been adopted (Scalco et al, 2012). Whilst the RTQ-R uses comfort criteria based on ISO 7730 (2005) Standard, considerable research efforts are also aimed at creating a Brazilian thermal comfort standard based on an adaptive model (Cândido et al, 2011; Lamberts et al, 2013; De Vecchi et al, 2015), demonstrating an acceptance of adaptive models for use in residential building performance assessment.

The merit of all of these approaches is that the use of comfort criteria addresses a more fundamental level of building performance than the assessment of the potential energy loads associated with the operation of heating and/or cooling appliances. Whilst it is likely that an adaptive model of thermal comfort may be most useful in this type of assessment due to the wide range of adaptive opportunities available to most occupants within their own homes (Peeters et al, 2009; Saman et al, 2013; Pacheco & Lamberts, 2013), existing models have not been extensively tested within Australian dwellings (Daniel et al, 2015b). In some recent studies of thermal comfort in residential buildings the slope of the relationship between the prevailing mean outdoor temperature and reported acceptable indoor temperatures is steeper than that of the adaptive model (Williamson et al, 2010; Yang et el, 2013; De Vecchi et al, 2015; Dhaka et al, 2015). This may indicate that these occupants have a higher level of adaption to their thermal environment than the occupants of the primarily non-residential buildings on which the model was based (de Dear & Brager, 1998), indicating the need for further studies in this area.

1.2 Limits of thermal acceptability for human occupancy

In order to make an assessment of the performance of an actual or a simulated thermal environment some judgement must be made on what is an acceptable range of thermal conditions. The range of acceptable conditions of both the Predicted Mean Vote (PMV)/Percentage Predicted Dissatisfied (PPD) indices and the ASHRAE adaptive model are based on the assumption of a relationship between a neutral thermal sensation vote and 'comfort'. This originates from Gagge et al's (1967) finding that the subjective responses of 'comfort' and 'neutral' from one male subject occur at the same temperature, and that discomfort begins to occur at 'slightly cool' or 'slightly warm' (corresponding to ±1 on the -3 to 3 scale, or 3 and 5 on the 1 to 7 scale). Fanger cites Gagge et al's findings in the formulation of the PPD index (Fanger, 1970), which is subsequently cited by de Dear & Brager (1998) in the development of the adaptive model upper and lower acceptability limits.

It is now apparent that occupants of actual buildings do not necessarily equate neutrality, the "neutral" sensation on the ASHRAE 7-point scale, with thermal comfort (Humphreys & Nicol, 2004). This has also been confirmed by Humphreys & Hancock (2007), Li et al (2010) and Tweed et al (2014) amongst others. In 2009, de Dear's (re)introduction of the concept of alliesthesia in thermal experience furthered this discussion by arguing that variation in indoor thermal environments is highly desirable where occupants have some level of control or adaptive opportunity. Alliesthesia has been offered as the 'fundamental theoretical underpinnings' to the adaptive model; demonstrating how a set thermal conditions can be perceived so differently by occupants in conditioned buildings compared to those in naturally ventilated buildings (Cândido et al, 2010; de Dear, 2011b; Parkinson et al, 2015; Parkinson & de Dear, 2015). This has clear benefits in the provision of thermally acceptable environments without heavy reliance on mechanical heating and/or cooling in residential buildings.

In the practical application of thermal comfort models, it is not necessarily neutrality (or lack thereof) that determines whether or not an individual deems their thermal environment acceptable. Therefore, it is important that a distinction is made between thermal comfort models/research that aims to describe the physiological phenomenon in detail and that which is aimed at describing the interaction between occupants and buildings that acknowledges the influence of culture, climate and associated issues of thermal expectations and adaptation (Fountain et al, 1996, p179). The relevance of the individual's subjective judgement of their thermal conditions is that their preference is likely to motivate operation of available controls (e.g. mechanical heating and/or cooling, windows, fans). In order to work towards a paradigm shift in the notion of comfort (Brager et al, 2015), it is important to continually re-examine the application and appropriateness of thermal comfort models, particularly in a residential context which is typified by the diversity of comfort related expectations, behaviours and preferences.

2 Methods

A longitudinal thermal comfort study was conducted in 40 households for an 11 to 12 month period in 2013 to 2014. Twenty households were located in Nillumbik Shire, a north-eastern suburb of Melbourne, Victoria and 20 households were located in or close to Darwin, the Northern Territory. The Melbourne households all incorporated earth wall construction, while the Darwin households were operated as partially or solely naturally ventilated. These households have previously been established 'low energy' forms of housing (Daniel et al, 2014; 2015a; 2015b). The comfort study was part of a larger investigation of the expectations, behaviours and preferences of the occupants of these forms of dwellings. Melbourne can be broadly classified as a cool temperate climate with four typical seasons, whilst Darwin has a hot humid climate with distinct dry and wet seasons, and a 'build-up' period in between that is characterised by high temperatures and humidity with little to no rain fall.

A paper based comfort vote survey in booklet form was distributed to all households. Occupants above the age of 18 years old were invited to complete the survey on a daily basis. Three widely used subjective measures of thermal comfort were included; thermal sensation vote (TSV) 1= "Cold" to 7= "Hot" (ASHRAE, 2013); thermal preference vote (TPV) 1= "Cooler", 2= "No change", 3= "Warmer" (McIntyre, 1980) and; thermal comfort vote (TCV) 1= "Very uncomfortable" to 6= "Very comfortable" (Brager et al, 1993; Luo et al 2014).

Indoor environmental conditions were recorded using two HOBO U12-013 data loggers that recorded temperature, relative humidity and globe temperature measurements at 30 minute intervals in each household. The loggers were located in the main living area as well as either the main bedroom or a secondary living area. In the Darwin households, an experimental system that recorded air movement was placed in the households' main living area (Daniel et al, 2014; Daniel et al, 2015c). External meteorological measurements were recorded every 30 minutes in proximity to the Melbourne households using a HOBO U30 weather station, whilst meteorological measurements for Darwin were attained from the Bureau of Meteorology (BOM) climate data service for the Darwin Airport weather station (Station number 014015). In general, the data collection met the requirements of a Class II field survey (ASHRAE, 2013). The internal and external environmental data were matched to the corresponding thermal comfort vote surveys and analysed using *Excel*. In the analysis of responses, the thermal comfort votes are often binned, either by indoor operative temperature or by the running weighted mean outdoor temperature (ASHRAE 55 (2013) Standard equation). The bins are in 1K increments, for example, the 24°C bin represents temperatures from 23.5°C to 24.49°C.

3 Results

Over 6,000 thermal comfort vote surveys were collected from the 40 households. A statistical overview of these data has previously been presented in (Daniel et al, 2015b). The following two sections examine the widely used methods to describe and assess thermal comfort with the aim of verifying the usefulness or otherwise of these methods within the context of residential thermal performance assessment.

3.1 Calculation of neutral temperature

The calculation of a single temperature is often used as a straightforward comparison between different subjects' or cohorts' thermal comfort, however there are many different methods to calculate this temperature, whether based on the data from the sensation, preference or comfort scales.

3.1.1 Regression analysis

The thermal sensation votes for each cohort were plotted against binned indoor operative temperatures (see Figure 1). Based on the linear regression equations developed from these, the temperature corresponding to a mean thermal sensation vote of 4= "Neutral" is 19.5°C for the Melbourne cohort and 27.4°C for the Darwin cohort.

Using quadratic regression based on the preference (Figure 2) and comfort votes (Figure 3) plotted against binned indoor operative temperature, the preferred and comfort temperatures are 21.7°C, 22.1°C and 25.3°C, 24.8°C for the Melbourne and Darwin cohorts respectively.

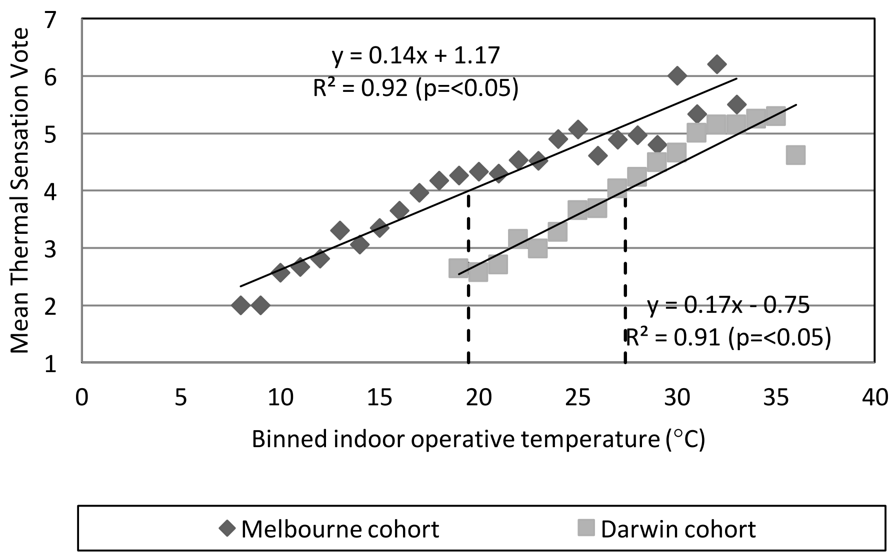

Figure 1. Mean thermal sensation vote of Melbourne and Darwin cohorts at temperatures binned in 1k increments, where 1="Cold" and 7= "Hot"

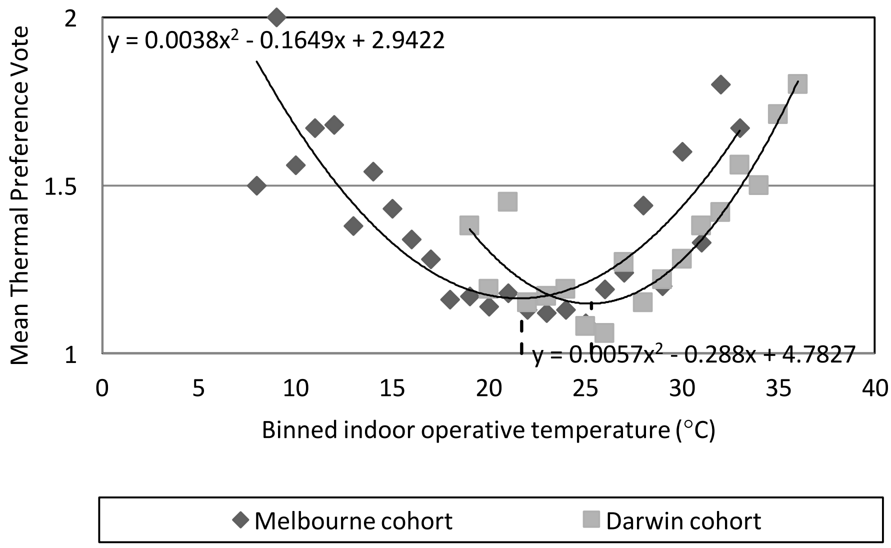

Figure 2. Modified mean thermal preference vote of Melbourne and Darwin cohorts at temperatures binned in 1k increments, where 1= "No change" and 2= "Change"

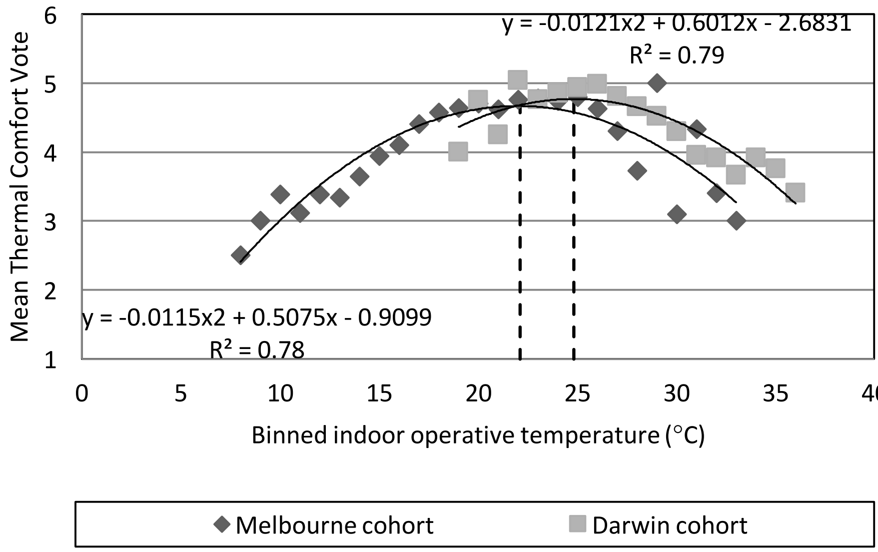

Figure 3. Mean thermal comfort vote of Melbourne and Darwin cohorts at temperatures binned in 1k increments, where 1= "Very uncomfortable" and 6= "Very comfortable"

3.1.2 Griffiths method

Using the Griffiths Method (Griffiths, 1990), (Equation 1) with an assumed slope of 0.5/K following Humphreys et al (2010) and Nicol et al (2012), the mean comfort temperature for the Melbourne cohort is 19.2°C (SD 3.3°C) and the mean comfort temperature for the Darwin cohort is 27.9°C (SD 2.4°C).

$$T_c = T_g - (C - 4) / G \quad (1)$$

Where T_c: comfort temperature, T_g: indoor operative temperature, C: thermal sensation vote and G: 'Griffiths slope'

However, if the actual slope values of the collected data are used to replace the 'Griffiths slope' (0.14 for the Melbourne cohort and 0.17 for the Darwin Cohort), the mean comfort temperatures are lower at 18.2°C (SD 7.6°C) and 26.5°C (SD 5.2°C) for the Melbourne and Darwin cohorts respectively.

3.1.3 Probit analysis: Fanger's method

Probit analysis using the Fanger method (Fanger, 1970) was completed for the Melbourne and Darwin data. The intersecting points of the regression lines for the proportion of cold dissatisfied and warm dissatisfied at each temperature bin for the two cohorts were 17.8°C and 27.1°C respectively. The PPD curves created for the Melbourne and Darwin data are very shallow when compared to the curves produced by Fanger (1970), see Figure 4 and Figure 5. This is likely because the collected data is from a field study where the internal environments are more varied; therefore, the natural distribution of the thermal comfort votes is not the same as can be produced by climate chamber. This is similarly reflected in Becker & Paciuk's (2009) findings from a comfort survey of approximately 200 Israeli dwellings. In comparing the collected data to the PPD model, they found that;

> *"discrepancies highlight the role of contextual variables (local climate, expectations, available control) in thermal adaptation in actual settings." (Beker & Paciuk, 2009, p948)*

3.1.4 Probit analysis: Ballantyne, Hill & Spencer method

An alternative method of probit analysis, used by Ballantyne et al (1977) to determine the preferred temperature of subjects from three different studies, was replicated and used to determine the preferred temperatures of the two case study cohorts: 18.2°C for the Melbourne cohort and 26.5°C for the Darwin cohort.

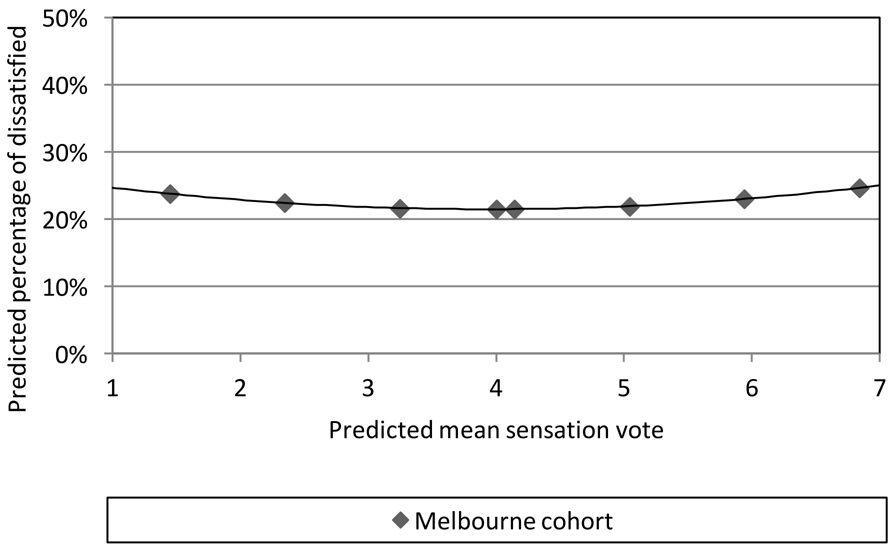

Figure 4. Percentage predicted dissatisfied for Melbourne cohort

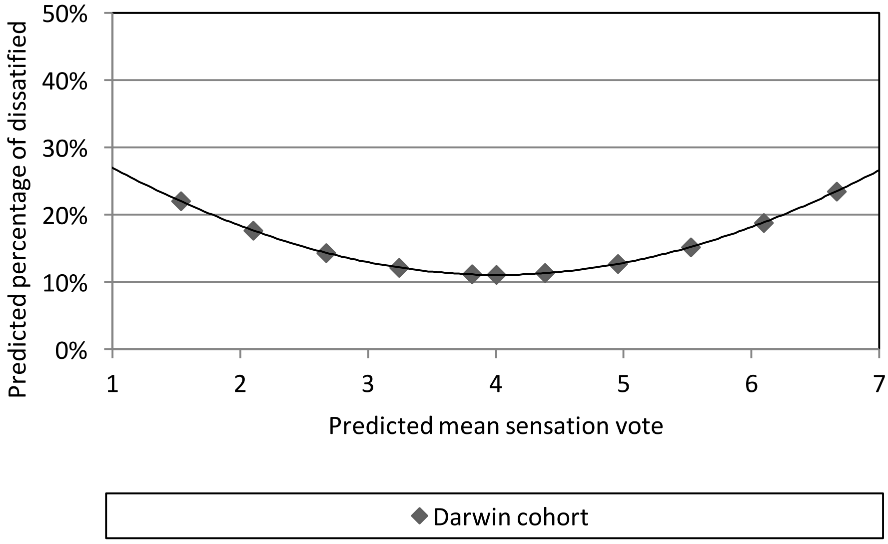

Figure 5. Percentage predicted dissatisfied for Darwin cohort

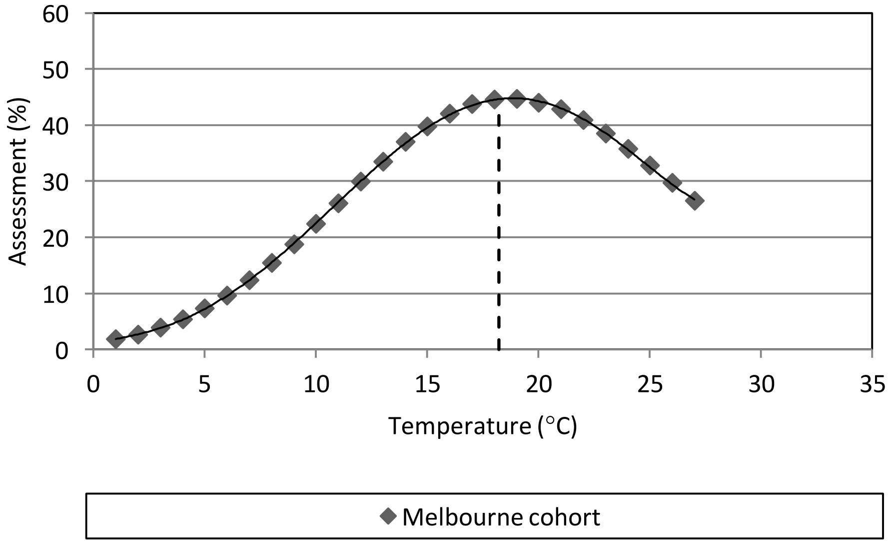

Figure 6. Proportion of votes within the neutral zone for Melbourne data

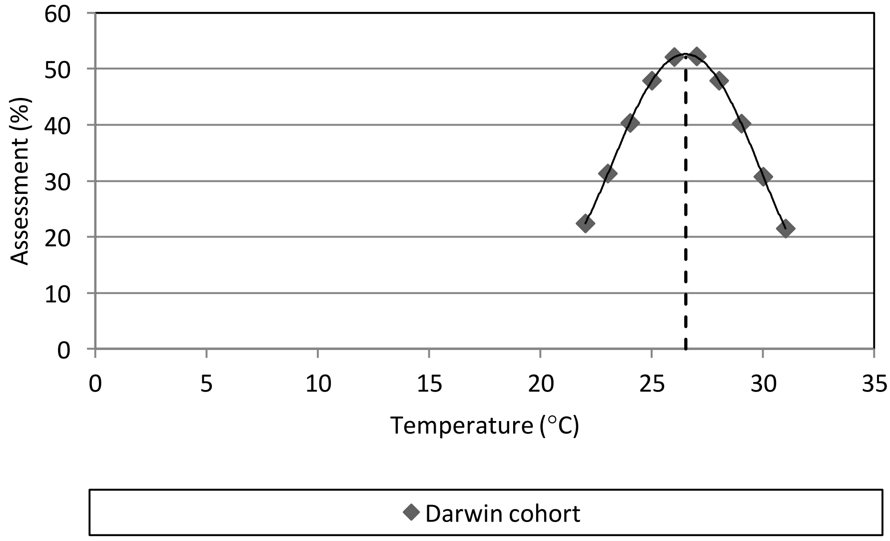

Figure 7. Proportion of votes within the neutral zone for Darwin data

3.1.5 Neutral, comfort or preferred temperature?

The temperatures calculated above, and summarised in Table 1, vary by 3.9K for the Melbourne cohort and 3.1K for the Darwin cohort, raising the question of the appropriateness of using a single temperature to describe the thermal comfort of a given cohort of subjects.

Importantly, the neutral temperatures attained using the Griffiths with the actual slope of the collected data corresponds with the preferred temperatures calculated using the Ballantyne et al method of probit analysis within one decimal place. Both the Fanger (1970) and Ballantyne et al (1977) methods of probit analysis use comfort vote data from climate chamber experiments conducted by the Kansas State University (KSU) in the late 1960s (Rohles & Nevins, 1971). To further test the outcome of the Griffiths and the Ballantyne et al methods, the analyses were completed for the KSU data. The calculated neutral and preferred temperatures again corresponded within one decimal place, confirming that to attain a comfort temperature it is more valid to use the actual slope of the collected data rather than the assumed slope of 0.5 more commonly used.

Table 1. Summary of neutral, comfort and preferred temperatures calculated from thermal sensation votes

Method	Melbourne	Darwin
Linear regression TSVs	19.5°C	27.4°C
Quadratic regression TPV	21.7°C	25.3°C
Quadratic regression TCV	22.1°C	24.8°C
Griffiths Method (0.5 slope)	19.2°C	27.9°C
Griffiths Method (actual slope)	18.2°C	26.5°C
Probit: Fanger method	17.8°C	27.1°C
Probit: Ballantyne et al method	18.2°C	26.5°C

3.2 Comparison with international thermal comfort standards

The following section compares the collected thermal comfort survey data with widely used international thermal comfort standards; the PMV index, the SET model, and the ASHRAE and CEN adaptive models.

3.2.1 Predicted mean vote: ASHRAE Analytical Comfort Zone Method

The PMV corresponding to the environmental conditions recorded at the time thermal comfort surveys were recorded was calculated using the Analytical Comfort Zone Method. The computer program was validated against figures shown in Table G1-1 (ASHRAE 55 Standard (ASHRAE, 2013)). Note that in the calculations the MET and CLO values are estimates only, based on the information provided by the participants about their activity and clothing level while responding to the thermal comfort survey. The data were then binned in 1K increments and the mean calculated PMV was compared with the mean thermal sensation vote cast by the subjects. Whilst the slope from the comparison of the PMV and the Melbourne data has good agreement, the higher *y* intercepts shows that the subjects are likely to cast a neutral vote at lower temperatures than the PMV model (see Figure 8). There is little correlation between the mean calculated PMV and mean thermal sensation vote of the Darwin cohort. The PMV calculations also appear to substantially over predict warmth sensation of this cohort (see Figure 9). For example, based on the thermal sensation votes, 5= “Slightly warm” corresponds to 33.2°C, while based on the PMV calculations it corresponds to just 29.3°C. This indicates that the Darwin cohort have a different perception of warmth than is accounted for in the PMV model.

3.2.2 Standard Effective Temperature (SET) Model

The collected thermal comfort survey data were similarly compared with SET as used in ASHRAE 55 (2013) Standard, defined by Fountain & Huizenga (1995). The calculated SET temperature was compared with the mean thermal sensation vote for both cohorts. This revealed that the SET model is a relatively weak predictor for the thermal sensation of the Melbourne subjects (see Figure 10); however, it does appear to be significantly more appropriate to describe the thermal sensation of the Darwin subjects (see Figure 11). This is likely associated with the effect of humidity and air movement on thermal sensation in hot humid environments. Much of the revision to the formative SET models was focused on improving its accuracy for these particular environmental variables (Auliciems & Szokolay, 2007).

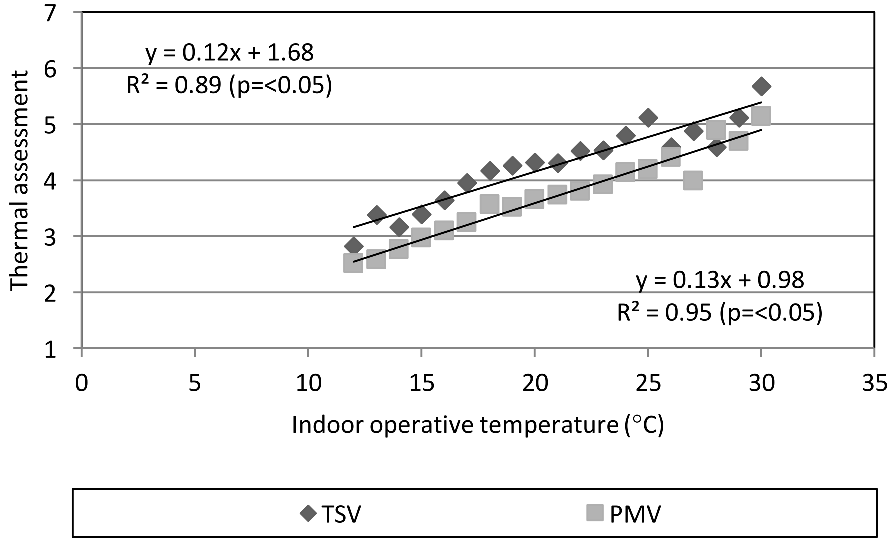

Figure 8. Comparison of the mean TSV and mean calculated PMV when binned by indoor operative temperature in 1k intervals for the Melbourne cohort

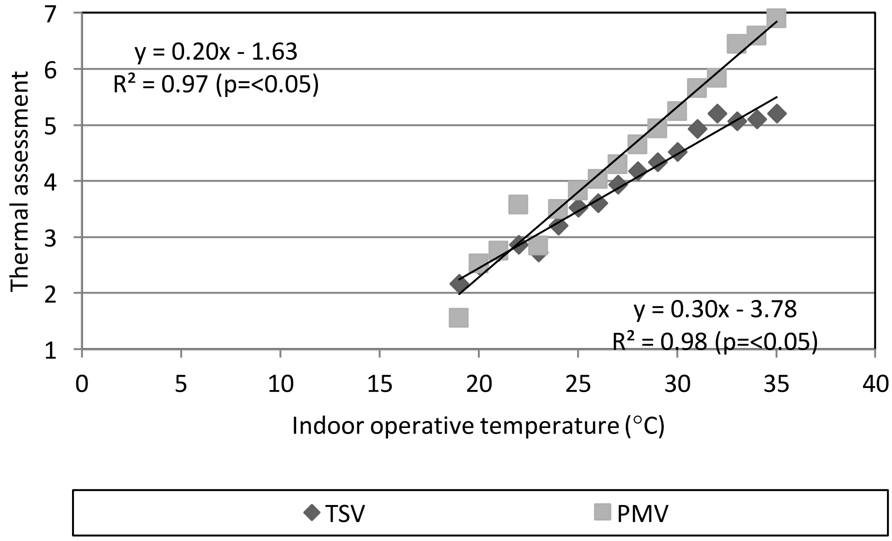

Figure 9. Comparison of the mean TSV and mean calculated PMV when binned by indoor operative temperature in 1k intervals for the Darwin cohort

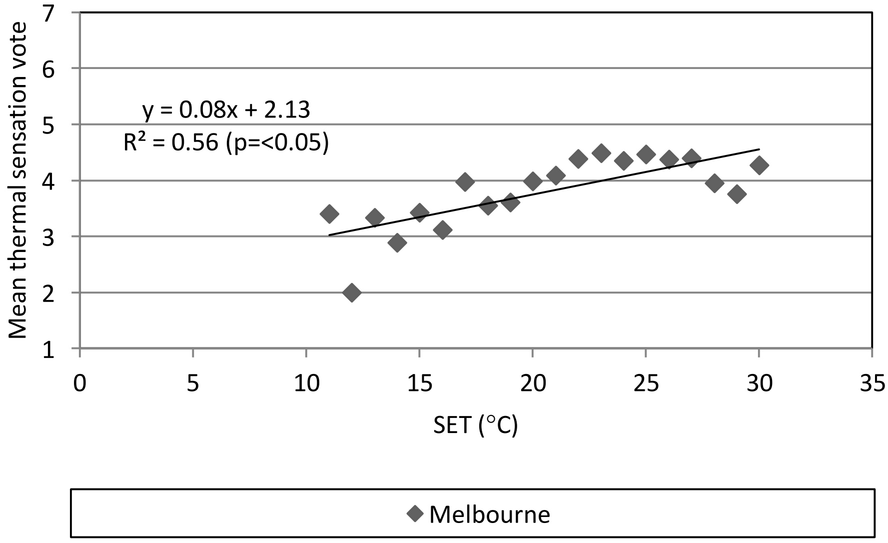

Figure 10. Mean TSV when SET binned in 1k increments for the Melbourne cohort

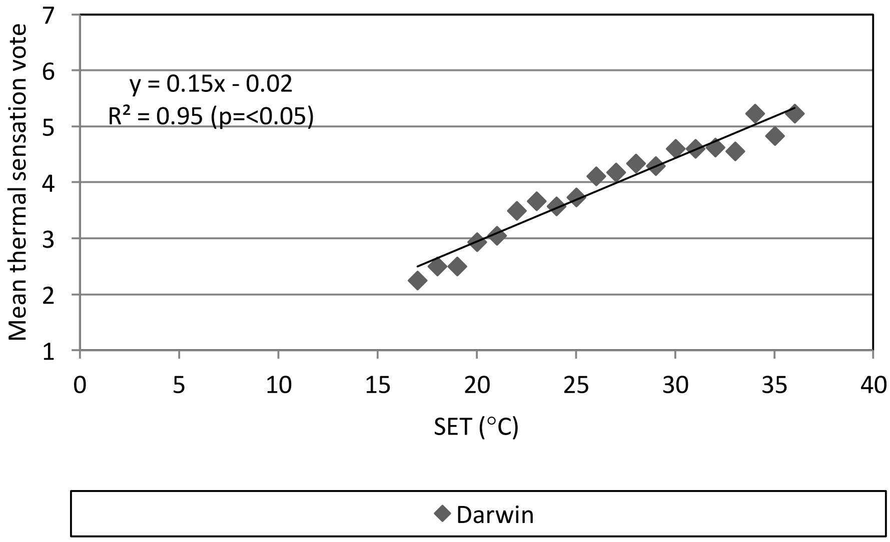

Figure 11. Mean TSV when SET binned in 1k increments for the Darwin cohort

3.2.3 ASHRAE 55 (2013) Standard Adaptive model

The thermal sensation votes that fall within the parameters for the application of the ASHRAE adaptive model (see section 5.4.1 of ASHRAE 55 Standard (ASHRAE, 2013)) were plotted against the 80% and 90% upper and lower acceptability limits (see Figure 12). Significant proportions of these votes sit outside of the upper and lower limits indicating that the two studied cohorts find a wider range of conditions comfortable than the adaptive model describes. Notably, the slopes of the two cohorts are very similar (y= 0.62x + 10.09 for Melbourne and y= 0.68x + 10.11 for Darwin) and steeper than that of the adaptive model (0.31).

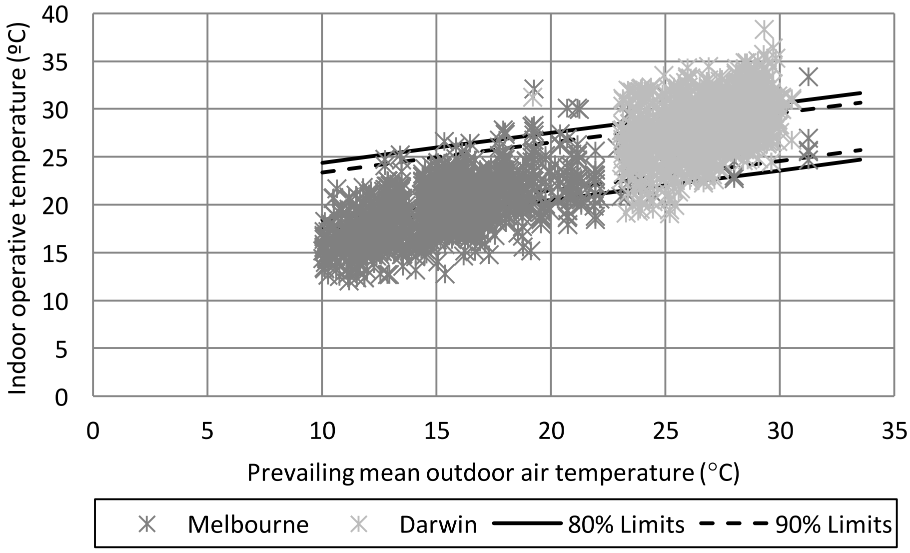

Figure 12. Comparison of the ‘slightly cool’, 'neutral' and ‘slightly warm’ TSVs from the collected data when parameters are within those described in ASHRAE55 (2013) Standard (section 5.4.1) with the acceptable operative temperature ranges for naturally conditioned spaces, where the prevailing mean outdoor air temperature is based on the running weighted 7-day mean

3.2.4 EN 15251 (2007) Standard Adaptive model

The thermal sensation data were compared against the EN 15251 (2007) Standard adaptive model category II and III limits (see Figure 13). The Darwin data appears to be in relatively good agreement with this model; however the model remains largely inappropriate for the Melbourne sample. The exclusion of running mean outdoor temperatures below 10°C (upper boundary values) and 15°C (lower boundary values) removed over 47% of the Melbourne comfort votes that would otherwise meet the requirements for application of the model. The stringency of this model in cooler conditions is likely due to the extent to which buildings are centrally heated in Europe, which is not reflected in residential buildings in Australia. Whilst this model does appear to be a reasonable description of the Darwin cohorts’ thermal comfort, the range of conditions nominated as acceptable by this cohort is wider than the category III design values.

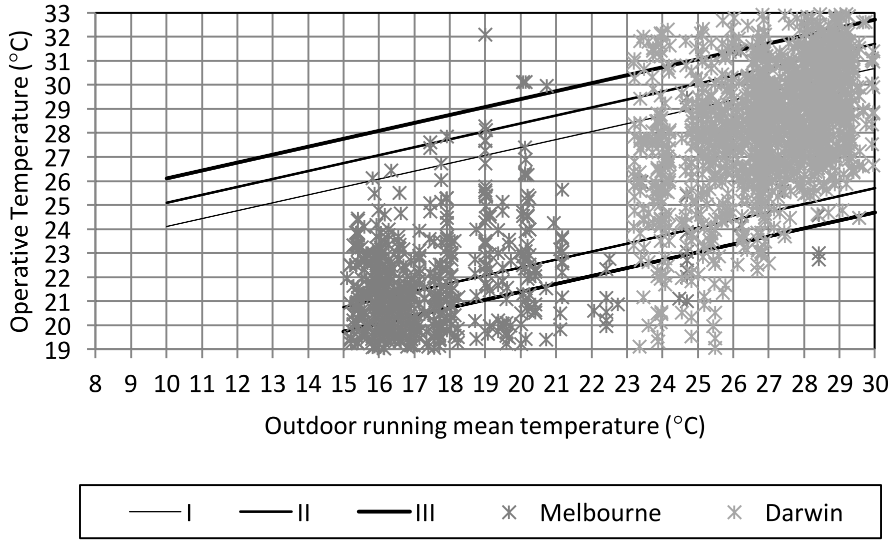

Figure 13. Comparison of the 'slightly cool', 'neutral' and 'slightly warm' TSVs from the collected data when parameters are within those described in EN 15251 (2007) Standard with the design values for the indoor operative temperature for buildings without mechanical cooling systems as a function of the exponentially-weighted running mean of the outdoor temperature

4 Development of preference model

The development of a model to describe the thermal preferences of the two case study cohorts is necessary for three reasons; (1) it is no longer useful to aim for a single temperature (i.e. thermostat setting) derived from neutral/comfort temperatures because the dwellings are designed to operate with little or no heating or cooling appliances; (2) section 3.1 reveals the ambiguity of describing a cohorts' thermal comfort using just one temperature and different approaches result in different neutral/comfort temperatures; and (3) it is clearly demonstrated in that existing models of thermal comfort do not sufficiently encompass the range of conditions that these *particular* occupants find acceptable.

A relationship between a neutral thermal sensation vote and 'comfort' is not apparent in the analysis of the thermal comfort surveys collected from the Melbourne and Darwin cohorts. The temperatures corresponding to 'neutral' (19.5°C for Melbourne, 27.4°C for Darwin, see Figure 1) and the comfort temperatures corresponding to the highest mean comfort vote response (22.1°C for Melbourne, 24.8°C for Darwin, see Figure 3) are considerably different; demonstrating a preference for warmer than neutral sensation by the Melbourne cohort and cooler than neutral sensation by the Darwin cohort.

Based on the results presented above, we propose a new thermal comfort model which is developed from the thermal preference votes rather than the thermal sensation votes. There are two reasons for choosing to use this scale. The first is that it has been demonstrated in the findings of this research that individuals do not necessarily want to feel 'neutral' (see Figure 14 and Figure 15); this is also widely supported by the literature presented above (e.g. Humphreys & Nicol, 2004). Secondly, it is expected that the thermal preference vote more close indicates when an individual is likely to take action to change their thermal environment because it reflects when they desire change (Brager et al, 1993; Williamson et al, 1995).

The proposed model will use the ASHRAE equation for the 7-day running weighted mean temperature to represent prevailing outdoor conditions (i.e. prevailing mean average (PMA)). The development of this equation was supported by observations of clothing patterns and outdoor temperatures in Sydney, making it more appropriate for an Australian context than the European based CEN 15251 (2007) Standard counterpart. A strong relationship can be observed between the 7-day running weighted mean temperature and acceptable indoor conditions reported by the occupants of the Melbourne and Darwin case study cohorts: $R^2 = 0.79$ ($p=<0.05$), further supporting the use of this equation.

Finally, it is important to note that this model has not attempted to distinguish between thermal comfort in living areas and bedrooms (e.g. following Peeters et al, 2009). To do so would be beyond the scope of this paper. The thermal experience of occupants in bedrooms in cooler climates is primarily influenced by bedding and clothing, rather than the indoor thermal environment (Lui et al, 2014; Wang et al, 2015). Both Liu et al (2014) and Wang et al (2015) found that occupants were quite comfortable sleeping in rooms with relatively low temperatures (15.8°C was cited as the thermal neutral temperature during sleep), as long as the bed temperature was approximately 30°C – 31°C). Studies of sleeping conditions in tropical climates indicate the need for air conditioning to achieve comfort (Tenorio, 2002; Dongmei et al, 2013), however many the subjects of the research presented in this paper reported that did not use air conditioning during nighttime hours, relying instead on air movement provided by natural ventilation and assisted by fans. When occupants use bedrooms for other purposes than sleeping, it is reasonable to assume that their thermal comfort will be adequately represented by the developed thermal preference model.

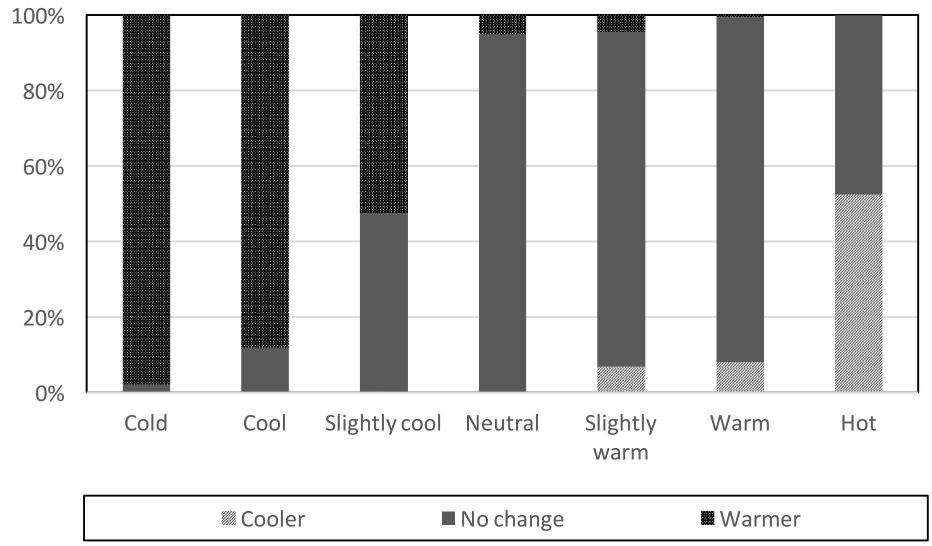

Figure 14. Total proportion of thermal preference votes at each thermal sensation vote scale for the Melbourne cohort

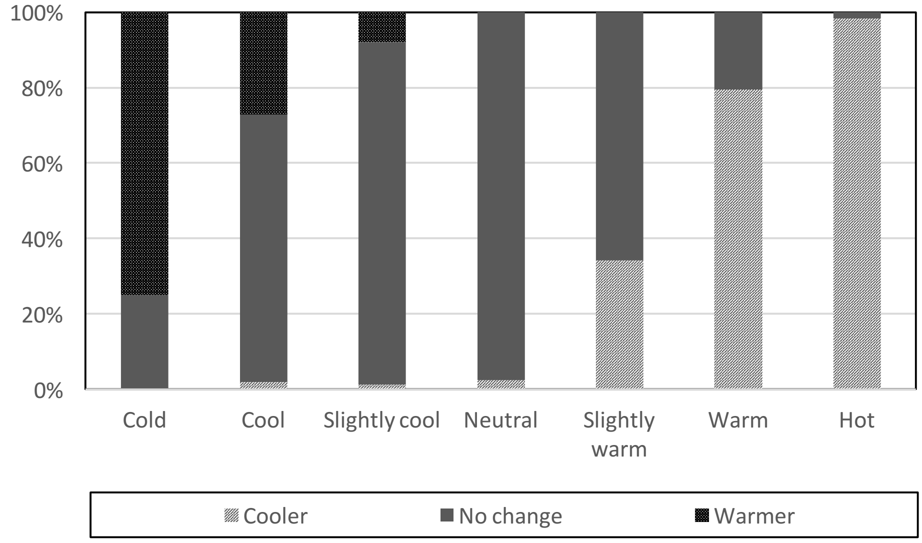

Figure 15. Total proportion of thermal preference votes at each thermal sensation vote scale for the Darwin cohort

4.1 Determination of preference limits

In order to determine the upper and lower limits of the two cohorts' thermal preference a statistical process was used to calculate the range of 90% of the 'no change' votes based on the prevailing outdoor air temperature and measured indoor operative temperature. The thermal preference votes were binned by the running weighted daily mean temperature and filtered to exclude votes that represented the desire for change (i.e. 1= "Cooler" and 3= "Warmer"). Outliers were deleted based on an interquartile range test of the indoor temperatures. The binned data were tested for normal distribution using the Shapiro-Wilk test. An *Excel* function was used to return the inverse of the normal cumulative distributions 0.05 and 0.95 based on the mean and standard deviation of the temperature bins. The process was completed for the aggregated data from both cohorts (see Figure 16). Equation 2 gives the lower limit of acceptable conditions and Equation 3 gives the upper limit of acceptable conditions.

$$\text{Lower limit} = 0.5529t_{pma(ext)} + 8.4608 \qquad (2)$$

$$\text{Upper limit} = 0.443t_{pma(ext)} + 18.431 \qquad (3)$$

Where: $t_{pma(ext)}$ = prevailing mean external air temperature

An important distinction to make between this model and the ASHRAE adaptive model is that it only represents conditions where the occupants reported no desire for change and is therefore taken to represent their preferred conditions. Because the thermal preference votes at 1= "Cooler" and 3= "Warmer" were excluded this model does not consider discomfort or non-preferred conditions per se. Note that a previous version of this model based on preliminary data was presented in Daniel et al (2014b).

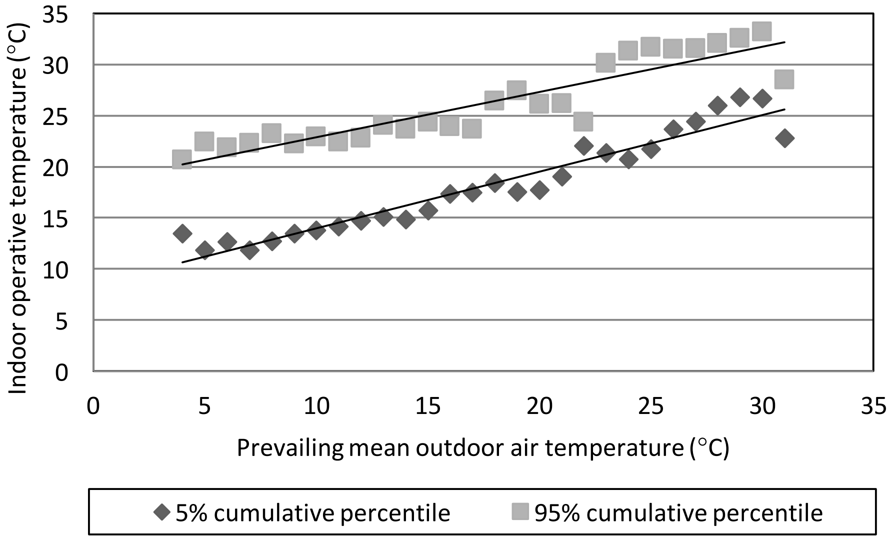

Figure 16. The 90% percentile preference boundaries for the aggregated data from both cohorts

5 Discussion

The relationship between the proposed thermal preference model and the thermal sensation votes cast by subjects from both cohorts is shown in Figure 17, demonstrating the better 'fit' of this model for the occupants studied compared with the existing ASHRAE 55 (2013) and EN 15251 (2007) Standards. It is possible to observe the preference for neutral or warmer sensation of the Melbourne cohort, and neutral or cooler sensation of the Darwin cohort in this plot by the slight trend of the bulk of the data points to sit towards the lower and upper boundaries respectively.

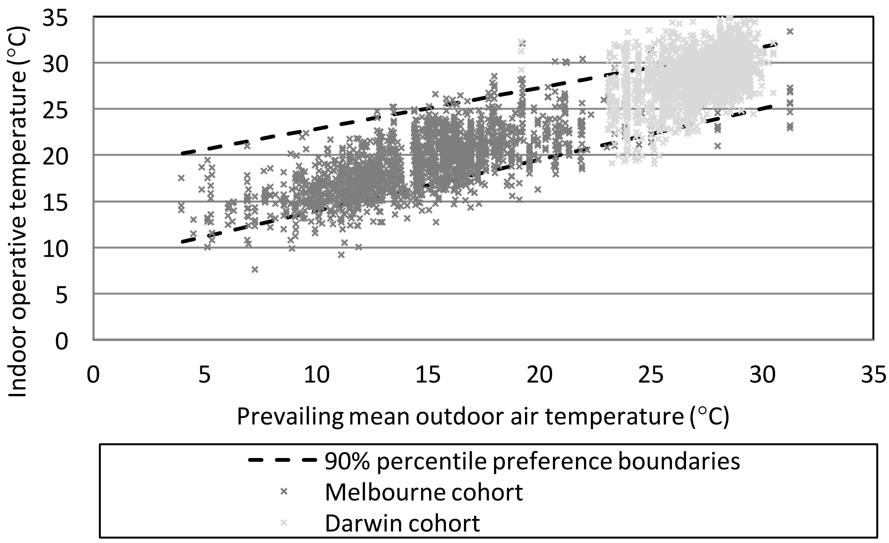

Figure 17. Comparison of the "Slightly cool", "Neutral" and "Slightly warm" thermal sensation votes when no heating or cooling appliances were in use with the proposed thermal preference model

6 Conclusion

The model of thermal preference presented in this paper has been developed for the occupants of two specific forms of construction with the aim of providing a tool to use in the regulatory assessment of new designs of dwellings incorporating earth construction components and naturally ventilated dwellings. Using comfort criteria in the thermal performance assessment of these houses could conceivably be incorporated into the existing NCC Energy Efficiency Provisions. A model for the cooling effect of air movement has been developed in parallel to fully capture the thermal comfort benefits of natural ventilation in hot humid climates such as Darwin (Daniel et al, 2015c). Importantly, this research acknowledges the fundamental difference in the design of free running buildings compared with that of conditioned buildings. Many houses in Australia do not require extensive heating and/or cooling if they are designed specifically for local conditions due to Australia's largely moderate climates. This research aims to encourage such design by providing an alternative pathway to compliance certification. Through the judicious or negligible use of heating and/or cooling, these households represent a means of reducing greenhouse gas emissions associated with residential energy consumption building, whilst still achieving acceptable levels of comfort and thermal performance.

Acknowledgements

The authors would like to acknowledge the advice and assistance provided by Dr Dong Chen, and the funding received from CSIRO.

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Designing Comfortable, Low Carbon, Homes in Dammam, Saudi Arabia: The Roles of Buildings and Behaviours

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Abstract
The present paper explores the thermal performance and comfort levels of seventeen air-conditioned homes monitored during the summer of 2013 in Dammam, Saudi Arabia. The comfort of occupants was assessed using the adaptive thermal comfort method. Neutral indoor air temperatures were, in several cases, surprisingly high. Most of the studied homes do not represent thermally comfortable homes as defined within either PMV or adaptive comfort limits. The study reviewed a wide range of factors that might strongly influence neutral temperatures indoors including the properties of dwellings, occupant's behaviours and attitudes towards high energy demand, loads and costs. This paper outlines the findings of that study and draws conclusions on individual design features of the studied homes that contribute to the comfort and discomfort experienced in Dammam's dwellings during the extreme summer weather. In late 2015 The Saudi Government hiked the price of domestic energy bills by 60% as a result of low oil prices, putting pressure on ordinary families to economise in their day to day living expenses. The lessons learnt from this study are discussed in relation to the challenge of maintaining comfort in Dammam's homes while reducing energy used for cooling them.

Keywords: Thermal comfort; architectural characteristics; hot humid climate; air-conditioned homes; residential energy consumption

1 Introduction
Summertime indoor conditions in Dammam's homes are of increasing concern, due to the potential for increased discomfort and higher energy costs resulting from more extreme outdoor weather. Temperatures as high as 35°C are occupied in Dammam's dwellings despite the ease with which indoor temperatures can be lowered instantly by adjusting the air conditioning (AC) system. During summer, outdoor and indoor discomfort are exacerbated during extreme hot spells, particularly when dust storms occur that prohibit the use of natural ventilation and the reduce the efficiency of AC systems. The rise in the occurrence of abnormally hot spells experienced in the region during summers and the transition seasons signal the emergence of acclimate that is less predictable and more adverse throughout the year (Tanarhte et al. 2015). Consequently, rising indoor temperatures driver higher levels of discomfort which in turn puts a growing financial burden on families impacting adversely on their lifestyles and standards of living. Similar pressures were key drivers in the collapse of the US and subsequent global economies in 2007 when American homeowners found that rising energy bills meant they could not longer pay their mortgages, providing some evidence that if not dealt with this too could be a major problem for Saudi Arabia (Roaf, 2014). Since the last world economic crisis, the cost

of living has risen remarkably in the region putting households under increasing financial strain to spend more while the income levels remain the same (Albaaz, 2008), with the rising cost of electricity over the last decade making up a considerable portion of the growing wedge between lifestyle aspirations and affordability.

Since all the contemporary Saudi buildings have been primarily designed to be cooled by artificial systems (Eben Saleh, 1998) the region is now recognised as having an AC dependent society (Elsheshtawy, 2008), a fact responsible for the very high comparative levels of energy consumption especially in homes. Furthermore, account needs to be taken of the fact that the historically low energy prices in Saudi Arabia have encouraged higher energy demand by consumers (Alyousef & Stevens, 2011). Over the past decade, there has been a dramatic increase in the use of electricity in the residential sector in Saudi Arabia, accounting now for around 50% of the total Saudi electricity consumption (MOWE, 2012). As there are projected to be 2.32 million further new dwellings in the Saudi market by 2020 (Ahmad, 2002), an significant increase in the electricity supplied for residential buildings will be needed in the coming years just to provide adequate indoor conditions in the building stock. Low awareness of energy and environmental issues, evidenced also in this study, leads also to more demanding and energy-intensive lifestyles. A December 2015 60% hike in Saudi Arabian domestic energy prices will disproportionately affect energy costs in low-performance homes, which consequently will put pressure on some families' budgets for those striving to maintain and affordable the comfort temperature in their homes.

This paper is based on the results of summer time fieldwork undertaken in seventeen homes in Dammam, the capital city of the eastern region of Saudi Arabia, a city with a well-established and growing population, designed to explore such issues on the ground. This study was conducted in three parts: a standard thermal comfort field study established those temperatures at which people reported thermal neutrality in their homes during very hot summer periods. The second part covers an investigation of the characteristics of the house occupants and their behaviours and attitudes towards their own homes. The third section details a physical review of the homes, their services and physical contexts and conditions. It was felt necessary to understand all of these aspects of the homes in order to get a clearer understanding of how their comfort 'ecosystem' worked in practice and develop the evidence from which could be drawn useful practical lessons for contemporary designers in the region. This paper outlines the findings arising from the study of the relationship between the physical design features of the Dammam's homes, and reported comfort, energy consumption and energy costs in the homes.

2 The Field Work Methodology

The Dammam field work was undertaken using a standard longitudinal thermal sampling method (Nicol, Humphreys, & Roaf, 2012) in seventeen air-conditioned homes. The survey involved dwellings that occupied by middle-class families with an average of six people in each home, distributed within a radius of 14 miles within the city. The field measurements and survey were carried out between the 10th to the 31st of August 2013 during an extremely hot season.

This study measured air temperature as its principal physical variable. Air temperatures and relatively humidity were obtained using (KG1001) data loggers that collected and stored

[1] Temperature accuracy +/-1.0°C under 0-50°C; Humidity accuracy +/-4% under 20-80%

results automatically in an optional strain choice. The data loggers were fitted in two different places in each dwelling, in the living rooms and the main bedrooms. The positions of the data loggers were located to minimize heat from direct radiation, either from solar radiation, material, mechanical or human sources with a proper distance implemented between the subjects in their normal physical places. Measurements of the environmental data were collected every five minutes.

The researcher developed a software for the comfort survey called "*ComfApp*" which includes twelve questions operable in all smartphones platforms, making it easier, and more enjoyable, for subjects to vote during day/night time and in any situation in those rooms. As the environmental variables were being recorded concurrently, each volunteer was asked to vote at least twice a day and all of the subjects used the smart phone platform to record their thermal sensation vote. The subjective data were collected over an average of ten days for each household at regular intervals of around eight hours between each vote over the day.

Furthermore, face-to-face questionnaires were undertaken to investigate the characteristics of the dwellers and their behaviours and attitudes towards their homes, such as number of hours/day spent indoors and the use of mechanical ventilation. Questions were also included related to general information about the design and construction of the dwelling. Seeking more in-depth information, semi-structured interviews were carried out for numerous cases, in order to identify specific information that could be compared and contrasted with information gained in the other case study homes. To do this, the interviews were comprised of open-ended questions included to explore occupant's attitudes and thoughts on the energy performance of their own home, including, for example, factors that influenced their choices to operate a fan or AC rather than open a window. The following sections describe the results of this field study and conclude with discussions on those findings.

3 The Experienced Temperatures and the Reported Thermal Neutrality

The temperature variation recorded during the fieldwork, as shown in Figure 1, ranged between just below 20°C to an unoccupied outlier room temperature of 47°C. Figure 1 has an illustration of a scatter plot of the whole set of the indoor and outdoor temperature recorded during August 2013 in these dwellings. Perfect temperature control could not be expected especially when all of the dwellings had operated different HVAC systems quite possibly with different temperature set points. The mean temperature of the whole sample is 27.2°C, a figure that appears to be well above the European guidelines of maintaining interior temperatures of between 22°C and 24°C. The scatter diagram of the ASHRAE adaptive standard of 80% and 90% acceptability limits of the whole set of measured indoor and outdoor temperatures (Figure 1) indicates that people in Dammam do live in what inhabitants of many other regions of the world would classify as very hot conditions. Surprisingly, 22% of the occupied temperatures that coordinated with thermal sensation votes were above 30°C.

The measurements taken in the summer of 2013 illustrated in Table 1, moreover, provide a valuable insight into the range of mean indoor relative humidity (RH) experienced in the study homes from 41% to 72% RH. These variations might be due to individual houses having different humidity distributions that result from the behaviours of the occupants (cooking, cleaning bathing, use of dehumidifying HVAC etc.) which will modify the humidity.

The mean RH of the whole sample, of almost 60% appears to be higher than the optimal standard of 55% followed as a rule of thumb by HVAC engineers for so long.

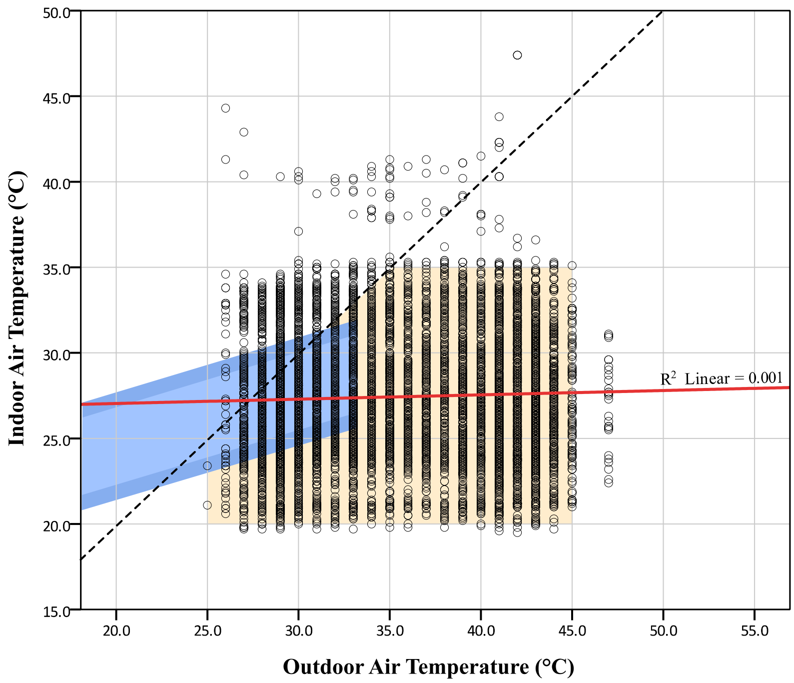

Figure 1 Scatter diagram of the ASHRAE adaptive standard of 80% and 90% acceptability limits of the whole set of indoor and outdoor temperature measured in Dammam's dwellings during the hot season, where the mean indoor and outdoor air temperatures were 27.4°C and 35.4°C respectively.

As the mean indoor air temperature in these homes range between 20°C to 35°C, it is evident that people live in a widely varying range of indoor temperatures, and that they accommodate them in the ordinary course of their day-to-day lives in their homes. Taking into consideration, the responses of all these houses, the thermal sensation votes have significant ($\alpha < 0.015$) positive weak correlation of 0.576 with the corresponding mean indoor temperatures, which indicate that the subjects are adapting to the mean indoor temperatures.

4 Occupant's behaviour

To explore the occupant's behaviours, the questionnaire used in the study interrogated the respondent's behaviours using a distributed survey that garnered four hundred and seventy-two votes from a total number of thirty-five subjects with a gender split of eighteen males and seventeen females. The ages of the subjects ranged from twenty to sixty years, with a mean age of 34 years old. All subjects were in good health during the time of the questionnaires. Calculation of their body mass indices showed that 72% of the subjects were overweight. On average the users stayed indoors at home around twelve hours per day, with women spending on average four hours more there. When asked about their electricity bills, more than the half (57.6%) of the participants replied that they often have high bills during summertime that ranged between £90 to over £200 per month. Despite the fact that the cost of a kWh of electricity delivered to the householder is ranging from only a penny to 29p for the highest consumer, around 62% reported that they considered their electricity bill was overpriced and inflated.

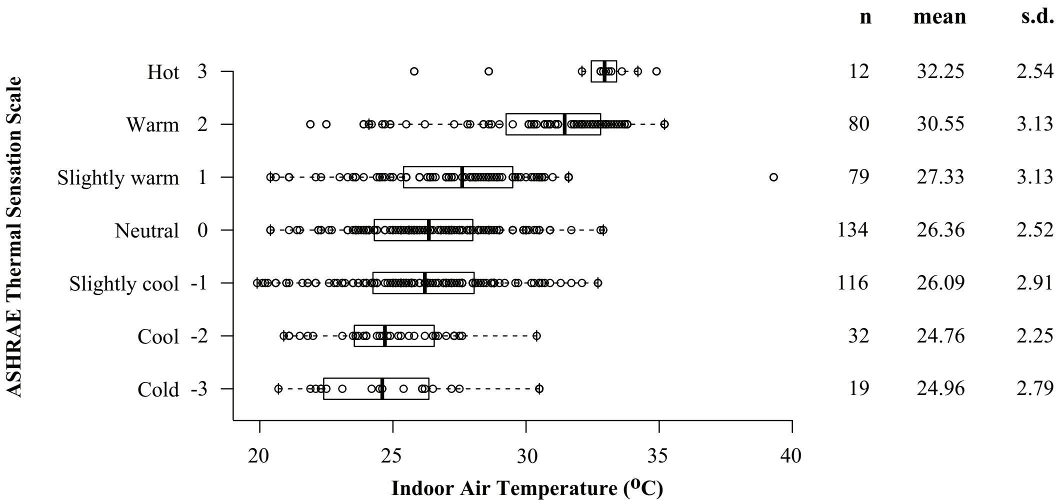

Figure 2: Boxplots and dot plots of ASHRAE thermal sensation (ASHRAE seven-point scale), and on the right hand scale a statistical summary of the indoor air temperatures associated with those ASHRAE votes (°C).

Table 1 shows the variation of all measured thermal sensations of the occupants who have a neutral pint of 0.1. From Figure 2 we can see that of the total 472 valid responses, 134 occupants described themselves as being thermally neutral. 79 respondents were slightly warm and 116 were slightly cool. 143 of the responses, or 27% of the dataset, reported being warm or hot, or cool or cold, (responses of 2, 3, or -2, -3) at the time they recorded their comfort vote. Interestingly, 92 of the respondents, or close to 20% of the dataset, were feeling warm or hot and half of these votes were experiencing a temperature equal or above 30°C. Moreover, around 20% of the latter responses preferred no change on the thermal preferences scale. The standard deviations of the thermal sensation in Table 1, furthermore, provide additional insight into how the perceptions of conditions in different houses vary, clearly influenced by the prevailing indoor temperatures.

During the longitudinal survey, occupants were asked to indicate what environmental controls were activated during the survey voting period. The adaptations noted among the controls include the use of AC, fans, windows and doors. Table 1 lists the mean and standard deviation of the control of AC and fans as well as the opening of windows and doors between the survey votes for all the dwellings. Surprisingly, only 17% of the total observations recorded occupants closing the AC system off at some point during the day of the vote. It indicates that the decision to shut down the AC system was seldom made and in some homes, it was never turned off. The main reasons for shutting the AC system were that the AC was not blowing cool enough cooling due to an over-long operation period, or because some occupants desired to be in the warmer conditions that resulted. However, the length of operation of the mechanical systems of homes in the region may reflect the low price of electricity in Saudi Arabia then. As domestic prices rise it will be interesting to see if the operation period of the mechanical systems is shortened to save money. The use of fans, moreover, were limited to seven dwellings only, and the mean value of operating the fan in those dwellings varied from 0.03 to 0.50. In those dwellings people were found to prefer to have some local air movement a one occupant reportedly preferred the cooling sensation resulting form the use of fans over those provided by activating the AC.

Table 1 The mean and standard deviation of all measured indoor air temperatures (T_a °C), Relative humidity (RH%) and the ASHRAE thermal sensation scale, besides the proportion of AC, fan, window and door's activation in all the seventeen Dammam's dwellings during summer 2013 (N: sample size; SD: standard deviation)

Dwelling #		T_a		RH		ASHRAE		AC		Fan		window		door	
	N	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	34	25.8	2.7	52.2	12.3	-1.1	1.5	0.88	0.33	0	0	0	0	0.26	0.45
2	32	27.3	2.8	64.6	6.7	-0.9	0.7	0.91	0.30	0.03	0.18	0.03	0.18	0.53	0.51
3	21	26.8	1.8	54.1	5.1	-0.5	0.7	1	0	0	0	0	0	0.10	0.30
4	28	28.8	2.1	65.1	6.8	0.4	1.3	0.64	0.49	0	0	0	0	0.61	0.50
5	39	27.5	1.9	62.4	3.7	-0.1	0.9	0.72	0.46	0	0	0	0	0.28	0.46
6	18	30.4	3.3	59.3	6.0	1.4	1	0.50	0.51	0.50	0.51	0.11	0.32	0.39	0.50
7	36	24.1	1	58.4	8.6	-0.3	1.1	0.89	0.32	0.06	0.23	0	0	0.28	0.45
8	25	26.8	3.3	64.8	7.6	0.4	1.2	0.96	0.20	0.04	0.20	0	0	0.16	0.37
9	23	22.5	1.7	65.0	5.8	-0.6	1	0.96	0.21	0	0	0	0	0.17	0.39
10	18	26.7	4.4	67.8	7.6	0.5	1	1	0	0	0	0	0	0.33	0.49
11	17	28.6	2.9	59.1	4.2	0.4	1.2	0.94	0.24	0.35	0.49	0	0	0.35	0.49
12	35	23.2	1.9	62.9	3.8	0.4	1.2	0.86	0.36	0.03	0.17	0	0	0.49	0.51
13	26	28.6	2.8	52.3	2.6	-0.2	1.5	0.77	0.43	0.23	0.43	0	0	0.62	0.50
14	27	28.2	2.3	41.3	7.9	0	1.1	0.56	0.51	0	0	0	0	0.85	0.36
15	50	31.6	2.1	60.5	6.1	1.8	0.9	0.92	0.27	0	0	0.04	0.20	0.58	0.50
16	22	27.7	2.7	55.7	8.5	-0.4	1.1	0.91	0.29	0	0	0	0	0.14	0.35
17	21	27.7	2.2	72.6	6.1	-0.6	1.8	0.76	0.44	0	0	0	0	0.52	0.51
Total	**472**	**27.2**	**3.4**	**59.7**	**9.6**	**0.1**	**1.4**	**0.83**	**0.37**	**0.06**	**0.23**	**0.01**	**0.10**	**0.41**	**0.49**

Although all of the surveyed dwellings have operable windows, almost a nil proportion (1%) of occupants operated the windows during the day and those were found in only three of the dwellings. In the other dwellings, windows were fully closed during the heat of the summer but opened at cooler times of the year. However interestingly the doors which opened into uncooled indoor or semi-outdoors areas were often constantly in operation, (10% - 85% of the time) in all dwellings with a mean value of 0.41. The decision to open internal doors to stimulate air movement around the house instead of windows to the outside was perhaps due to the preconception of the adversity of the outdoor condition (i.e. high humidity, temperatures and dust storms) making the opening of internal doors always a more effective choice.

5 A physical review of the homes, their services and physical contexts and conditions in relation to comfort experienced in them

Levels of comfort experienced in the homes, and the extent of adaptations required to achieve that comfort, were patently influence by the design of the individual house itself. The form, orientation, envelopes and construction of the dwellings and their HVAC systems differed substantially from each other as a result of being randomly selected (Table 2) to represent a broad corpus of homes in the region. All homes were differently planned. Some homes had envelopes with very high thermal integrity, high levels of insulation, double-glazing, minimal thermal bridging and efficient HVAC systems. Others had minimal or no insulation, single glazing, air leaks, thermal bridges and inefficient cooling machines. Most of the homes were built of typical concrete block construction, single/double block and externally rendered. All of the houses had operable windows, and all occupants had potential for visual contact with the outside. In the next section the energy efficiency potential of each home, and its actual energy performance are reviewed and the thermal experiences within the studied dwellings are discussed.

Moreover, tracing the behaviour of the mean indoor temperatures in the living and bed rooms of each dwelling in twenty-four hours' strings, Figure 3, demonstrate the range of temperatures experienced in the different homes vary significantly between the dwellings. The reasons behind these differences in what constitutes occupied, acceptable and reportedly uncomfortable internal temperatures are sought.

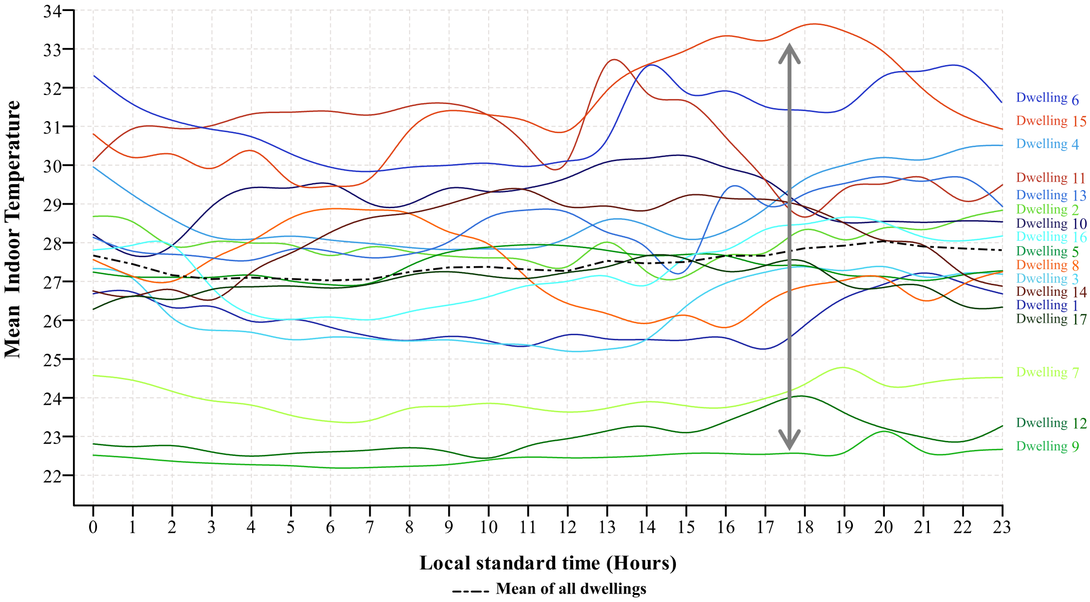

Figure 3 The traces of the mean indoor air temperature in the string of 24 hours in the studied Dammam's homes during August 2013

One of the most effective strategies for reducing domestic energy consumption and increasing occupant comfort was found to be simply the existence of a high performance dwelling envelope, with sensibly sized openings facing in a good orientation taking in requirements of heat gain and loss, lighting and air movement. Achieving both comfort and low energy consumption demonstrably benefits from 'whole system thinking', as they can be seen to result from the sum of many different building parts and behavioural and attitudinal attributes of the occupants. The main physical attributes that appear to determine performance most are discussed below individually and as clusters in the case study houses and include:

1. orientation
2. internal spatial planning
3. allocation and sizing of fenestration
4. day lighting and shading provision
5. cooling and ventilation strategies
6. construction materials

Table 2: The dwellings characteristics, the comfort survey result and electricity consumption details of the seventeen dwellings collected in Dammam during summertime 2013, arranged in ascending order of good house performance recorded in terms of energy consumption per meter square.

	Dwelling Number	Dwelling Type	Dwelling Age	Building Material	HVAC system	Dwelling Orientation	Double\Single Windows	Percentage of openings	Insulation	Mean T_a (°C)	ASHRAE	Annual bill £ / m^2	Energy kWh /m^2
Well behaviour homes ↔ Badly behaviour homes	6	House	11	Concrete block	Fans, Central HVAC and AC Unit	NE	D	18.70%	Yes	30.4	1.4	1.9	89.3
	9	Apartment	20	Concrete block	Central HVAC	NE	D	7.70%	Yes	22.4	-0.6	1.1	90.9
	1	Apartment	10	Concrete block	Window AC and AC Unit	NE	D	10.80%	Yes	25.7	-1.1	1.1	95.1
	2	Apartment	10	Concrete block	Fans, Window AC and AC Unit	SE	D	N/A	Yes	27.2	-0.9	1.4	97.1
	17	House	2	Red bricks	Central HVAC	E	S	N/A	Yes	27.5	-0.6	1.5	101.2
	10	Apartment	5	Concrete block	AC Unit	N	S	N/A	Yes	26.7	0.5	1.1	101.4
	16	Apartment	12	Concrete block	Fans, Window AC and AC Unit	NE	D	19.90%	Yes	27.6	-0.4	1.3	104.1
	12	Apartment	15	Concrete block	AC Unit	SW	S	9.70%	Yes	23.1	0.4	1.6	106.5
	5	House	22	Concrete block	Central HVAC and AC Unit	SE	S	11.90%	Yes	27.5	-0.1	2.8	108.8
	4	House	12	Concrete block	AC Unit	NW	S	N/A	No	28.7	0.4	1.8	111.7
	7	House	20	Red bricks	Central HVAC	SW	S	N/A	Yes	24.1	-0.3	2.3	118.7
	3	House	25	Concrete block	Window AC and AC Unit	NW	S	31.30%	No	26.8	-0.5	2.1	125.2
	14	House	4	Concrete block	Window AC and AC Unit	NW	S	N/A	No	28.1	0	1.7	125.9
	11	House	18	Concrete block	AC Unit	SE	S	N/A	No	28.6	0.4	2.9	148.3
	8	Apartment	15	Concrete block	Window AC	SW	S	45.80%	No	26.8	0.4	1.9	165.8
	15	House	28	Concrete block	Window AC and AC Unit	W	S	48.60%	No	31.5	1.8	4	201.7
	13	House	27	Concrete block	Window AC and AC Unit	W	S	31.10%	No	28.6	-0.1	3.9	206.4

5.1 Orientation

In the extremely hot climate of the Dammam region, southern and mainly western facing windows result in solar gain in the afternoon, evening and at sunset, times of day that coincides with the hottest external temperatures. Overheating of rooms facing south and west builds up gradually from noon onwards. A western/southern orientation was found to be the typically the most uncomfortable one for rooms in Dammam's homes. In this study, most dwellings appear to have been oriented with little or no consideration of orientation or attention to the solar radiation and the thermal context of the local micro-climate. It is clear in this study that the orientation of the dwelling plays a massive part of the dwelling's energy consumption. Not surprisingly, two of the highest performing dwellings in this study are oriented with their longer façade facing the North-Northeast, with around 90 kWh/m^2 energy consumption per annum. However, the seven most energy-intensive dwellings in this study are improperly oriented, with the annual consumption of these homes ranging from 118 kWh/m^2 to a maximum of 206 kWh/m^2 per annum.

Proper orientation demonstrably enhances a dwelling's indoor climate: for well-performing dwellings constraints, as in numbers one and nine, the orientation of the longer façade of the dwellings have a tremendous impact on the mean indoor temperatures and the average daily temperatures of these dwellings was below the neutral temperature found in this study. Properly oriented dwellings with bedroom windows facing between North and East had average daily temperatures of less than 25°C, apart from house number six where the preference of the occupant was to occupy warmer conditions. On the other hand, when a dwelling was improperly oriented, with its bedroom windows facing west, as in cases thirteen and fifteen, the indoor temperatures exceeded the neutral temperature by at least 3K.

5.2 Internal Space Arrangement

The internal layout and room arrangements is fundamentally affect the heat distribution within the spaces in the home. As the western façade is likely to receive maximum radiation at the hottest time of day, and in turn all spaces adjoining this façade will experience the maximum heat gain. A good example was found in dwelling number nine uses the buffer space adequately, with a reasonable internal layout. The closed hall space in the outdoor entrance buffers the guest room and the living room, and the location of the least used guest room to the south, leaving all the main bedrooms to the north, which has worked perfectly. Placing the lounge in the buffered middle of this apartment reduced discomfort, as it limited the heat gain to the most used room. However, the deliberate use of thermal buffering spaces was found in this study to be limited and, in fact, in some cases they were misused. Dwelling thirteen, for instance, has a massive entrance into the guest area oriented to the north, while the main bedroom lying to the west with a mean internal temperature in the evening in this room above 30°C.

A closer study of the design and room arrangements shows that there are a lot of wasted areas in most homes. It is clear that people have little understanding of the thermal and energy implications of room location and zoning. People lend more weight to the value of ‘making a show’ in front of their guests, rather than valuing their own comfort, wellbeing and energy economy in their own homes. In most of the dwellings in the current study, the *majlis,* or guest reception room, was hardly used throughout the year but its size and location significantly affected the internal layout and orientation of the rooms in the home, being treated as a priority to be displayed prominently to guests. In dwellings number eight and thirteen, the guest sections take up the best location in the houses, oriented to the north, and bedrooms were then oriented to the west and south, significantly increasing energy needed for cooling load those occupied rooms of the dwelling.

5.3 Opening Choices and Solar Access

In considering the orientation of the dwelling, the issue with most climatic impact is the orientation of the glazed openings. Most of contemporary dwellings in the Dammam region seem to be designed with large window openings and with relatively little attention given to the local climate. In fact, in some cases, a window was placed in every possible wall inside the rooms, which may prove to be completely unnecessary.

Windows typically have a higher conductance coefficient than the rest of the building envelope. Therefore, dwellings with a high glazing ratio have greater heat gain, compared to similar homes with a lower glazing ratio. Solar gain through large windows in summer can elevate a dwelling’s indoor temperature well above the outdoor day or night temperature levels and thus cause intolerable conditions indoors and significant thermal stress, consequently increasing the building's cooling load to compensate for this poor design. In house number fifteen, for example, where the glazing ratio is around 49% of the façades area, the indoor temperature been found usually close to or sometimes higher than the outdoor temperature. There appears in this study to be a clear relationship between the amount of the window opening to wall ratio and energy consumption. The larger the window area is in the façade, the more intense the energy demand for cooling is in the dwellings. For instance, as the size of windows in homes one, five, six, nine, twelve and sixteen is very reasonable, that less than 20% of the façades area, the consumption was 90 - 108 kWh/m^2 per annum, being the lowest average consumption of all studied homes. Whereas in dwellings three, eight, eleven and fifteen where the ratio of window to façade wall area ranges between 31% to 49%, the energy consumption ranges between 125 and 206 kWh/m^2 per annum. Therefore, as one intuitively suspects, the homes with smaller areas of fenestration that are also well oriented, provide much better protection against heat gain during the day.

5.4 Daylight and Shading

It has commonly been assumed that daylight as a natural source of light can be used for the satisfactory illumination of rooms during the day. However, due to the adverse hot conditions from the intense internal heat and intolerable visual glare experienced in Dammam, adaptable shading used at different times of day and year is vital. The current study, however, found that the occupants do not use external fenestration shading at all and rely solely on internal blinds and curtains to just screen the internal glare.

Although not used in the most of the case study homes, trees to the eastern and western sides of the house could create a cooler environment around the dwelling as an alternative shading strategy for the home. Although all homes in Saudi Arabia are surrounded by set-back spaces behind walls, creating front, side, and rear yards, it appears that people do not have an interest in planting vegetation around their dwellings to provide shade. The occupant of dwelling number six, however, was very pleased with the planting and pergola he had completed in his house's yard and was very satisfied with the resulting outside environment. Therefore, with the right kind of soil and plants, and perhaps more importantly, with a sustainability-oriented user attitude, it is possible to grow plants properly for adequate passive shading of façades, potentially using grey water from the numerous showers often taken to do so.

5.5 Cooling and Ventilation Strategies

Installing, operating and maintaining an efficient AC system is considered to be more expensive, possibly prohibiting users from adopting optimal solutions. In house number thirteen, with the highest home energy consumption per square metre, an enormous amount, in Saudi terms, was paid for energy of £3.85/m^2 per annum. The occupant stated that they also spent an excessive amount of money maintaining the AC equipment, of around £400 every six months without the cost of failing parts, due to the fact of it being an inefficient type of AC system, set also in a poor house design. In dwellings number nine and one, the energy costs, for example, are £1.14 and £1.10 per annum, respectively. Taking into account the fact that these dwellings have among the top performance envelopes, these particular two homes also have efficient cooling systems that are periodically maintained with a maintenance contract of around £400 per annum without the cost of failing parts. Accordingly, it is likely that the very cheap operational cost is a result of an efficient AC system in a more highly-performing home.

Sleeping discomfort is a significant issue, exacerbated by high humidity, especially in homes like six and twelve with high indoor temperatures. Standard ceiling fans, however, can create a comfortable environment when temperature and relative humidity levels are high but within acceptable ranges. In house number six, for instance, the occupants were shutting down the air-conditioners for around 20 to 45 minutes every two hours in the day time, even when the indoor temperatures exceeded 29°C and operating the ceiling fan. This house, with its active occupants, was subsequently able to achieve the highest performance and least energy demand per square metre among the studied homes. Whereas in dwelling fifteen, that without ceiling fan, 85% of the sensation votes during bedtime were warm and hot sensation votes preferring much more cooling as the indoor temperature never goes as low as 28°C until 2am.

The number of operating hours / days required to achieve thermal comfort can be substantially reduced by careful design of homes. It has been found that the air-conditioning in a poorly-designed dwelling (cases eight, eleven, thirteen and fifteen) with an inefficient AC system remains in operation for around nine months through the year, three more months of operating the air-conditioning than in well-designed dwellings. Furthermore, the operation of fans may reduce the number of months of operating the AC system at night, when the outdoor temperature is tolerable with adequate air movement, like in homes numbers six, seven and twelve, the operation of the AC system is limited to six months through the year. Therefore, it is favourable to install fans in bedrooms and all living areas, which would significantly reduce the use of the cooling systems.

5.6 Energy Efficient Construction

Contemporary construction of residential buildings throughout Saudi Arabia is typically with reinforced concrete systems. Various types of concrete products are employed including concrete blocks, floor tiles and precast concrete. Walls in Dammam were found to be constructed with concrete brick of 20 to 25 cm thickness, with very high conductivity and insufficient thermal resistance. Insulating the mass externally, which would significantly improve performance, is seldom done in Saudi Arabia Most well-performing homes had an external wall thickness of 30cm, whereas almost badly-performing homes had an external wall thickness of 25cm or less, including the insulation, if available. Moreover, most of the studied Dammam's homes seemed to be constructed without benefiting from the available passive summer cooling so they act as a hot bridge rather than a coolth store. Dwellings built fifteen years or more ago had no insulation, except those with high income owners who could build their dwelling to a higher standard. Dwellings without insulation in this study consumed 125kWh/m2 up to 206kWh/m2whereas all the better-behaved homes had insulation installed.

6 Conclusion

This study has shown that people in the selected homes in Dammam occupied mean indoor air temperatures widely ranging between 20°C to 35°C. The thermal sensation votes reported demonstrated that people largely adapted to be more or less comfortable in the temperatures they occupied. A survey of occupant’s behaviours showed that adaptation was achieved through a range of attitudinal adjustments, behaviours and actions including the use of fans and AC systems and the opening of internal doors and to a lesser extent in summer, windows at different times of day and year.

Perhaps the most useful finding of the work is the extent to which the physical design and construction of the building itself is instrumental in determining the comfort and quality of life of the occupants of the homes. In most cases, the existence of well-oriented, high performance envelopes and internal thermal buffer spaces result in lower energy running costs and higher reported comfort levels. Buffering of living areas from the worst extremes of this often very hot climate was shown to improve comfort levels experienced in the homes. In some cases, the occupant’s comfort was compromised by the desire to provide impressive guest facilities in homes. Good client briefing on design priorities and their impact on comfort and energy use is needed and the benefits of, for instance, smaller and fewer windows and good orientation promoted. Modification of the external environment of a home by creating an external thermal buffer zone, for example the shading of outdoor areas and walls of a home with trees, showed a positive effect on the energy consumption in the adjacent home. The highest performing homes had higher levels of insulation. Although the energy consumption in the dwellings was not clearly linked to the indoor temperature experienced in them, occupants who pay less per annum were more satisfied with the thermal comfort experienced. Comprehension of what creates and enables comfort to be experienced in the studied dwellings is undeniably a complex phenomenon. While clear connections between the physical condition of the buildings and their services and the indoor thermal environment are evident, however attitudes, social contexts and associated behaviours appear to be leading factors in the recorded occupied temperatures in these homes, and in turn to the everyday comfort, and discomfort, experienced in them.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
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Longitudinal Survey of Adaptive Thermal Comfort of Office Workers in the Hot Humid Climate Zone of Enugu, Nigeria

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Abstract

The aim of this paper is to investigate the acceptable comfort temperature range of office workers in Enugu, Nigeria, in the hot humid climate zone, focusing on adaptation. A longitudinal approach, which surveyed occupants' subjective thermal perception over the dry and the rainy seasons, was adopted for this study. A mixed-mode methodology, combining a quantitative and qualitative methods, was employed in the collection and analysis of data relating to occupants' subjective thermal perception. Both the indoor and outdoor environmental variables were monitored simultaneously throughout the period of the survey in 2014 from the dry season; January to March, and the rainy season; from May to June. The analysis of the thermal performance of the office spaces surveyed found that they were in compliance with the ASHRAE Standard 55-2013 adaptive thermal comfort. The thermal sensation component of the results suggests a neutral temperature of 28.8^{0}C; with 80% thermal satisfaction, in a comfort range of between 25.4^{0}C and 32.2^{0}C. These results were consistent with a number of earlier studies on thermal comfort conducted in other climate zones in Nigeria.

Keywords: Adaptive thermal comfort, hot humid climate zone, Nigeria, neutral temperature and comfort range

1 Introduction

With a population of over 180 million, according 2015 estimate, Nigeria is the most populous country in African and the seventh in the world. According to the United Nations, it is estimated that by 2050, the population of Nigeria will be more than that of the United States (United Nations, 2015). This will put the country as the third most populous country in the world after India and China. Apart from population, Nigeria is also the largest economy in Africa with an annual Gross Domestic Product (GDP) of more than 568 billion US dollars in 2015 (World Bank Group, 2016). The Country's GDP experienced 6.3% growth in 2014. The World Bank Group has also projected an annual growth of 4-6% in GDP for the Country's economy.

An effect of this level of increased population and economic growth has been the demand for more buildings and infrastructural development in Nigeria. Also, the process of building and the running of physical infrastructure requires energy. In Nigeria as elsewhere in Africa this energy need is usually met by electricity. However, according to the Africa Progress Report 2015, more than 90 million Nigerians lack electricity (African Progress Panel, 2015). By way of comparison with other developing economy, Nigeria has nearly double Vietnam's population but generates less than 25% of the electricity that Vietnam does. Furthermore

Nigeria’s main businesses are Small and Medium Enterprises (SMEs), of which more than 80% rely on fuel-powered electricity generators to sustain their business (Scott et al., 2014).

In addition to this pathetic power supply situation, there is also the issue of climate change. Nigeria, as with Africa in general, is experiencing the most damaging effects of climate change (African Progress Panel, 2015). In order to mitigate the impact of climate and to reduce reliance on the poor electricity supply, there is need to focus on more energy efficient ways of designing and constructing buildings. This is especially important since cooling load alone is responsible for about 40% electricity consumption in buildings, especially in office buildings, in Nigeria (Batagarawa et al., 2011). However, in Nigeria; there is no standard energy efficiency code for buildings, nor is there a national thermal comfort standard. The current National Building Code in Nigeria provides guidelines for the design and specification, costing, construction, alteration, addition to, moving, demolition, location, repair and use of any building or structure; but has no reference to either thermal comfort or energy efficiency (Federal Ministry of Housing and Urban Development, 2006).

Some researchers have conducted research work, into thermal comfort in buildings in Nigeria. These include; Adunola (2012); on residential comfort in relation to indoor and outdoor air temperatures in Ibadan. Also Akande and Adebamowo (2010), conducted field research on indoor thermal comfort for residential buildings in Bauchi, in the hot dry climate zone. In another study, Ogbonna and Harris (2008) undertook field studies examining thermal comfort in residential buildings in the temperate climate of Jos. Furthermore, a study of thermal comfort in the urban residential buildings in the warm humid climate of Lagos was undertaken by Adebamowo (2007). These are in addition to the historic research undertaken by Ambler in the warm humid climate of Port Harcourt in the 1950s and the one done by Ojosu et al. in the 1980s (Ambler, 1955; Ojosu et al., 1988). The results from these studies are summarised in Table 1.

Some of the research work has only been carried out for a short period of time and not covering the two seasons usually experienced in Nigeria. This highlights the need for a more comprehensive research focusing on adaption, over at least an annual period, taking into account both the dry and rainy seasons as well as Nigeria’s different climate zones that have not been covered in the existing works. In addition to filling the gaps in the field of adaptive thermal comfort research in Nigeria, this paper also proposes that there should be either the inclusion of adaptive thermal comfort standard in future revision of the National Building Code or the development of a new thermal comfort standard for use in building design and construction.

Table 1: Summary of thermal comfort research done in Nigeria on neutral temperature and acceptable comfort range

Year	Researcher	Location (Climate Zone)	Building	Period (Season)	Key Research Findings
2012	Adunola A. O.	Ibadan (Hot Humid)	Residential	April	1. Regression equation: Y = 0.483*X – 15.59 (TSENS with respect to TOP*) 2. Neutral temp. = 32.3^0C TOP*
2010	Akande & Adebamowo	Bauchi (Hot Dry)	Residential	Dry and Rainy Season	1. Regression equation: Y = 0.357*X – 10.2 (Dry Season) 2. Regression equation: Y = 0.618*X – 15.4 (Rainy Season) 3. Combined neutral temp. = 28.44^0C TOP* 4. Acceptable comfort range = 25.5 – 29.5^0C TOP*
2008	Ogbonna & Harris	Jos (Temperate Dry)	Residential and Classrooms	July & August (Rainy Season)	1. Regression equation: Y = 0.3589*X – 9.4285 2. Neutral temp. = 26.27^0C TOP* 3. Acceptable comfort range = 25.5 – 29.5^0C TOP* (-0.5 ≤ TSENS ≤ +0.5) 4. PMV neutral temp. = 25.06^0C
2007	Adebamowo	Lagos (Warm Humid)	Residential		1. Neutral temp. = 29.09^0C
1988	Ojosu et al	Hot Dry			1. Acceptable comfort zone = 21 – 26^0C
		Temperate Dry			2. Acceptable comfort zone = 18 – 24^0C
		Hot Humid			3. Acceptable comfort zone = 21 – 26^0C
		Warm Humid			4. Acceptable comfort zone = 21 – 26^0C
1955	Ambler H. R.	Port Harcourt (Warm Humid)	Office		1. Neutral temp. = 23.13^0C ET*

Note: *ET* (Effective Temperature), TOP* (Operative Temperature), TSENS (Thermal Sensation Vote)*

2 Methodology

2.1 The Study Area

The field research for this study was conducted in Enugu, a city in the hot humid climate zone of Nigeria. It is located at an altitude of approximately 223m above sea level and it lies between latitudes 5°55'15''N and 7°6'36''N, and longitudes 6°55'39''E and 7°54'26''E. It has an undulating topography with scattered hills and knolls (Reifsnyder et al., 1989; Sanni et al., 2007). It covers an approximate area of about 7,161km^2.

Being in tropical Nigeria, Enugu is hot all year round with a mean daily temperature of 26.7^{0}C (Sanni et al., 2007). The climate of Enugu is humid and the peak of the humidity is experienced between March and November (Reifsnyder et al., 1989). As with the West African geographical land mass, Enugu experiences two major seasons, the rainy and dry seasons. During the dry season months of December and January, the city is also affected by the 'Harmattan', a dust-laden trade wind from the Sahara desert, usually occurring over two to three week period, which can also affect visibility.

2.2 Data Collection

Six typical office spaces were selected for this study—three from the office complex of the Federal Radio Corporation of Nigeria (FRCN) and three from Federal Road Safety Corps (FRSC), Enugu. The surveys were conducted during the dry and rainy seasons in 2014. In order to determine the wide range of environmental conditions that office workers in the climate zone can adapt to, surveys were carried out in office spaces that were both naturally ventilated and others which had mixed-mode[1] ventilation in place. Also, spaces included open plan (OP) offices and enclosed space (ES) offices.

Throughout the period of the field survey conducted during the dry season, from January to March 2014, and during the rainy season; May to June 2014, dataloggers were placed in all the office spaces surveyed to record indoor operative temperature and humidity at 15 minute intervals. The dataloggers were located within 1 meter of each participants' workstation to record the actual thermal conditions being experienced by participants during normal working hours. Dataloggers were also placed outside the buildings to simultaeneously record the corresponding air temperature and humidity of the immediate outdoor environment at the same time intervals as the indoor dataloggers. A Hand-held instrument was used to measure the air speed in the different spaces surveyed at different instances during the study period.

The field study questionnaires were administered in two parts. Part One of the questionnaire was used for the recruitment of participants on a voluntary basis. Paper copies of the first part of the questionnaires were distributed to a self-selected group of participants, who were office workers in both offices of FRCN and FRSC. For the purpose of anonymity, codes were assigned to each participants that completed the first part of the questionnaires. Part One of the questionnaire was only administered during the first stage of the field research, since the information collected from that part of the questionnaire remained unchanged throughout the course of the survey.

[1] Mixed-mode ventilation in this research refers to office spaces that utilises a combination of natural ventilation from operable windows and some form of air-conditioning cooling system

Part Two of the questionnaire was administered in both stages of the field research work using a longitudinal approach. In contrast with a one-off 'point-in-time' assessment, a longitudinal approach that studies the same subject repeatedly over time can yield more comprehensive results (Langevin et al., 2013). Hence, this study adopted the longitudinal approach in administering Part Two of the thermal comfort questionnaires during both stages of the survey. For each day of the survey, three thermal comfort questionnaires were administered to each participant; one in the morning (before 11am), another one at mid-day (between 11am and 1pm), and the last one in the afternoon (after 1pm). This process was repeated for different days throughout the period of the two stages of the survey. Subjective thermal variables collected included: participants' subjective thermal comfort votes (COMF), thermal sensation (TSENS) and thermal preference (TPREF).

3 Analysis and Results

3.1 Participants

At the initial stage of the survey, 47 staff from both FRCN and FRSC were recruited on a voluntary basis for the survey. However, only 38 (approximately 80%) of the initial participants completed the longitudinal survey, for both the dry and rainy seasons. A total of 201 valid responses were obtained during the first stage of the survey. While a total number of 249 valid responses were obtained from participants during the survey. In all, 450[2] valid responses were obtained from the field research work.

Table 2 gives a summary of participants' background information on gender, age and the duration of years they have lived in the hot humid climate conditions of Enugu. During both stages of the survey, there were slightly more female participants (56.7% during the dry season and 54.2% during the rainy season). The majority of the participants (more than 89%) were below 39 year of age. While about half of the participants had lived in the hot humid climate of Enugu for more than 1 year but less than 5 years.

3.2 Comparison Between Indoor and Outdoor Temperature

In order to show the environmental comparison between the indoor and outdoor temperature obtained from the dataloggers a Paired-Samples T test and Bivariate Correlation testing was carried out. The results from these tests are summarised in Table 3. The comparisons of measured indoor and outdoor thermal conditions show that the indoor operative temperature were correlated with the outdoor air temperature. With the exception of the naturally ventilated office spaces where the significance of the correlation between indoor and outdoor air temperature was 0.05, all the mixed-mode ventilated spaces had a correlation significance of 0.01.

3.3 Comparison With ASHRAE Adaptive Comfort

In order to compare the buildings' thermal performances with ASHRAE Standard 55 adaptive comfort, the prevailing daily mean outdoor temperature from the loggers were plotted against the corresponding mean indoor operative temperature for office spaces used for the survey in FRCN and FRSC complexes. As shown in Figure 1 and Figure 2, these were compared with the 80% and 90% acceptable comfort ranges of the ASHRAE Standard 55-2013 adaptive comfort model (ASHRAE, 2013). The results from the comparisons show

[2] A total number of 564 questionnaires were administered during the survey periods. About 20% of the administered questionnaires, which is 114, were either invalid or not returned by participants.

that all the office spaces surveyed comply with the ASHRAE Standard 55 adaptive comfort standard.

Table 2: Summary of respondents' background information

		Total (n=450)		Dry season (n=201)		Rainy season (n=249)	
		Sample size	Percentage	Sample size	Percentage	Sample size	Percentage
Gender	Male	201	44.7	87	43.3%	114	45.8%
	Female	249	55.3	114	56.7%	135	54.2%
Age (years)	19-29	192	42.7	102	50.7%	90	36.1%
	30-39	210	46.7	78	38.8%	132	53.0%
	40-49	24	5.3	15	7.5%	9	3.6%
	50-59	24	5.3	6	3.0%	18	7.2%
Years in Enugu	<1	36	8.0	18	9.0%	18	7.2%
	1-5	207	46.0	99	49.3%	108	43.4%
	6-10	75	16.7	30	14.9%	45	18.1%
	11-15	12	2.7	3	1.5%	9	3.6%
	>15	90	20.0	39	19.4%	51	20.5%
	Missing	30	6.7	12	6.0%	18	7.2%

Table 3: Paired-Samples T Test and Bivariate Correlations testing between indoor operative temperature and outdoor temperature

	Office Spaces						
	Combined	A	B	C	Da	Db	Dc
Sample Size	450	72	168	57	51	39	63
Mean Indoor Temperature (^{0}C)	28.5	27.8	28.0	29.5	28.9	29.4	28.7
Mean Outdoor Temperature (^{0}C)	33.2	33.3	33.1	33.3	33.0	33.4	33.1
Differences in Mean	-4.7	-5.5	-5.1	-3.8	-4.1	-4.0	-4.4
Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pearson Correlations	0.520	0.502	0.680	0.774	0.577	0.397	0.253
Correlations Sig.	0.000	0.000	0.000	0.000	0.000	0.012	0.046

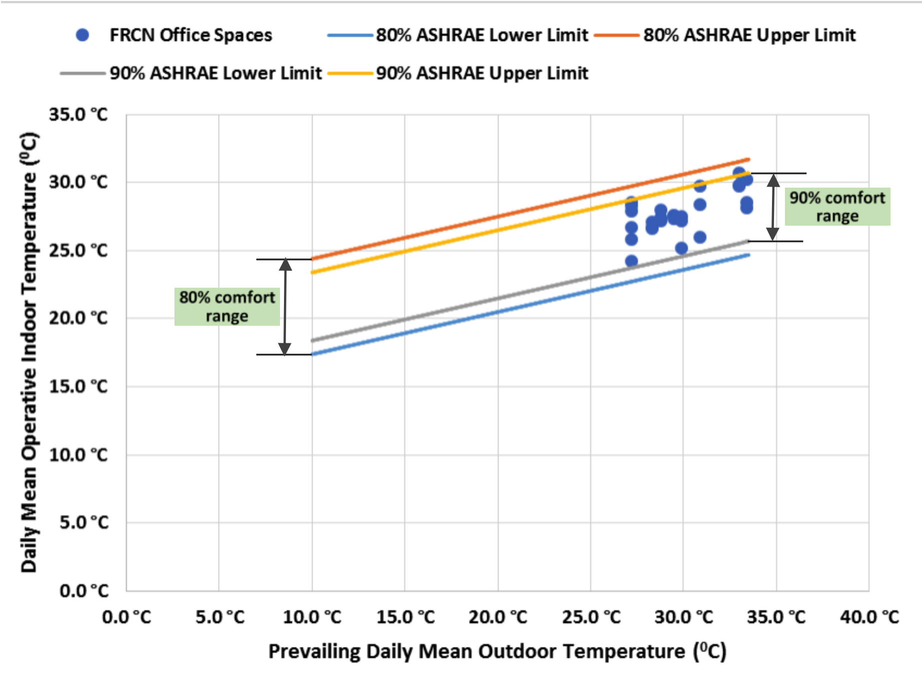

Figure 1: Daily mean indoor operative temperature for Office Spaces in FRCN Complex plotted against the prevailing mean outdoor temperature and overlaid with the adaptive model of ASHRAE Standard 55-2013

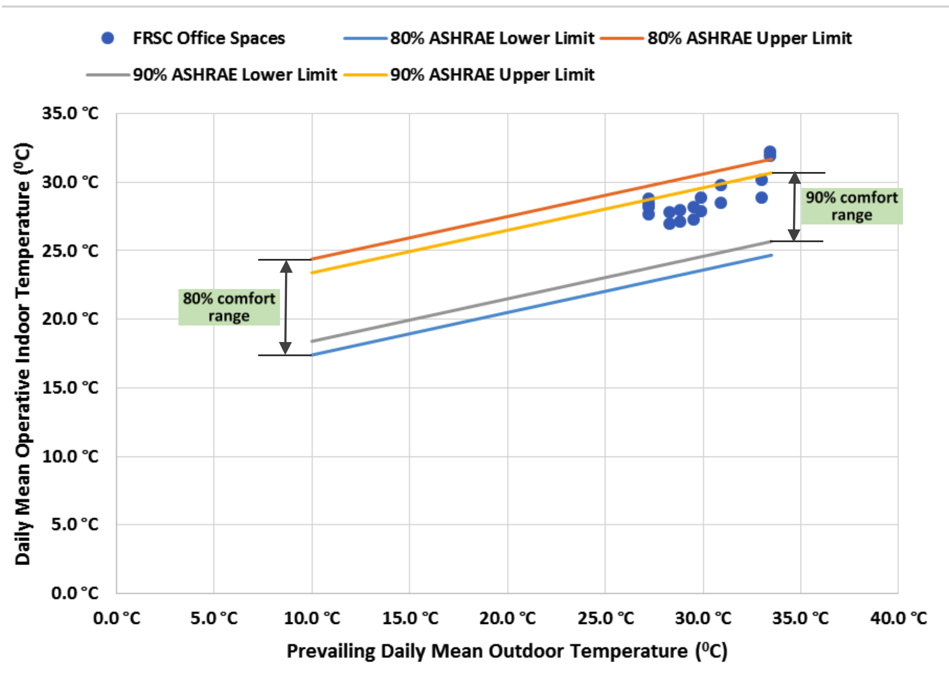

Figure 2: Daily mean indoor operative temperature for Office Spaces in FRSC Complex plotted against the prevailing mean outdoor temperature and overlaid with the adaptive model of ASHRAE Standard 55-2013

3.4 Neutral temperature and comfort range

The questionnaire adopted the ASHRAE seven-point thermal sensation scale (-3 = Cold, -2 = Cool, -1 = Slightly cool, 0 = Neutral, 1 = Slightly warm, 2 = Warm, 3 = Hot). Participants were allowed to select all the options that apply and the resulting mean from options selected was used to determine the participants vote. The mean TSENS vote for all participants in the survey was slightly below "Neutral", between "Slightly cool" and "Neutral" with a value of -0.08.

In order to determine the neutral temperature and comfort range, a linear regression analysis of thermal sensation was carried out with respect to weighted indoor operative temperature using SPSS software package. The resulting linear regression models was fitted according to the format as shown in Equation 1. Table 4 is the summary of the linear regression analysis of thermal sensation on weighted operative temperature.

$$Y = m*X + b \qquad (1)$$

Where,

m is coefficient or gradient

b is constant

Y is mean thermal sensation

X is operative temperature

The approach employed in ASHRAE adaptive comfort standard was used to define the indoor operative comfort range, it defines the 80% operative comfort range as -0.85≤TSENS≤+0.85 (de Dear and Brager, 1998). This corresponds to approximately 80% thermal satisfaction, where Predicted Percentages Dissatisfied (PPD) is less than 20%. The neutral temperature corresponding to TSENS value equalling "0" was also calculated.

As shown in Table 4, the linear regression for the mean TSENS on weighted indoor operative temperature resulted to the equation: Y = 0.250*X – 7.197 with a correlation coefficient of 0.245 and a p-value of 0.000 (less than 0.05). This equation yielded a subject neutral temperature of 28.8^{0}C and comfort range (TSENS between -0.85 and +0.85) of between 25.4^{0}C and 32.2^{0}C. The gradient of the linear regression which is represented as "m" in Equation 1, indicates how much the thermal sensation (TSENS) changes with each operative temperature unit.

Table 4: Summary of thermal sensation votes responding on weighted indoor operative temperature

Sample size (n)	Comfort Range -0.85≤TSENS≤+0.85 (^{0}C)	Regression Equation	Pearson correlations	P-value
450	25.4 – 32.2	Y = 0.250*X-7.197	0.245	0.000

4 Discussion

The adaptive model relates the indoor neutral temperature to the monthly outdoor mean temperature. The results of the comparison of indoor and outdoor temperature as shown in Table 3, shows a strong correlation between indoor and outdoor temperature conditions. The relationship also shows statistical significance, at a value of 0.01. Also, the results of the comparison with the ASHRAE adaptive comfort chart also shows that office spaces surveyed comply with the adaptive component of ASHRAE Standard 55-2013.

The neutral temperature of 28.8^{0}C obtained from this study is outside the comfort range of the results of Ojosu et al (1988), which predicted a PMV comfort range of 21–26^{0}C for the climate zone. However, it is more consistent with some more recent studies, such as those of Akande and Adebamowo (2010) in the hot dry region, northern Nigerian city of Bauchi which is 28.44^{0}C. The neutral temperature is also slightly closer to the 29.09^{0}C obtained by Adebamowo (2007) in the southern city of Lagos in the the warm humid climate zone. While it is within the 90% comfort range of the works of Ogbonna and Harris (2008), which was carried out in the city of Jos in the temperate dry zone; the neutral temperature is slightly higher than the 26.7^{0}C obtained. Taking into consideration the characteristic of the city of Enugu's hot humid climate zone where this study was carried out in comparison with the temperate dry zone where Ogbonna and Harris carried out their studies, there is a clear indication that there is little or no disparity in the thermal neutralities obtained.

Apart from the climate zone of study location, other factors that might account for the little disparity in thermal neutrality of this study with some of the selected previous works done in Nigeria might be time and duration of study, methodology used or accuracy of reading of equipment used. For example, the result obtained from work carried out in another hot humid climate zone of Ibadan by Adunola (2012), yielded a thermal neutrality of 32.3^{0}C. This result is much higher than the 28.8^{0}C obtained from this study. The neutral temperature is also outside the 80% comfort limits ($-0.85 \leq TSENS \leq +0.85$) of 25.4^{0}C – 32.2^{0}C obtained from this study. Several factors might account for this disparity. Compared with this study which was carried out in office buildings, the work of Adunola was done in residential buildings. Also, in contrast with this work that was done in both the rainy and dry seasons, Adunola's work was carried out during the month of April only. Another important factor to highlight is that, this study also adopted a longitudinal approach instead of the traditional one-off 'point-in-time' assessment.

In summary, the comparison of the results obtained from this study with other similar works carried out in the different climate zones in Nigeria suggest that occupants of naturally ventilated buildings are more adaptable to a much warmer temperature than those specified in International Standard such as the ISO 7730. The observation and semi-structured interviews components of the survey further revealed the different actions that participants took in order to adapt to the thermal conditions surrounding their work places. This included: clothing adjustment (Efeoma and Uduku, 2015), the opening of doors and windows, taking a walk and turning fans on or off depending on the weather condition. Adaptive thermal comfort therefore is certainly becoming a better standard for the assessment of thermal comfort in the tropical climate of Nigeria. It is also a possible solution to achieving sustainable design that will enable building designers to combat the impact of climate change and to cope with the poor electricity supply situation being experienced in Nigeria. This is my view will help to reduce reliance on the Country's epileptic power supply and to free up money that could have been used for the installation, maintenance and running of mechanical cooling devices in the design and construction of buildings.

5 Conclusion and Recommendations

The results and analysis from this study clearly showed that the ASHRAE adaptive comfort is certainly applicable to the different climate zones of Nigeria, especially the hot humid climate zone where this research work was carried out. In view of the poor electricity situation currently being experienced in Nigeria; the adaptive comfort appears to be a possible solution to the design and construction of buildings in Nigeria. This will no doubt reduce reliance on mechanical cooling systems that require constant electricity supply to run effectively. In turn, reliance on backup generators, which are currently the main source of power supply in Nigeria today can be reduced significantly, if buildings are better able to adopt passive means of cooling and take into account local adaptive thermal comfort levels, which give more realistic comfort tolerances amongst populations than other international standards.

In view of the findings from this field study and associated research; the inclusion of adaptive thermal comfort assessments in future revisions of the Nigeria Building Code, would be justified in order to improve comfort standards and reduce reliance on energy-hungry mechanical cooling systems. Also, there is the need for the development of a local adaptive thermal comfort standards that respond better to the different climate zones in Nigeria.

Finally this study also recommends that future studies should include specific investigation of the relationship of clothing and air velocity to the subjective thermal perception of the environmental conditions experienced by local residents of different climate zones in Nigeria.

Acknowledgements

The authors would like to thank the United Kingdom Commonwealth Scholarship Commission for funding this research work. Also, they are also grateful to both the management of FRCN and FRSC for their approval to use their office complexes for the survey and respondents who participated in this study.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
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Thermal comfort studies of primary school students in Tangerang, Indonesia

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Abstract
A thermal comfort study has been conducted in two primary schools in Tangerang, West Java, Indonesia. The first school was a state school with all of its classrooms were naturally ventilated (NV). The second one was a private school with its classrooms was air conditioned (AC). Climatic parameters, i.e. air and globe temperatures, relative humidity and air velocity were recorded along with the seven-scale subjects' comfort vote. There were 501 pupils in the state school, consists of 252 males and 249 females involved in this study, while in the private school 207 pupils involved in this study, consists of 125 males and 82 females. Subjects were between 8 and 13 years old in the state school and 9 and 13 years old in the private school. Subjects' comfort temperature in the NV state school was about 1.5 °C higher than comfort temperature of subjects in the AC private school. The pupils' comfort temperatures in both schools were higher than the current Indonesian comfort standard. This paper discusses the whole study and draws some conclusions from it.

Keywords: air conditioning (AC), comfort temperature, Indonesia, naturally ventilated (NV), primary school

1 Introduction

A thermal comfort study has been conducted in two primary schools in the town of Tangerang, Indonesia. Tangerang is a medium town located next to the Indonesian capital city of Jakarta at 6° south latitude, This town is in the warm, humid tropical climate, and has two main seasons throughout the year: dry and rainy seasons. Like in most of the other Indonesian towns, the diurnal and annual outdoor temperature variation in Tangerang is very small. There has been almost no temperature difference throughout the year. The monthly average outdoor temperature and daily temperature are about the same throughout the year, which is around 28 °C. During the rainy season, the outdoor temperature tends to be slightly lower by about 1 to 2°C than in the dry season (Indonesia Climate, online, 2015).

The study was conducted in two primary schools, the one which is naturally ventilated (NV) is belonged to the government and the other, which is air conditioned (AC) belongs to a private institution. Not all the state schools are naturally ventilated, neither all the private schools are air conditioned. However, on average, the private primary schools tend to be air conditioned, while most of the state primary schools are naturally ventilated. In this private school, the split-unit AC system was used in every classroom and also in the school offices. The AC units started to turn on at about 6.15 am, just about 15 minutes before the class begins at 6.30. The units were turned off soon after the class end at about 3 pm.

There might be some small socioeconomic backgrounds between pupils in the state and private schools. However, there was no further investigation in this study whether or not pupils were using AC in their homes. In terms of socioeconomic backgrounds, on average, pupils in the private school have a better economical background than those in the state school. Entering the state schools is free, while it does not apply to private schools, in which pupils must pay. Therefore, on average, pupils in the private school tend to come from rich families, although the gap might be not so big. Some good students tend to go to the state schools as they are free and the schools' qualifications tend to be higher than in the private ones. Since these two schools were closely located, only separated about 200m, pupils from both schools tend to live side by side.

In the Indonesian educational system, a primary school has six grades; started from grade one and ended at grade six. In some established and good schools, pupils start their first grade at the age of 7 or 6.5 years old; however, most of ordinary school pupils can start their first grade at the age of 6 or even 5 and can be at 8 years old. So, they finish their study at the age of between 11 and 13 years. Following the primary school, pupils will continue their studies for three years in the secondary school and another three years in the high school. This study intends to select the subjects of pupils in the primary schools, from grade four and above, therefore, pupils participated in this study were between 8 and 13 years old.

A number of thermal comfort studies have been conducted in the primary schools (Humphreys, 1977; Teli, et al, 2012; Wong, 2003), however, there has been no report on thermal comfort study of young people, involving school pupils in Indonesia. About 9% of the Indonesian population are those in the age of between 5 and 14 years old (Index Mundi, 2015), and most of them are primary school pupils who also need to be thermally comfortable when engaging their school activities in the classrooms. An Indonesian comfort standard based on the SNI 6390:2011 (BSN, 2011) states a comfort range for adults who work mainly in the office building. Having no thermal comfort studies of people in younger age in this country, this study is an attempt to see whether the young people aged between 8 and 13 may have a similar comfort temperature such as adult people.

To answer this kind of curiosity, two primary schools, which are separated about 200 meters, are selected for thermal comfort studies. The first primary school is a state-own school, with all of the classrooms were naturally ventilated, with a small fan attached to the wall above the open windows in every classroom. The second primary school is a private-own school, with every classroom had one split-unit air conditioner (AC), attached to the wall above the closed windows. There was also a ceiling fan provided in every classroom in this private school.

In terms of the number of subjects, there were 501 pupils in the state school, consisting of 252 males and 249 females aged between 8 and 13 years old involved in this study, while in the private school there were 207 pupils, consisting of 124 males and 83 females, aged between 9 and 13 years old participated in this study.

Figure 1 shows the state primary school buildings. The buildings are single floors with tile pitch roofs. There are verandas at the front of the classroom used as corridors to access to the classrooms. The buildings were naturally ventilated, having high-level windows on the corridor sides and low-level windows on the opposite walls.

Figure 1 Tangerang state's primary school

Figure 2 shows the private primary school building. The building consisted of four floors with its top level was used as an auditorium. The building was air conditioned with a minimum cooling, aimed to minimize the use of electricity energy, creating the indoor temperatures not quite low, about 27.8 ^{o}C on average.

Figure 2 Private primary school buildings

The basic reasons for comparing these two school buildings is, firstly, these two schools were located closely in the same area with about 200 m away between each other; secondly, they had a different rooms' cooling systems, one was naturally ventilated and the other was air conditioned. The thing to be investigated is whether subjects, with similar ages, participating in this comfort study would have different comfort temperatures due to the different cooling systems in the classrooms; one was naturally ventilated and the second was air conditioned.

A number of thermal comfort studies showed that comfort temperatures of subjects in NV buildings tended to be higher than subjects in AC buildings. Yang and Zhang's comfort study (Yang et al, 2008) showed that subjects in the NV buildings felt comfortable at 28.3 °C, while those in the AC buildings were comfortable at 27.7 °C, which is about 0.6 degrees lower. A comfort study by de Dear, et al in Singapore (de Dear et all, 1991) showed that subjects in the NV buildings were comfortable at 28.5 °C T_o, while subjects in the AC buildings were comfortable at a lower temperature of 24.2 °C T_o. Busch (Busch, 1990) has done a comfort study in Bangkok, Thailand, showed that subjects in NV buildings were comfortable at 28.5 °C effective temperature (*ET*), which was higher than the subjects in AC buildings who were comfortable at 24.5 °C *ET*.

A comfort study by Karyono (Karyono, et al, 2015) involving students from two different universities in Jakarta showed that students having full AC in their homes tend to have a lower comfort temperature than those homes were not air conditioned. It seems that people tend to adapt to their surrounding thermal environment. Karyono's study (Karyono, 1996) showed that, on average, people live in the warm and humid tropical climate in South East Asia countries have a higher comfort temperature than people live in the temperate regions. The long exposure to the high temperatures in the tropics tends to raise comfort temperatures of people in these regions. A comfort study done by De Vecchi, et al showed that subjects being exposed to AC were more intolerable with the higher temperatures compared to those unexposed (De Vecchi, et al). de Dear and Brager develops the adaptive ASHRAE comfort standard by reanalyzing data on thermal comfort studies across the world (de Dear, et al, 1997; Brager, et al, 2001) showed that comfort temperatures tend to have a correlation with the average monthly temperature at any given location. It was found that, the higher the average running mean temperature experienced by a person, the higher the comfort temperature would be for this person (Nicol, et al, 2012).

2 Methodology

There were 501 pupils in the state school, consists of 252 males and 249 females ages between 8 and 13 years old involved in this study, while in the private school there were 207 pupils, consists of 124 males and 83 females, ages between 9 and 13 years old participated in this study.

Subjects were asked to give their personal data such as age, weight and height, and their thermal sensations votes (*TSVs*) based on the ASHRAE (ASHRAE, 2010) seven-point thermal sensation scale [19]: Cold (−3), Cool (−2), Slightly cool (−1), Comfort (0), Slightly warm (+1), Warm (+2) and Hot (+3). All the questions were written on the questionnaire sheets, using the Indonesian language. The ASHRAE seven-point scale was translated carefully to this language to have the same thermal meaning. A similar seven-point scale's translation has been used many times in the thermal comfort studies carried out in this country. In terms of '0' category, it's described as 'comfort' not 'neutral' as it usually did to ask adult subjects in some thermal comfort investigations. The word 'neutral' was avoided to be used in this study as the central category in the thermal sensation choices as we suspect the pupils would not understand the meaning. The word 'comfort' was used instead, assuming that this would be easier to be understood by the pupils. Pupils filled in the questionnaire by themselves independently.

There were short of instruction given to the pupils in both of the schools before the investigation took place in every classroom. The researchers introduced briefly about the purpose of the research and the way to fill in the questionnaire sheets. Pupils were instructed to fill in the questionnaire independently based on their own thermal sensation feeling. This study involved pupils who were already in the grade 4, 5 and 6, not in the lower grades. The reason was, pupils in the upper grades might have more understanding and more awareness about their thermal sensation occurred in their immediate environment than those in the lower grades. In terms of the ability to read the text, in the Indonesian educational system, starting in grade 2 pupils should be able to read a rather complex text like a newspaper. So, the reason not to involve pupils in the lower grades in this study was not related to this matter. During the investigation, the researchers were easily supervising the pupils to answer the questions independently since there were only three to five pupils in a group. While pupils filled in the questionnaires, some climatic parameters were recorded: air temperature (T_a), globe temperature (T_g), relative humidity (*RH*) and air velocity (V_a).

The air temperature was recorded using an alcohol thermometer (resolution 0.1°C), the globe temperature was recorded with a 15cm-diameter globe thermometer of thin-walled coppersphere painted black (resolution 0.1°C), the relative humidity (*RH*) was recorded with DEKKO 642 Digital Thermo-Hygro Meter (resolution 0.1%) and the air velocity was measured by a digital anemometer SANVIX GM8908 (resolution 0.1m/s). The anemometer, thermometer and the thermo-hygrometer were checked for calibration by using similar laboratory equipment.

Figure 3 shows the atmosphere of the measurement in the state primary school, while Figure 4 shows the atmosphere of the measurement in the private primary school. Since all the pupils were sitting during the investigation, and due to the limitation of spaces, the probes were mounted on the tables, about 70 cm above the floor, which did not fulfil compliance with ISO 7726, which requires 0,10 m, 0,60 m, 1,10 m for a seated person (ISO 7726, 1998).

Figure 3 Atmosphere of the measurement in the state primary school

Measurements were taken mostly during the rest hours when the pupils had no formal lectures. Pupils were seated in a group of three to five, when the measurements were taken. The measurements were repeated in different time with similar subjects. Therefore, most of the pupils had voted twice during the investigation. All the measurements took place between September and November 2014, between 8am and 2pm. All the data were tabulated and analysed by Microsoft Office Excel 2007, while the statistical tests were done with Statistical Package for the Social Sciences (SPSS) version 17.

Figure 4 Atmosphere of the measurement in the private primary school

3 Data and Analyses

3.1 Data on Participants

Subjects were primary school pupils with their school uniforms and engaging light activities in the classrooms. Table 1 shows the statistical data of subjects participating in this study. In the state primary school, subjects were between 8 and 13 years old, with an average of 10.4 years and SD of 0.8 years. In terms of height, only 301 out 501 subjects indicated their heights. The shortest subject was 110 cm and the tallest was 165 cm with an average of 138.6 cm and standard deviation (SD) of 10 cm. In terms of weight, only 350 out of 501 subjects indicated their weights. Subjects' weights were between 20 and 65 kg with an average of 32.8 kg and SD of 7.5 kg. The estimated clothing insulation of the subjects, wearing their school uniforms, were between 0.26–0.44 clo.

Table 1 Data of the subjects in the state and private primary schools.

Type of School	Gender		Descriptive statistic	Age (years)	Height (cm)	Weight (kg)	Estimated clothing value (clo)
	Male	Female					
State Primary School	252	249	n	501	301	350	0.26-0.44
			Min	8	110	20	
			Mean	10.4	138.6	32.8	
			Max	13	165	65	
			SD	0.8	10	7.5	
Private Primary School	124	83	n	207	151	196	0.26-0.44
			Min	9	120	20	
			Mean	9.8	141.2	31.4	
			Max	13	165	69	
			SD	0.8	9.9	5.9	

In the private primary school, subjects were between 9 and 13 years old, with an average of 9.8 years and SD of 0.8 years In terms of height, only 151 out of 207 subjects indicated their heights. The shortest subject was 120 cm and the tallest was 165 cm with an average of 141.2 cm and standard deviation (SD) of 9.9 cm. In terms of weight, only 196 out of 207 subjects indicated their weights. Subjects' weights were between 20 and 69 kg with an average of 31.4 kg and SD of 5.9 kg. The estimated clothing insulation of the subjects, wearing their school uniforms, were between 0.26–0.44 clo.

3.2 Data of Indoor Climatic Parameters and the distribution of subjects' Thermal Sensation Vote

Table 2 shows data of indoor climate, while Table 3 shows the distribution of the thermal sensation vote (*TSV*) in the state and private primary schools. In the state primary school, the measured indoor air temperatures were between 28 and 34.7 °C with an average of 32.3 °C and SD of 1.7 °C. The globe temperatures were between 28 and 34.8 °C with an average of 32.2 °C and SD of 1.7 °C. Both in the state and private schools, the air and globe temperatures tend to be identical. This is a reflection of the small variation of outdoor temperature in the warm and tropical climate such as Indonesia, and due to the small difference between the indoor temperature of the classrooms and the outdoor temperatures of the surrounding building.

The indoor *RH* ranged between 55 and 83% with an average of 65.7% and SD of 8%. Measured by an anemometer, the air velocities were between 0 and 0.4 m/s with an average of 0.01 m/s and SD of 0.05 m/s. In the humid and tropical climate such as Tangerang, air movement is very low and tend to be still in the indoor environment. Only in some spots of measurements which were close to the fan, the air movements reached the highest speed about 0.4 m/s, while in many spots away from the fan, the air movements were still (V_a = 0 m/s).

Table 2 Data of indoor climatic parameters in the state and private primary schools

Type of School	Descriptive statistic	Air temp (°C)	Globe temp (°C)	RH (%)	Air velocity (m/s)
State Primary School	Min	28	28	55	0
	Mean	32.3	32.2	65.7	0.01
	Max	34.7	34.8	83	0.4
	SD	1.7	1.7	8.0	0.05
Private Primary School	Min	24.4	24.5	53	0
	Mean	27.8	28	66.9	0.1
	Max	30.8	31	81	0.4
	SD	1.8	1.9	8.1	0.1

Table 3 *TSV* distributions in the state and private primary schools

Type of School	No of Subject	−3 Cold	−2 Cool	−1 Slightly cool	0 Comfort	+1 Slightly warm	+2 Warm	+3 Hot	Mean vote
State Primary School	501	0	6	19	46	138	229	63	1.5
Private Primary School	207	0	23	19	28	69	53	15	0.7

Figure 5 shows the atmosphere of the classroom at the state primary school. A single fan is attached above the window of the classroom. Figure 6 shows the atmosphere of the classroom at the private primary school where a ceiling fan is provided, including a single split AC unit attached above the windows.

Figure 5 A single fan is attached above the window in the state school's classroom

Subjects' thermal votes were distributed in such a way in which out of 501 respondents, 46 (9.2%) were neutral, 430 respondents (85.8%) voted in the warm and hot sides and only 25 (5%) were in the cool sides. The mean vote was 1.5, which means, on average, subjects were felt uncomfortably warm.

In the private primary school, the measured indoor air temperatures were between 24.4 and 30.8 °C with an average of 27.8 °C and SD of 1.8 °C. The globe temperatures were between 24.5 and 31 °C with an average of 28 °C and SD of 1.9 °C. The indoor *RH* ranged between 53 and 81% with an average of 66.9% and SD of 8.1%. Measured by an anemometer, the air velocities were between 0 and 0.4 m/s with an average of 0.1 m/s and SD of 0.1 m/s. About at the centre of the classroom below the ceiling fan, the air movements reached the highest speed about 0.4 m/s, while in many spots away from the fan, the air movements were still (Va = 0 m/s).

Figure 6 A ceiling fan is provided in the private school classroom, including a single unit of AC split.

Subjects' thermal votes were distributed in such a way in which 28 respondents (13.5%) were neutral, 137 respondents (66.2%) voted in the warm and hot sides and only 42 respondents (20.3%) were in the cool sides. The mean vote was 0.7, which means, on average, subjects were felt toward a slightly warm.

3.3 Comfort temperature and comfort range in the State Primary School

To find out the neutral temperature and comfort range of the subjects, linear regression analyses were conducted by using Microsoft Office Excel 2007, while the statistical test were analysed by SPSS version 17. Comfort temperature is defined as a temperature where the *TSV* is zero, while a comfort range is defined as a range of temperatures where the *TSV* is between -0.5 and +0.5 (Fanger, 1970). When the comfort temperature is achieved, it's expected that about 95% of the subjects are comfortable, while within the comfort range, about 90% of subjects would be comfortable (Fanger, 1970).

Figure 7 shows the regression line of thermal sensation votes (*TSV*) on air temperature (T_a) in the state primary school. This regression produces an equation of $TSV = 0.375T_a - 10.575$, with a coefficient of determination (R^2) of 0.37. The correlation between *TSV* and T_a is significant (p<0.01). This has produced a neutral temperature of subjects as 28.2 ^oC and subjects comfort range of between 26.9 and 29.5 ^oC.

Analysing the regression line of thermal sensation votes (*TSV*) on globe temperature (T_g) of the state primary school (SPS), it produces an equation of $TSV = 0.386Tg - 10.928$, with a coefficient of determination (R^2) of 0.37. The correlation between TSV and T_a is significant (p<0.01). This has produced a neutral temperature of subjects as 28.2 ^oC and subjects comfort range of between 27.0 and 29.6 ^oC. The result was almost identical to the air temperature, therefore the regression graphic is not provided in this paper.

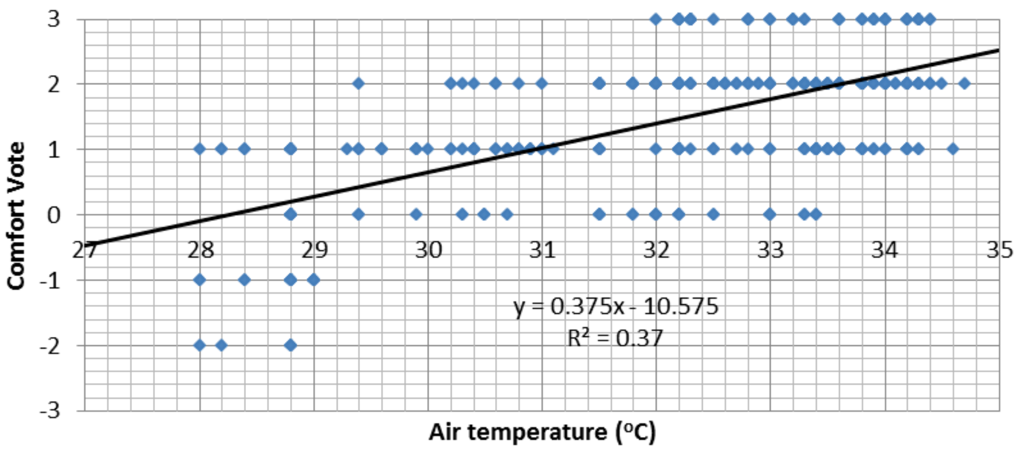

Figure 7 Regression line of thermal sensation vote on air temperature in the state primary school

3.4 Neutral Temperature and Comfort Range of Subjects in the Private Primary School

Figure 8 shows the regression line of thermal sensation votes (*TSV*) on air temperature (T_a) in the private primary school. This regression produces an equation of $TSV = 0.576Ta - 15.282$, with a coefficient of determination (R^2) of 0.54. The correlation between TSV and T_a is significant (p<0.01). This has produced a neutral temperature of subjects as 26.7 ^oC and subjects comfort range of between 25.7 and 27.4 ^oC.

Analysing the regression line of thermal sensation votes (*TSV*) on globe temperature (T_g) of the private primary school. This regression produces an equation of $TSV = 0.539T_g - 14.338$, with a coefficient of determination (R^2) of 0.52. The correlation between TSV and T_a is significant (p<0.01). This has produced a neutral temperature of subjects as 26.6 ^oC and subjects comfort range of between 25.7 and 27.5 ^oC. The result was almost identical to the air temperature, therefore the regression graphic is not provided in this paper.

Table 4 shows the neutral temperatures, comfort ranges, regression equations and the R^2 values of of the study in the state and private primary schools

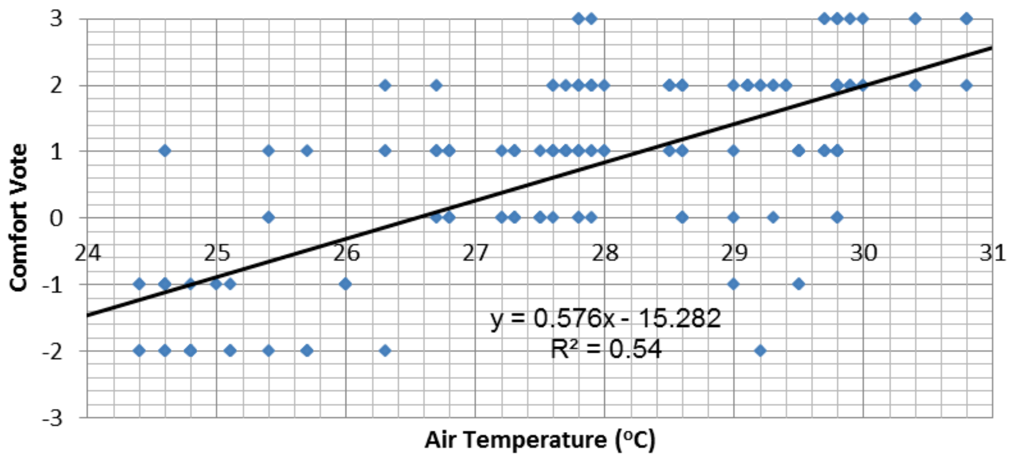

Figure 8 Regression line of thermal sensation vote on air temperature in the private primary school

3.5 Neutral Temperature and Comfort Range of Subjects in the State and Private Primary School

Table 4 shows the subjects' comfort temperature and comfort range in the state and private schools. In terms of air temperature, subjects in the state school were comfortable at 28.2 °C, which was about 1.5 °C higher than subjects' comfort temperature in the private school, which were comfortable at 26.7 °C. The difference was significant ($p<0.01$). In terms of globe temperature, subjects in the state school were comfortable at 28.2 °C, which was about 1.7 °C higher than subjects' comfort temperature in the private school, which were comfortable at 26.6 °C. The difference was significant ($p<0.01$).

The comfort temperatures of both pupils in the state and private schools are about 1 to 2.5 °C higher than the current Indonesian comfort standard based on the SNI 6390:2011 (BSN, 2011), which states a comfort temperature of 25.5 °C with a range of $\pm$ 1.5 °C.

Comparing this study with a previous comfort study in the NV buildings in Jakarta (Karyono et al, 2015) with a similar prevailing outdoor temperature, the comfort temperature of subjects in the NV schools was slightly lower. The previous study shows that subjects with the NV buildings (Cathedral, museum and market) were comfortable at 27.7 and 27.3 °C (Karyono et al, 2015), which were about 0.5 to 0.9 °C lower than in the NV school.

Wong et al study in Singapore showed that the neutral temperature of the pupils in the NV classrooms was 28.8 °C, which was relatively close to the comfort temperature of the Indonesian pupils in the state NV buildings (Wong et al, 2003). Kwok et al study in Hawaii showed that pupils in the NV buildings were comfortable at 26.8 °C, while in the AC buildings was 27.4 °C. Hawaii's study showed an opposite result with the Indonesian study, in which pupils in the Indonesian state NV schools were more comfortable at a higher temperature than in the private AC schools (Kwok et al, 1998). de Dear et al found the neutral temperature of Australian school students aged 10 to 18 years were about 22.5 °C operative temperature (de Dear et al, 2014), which was lower than the comfort temperature of the Indonesian pupils in this study.

In this study, the R^2 of *TSV* in both air and globe temperatures were lower in the state school than in the private school. The spread of the subjects' comfort range was wider in the state school than in the private one. The range was about 2.6 ^{o}C in the state school while in the private school was narrower, about 1.7 ^{o}C. This figure shows that there was a larger variation in thermal responses in the state school than in the private school. The low R^2 in the state school also gives the same indication that the pupils' thermal responses had larger variation.

This has been indicated in the thermal comfort study by Teli et al in the UK primary school (Teli, et al, 2012) that even when the average assessed thermal sensation were neutral, slightly warm or slightly cool, there were a number of pupils who gave a more extreme evaluation, such as voting within (-3,-2) or (+2, +3).

The lower the R^2 and the wider the spread of comfort temperature in the state school than in the private school could be a matter of adaptation, in which subjects in the NV buildings tend to be more tolerable and adaptable to the changing of their thermal environment.

Table 4 Neutral temperature (T_n) and comfort range (T_{cr}) in the state and private primary schools

	Climatic parameters	**Comfort temp (^{o}C) (T_c $\pm$ 95% comfortable)**	**Comfort range (^{o}C) (T_{cr}, $\pm$ 90% comfortable)**	**Regression equation**	**Coefficient of determination /correlation (R^2/ r)**	**Significance**
State Primary School	Air Temperature	28.2	26.9 to 29.5	$TSV = 0.375T_a - 10.575$	0.37/ 0.61	p<0.01
	Globe Temperature	28.3	27.0 to 29.6	$TSV = 0.386T_g - 10.928$	0.37/ 0.61	p<0.01
Private Primary School	Air Temperature	26.7	25.7 to 27.4	$TSV = 0.576T_a - 15.282$	0.54/ 0.73	p<0.01
	Globe Temperature	26.6	25.7 – 27.5	$TSV = 0.539T_g - 14.338$	0.52/ 0.72	p<0.01

4 Conclusions

Thermal comfort study in the two primary schools in the town of Tangerang, Indonesia has shown that pupils aged between 8 and 13 years in the state NV school have a higher comfort temperature than pupils in the private primary school. In terms of air temperature, the state school pupils were comfortable at 28.2 ^{o}CT_a, which was about 1.5 ^{o}C higher than pupils in the private school, which were comfortable at 26.7 ^{o}CT_a. The difference was significant at 95% confidence level. In terms of globe temperature, subjects in the state school were comfortable at about 1.7 ^{o}C higher than subjects' comfort temperature in the private school. Subjects' comfort temperature in the state school was 28.2 ^{o}CT_g, while in the private school subjects were comfortable at 26.6 ^{o}CT_g. The difference was significant (p<0.01). The comfort temperatures of the pupils both in the state and private schools were about 1 to 2.5 ^{o}C higher than the Indonesian comfort standard.

The comfort temperature and comfort range both in the air and globe temperatures are practically identical. In the warm and humid tropical climate, the daily, monthly and annual outdoor temperature variations are very small. This tends to create a small difference between air temperature and globe temperature in a number of investigations, such as in this study.

Acknowledgments

The authors would like to thank all the pupils who participated in this study voluntarily and also the teachers who gave the permission to conduct this study in their classrooms.

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Improving thermal comfort using cost-effective passive strategies Lessons from a single-floor detached dwelling in Nicaragua

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Abstract

About 40% of the world population lives in the tropics. This region represents the highest urban growing potential few decades from now; therefore, building energy efficiency would be a key strategy from a global energy perspective. Building techniques used today in most developing countries situated in this region are associated with high-energy consumption and lack of thermal comfort due to the absence of energy policy framework for buildings. In this context, this study intends to improve thermal comfort of dwellings in Nicaragua using cost-effective passive strategies. To achieve this goal, a representative house of Nicaragua is studied through a parametric analysis using Energy plus V8.2 and MatlabR2014. Solar absorptance and thermal transmittance of the opaque envelope, as well as the solar heat gain coefficient are the variables selected to be analyzed. Discomfort hours based on the adaptive comfort model are used as performance indicator. Results indicate that the main variables affecting thermal comfort are associated with the roof and glazed areas. The solely implementation of a roof solar absorptance equal to 0.3, a Roof U-value equal or less than 2W/m^2-K and a solar heat gain coefficient equal or less than 0.4, allows reaching comfort 80% of the time within 80% Acceptability limits. This work is a step towards wider researches and may significantly contribute to guidelines and regulations, particularly in developing countries with cooling dominated climates.

Keywords: Parametric analysis, thermal comfort, adaptive model.

1 Introduction

Building techniques used today in developing countries are associated with high-energy consumption and lack of thermal comfort due to the absence of energy policy framework for buildings (Liu et al. 2010; Janda 2009). Those countries area mainly situated in the tropical region, that plays a critical role in the global energy panorama due to its rapid population growth (PNUD 2012). Giving this situation, the definition of cost-effective passive strategies for hot climates becomes crucial; however, it is a complex task due to the interaction between several independent variables influencing thermal behaviour of buildings.

In such a context, building energy simulation tools help understanding the complex interrelation between design decisions and performance parameters allowing the identification of potential problems and the appropriate design solutions in a reduce time and cost (Clarke 2001). Those tools have continuously evolved and matured during the last 50 years (Clarke 1989; Malkawi, Ali;Augenbroe 2003; Crawley et al. 2008). In spite of that, their potential have rarely been harnessed because their use have been mostly restricted for code compliance checking and thermal load calculations for sizing HVAC equipment (Hensen 2004).

In order to overcome this situation, new approaches combining computer programming and parametric simulation methods have emerged in the last decades (Nguyen et al. 2014). Those methods allow the analysis of several parameters simultaneously through numerical sequences achieving solutions near the optimum according to pre-established criteria. The application of those methods has proven great potential in order to define predictive-based and performance-based requirements for building energy efficiency programs (Crawley 2008; ADEREE UNEP/GEF 2011).

In Latin-American countries, there are also efforts to find suitable solutions for thermal performance enhancement using parametric simulation (Westphal et al. 2011; Silveira & Labaki 2012).However, any of those studies are conducted in the context of Central America, where prevails a lack of building thermal regulations.

Against this background, this paper intends to apply robust and proven methods of thermal analysis based on simulation and automation in order to enhance the thermal performance of residential typologies in Nicaragua, taking into account different climatic conditions.

The context

Nicaragua is the biggest country of Central America and one of the poorest of the continent, classified as Lower middle income (World Bank 2015). It is situated in the tropics, between 12˚ and 15˚ North Latitude and 86˚ and 87˚ West Longitude. Its prevailing climate conditions are classified as savannah climate, monsoon climate, and tropical rainforest according to Koppen-García (García 2004; INETER 2001).

The Country is divided into three geographical regions, the Pacific, Central and Atlantic Region. The first one agglomerates 61% of the total population and its exposed to the highest levels of solar radiation in the country (MEM 2013). See (figure 1).

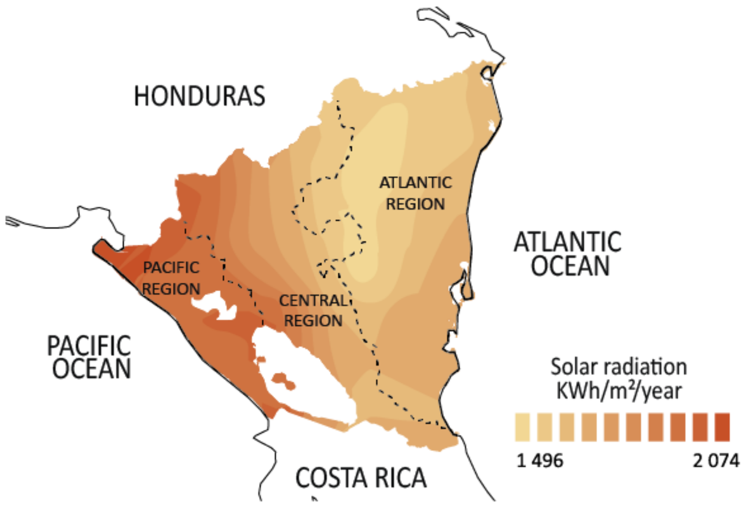

Figure 1 Geographical distribution and solar radiation map of Nicaragua

The single-family detached dwelling is the dominant housing typology of this country, due to, among other factors, its extensive history of earthquake activity. This fact has influenced people’s preference for low-rise buildings.

Most of those single-family detached dwellings are built without any thermal comfort criteria, due to the lack of National thermal regulations. Sample of this is the use of prevailing materials for the building envelope having a poor thermal performance, since at least two-thirds of the existing houses have a Zinc corrugated roofing without any ceiling and at least one-third of the houses have concrete blocks walls (INEC, 2001) (See fig.2). As a result overheating often occurs affecting the health and thermal comfort of most of the population.

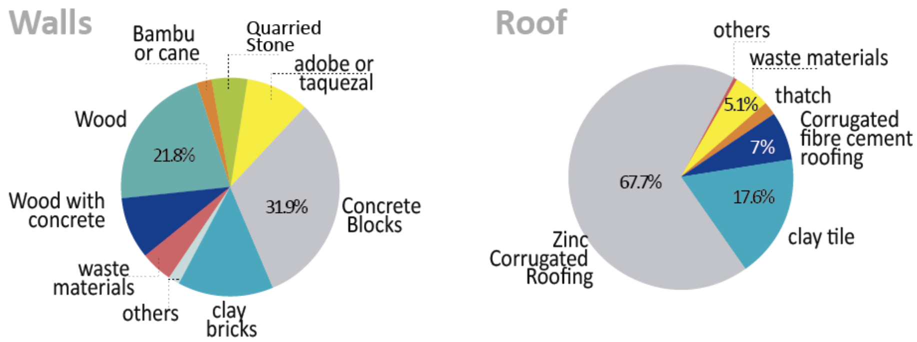

Figure 2 Predominant envelope materials of dwellings in Nicaragua

2 Methodology

The applied methodology is divided into four phases: 1) Selection of case studies, 2)Parametric variation, 3) Simulation using Energy plus V8.2 with the aid of Matlab R2014, and 4) Sensitivity analysis.

2.1 Selection of case studies

We analyzed one single-detached dwelling situated in the Pacific Region of Nicaragua. The selection of this model was based on its representativeness of Nicaraguan residential predominant type. The model information was obtained from databases of the Nicaraguan Urban and Rural Housing Institute (INVUR) and the Chamber of Nicaraguan Housing Developers (CADUR).

The overall floor area of the model is 56m^2 and its occupation is determined based on the standard average Nicaraguan family size with 6 people (PNUD 2002). Its envelope composition is described in figure 3.

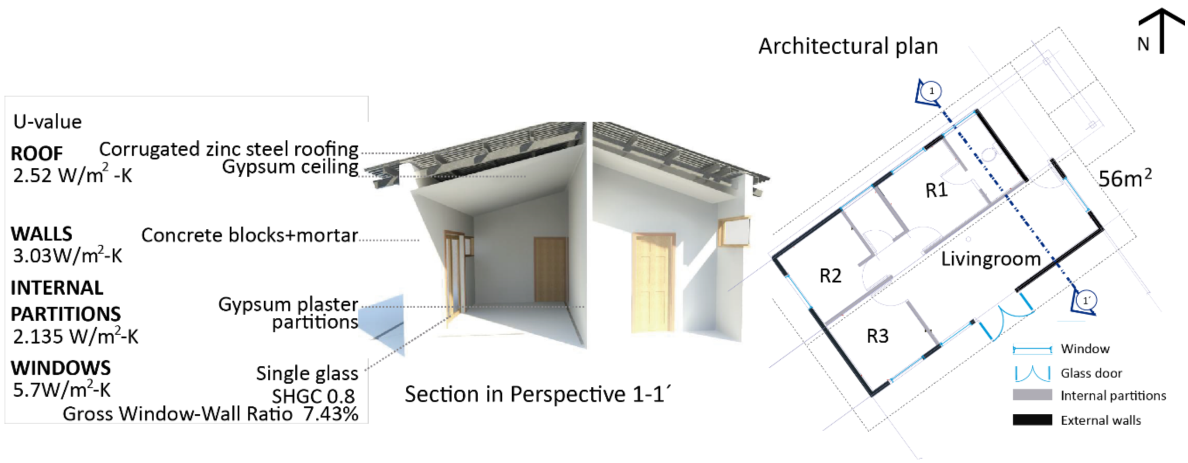

Figure 3 Base case description

Climate

Parametric simulation was done for five different climatic conditions (Figure4b). Three of them are locations from the Pacific region of Nicaragua, where live 61% of the national population (Managua, Chinandega and Rivas) (Figure4a) and two locations from the central region and Atlantic region of Honduras situated less than 50km from Nicaraguan border (Catacamas, Puerto Lempira). For each location, 500 simulations were performed. The final results were compared and synthetized in order to extract the main results. Samples of one site location are used in order to illustrate those results.

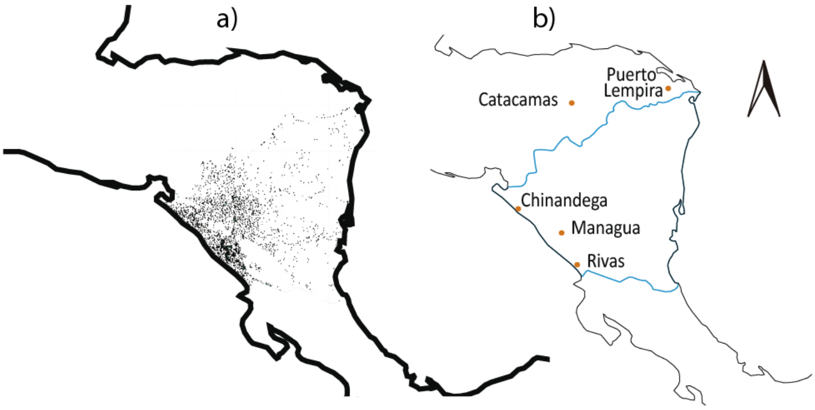

Figure 4 a) Graphical representation of population density in Nicaragua, b) Geographical location of weather data files used in this study

2.2 Parametric variation

The thermal transmittance (U-Value) and solar absorptance of the building envelope opaque surfaces as well as the Solar heat gain coefficient (SHGC) of the glazed surfaces are the variables selected to be automatically modified during the simulations. Combinations of parameters were conducted simultaneously through a random choice based in the Multiplicative Congruential Method (Harris 2013).

Other passive strategies such as building and openings orientation, ventilation and solar shading systems are considered very important for tropical architecture, however they are not implemented in this study because they are more difficult to apply in existing buildings.

The base case thermal properties were established according to the real dwelling characteristics. Alternative solar absorptance and U-values were collected and calculated from constructions materials available in Nicaragua. Table 1. Summarizes those parameters.

Table 1 Summary of base case and alternatives input

	Input parameters	Base case energy model	Range of values for alternative energy models
U-Value [W/m^2-K]	External walls	3.03	1.045-2.45
	Internal partitions	2.135	1.045-3.877
	Roof	2.52	1.042-3.01
Solar absorptance	External walls	0.8	0.3-0.8
	Roof	0.55	0.3- 0.8
	SHGC	0.8	0.2 - 0.8

2.3 Simulation using Energy V8.2 plus with the aid of Matlab R2014.

We executed 500 simulations for each location using Energy plus V8.2 (EERE 2009). The geometry of the base case was edited and imported from SketchupMake2015 to Energy plus V8.2 using Legacy1.6 Plug-in. To automatize the process of input and output data, we executed four routines in MatlabR2014 (MathWorks 2014) according to the following sequence:

- Automatic substitution of input values through a random choice based in the Multiplicative Congruential Method(Harris 2013), running simulations and storing outputs.
-
- Data extraction and generation of scatter plots of internal discomfort hours based on the ASHRAE 55 Adaptive model (80% acceptability status).
- Automatic extraction of indoor operative temperatures.
- Extraction of Resulting U-values.

2.4 Sensitivity analysis

We performed a global sensitivity analysis (Heiselberg et al. 2009; Tian 2013; Moore 2007) in order to identify the influence of each parameter in the thermal internal conditions as a result of several random combinations. For this, Pearson coefficient(r) was used considering the strength of relationship among variables according to table 2.

Table 2 Strength of relationship according to Pearson coefficient

Absolute Value of r (Pearson coefficient)	Strength of Relationship
r < 0.3	None or very weak
0.3 < r < 0.7	Moderate
r > 0.7	Strong

Comfort hours based on the adaptive comfort model ASHRAE Standard 55-2010, Thermal Environmental Conditions for Human Occupancy were used as performance indicator. In this model, comfort temperature is defined according to the monthly mean outdoor air temperature, calculated as the simple average of the previous thirty daily average outdoor air temperatures.

Two comfort regions are defined, 80% Acceptability and 90% acceptability.

For this study, the 80% Acceptability status is considered, which means that upper and lower limits of the comfort region are calculated according to the next formula.

$$\text{80\% Acceptability Limits: } Tot = 0.31 * To + 17.8 \pm 3.5 \qquad (1)$$

Where:

Tot=operative temperature (°C), calculated as the average of the indoor air dry-bulb temperature and the mean radiant temperature of zone inside surfaces.

To – monthly mean outdoor air dry-bulb temperature (°C).

Comfort hours were calculated for 24 hours of the day in order to reach a wide group of the society with diverse occupational patterns. In Nicaragua, most of the children and elderly people stay at home most of the time.

2.5 Limitations

This study is performed for one model of dwelling in order to make a parametric analysis, which is appropriated for a specific case without taking into account other variables; though, further research is needed in order to generalize the results. However, the representativeness of Nicaraguan dwellings through this model is considered significant, because at least 68% of Nicaraguan houses have a zinc corrugated roof and almost 32% of houses are made of concrete blocks (INEC 2001).

3 Results

Summarised results for the five climates are presented through a comparison between the base case and the improved case thermal performance, indicating the thermal potential reduction due to the parametric variation for each climate.

In order to illustrate deeper analysis, samples of simulations for one site location (Managua) are presented, indicating correlations of input and output data, sensitivity analysis as well as the thermal behaviour of one of the main rooms of the dwelling.

3.1 Thermal comfort improvement potential

In Managua, the combined effect of parametrical variation achieves 85% reduction of discomfort hours. This potential reduction varies from 78% to 83% in other climates of the Pacific, Central and Atlantic Region of the study area (Figure 5).

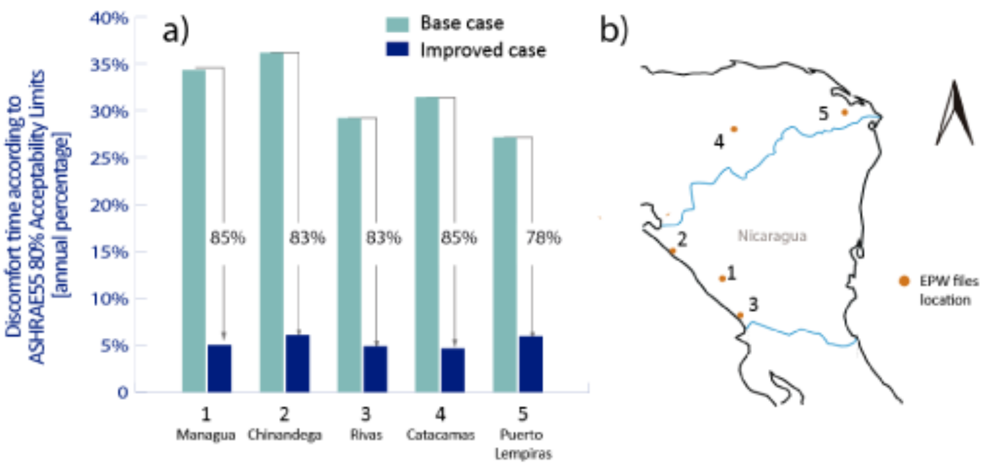

Figure 5 a) Discomfort potential reduction in different climates, b) Climate location

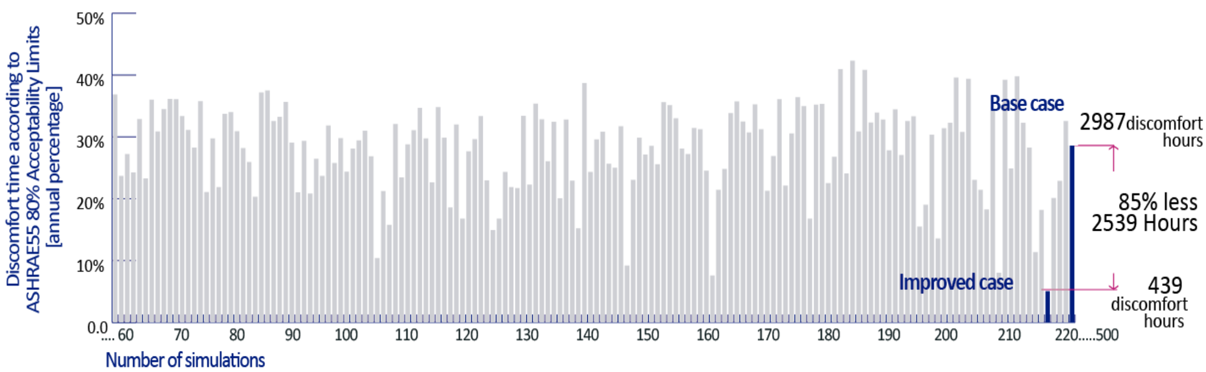

Figure 6 Thermal comfort improvement potential in Managua

A sample of simulation results from Managua is shown in Figure 6 in order to illustrate a deeper analysis. As it can be noticed, the most efficient case encountered during simulation presents 2539 less annual discomfort hours than the base case. Such a reduction is equivalent in average to 7 hours per day. This reduction potential fluctuates through the year according to climate conditions and orientation of the building. An example of this behaviour can be observed in Figure 7, where the average daily discomfort hour reduction potential of the living room is illustrated for each month. As it can be seen, during the months of January and February, the discomfort reduction potential is lower than in the period of June, July and August due to climatic variations such as solar radiation affecting that room which is orientated to the southeast.

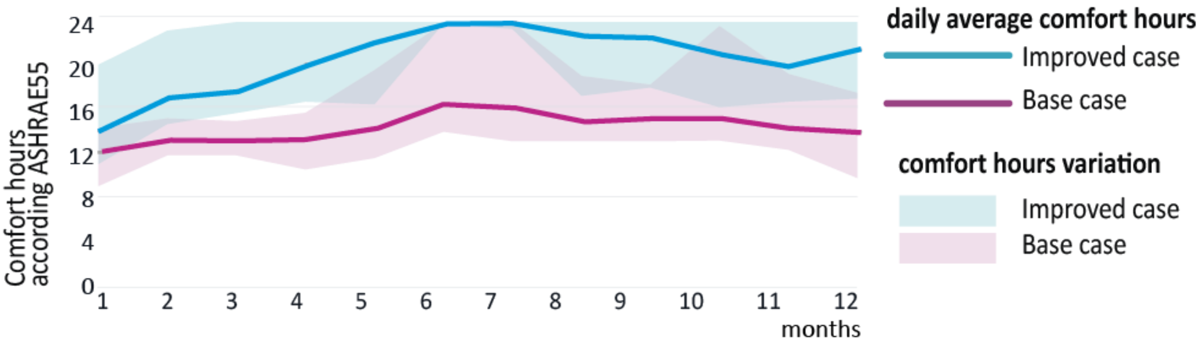

Figure 7 Average daily potential reduction of discomfort hour's in the living room

Thermal oscillation inside the living room is clearly reduced as well as a result of the parametrical variation. Figure 8 shows a comparison between the base case and improved case relationship of indoor operative temperature in the living room and the mean outdoor temperature according to the adaptive comfort model.

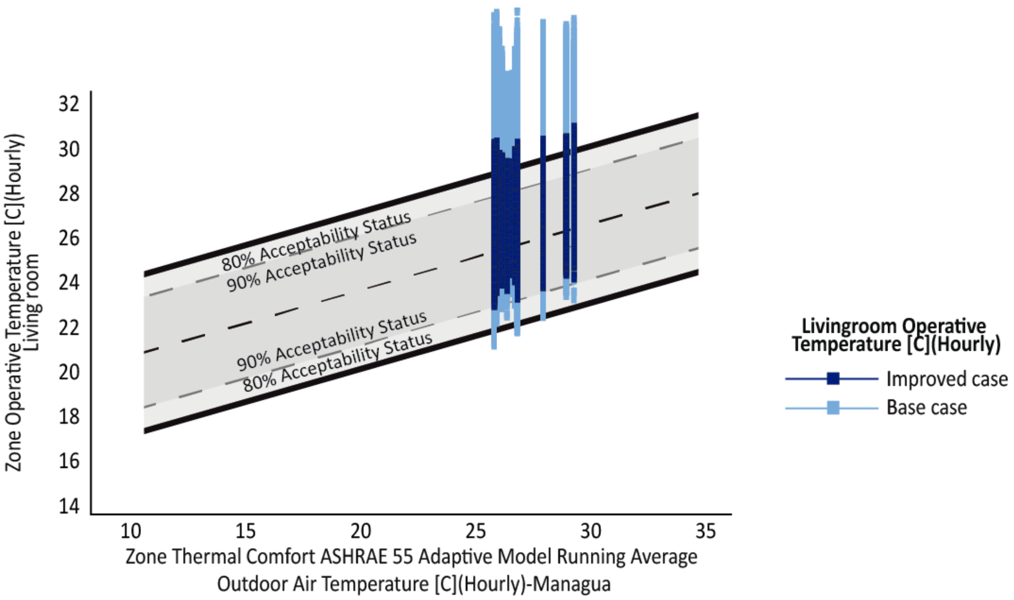

Figure 8 Relationship between indoor operative temperatures of the living room and mean outdoor temperatures according to the adaptive comfort model in Managua.

Considering one of the hottest days in the area of study, it is possible to observe a reduction of 4.6˚C in the peak operative temperature of one of the main rooms of the dwelling (living room). This is equivalent to reducing the number of discomfort hours in almost 43 %. (Figure 9).

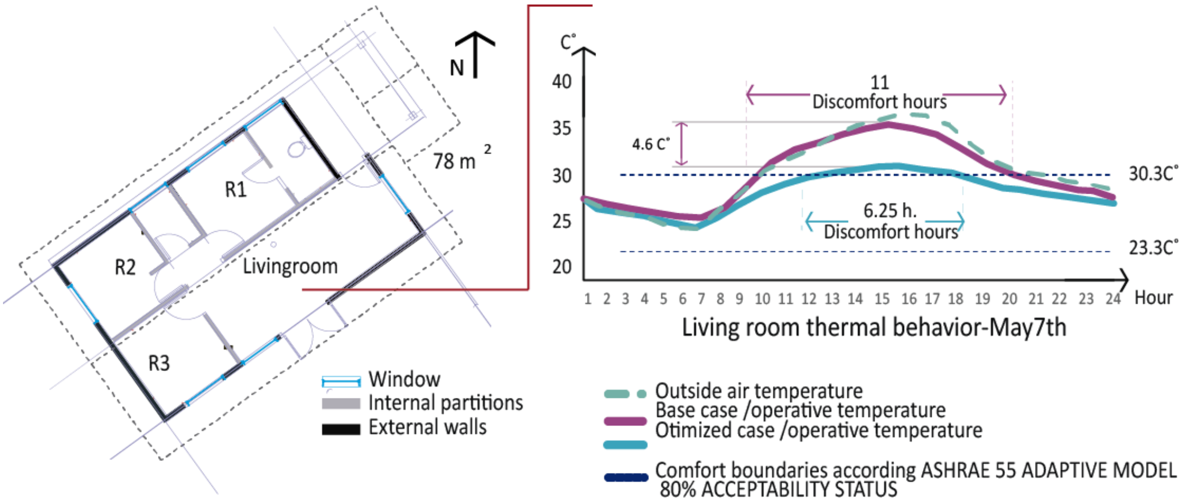

Figure 9 Living room thermal conditions during one of the hottest days in Managua

3.2 Sensitivity analysis

As a result of 500 simulations, a correlation between the input variables and the amount of discomfort hours of the four main rooms of the dwelling is calculated. Comfort hours are based on the Adaptive model 80% acceptability status.

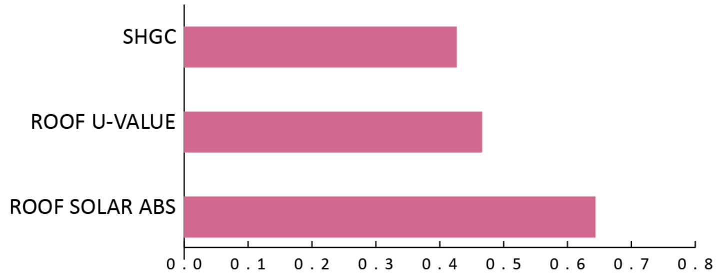

Figure 10 Correlation between input variables and discomfort hours

As it can be seen in figure 10, the roof solar absorptance is the most influencing parameter in our case study, having a positive moderate correlation of 0.64 with discomfort hours. This behaviour is persistent in the five climates simulated in this study. As much as the roof solar absorptance increases, the number of discomfort hours increases. A more detailed relation between this parameter and the thermal performance of the case study appears in Figure 11a. As it can be seen, the most efficient cases tend to have a lower solar absorptance value; however, that relation is not linear, because there are other factors that also have a moderate influence in thermal comfort such as the roof thermal transmittance and solar heat gain coefficient (SHGC).

Thermal transmittance of the roof is the second most important parameter on the thermal performance of the dwelling. This parameter has a positive moderate correlation coefficient of 0.47 with discomfort hours. As much as it increases, the number of discomfort hours also increases. Figure 11b shows a correlation between this variable and the discomfort hours.

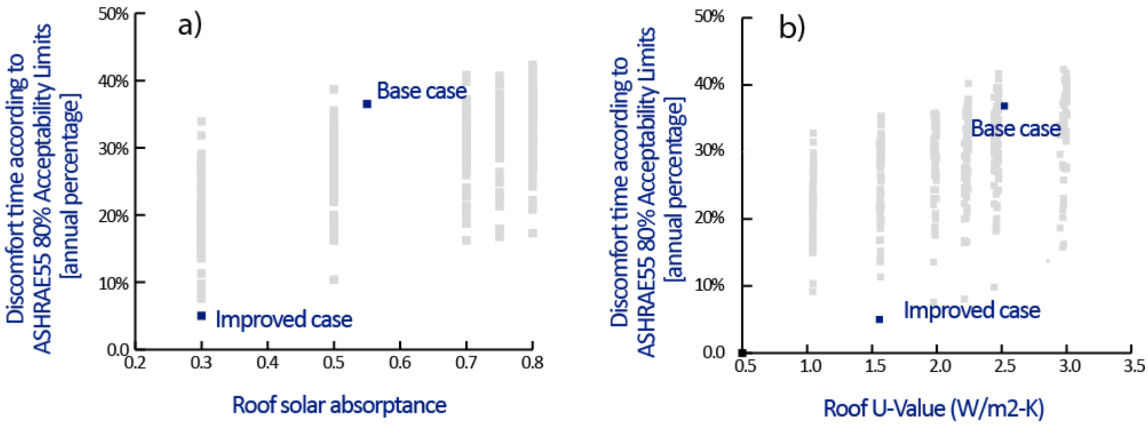

Figure 11 a)Roof Solar Absorptance vs Discomfort time, b)Roof-u-value vs discomfort time

SHGC is the third most important parameter on thermal comfort of this study with a positive moderate correlation coefficient of 0.43. Figure 12 presents its relationship with discomfort time.

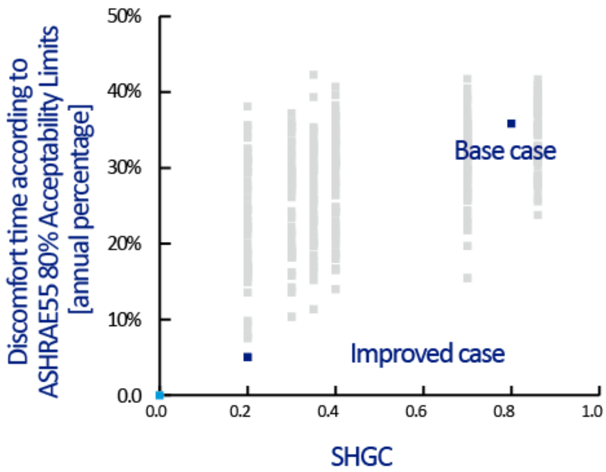

Figure 12 SHGC vs. Discomfort time

Other parameters such as the walls solar absorptance and walls transmittance have small correlation coefficients (less than 0.3), indicating a weak influence on discomfort hours when compared with roof solar absorptance, roof transmittance and SHGC.

This behaviour was also observed in other climatic conditions analyzed in this study, having small variations in the correlation coefficient, but keeping the same pattern.

3.3 Thermal properties of the most efficient cases.

Giving that the most important parameters in terms of comfort analyzed in this study are associated with the roof and glazed surfaces, their values were identified for two groups. A first group of cases having less than 20% discomfort hours, and a group of cases having more than 30% discomfort hours (Figure13). From this, it is possible to extract valuable information about the suitable values that can significantly contribute to a better thermal performance for housing in Nicaragua, as well as the values that should be avoided. A brief description of each parameter is presented below.

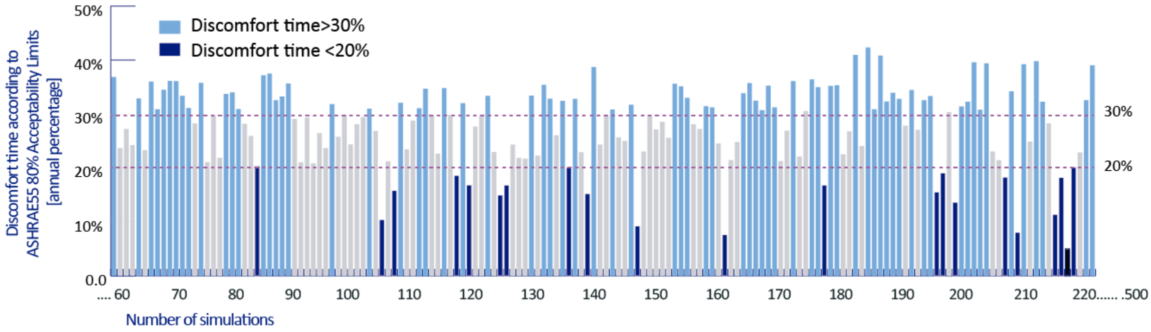

Figure 13 Most efficient and less efficient cases

Around 76% of the cases presenting less than 20% discomfort hours have a roof solar absorptance equivalent to 0.3. In contrast, most of the cases presenting more than 30% discomfort hours have a solar absorptance of 0.7 to 0.8 (Figure14).

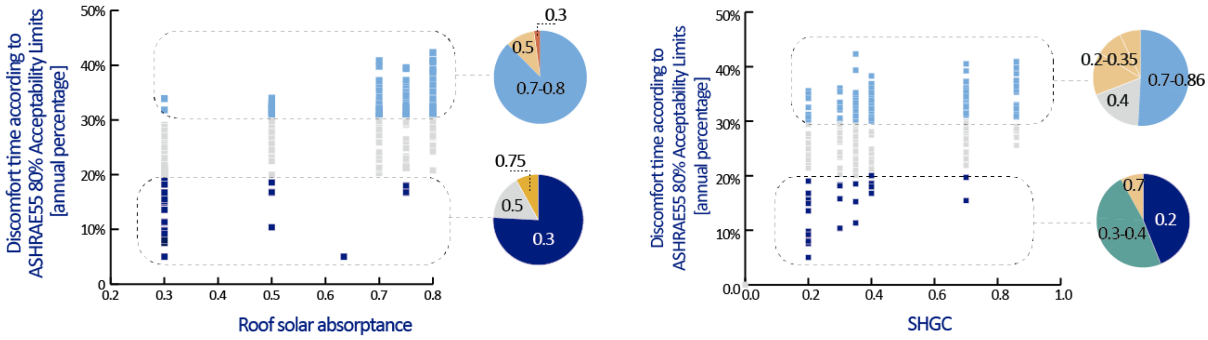

Figure 14 Thermal properties of the most efficient and less efficient cases

Considering solar heat gain coefficient, most of the cases having less than 20% discomfort hours present values from 0.2 to 0.4 in a model with 7.43% glazed areas. On the other hand, the cases presenting more than 30% discomfort hours present values between 0.4 and 0.8. It is important to highlight that the influence of a lower solar heat gain coefficient has a similar impact than reducing the window-to-wall ratio, though the importance of this parameter is strongly influenced by the surface of glazed area and their orientation (Figure14).

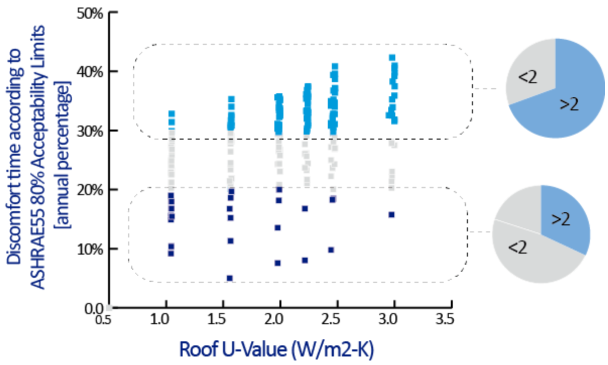

Figure 15 Thermal properties of the most efficient and less efficient cases

Roof solar transmittance tend to be lower than $2W/m^2$-K in the cases having less than 20% discomfort hours and higher than $2W/m^2$-K in the cases having more than 30% discomfort hours (Figure15).

None of those parameters applied solely can warrantee significant improvements on thermal performance of housing in such a context, but their combination may reduce significantly the number of discomfort hours. The use of low roof solar absortance equal or less than 0.3, a Roof U-value of less than 2W/m^2-K and a low solar heat gain coefficient equal or less than 0.4, are three cost effective measures having significant influence on thermal performance of the case study analyzed in this paper.

The solely implementation of those three measures can reach annual comfort 80% of the time within 80% Acceptability limits according to the adaptive comfort model. This occurs in the worst case scenarios simulated in Managua.

4 Conclusion

This paper has shown the potential of thermal improvement of a representative dwelling of Nicaragua, supported by robust and proven methods based on parametrical simulation using cost-effective passive strategies.

The sensitivity analysis showed that among the parameters analysed, the most important ones in terms of comfort are associated with the roof and glazed surfaces. The angle of incidence and high levels of solar radiation in tropical latitudes influence this fact.

In all the climates studied, solar absorptance presented a higher correlation coefficient with discomfort hours than the roof u-value. This fact has been largely discussed by the scientific community that support the implementation of cool roof systems in hot climates. Solar absorptance has the advantage of reducing solar heat gains without reducing heat dissipation.

None of those parameters applied solely can warrantee significant improvements on thermal performance of housing in such a context, but the combination of them may reduce significantly the number of discomfort hours. An example of that is the potential reduction of 85% of discomfort hours achieved in Managua, which is equivalent in average to more than 7 hours of per day. Such a potential reduction varies from 78% to 83% in other climates of the Pacific, Central and Atlantic Region of the area in study. This reduction is considered significant and cost-effective.

The solely implementation of a low roof solar absortance (equal or less than 0.3), a Roof U-value of less than 2W/m^2-K and a low solar heat gain coefficient (equal or less than 0.4), are three cost-effective measures having significant influence on thermal performance of the case study analyzed in this paper. Those three measures can reach annual comfort 80% of the time within 80% Acceptability limits according to the adaptive comfort model. This occurs in the worst case scenarios simulated in Managua.

Most of the Building Energy Codes tend to consider that technical solutions for energy conservation have to be complex; however, this work shows through a simple case the huge potential of thermal improvement of housing in such a context by the simple variation of parameters involving the thermal properties of the envelope.

These statements are applicable for a specific geometry, without taking into account other variables not discussed in this paper; however, this is a step towards wider research. Similar improvements can be achieved and validated in other countries with cooling dominated climates, fact that transcends this study and should be confirmed with future researches.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
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Study on thermal adaptation in naturally ventilated office buildings in Japan

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Abstract

This paper discusses the relationship between thermal environment and adaptive thermal comfort in Japanese office buildings of Japan where occupants are able to open the windows. With the use of adaptive thermal control opportunities in offices, it is possible to reduce the heating and cooling energy consumption. There are very limited studies on buildings that are ventilated naturally with open windows versus numerous studies on air-conditioned buildings for constructing an adaptive model based on Japanese lifestyle and climate. In this context, this research focused on thermal comfort and adaptive opportunities in a naturally ventilated office building. In this study we conducted a questionnaire based field survey in autumn and winter seasons of year 2015 in the administration building of the University of Tokyo. Simultaneously we also carried out environmental measurements and recorded thermal comfort responses from occupants. Analyzing the data we found that the measured value of comfort temperature can be closely predicted using nonlinear regression analysis. Also the adaptive model which can be used over a wide range of outdoor air temperatures is proposed. It is found that the change of comfort temperature becomes less as the outdoor air temperatures becomes higher than 30ºC and lower than 20ºC.

Keywords: Thermal adaptation, Comfort temperature, Natural ventilation, Window opening, Office building

1 Introduction

Research suggests that offices ventilated naturally by open windows not only improved the thermal comfort for occupants but also energy savings for the building (de Dear et al., 1997). It is also well established that occupants comfort feeling and preferences are different in HVAC buildings versus naturally ventilated buildings. In Japan, the indoor temperature setting for air-conditioning systems in offices is 28ºC and 20ºC (as per Japanese Government recommendation) in summer and winter in general. Availability of cool biz and warm biz (a Government of Japan initiative to allow office workers wear light clothes in offices in summer and winter) makes it easier for occupants to take adaptive actions to make themselves comfortable based on outdoor thermal environments. Therefore, if these offices are designed taking thermal comfort adaptation into consideration, energy consumption for heating and cooling can be reduced because temperature setting can be relaxed and a period of use air conditioning can be shorter. To build an adaptive thermal comfort model, large data sets on Japanese life style and climate is required because Japan experiences high temperature and high relative humidity in particularly summer months.

The adaptive thermal comfort in houses and offices has been widely investigated with field studies in Japan (Rijal et al., 2013; Takase et al., 2015; Goto et al., 2007). There are very limited studies done in naturally ventilated buildings compared to air-conditioned buildings. In this context, this research focused on the thermal comfort and adaptive opportunities in a naturally ventilated office building.

2 Method

We conducted a questionnaire based field survey in autumn and winter (October to December) of year 2015 in the administration building of the University of Tokyo (Figure 1). 49 subjects including 20 male and 29 female participated in the survey. The average age of the subjects is 41.6 years. 6 rounds of field surveys are conducted spread over the months of October – December, 2015. Simultaneously we also carried out environmental measurements and recorded thermal comfort responses. Total 217 data sets are collected. Table 1 list the parameters that were collected and considered in this study for analysis. Environmental controls in offices are recorded. For outdoor environmental parameters weather data from the Japan Meteorological Agency is used.

Table 1. The environmental measurements and the thermal comfort survey responses list

<table>
<tr><td rowspan="5">The environmental measurements</td><td colspan="2">Air temperature at 1.2 m above floor (°C)</td></tr>
<tr><td colspan="2">Globe temperature at 1.2 m above floor (°C)</td></tr>
<tr><td colspan="2">Surface temperature (°C)</td></tr>
<tr><td colspan="2">Relative humidity (%)</td></tr>
<tr><td colspan="2">Air velocity (m/s)</td></tr>
<tr><td rowspan="11">The thermal comfort responses</td><td rowspan="4">Thermal environment</td><td>Thermal Sensation Scale</td></tr>
<tr><td>Thermal Preference</td></tr>
<tr><td>Thermal Acceptability Question</td></tr>
<tr><td>Predicted Temperature</td></tr>
<tr><td rowspan="2">Humidity</td><td>Humidity Sensation</td></tr>
<tr><td>Humidity Preference</td></tr>
<tr><td rowspan="2">Air velocity</td><td>Air velocity Sensation</td></tr>
<tr><td>Air velocity Preference</td></tr>
<tr><td>Comfort level</td><td>Overall thermal comfort right now</td></tr>
<tr><td>Activity</td><td>Activity in last 15 minutes</td></tr>
<tr><td>Amount of clothing</td><td>Check each item of clothing that you are wearing right now</td></tr>
</table>

(a) (b)

Figure1. (a) A survey building and (b) measuring instrument

In this research, the ASHRAE thermal sensation scale is translated in two types. First is thermal sensation scale A i.e. cold - cool - slightly cool - neutral - slightly warm - warm – hot and second is thermal sensation scale B i.e. very cold - cold - slightly cold - neutral - slightly hot - hot - very hot. In Japanese expressing cool and warm sensation as described in ASHRAE is very difficult and may lead to error in analysing the data. Horikoshi and Kuno suggest that arranging the Japanese “syo (hot),” “kan (cold),” “dan (warm),” and “ryo (cool)” into such a unidimensional disposition is a problem (Horikoshi et al., 1974; Kuno et al, 1984; Kuno et al., 1987). Japanese people may feel comfortable but may also feel “dan (warm)” or “ryo (cool)” (Kaneko et al., 2001). “Dan (warm)” and “ryo (cool)” are comfortable feelings, whereas “syo (hot)” and “kan (cold)” are uncomfortable feelings. Furthermore, SET* shows more significant correlation with thermal sensation scale B than with thermal sensation scale A (Kaneko et al., 2001). To address this complex issue of expression of thermal sensation both scale B as well as scale A was added to the questionnaire (Table 2).

Table 2. The thermal sensation scale and overall comfort scale

Scale	1	2	3	4	5	6	7
Thermal sensation scale A	Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
Thermal sensation scale B	Very Cold	Cold	Slightly Cold	Neutral	Slightly Hot	Hot	Very Hot
Overall comfort	Very uncomfo-rtable	Uncomfo-rtable	Slightly uncomfo-rtable	Slightly comfort-able	Comfort-able	Very comfort-able	

The data is divided into five groups depending on usage of air-conditioning and operation of windows. Following terminology is used to represent the cases.

CL : Cooling by air conditioning is under use

FR : Free running mode i.e. air conditioning is not in use

FRo : Free running and window open

FRc : Free running and window closed

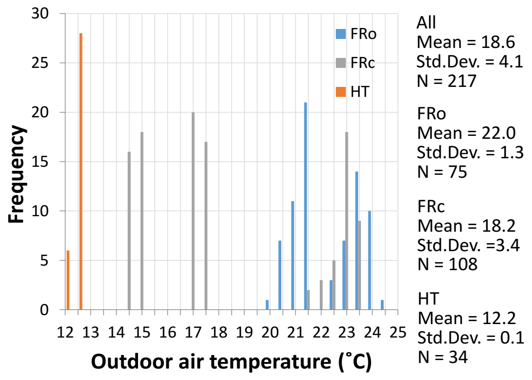
HT : Heating by air conditioning

3 Results and discussion

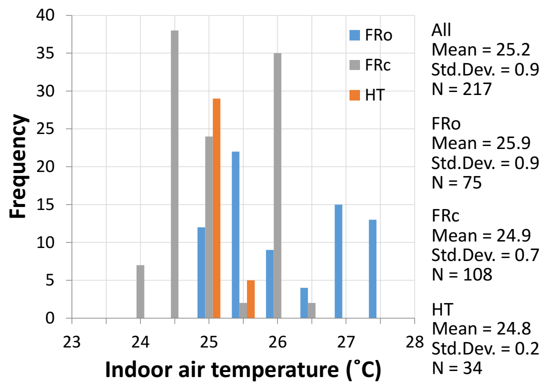
3.1 Thermal condition and behavioral adjustment

3.1.1 Thermal condition during field survey

The data is divided into three categories (FRo, FRc and HT) base on the mode of operation of building. This done to show the relationship between 3 categories, with outdoor and indoor air temperatures. In field survey few data during heating mode is collected because of its limited use during autumn and winter. Both the mean outdoor air temperature and indoor air temperature are the highest during the FRo mode and the lowest during the HT mode (Figure 2). The maximum outdoor air temperature during the voting is 24.3°C, and minimum is 11.9°C. The maximum indoor air temperature is 27.3°C, and minimum is 24°C. Because of autumn and winter seasons the standard deviation of the outdoor air temperature is large.



(a)



(b)

Figure 2. Distribution of the (a) outdoor air temperature and (b) indoor air temperature

3.1.2 Window opening behaviour

In this section we are analyzing the window opening behaviour in the surveyed building. Figure 3 shows the relationship between windows opening with respect to outdoor temperature. The proportion of windows open which varies with the outdoor temperature is predicted by logistic analysis (Nicol et al., 2004). The following regression equation is obtained from the collected the data.

$$\log\{p/(1-p)\} = 0.517\,T_o - 10.96 \qquad (1)$$

$$(N = 217, r = 0.61, S.E. = 0.075, P < 0.01)$$

From the statistics we found that the proportion of windows open has a strong correlation with the outdoor air temperature. A regression coefficient obtained in this study (0.517) is higher than that of the study conducted on Japanese houses (0.210) (Rijal et al., 2013). It seems that the occupants are more sensitive towards change in outdoor air temperature in Japanese office than Japanese houses. From the analysis it has been found that fifty percent of windows are open when outdoor temperature reaches approximately 21°C (Figure 3). In Japanese houses fifty percent of windows are open when the outdoor air temperature is approximately 24°C (Rijal et al., 2013). The difference in outdoor temperature and window opening behaviour in offices and houses can be attributed to the prevailing indoor thermal environment. As in offices the heat generated by computers and other electronic gadgets extends the cooling requirements. Also compared to houses, occupants in offices have low degree of freedom to change clothing level because occupants have to adhere to the requirement of clothing level in office environment. Thus making them feel uncomfortable thus increasing the cooling requirements. So in this case natural ventilation assisted with window opening behaviour can be a measure source of energy consumption reduction of air conditioning in offices compared to houses.

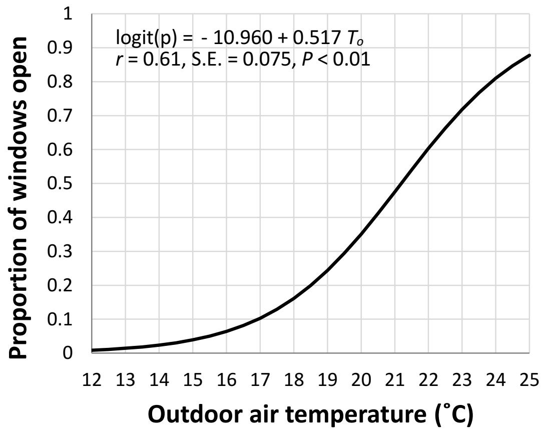


Figure 3. Predicted proportion of windows open

The mean air velocity recorded in the FRo is highest. However, air velocity was very low during survey. Maximum air velocity recorded during the survey was 0.16 m/s.

3.1.3 Clothing insulation

Under the adaptive mechanism, clothing behaviour provides the maximum adaptive opportunities and flexibility to occupant to adjust itself to the changing thermal environment. But in office environment there is some kind of restriction to clothing choices. This nature of adaptation is visible in figure 4. In the polynomial regression (as shown in equation 2) line we see that the lines at higher temperature bent upwards showing the adaptation. This shows that despite high temperature occupants get accustomed to particular clothing level. During the survey clo value varies from 0.5 clo to 1.4 clo with mean at 0.76 for all data. We adopt the quadratic polynomial regression since it is showed that clo value have a higher correlation with the outdoor air temperature than the linear regression.

$$I_{cl} = 0.0011T_o^2 - 0.0548T_o + 1.3921 \quad (N = 216, r = 0.43) \tag{2}$$

When substitute the maximum and minimum outdoor air temperature for T_o in equation (2), it is predicted that clo value varies from approximately 0.7 clo to 0.9 clo during the survey.

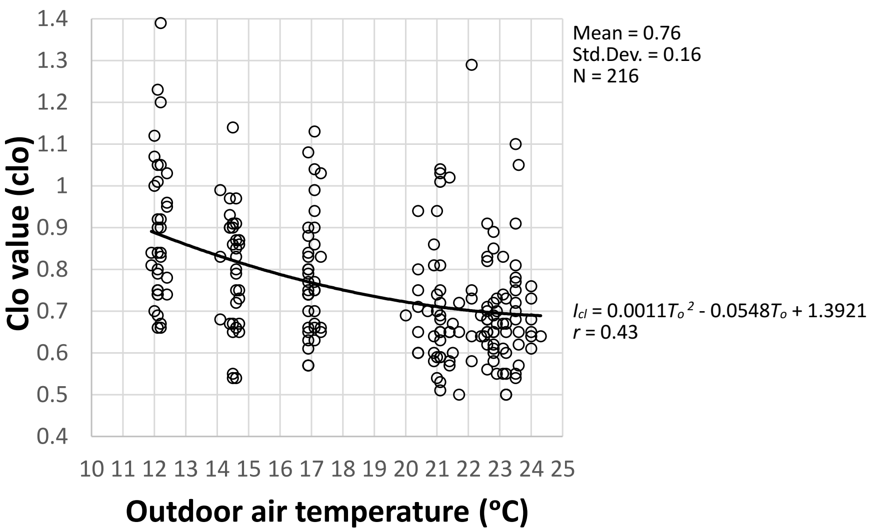
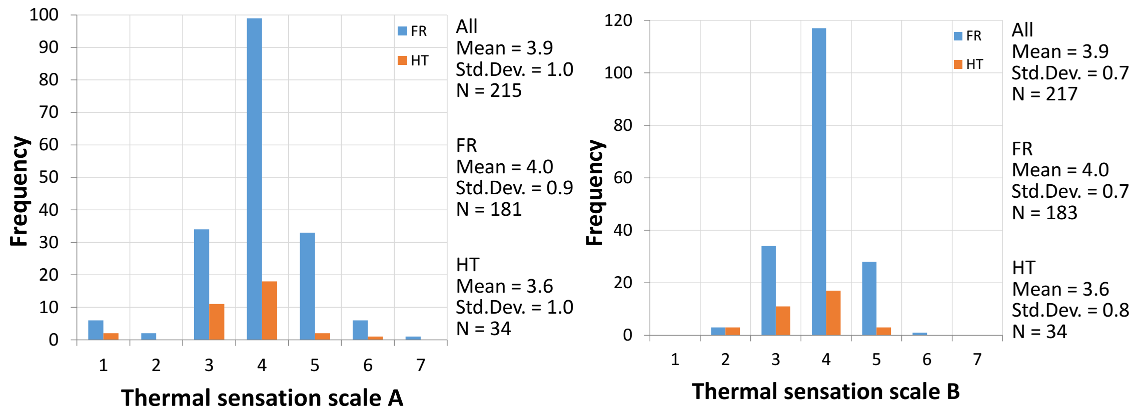


Figure 4. Relationship between clo value and outdoor air temperature

3.2 Differences of the translation effect on the results

This section discusses the critical aspect of culture and perception that can have a big influence on results. To address this issue two types of scales thermal sensation scale A and the thermal sensation scale B are used in same survey and occupants were asked to record their thermal sensation on both the scales. Figure 5 shows the distribution of the thermal sensation scale A and the thermal sensation scale B. The standard deviation of the thermal sensation scale A is larger than the thermal sensation scale B in any mode. The thermal sensation votes corresponding to neutral (4) on thermal sensation scale B is more than that of neutral votes (4) on the thermal sensation scale A.



(a) (b)

Figure 5. Distribution of (a) thermal sensation scale A and (b) thermal sensation scale B

To show the correlation between thermal sensation and indoor air temperature, we perform linear regression analysis (Figure 6). The regression equations are given below:

$$C_A = 0.223T_i - 1.73 \;\; (N = 215, r = 0.21, S.E. = 0.072, P < 0.01) \qquad (3)$$

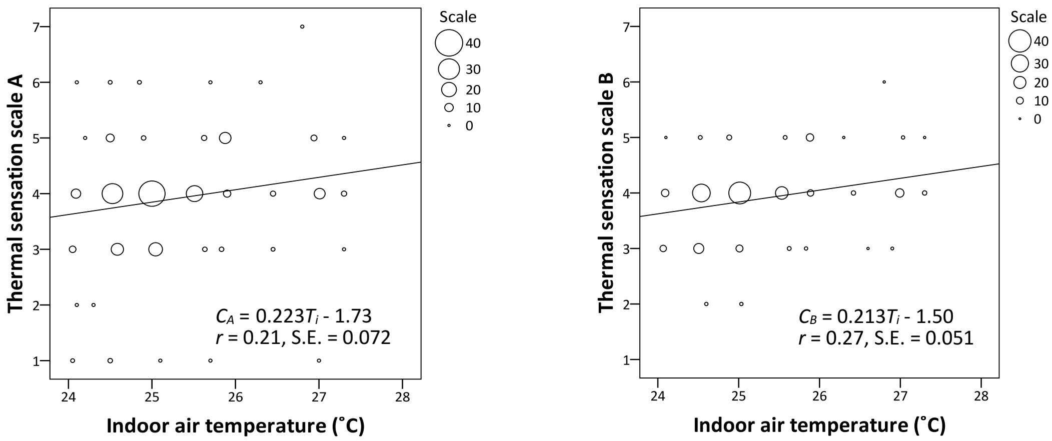
$$C_B = 0.214T_i - 1.50 \;\; (N = 217, r = 0.27, S.E. = 0.051, P < 0.01) \qquad (4)$$

$where$

C_A : Thermal sensation A

C_B : Thermal sensation B

From regression analysis we find that correlation coefficient for thermal sensation scale B is higher than that of thermal sensation scale A thus thermal sensation scale B had a higher correlation with indoor air temperature than the thermal sensation scale A. This result corresponds to the result by Kaneko et al. (2001). From this result, it can be concluded that ASHRAE thermal sensation scale must be used with caution and required changes must be done when it is translated to other languages for questionnaire based thermal comfort surveys.

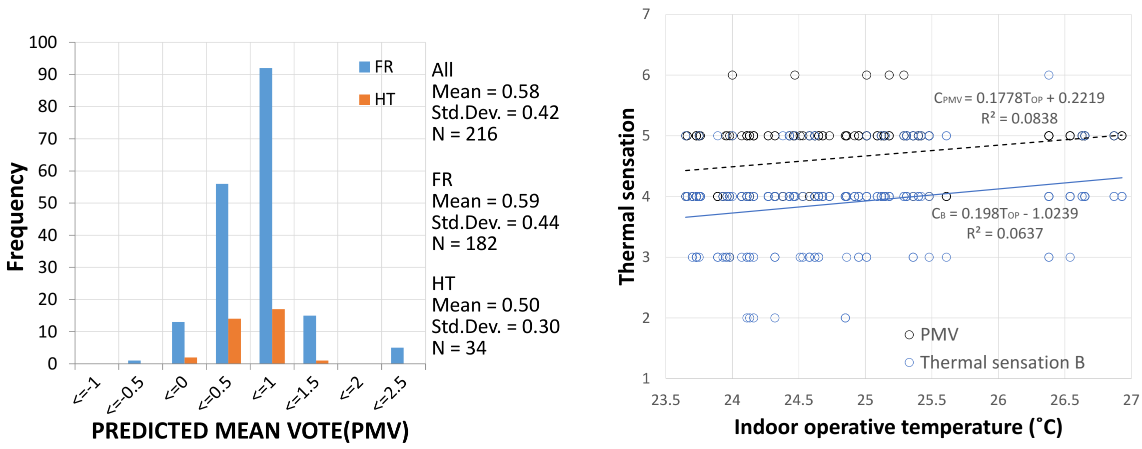


(a) (b)

Figure 6. Relationship between indoor air temperature and
(a) thermal sensation scale A and(b) thermal sensation scale B

3.3 Comparison of thermal comfort responses and PMV

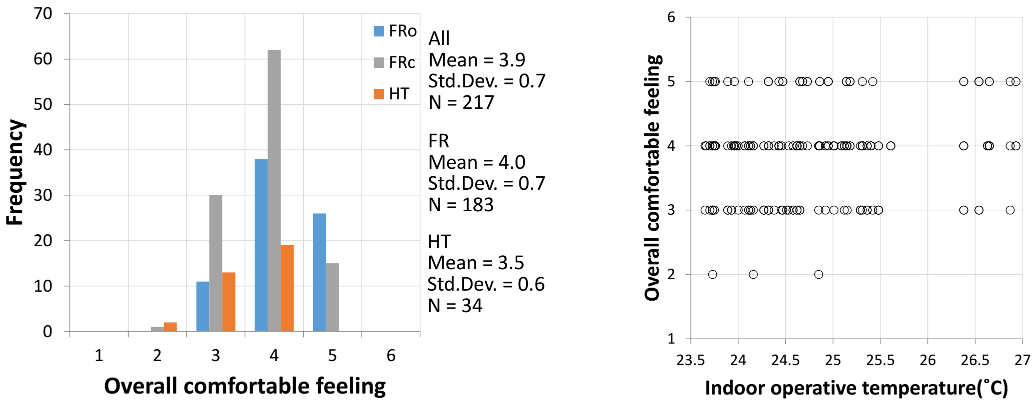
Figure 7 (a) shows distribution of PMV corresponding to FR and HT mode of operation of building. From the plot we observe that there are large number of votes which are on the warmer side of the scale. The mean PMV for all data is 0.58 and it is between slightly hot and neutral. By contrast, mean of thermal sensation is in the cold side (Figure 5). Figure 7 (b) shows that PMV is in the hot side even though the thermal sensation in scale B is slightly cold or cold. Same is shown by the regression line of PMV as it is higher than that of thermal sensation on scale B. For this reason, it can be concluded that thermal sensation is predicted too hot by PMV. These results are similar to the study by Humphreys (2008).



(a) (b)

Figure 7. (a) Distribution of PMV and
(b) relationship between thermal sensation scale B, PMV, and the indoor operative temperature

In this study we also tried to assess the overall comfort of the occupants in office. From figure 8 (a) we find that the mean overall comfortable is 3.99 and 3.50 in the FR mode and the HT modes respectively. The mean overall comfortable in the FR mode is closer to comfortable side than the HT mode. The overall comfortable has a poor correlation with the indoor air temperature because a regression coefficient is lower than 0.20 (Figure 8 (b)).



(a) (b)

Figure 8. (a) Distribution of overall comfortable,
(b) relationship between overall comfortable and indoor operative temperature

3.4 Comfort temperature by Griffith's method

In this study the comfort temperature is also predicted by Griffith's method (Griffiths, 1990) using the thermal sensation scale A and the thermal sensation scale B. The comfort temperature by Griffith's method can be calculated by following equation (5).

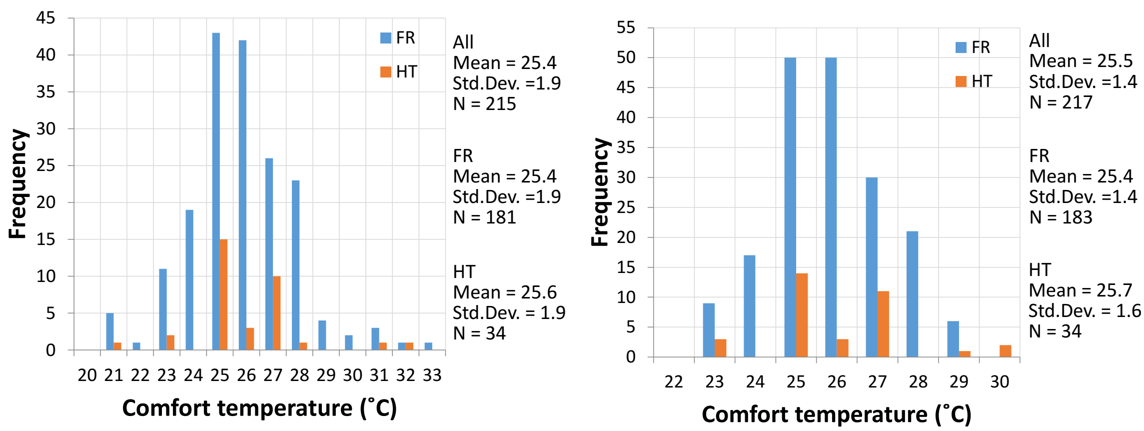
$$T_{cg} = T_i + (4 - C)/a \tag{5}$$

where

T_{cg} : Comfort temperature by Griffith's method, °C

a : Regression coefficient (0.5)

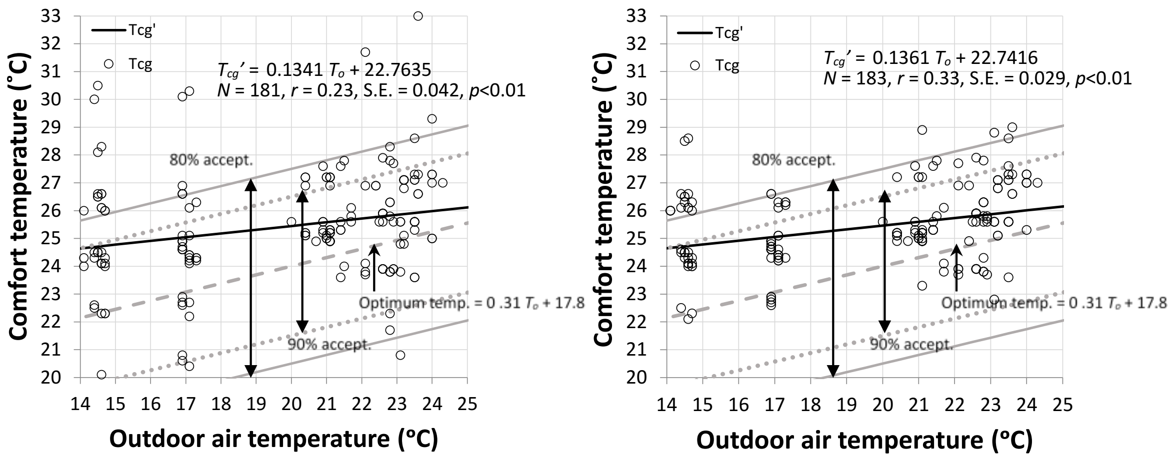
For Japanese houses Rijal used the constants 0.5 to predict the comfort temperature (Rijal et al., 2013). Therefore in this study the comfort temperature calculated with the coefficient 0.5 and further analysis is done. Figure 9 shows the distribution of comfort temperature calculated using Griffiths method. The comfort temperature is the highest from temperature 25 to 26°C both figure 9 (a) and (b).



(a) (b)

Figure 9. Distribution of comfort temperature using Griffiths method
using (a) thermal sensation scale A and (b) the thermal sensation scale B

In adaptive thermal comfort model indoor comfort temperature is predicted using outdoor air temperature (ASHRAE, 2004). The linear regression analysis is conducted for the FR mode with the outdoor air temperature as the independent variable and comfort temperature by Griffith's method as the dependent variable. Figure 10 shows the relationship between the comfort temperature, the outdoor air temperature and the 90% and 80% limits of the ASHRAE's adaptive model (de Dear et al., 2001). In comparison with ASHRAE's adaptive model, the comfort temperature is higher in this case. The 86.7% data of comfort temperature calculated by the Griffith's method (Equation 5) is within the 80% acceptability of the ASHRAE's adaptive model. The correlation coefficient is 0.23 and 0.33 when using the thermal sensation scale A and the thermal sensation scale B showing low correlation between the comfort temperature and the outdoor temperature.



(a) (b)

Figure 10. Relationship between comfort temperature and outdoor air temperature,and comparison with ASHRAE's adaptive mode using (a) thermal sensation scale A and (b) thermal sensation scale B

3.5 Predicted comfort temperature during the FR mode

3.5.1 Methods of analysis

The data collected in four office buildings of the Tokyo University, in Tokyo during the months of July – September in 2012 (Indraganti et al., 2013; Ooka et al., 2014) added to the data collected in this survey to predict the annual comfort temperature. We collected 2402 data sets in 2012 and this is combined with present data sets to carry out this analysis (total data set 2402 + 217 = 2619)

As discussed in section 3.3, the correlation between comfort temperature and outdoor air temperature is low by using Griffith's method in this study. Therefore, in this section, Griffith's method is not used. For further analysis we assumed that indoor comfort temperature is indoor operative temperature when the thermal sensation votes are neutral on thermal sensation scale A (Met: 1; and air velocity nearly equal to 0.1 m/s).

Although indoor comfort temperature is predicted by linear regression analysis in earlier studies, we suggest the indoor comfort temperature by nonlinear regression analysis because there is a difference between measured and linear regression comfort temperature when outdoor air temperature is high or low. The following are probable main reasons to explain the phenomenon.

1) Clothing level limitation: Clothing levels can't be unlimitedly reduced or increased especially in the office environment. Therefore a range of temperature to which occupants can adapt is limited.

2) Physiological limitation: Human/Occupant's physiology limits the temperature range or set of environmental conditions to feel comfortable.

Therefore in this situation nonlinear regression analysis is used to solve this problem.

3.5.2 Corrected comfort temperature by residual

One method of predicting the comfort temperature by nonlinear regression analysis is the method of correcting the linear regression analysis using the residual.

The predicted comfort temperature are calculated by executing linear regression analysis for the FR mode with the outdoor air temperature as the independent variable and indoor operative temperature as dependent variable when the thermal sensation votes are neutral on thermal sensation scale A (Equation 6).

$$T_c' = 0.4355T_o + 16.6788\ (N = 203, r = 0.869, S.E. = 0.017, p < 0.01) \qquad (6)$$

$where$

T_c' : Predicted comfort temperature by linear regression, °C

The comfort temperature by linear regression constantly varies in response to the outdoor air temperature. However, it is seen that the change of comfort temperature becomes lower as the outdoor air temperature becomes higher or lower. Therefore, we corrected the comfort temperature by adding the residual to the comfort temperature by linear regression analysis as shown in equation (9). The residual is calculated by

$$e = T_c - T_c' \qquad (7)$$

$where$

e : Residual, K

Assuming that the change of comfort temperature becomes lower as the outdoor air temperature is higher and lower, the residual can be predicted by the cubic regression analysis (Figure 11). The cubic regression is obtained by least-squares method.

$$e = aT_o^3 + bT_o^2 + cT_o + d \qquad (8)$$

$where$

a, b, c, d : Regression coefficient

Equation (9) shows the corrected comfort temperature.

$$T_c'' = T_c' + e \qquad (9)$$

$where$

T_c'' : Corrected comfort temperature by residual, °C

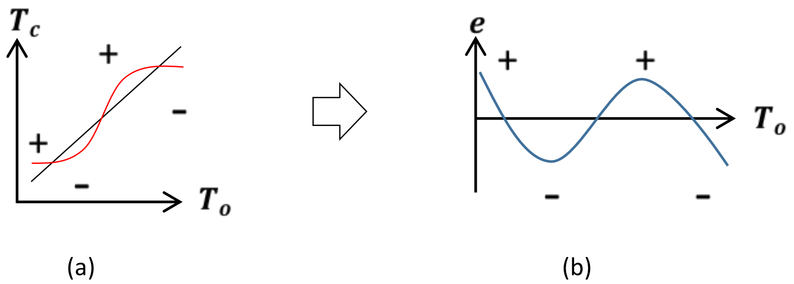


Figure 11. The conceptual diagram of the relationship between outdoor air temperature and (a) corrected comfort temperature by residual and (b) residual

Figure 12 (a) shows relation between the residual and the outdoor air temperature. The residual was calculated by executing cubic regression analysis (Equation 10).

$$e = -0.0006T_o^3 + 0.0547T_o^2 - 1.5831T_o + 14.049 \ \ (N = 203, r = 0.30) \qquad (10)$$

T_c' is corrected using the residual in order to increase the correlation between comfort temperature and outdoor air temperature. The equation (11) is constructed using the equation (10), equation (6) and equation (9).

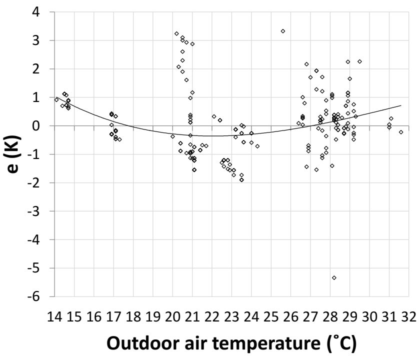
$$T_c'' = (0.4355T_o + 16.6788) + (-0.0006T_o^3 + 0.0547T_o^2 - 1.5831T_o + 14.049) \qquad (11)$$
$$(N = 203, r = 0.882)$$

The correlation coefficient of regression curve is 0.013 higher than that of linear regression. To validate this characteristic, more subjective responses will be used in future research.

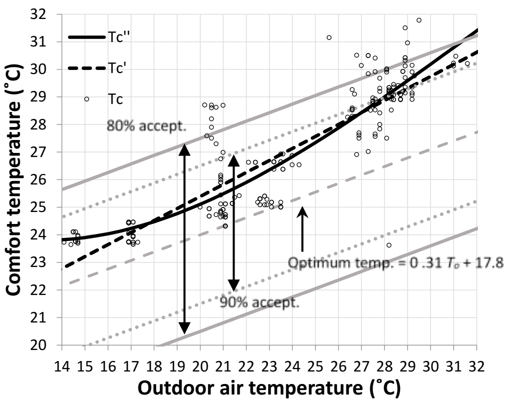
The corrected comfort temperature which is lower than 24°C is almost constant value because of the gradient of curved line become very small when the outdoor temperature is lower than about 20°C. The gradient of curved line is larger than that of simple regression line when the outdoor air temperature higher than about 22°C.

The comfort temperature is higher than the optimum temperature of ASHRAE's adaptive mode. Furthermore, it is predicted that the comfort temperature becomes higher in the high outdoor air temperature. It is predicted that occupants also feel comfortable when indoor operative temperature is higher than 28°C during the FR mode.

It is found that occupants in the office building in Japan feel comfortable at the higher temperature than the office buildings in European countries which are included in ASHRAE's adaptive model.



$e = -0.0006\,T_o^{\,3} + 0.0547\,T_o^{\,2} - 1.5831\,T_o + 14.049$
$N = 203$, $r = 0.303$



$Tc'' = (0.4355\,T_o + 16.6788) + (-0.0006\,T_o^{\,3} + 0.0547\,T_o^{\,2} - 1.5831\,T_o + 14.049)$
$N = 203$, $r = 0.881$

(a) (b)

Figure 12. Relationship between (a) residual and outdoor air temperature and (b) corrected comfort temperature by residual and outdoor air temperature, and comparison with ASHRAE's adaptive model

3.5.3 Predicted comfort temperature by logistic regression analysis

The second method of predicting the comfort temperature by nonlinear regression analysis is using logistic regression analysis. The generalized logistic regression is shown in equation (12).

$$T_c''' = \frac{\gamma - \delta}{1 + e^{\alpha - \beta T_o}} + \delta \tag{12}$$

$where$

T_c''' : Comfort temperature by logistic regression, °C

α, β : Regression coefficient

γ : Limit as T_o approaches positive infinity of T_c'''

δ : Limit as T_o approaches negative infinity of T_c'''

The equation (12) rearrange into equation (13). The least-squares method is used for obtaining α and β. Then the values of γ and δ are calculated from the highest value of the correlation coefficient *r* of the correlation between $f(T_o)$ and T_o in equation (13).

$$f(T_o) = \log\left(\frac{\gamma - \delta}{T_c''' - \delta} - 1\right) = \alpha - \beta T_o \tag{13}$$

Equation (14) is given by using this method.

$$T_c''' = \frac{9}{1 + e^{6.088 - 0.244 T_o}} + 23 \quad (N = 203, r = 0.870, S.E. = 0.001, p < 0.01) \tag{14}$$

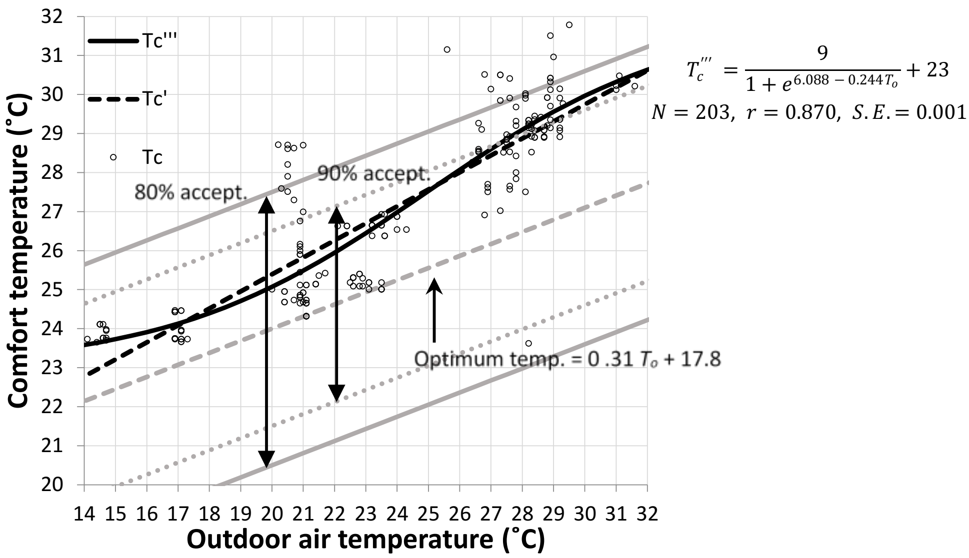


Figure 13. The logistic regression of comfort temperature versus outdoor air temperature and its comparison with the ASHRAE's adaptive model

The gradient of logistic regression curve is small when the outdoor air temperature is higher than 30ºC as well as lower than 20ºC. The correlation coefficient of logistic regression is 0.001 higher than that of linear regression, and the logistic regression is more expressing more information out of the research data.

3.6 Predicted comfort temperature during FR, CL, and HT modes

This section presents the predicted comfort temperature for all data including the FR, CL and HT mode. The corrected comfort temperature by residual is used since the outdoor air temperature has a higher correlation with it than the comfort temperature by logistic regression.

The cubic regression in figure 14 is similar to the assumed cubic regression in figure 11 (b). Negative residuals are obtained between 12ºC to 24ºC and above 31ºC. Positive residuals are obtained from 24ºC to 31ºC. It is assumed that occupants feel comfortable adapting the outdoor air temperature because clo value becomes higher from 12ºC to 24ºC, and by open windows from 24ºC to 31ºC. Since the comfort temperature is close to upper limit, residuals become negative after 31ºC.

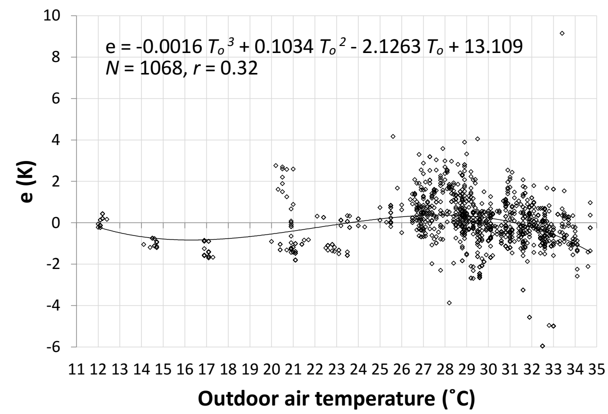


Figure 14. Relationship between the residual and outdoor air temperature

Figure 15 shows the relation between corrected comfort temperature by residual and outdoor air temperature, and the comparison with ASHRAE's adaptive model. The correlation coefficient of regression curve is 0.06 higher than that of linear regression. In comparison with the predicted comfort temperature for the FR mode (Figure 12 (b)), the result is distinct in the high and low outdoor air temperature. It is found that the comfort temperature becomes higher when the outdoor air temperature is lower than 14°C. This is similar to the statistical dependence of indoor thermal neutralities on climate by Humphreys (de Dear et al., 1997). In addition, the comfort temperature tends to decrease as the outdoor air temperature becomes higher than 31°C.

The gradient of regression curve is comparatively large between 18°C to 28°C to adapt outdoor air temperature (Figure 15) because of the occupants' adaptive behaviour in this range of the outdoor air temperature. The major causes of this behaviour are changing the clothing and controlling the proportion of windows open (Figure 16).

This finding indicates that the comfort temperature changes according adjustment behavior all the seasons.

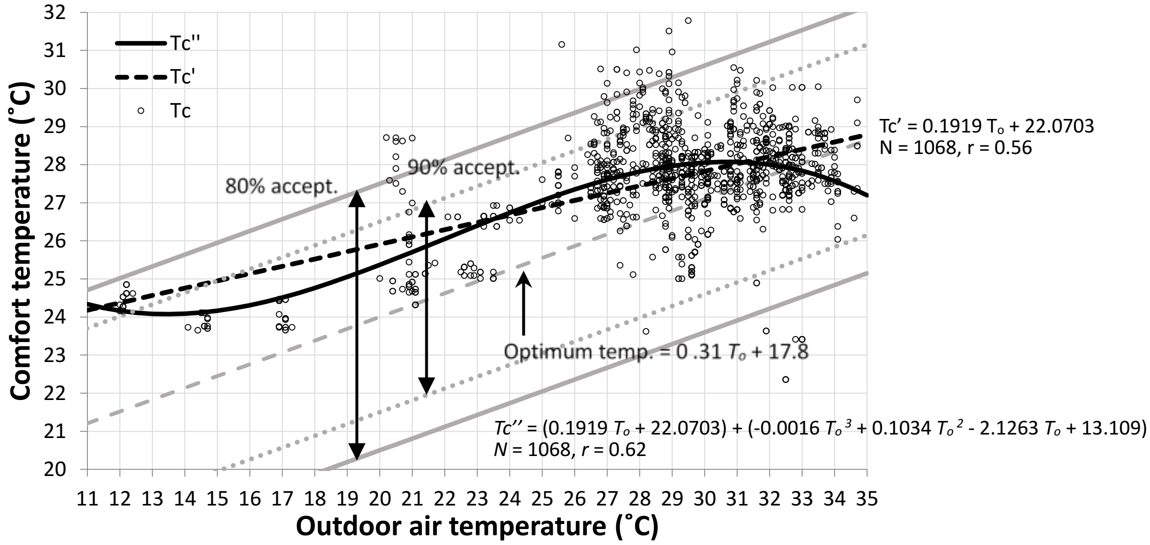


Figure 15. Relationship between corrected comfort temperature by residual and outdoor air temperature and comparison with ASHRAE's adaptive model

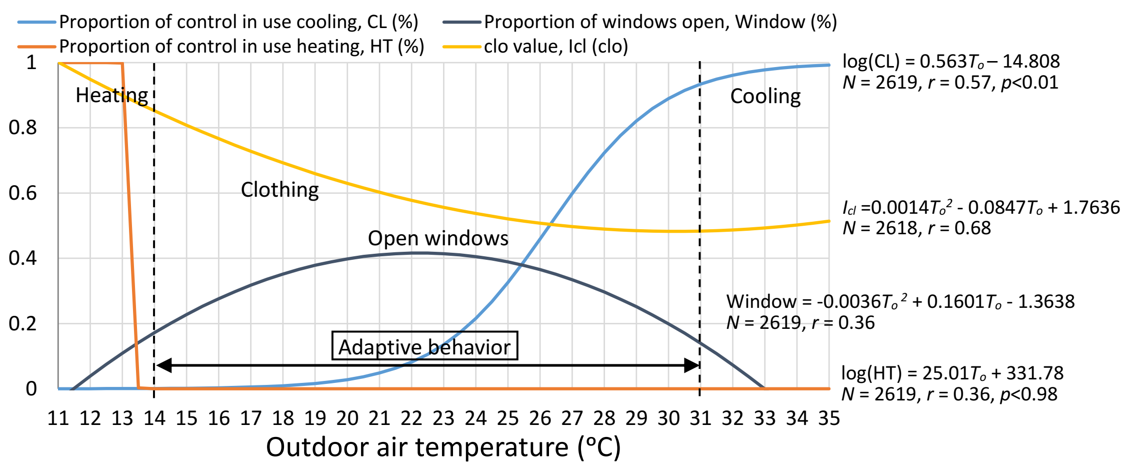


Figure 16. Relationship between outdoor air temperature and adjustment behavior for all data

4 Conclusions

A thermal comfort survey of a Japanese office building where occupants were able to open the windows was conducted during the months of October – December in 2015. The analysis using the linear regression is carried out to predict the comfort temperature in previous studies. However, it is assumed that the change of comfort temperature becomes lower as the outdoor air temperature becomes high and low. Therefore, we suggest the methods of predicting the comfort temperature by using nonlinear regression analysis. The following results are found:

1. The proportion of windows open increase rapidly as the outdoor air temperature increase when the outdoor air temperature is higher than 20ºC. It is nearly 90% when the outdoor air temperature is 25ºC.
2. Thermal sensation scale B has a higher correlation with indoor air temperature than thermal sensation scale A did, as has been seen in previous studies (Kaneko et al., 2001).
3. PMV predicts a "too hot" thermal sensation.
4. The correlation between comfort temperature and outdoor air temperature is lower using Griffith's method in this study than that using indoor operative temperature when the thermal sensation votes are neutral on thermal sensation scale A.
5. The comfort temperature, which is close to the measured value, is predicted by using nonlinear regression analysis. Therefore, the adaptive model, which can be used over a wide range of outdoor air temperatures, is suggested. The correlation between comfort temperature and outdoor air temperature is higher than it is for the linear regression analysis.
6. After analyzing the comfort temperature using nonlinear regression analysis for all the data, it is found that the comfort temperature decrease as the outdoor air temperature increase when the outdoor air temperature is high, and the comfort temperature increase as the outdoor temperature decrease when the outdoor air temperature is low.

List of Abbreviations

ASHRAE : American Society of Heating, Refrigerating and Air-Conditioning Engineers

CL : Cooling by air conditioning is under use

FR : Free running mode i.e. air conditioning is not in use

FRo : Free running and window open

FRc : Free running and window closed

HT : Heating by air conditioning

SET* : Standard new effective temperature, °C

PMV : Predicted mean vote

T_o : Outdoor air temperature, °C

T_i : Indoor air temperature, °C

T_{op} : Indoor operative temperature, °C

N : Sample size

r : Correlation coefficient

R^2: Coefficient of determination

$S.E.$: Standard error

P : *p*-value

I_{cl} : Ensemble clothing insulation, clo

C : Thermal sensation vote

C_A : Thermal sensation A

C_B : Thermal sensation B

T_{cg} : Comfort temperature by Griffith's method, °C

$T_{cg}^{'}$: Predicted comfort temperature by Griffith's method, °C

T_c : measured indoor operative temperature when the thermal sensation votes are neutral on thermal sensation scale A, °C

$T_c{}'$: Predicted comfort temperature by linear regression analysis, °C

e : Residual, K

$T_c^{''}$: Corrected comfort temperature by residual, °C

$T_c^{'''}$: Predicted comfort temperature by logistic regression, °C

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Retrofit of educational facility through passive strategies in hot climate

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Abstract

Many countries worldwide are restricting their performance requirements for buildings, either by reducing energy consumption or air pollution. In Brazil, this is a growing scenario in regulation for the construction sector for new and old buildings. In the country, there is an old buildings stock in university campuses (mainly built between the 60's and the 70's). Most of these buildings must undergo a retrofit process to comply with those performance regulations at the same time improving thermal comfort. In this sense it is interesting to use passive strategies for this retrofit. This study is based on an existing building at the campus of Unicamp (State University of Campinas) in Campinas, Brazil. The building, from 1985, is used for research, office and teaching purposes. Indoor temperatures and humidity of a room were measured to calibrate a computer model and to simulate the effect of a solar chimney. The building was simulated with the software EnergyPlus and the air flow through the chimney with the Airflow Network module. Positive results were obtained providing thermal comfort for occupants and indoor air quality due to air renovation during working hours in summer according to ASHRAE Standard 55.

Keywords: Retrofit, solar chimney, thermal comfort, EnergyPlus

1 Introduction

There is a significant concern about the thermal performance of educational buildings. A comfortable environment is an important factor to the development of the activities of its occupants. Discomfort conditions caused by extreme temperatures, inadequate ventilation, high humidity among others may be harmful in a school environment for causing undesirable physiological and psychological effects like: somnolence, sweating and apathy (Labaki and Bueno-Bartholomei, 2001).

Researches carried out in educational buildings in Brazil reveal thermal discomfort of their occupants (Bernardi and Kowaltowski, 2006; Moraes, 2007; Moraes, Torres and Kiperstock, 2007). It was found high temperatures most time of the year that lead to punctual interventions and waste of energy. Researches worldwide also reveal thermal discomfort, waste of energy but also a potential of energy conservation and improve of thermal comfort (Neves, 2009; Saraiva, 2010; Dimoudi and Kostarela, 2009). This potential indicates an opportunity of intervention to improve the performance of buildings.

Retrofit of buildings is an important strategy to achieve energy conservation and satisfactory environmental conditions in the built environment. Accordingly to Bloom and Wheelock (2010) a deep retrofit can reduce more than 60% of the operational costs. In order to achieve good results from a retrofit process, planning of intervention actions is needed.

There are many procedures in literature to help planning retrofit actions. However their focuses are only on reducing energy or air pollution (in response to current standards of performance). Based on these procedures some tools have been developed to assist retrofit planning in its different levels as: diagnosis, evaluation of performance of strategies and decision of intervention. Recently, tools for decision interventions have been developed based on computational optimization but this procedure has not been yet adopted by the building industry (Murray et al., 2014).

Applying passive strategies can provide thermal and energetic benefits as shown by Hestnes and Kofoed (2002), Dascalaki and Santamouris (2002), Fernandes et al. (2014) and Li et al. (2014). The performance of passive strategies can be estimated by dynamic simulation with softwares that have become important tools to assess the retrofit process.

Retrofit actions are regulated in the United States and Europe (Moraes and Quelhas, 2011), while is not a much explored topic in Brazil. Recently the RTQ-C (Quality Technical Requirements for Energy Efficiency Level of Commercial, Service and Public Buildings) was released focusing on the energy efficiency of existing and new buildings (Brasil, 2010) and promoting the use of passive strategies. Despite this initiative there is no specific regulation for retrofit actions in Brazil and the lack of planning causes high investments with low return.

There is a need for retrofitting educational buildings in Brazil. There is an old building stock in Brazilian universities due to an expansion process from 1960 (Esteves, 2013) and the establishing of new standards focusing on energy efficiency. The aim of this paper is to apply a simple methodology for retrofitting an educational building with a passive strategy. Therefore, the thermal performance of a room with a solar chimney is evaluated by the adaptive method (de Dear and Brager, 1998).

2 Methodology

For the purpose of this paper an educational building located in the campus of the State University of Campinas, in the city of Campinas (Brazil), was chosen. Data from the construction, the use profile of the building together with measurements of indoor dry bulb temperature and relative humidity were used for modelling. The building was modelled with the plug-in Legacy OpenStudio of the software SketchUp and simulated with EnergyPlus.

A calibration process was taken to minimize differences between the virtual model and the real building. With the calibrated model, the solar chimney was modelled and simulated. The chosen period to calibrate the model and analyze the results is February, 2^{nd} to 6^{th}, 2015. It is important to note that differences exist in between measured and simulated data. Therefore in this study, the simulation tool was used to illustrate the difference between the same building in two scenarios in the same weather.

2.1 The city and the building

Campinas is a city located in the state of São Paulo (Latitude 23° and Longitude 47°). Its average temperatures and relative humidity through the year are presented in Figure 1. An important recommendation for designing buildings in Campinas is to utilize the prevailing Southeast wind and to have adjustable openings to control the air flow.

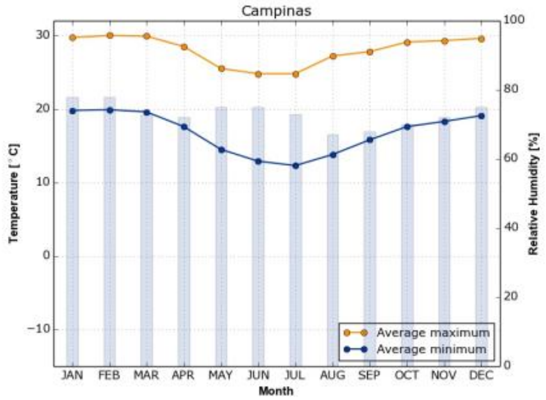


Figure 1 – Average temperatures and relative humidity through the year in Campinas.
Source: CEPAGRI (2015)

The three-storey building was built in 1985 and has a prismatic geometry. It is Southeast-Northwest oriented and surrounded by high trees. All the windows allow natural ventilation and they are shaded by external vertical elements (Figure 2). It is mainly used for teaching, research and office purposes.

Figure 2 – Southwest façade of the building.

2.2 Data measurements

Visits and interviews helped to characterize the building construction and the profile of use of the rooms. A sensor of dry bulb temperature and relative humidity was installed in an office room (room 23A, Figure 3 and Figure 4) at the third floor of the building. The measurements were taken hourly from December, 9th, 2014 to August, 3rd, 2015. During the period of measurements the room was normally occupied. It means that doors and windows were handled by the user and the researcher had no control of their operation.

Figure 3 – Plan of the third floor.

Figure 4 – Room 23A with sensor of temperature and humidity.

2.2 Modelling and calibrating the base-case

From acquired data, the building was modelled with the software SketchUp using the plug-in Legacy OpenStudio (Figure 5). The weather file used for the simulations was from the year 2002 edited with dry bulb temperature and relative humidity for the analyzed period (from February 2nd to 6th 2015). It can be seen in Figure 4 that there is a HVAC in the room. The air conditioner is old and inefficient, so that in the calibration process, best results were achieved without it.

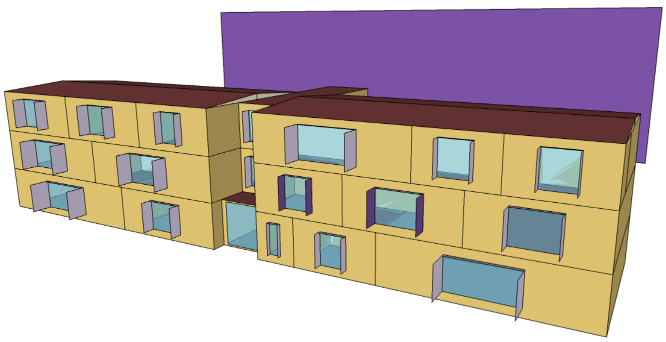


Figure 5 – Southwest view of the model.

The methodology adopted for calibrating the model was the same used by Pan, Huang and Wu (2007) and Raftery, Keane and O'Donnell (2011). An initial model was simulated and some parameters (shown in Table 1) were changed until the difference between the measured and simulated temperatures were within the limits, resulting in a base-case. The chosen indicators to validate the model are: NMBE (Normalized Mean Bias Error, Eq.2.1, CV(RMSE) (Coefficient of Variation of the Root Mean Square Error, Eq.2.2) and R^2 (Coefficient of Determination, Eq.2.3). For hourly data, according to ASHRAE (2002), a model is validated when NMBE ±10% and CV(RMSE) ±30%.

Table 1 – Tested parameters in calibration process.

Tsetpoint		Lunch break		People		Air change	
Initial	**Base**	**Initial**	**Base**	**Initial**	**Base**	**Initial**	**Base**
24°C	x	x	x	2	1	0	2

$$NMBE = \frac{\sum(y_i - \hat{y}_i)}{n \times \bar{y}} \times 100 \qquad \text{Eq.2.1}$$

where:

y_i = measured data

$\hat{y}_i$ = simulated data

n = number of data points in the period

$\bar{y}$ = arithmetic mean of the sample of n observations

$$CV(RMSE) = 100 \times \frac{\sqrt{\left(\frac{\sum(y_i - \hat{y}_i)^2}{n}\right)}}{\bar{y}} \qquad \text{Eq.2.2}$$

and

$$R^2 = \left(\frac{n \sum y_i \hat{y}_i - \sum y_i \sum \hat{y}_i}{\sqrt{\left(n \sum {y_i}^2 - (\sum y_i)^2\right)\left(n \sum {\hat{y}_i}^2 - (\sum \hat{y}_i)^2\right)}} \right)^2 \qquad \text{Eq.2.3}$$

2.3 Modelling the solar chimney.

The purpose of using a solar chimney is to increase the natural ventilation inside the room together with the natural ventilation provided by the existing openings. The windows face Northeast and they are not shaded by the surrounding trees. This situation results in too much heat entering the room by windows. The solar chimney was installed to take advantage of this situation, as the heated air inside the cavity will increase the air flow inside it.

The airflow through the solar chimney was modelled with the module AirflowNetwork from EnergyPlus (Figure 6). The chimney has a section of 1,0 m x 0,20 m that extends from the bottom to the top of the building. It has two openings, one on the top and another on the bottom that always allow the airflow (Figure 7). It was modelled an opening between the room and the chimney that is also always available for the airflow (Figure 8). The chimney is made of four layers: a common glass of 4 mm, an air cavity and a metal absorber plate and thermal insulation (rock wool, as suggested by Neves and Roriz (2012)) between the room and the cavity. The properties of the thermal insulation and the metal plate are presented in Table 2.

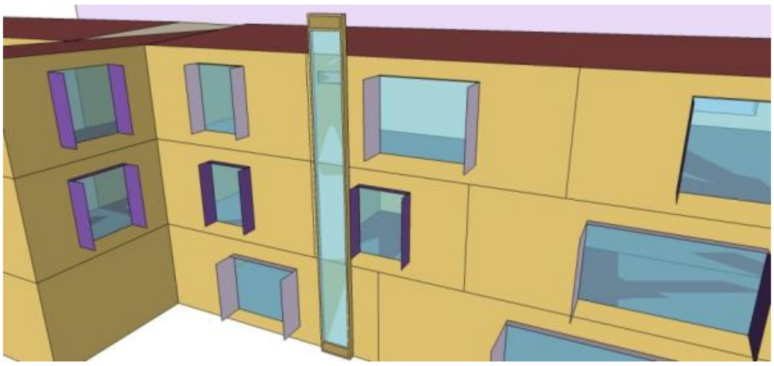


Figure 6 – View of the solar chimney modelled for the simulation.

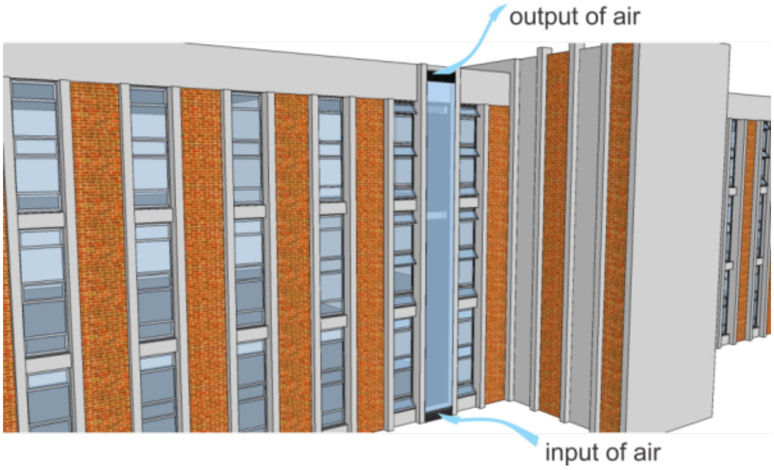


Figure 7 – The solar chimney in the building.

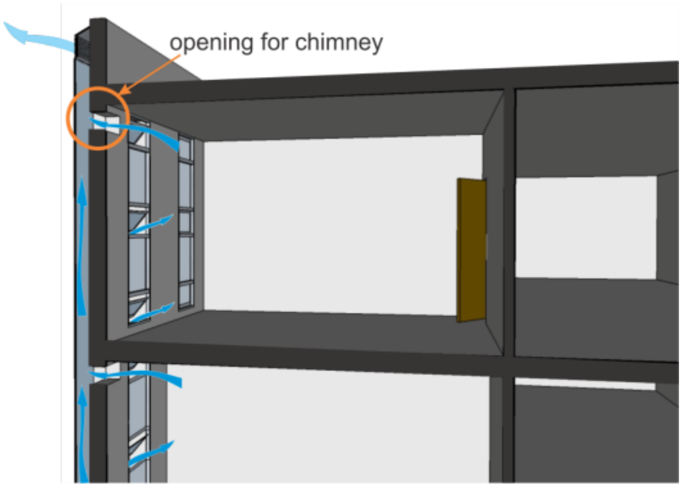


Figure 8 – The opening between the room and the chimney and a representation of the air flow through the openings.

Table 2 – Properties of the insulating and absorbing layers.

Properties	Thermal insulation (rock wool)	Absorber plate (aluminium)
Thickness	0,05 m	0,05 m
Thermal conductivity	0,03 W/mK	230 W/mK
Density	100 kg/m³	2700 kg/m³
Specific heat	754 J/kg°C	461 J/kg°C
Thermal absortance	0,9	0,8

3 Results

The result of the calibration process is presented in Figure 9. Although it was found differences up to 5°C between measured and simulated temperatures, the pattern of the simulated data is similar to the measured one and the model was validated according to ASHRAE (2002). The errors are within the acceptable range: CV(RMSE) of 12% (the limit is 30%) and NMBE of 1% (the limit is 10%).

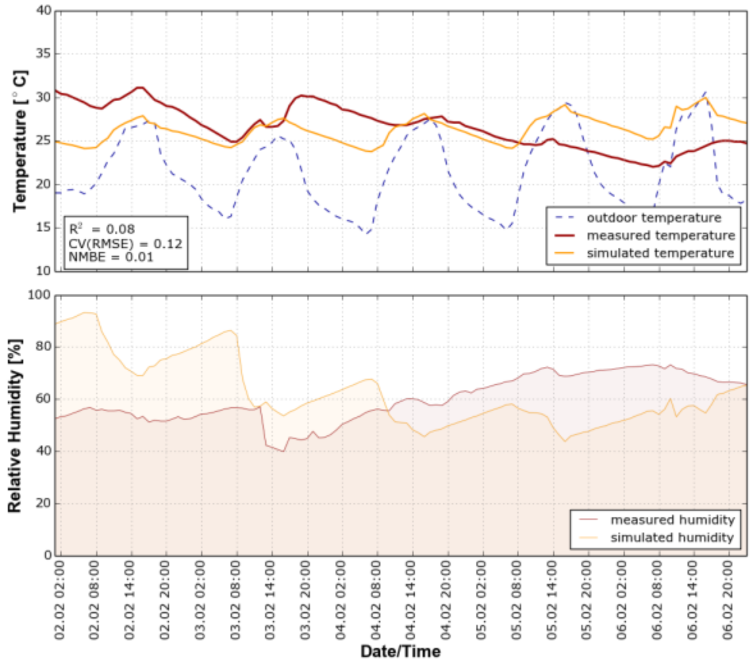


Figure 9 – Measured and simulated temperatures and relative humidity.

The heat removal provided by the solar chimney (Figure 12) helped reducing the humidity and up to 2°C inside the room (Figure 10). This infiltration brings air renovation improving the air quality of the room. For the thermal comfort analysis it was taken only the occupied hours during the week (total of 32 hours, Figure 11). The base-case presents 1 hour of comfort in the week (97% of working hours out of comfort limits), while the model with the solar chimney presents 8 hours of comfort (75% of working hours out of comfort limits).

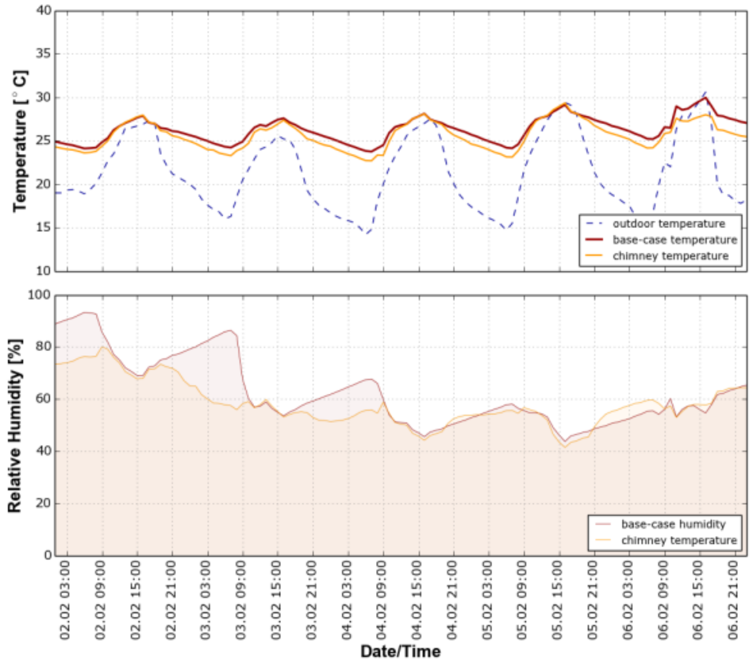
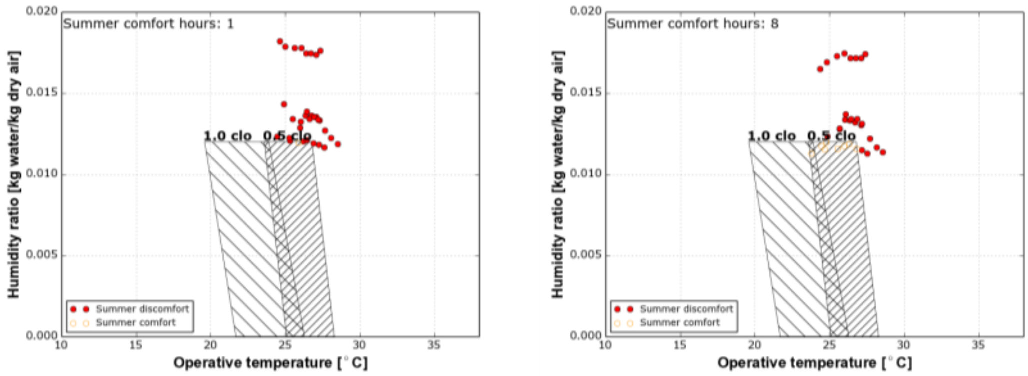
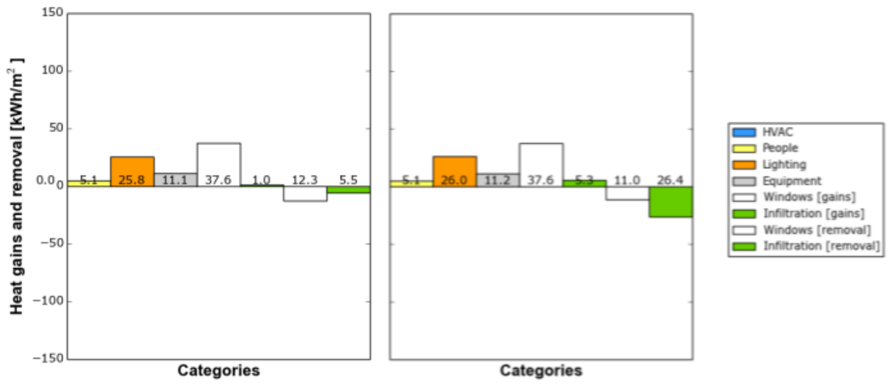


Figure 10 – Simulated temperatures and relative humidity for the base-case and the model with the solar - chimney.



(a) (b)

Figure 11 – Hours of thermal comfort in summer for the base-case (a) and the model with the solar chimney (b).



(a) (b)

Figure 12 – Sensible heat gains and removal for the base-case (a) and the model with solar chimney (b).

4 Conclusions

There is an old building stock in Brazil that needs to undergo retrofit actions to adequate its installations and improve its performance. Despite a reality of educational buildings with uncomfortable environments and waste of energy, most of the current standards of performance focus on the energy consumption and air pollution.

Passive strategies may be a good solution for thermoenergetic improvements in retrofit actions. Campinas has a very humid summer and one of the recommended design strategies is to take advantage of the local wind to remove the heat inside the building. The orientation of the studied building does not allow it to take advantage of the local wind for that. However the use of a solar chimney was useful to remove the sensible heat indoors reducing temperature and humidity.

The applied methodology was intended to be simple but reliable, based on the output variables from the measurements and the simulation and error indexes to calibrate the model.

The proposed strategy was designed in a way that has no much impact on the current design and it was marginally efficient on improving the thermal comfort of the occupants (from 97% to 75% of uncomfortable hours). The use of a passive strategy for retrofitting can be a good solution in terms of design and thermal comfort for this climate.

Acknowledgements

Luciana O. Fernandes would like to thank CAPES – *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior,* FAPESP – *Fundação de Amparo à Pesquisa do Estado de São Paulo* and CNPq – *Conselho Nacional de Desenvolvimento Científico e Tecnológico* for their financial support to this research.

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Thermal comfort of occupants during the dry and rainy seasons in Abuja, Nigeria

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Abstract
The paper presents the results of a recent study on the thermal comfort of occupants in four low-income residential buildings, at two different locations, within the hot-humid climate of Abuja. A comfort survey questionnaire was administered to occupants of four case studies to assess their perception of their thermal environment. Simultaneously, the indoor temperatures and relative humidity of the living room and bedroom spaces were monitored as well as outdoor parameters to evaluate the actual building performance. To support the comfort survey, a post-occupancy survey was carried out to evaluate an additional 86 buildings nearby in the case studies areas. The paper focuses on analysing the thermal conditions of respondents of the post-occupancy survey, the comfort survey and indoor monitoring findings from the case studies. The maximum daytime average temperature of the naturally ventilated buildings was only 2.0°C more than in the air-conditioned buildings. The maximum indoor air temperature in the living spaces during the dry season was 36.8°C (and 26.4% RH) and the minimum 28.4°C (and 66.6% RH), while during the rainy season these were respectively 35.9°C (and 43.7% RH) and the minimum 24.3°C (and 75.5% RH). The results suggest that there was significant thermal discomfort in the low income residential buildings.

Keywords: Thermal comfort; hot-humid climate; low-income residential buildings

1 Introduction

Dry season temperatures in residential buildings in tropical regions like Nigeria are becoming a major concern. High levels of solar radiation influence the heat produced in this region which increases the heat intensity felt by residents within the building as seen in high indoor temperature levels. These indoor temperatures can be a health hazard and as global temperatures are expected to rise, they can also be life threatening to occupants. Also, Indoor activities, rural urban migration, industrial process and deforestation contribute to the increase of these high indoor temperatures (Adunola, 2012).

The current high indoor temperatures experienced in residential buildings, especially those in the big cities like Abuja in Nigeria are thermally uncomfortable for a substantial period of time (Adunola and Ajibola, 2012). Unfortunately, the housing condition in the country is of extreme worry as it is largely of poor quality and standard in both rural and urban centres. The increase in the quantity of housing needs has led to a major and evident concern about the quick deterioration of current housing stock leading to a shortage of housing units (Olayiwola et al., 2005). Hence, because of the rush to meet demand, builders tend to focus more on quantity rather than quality, therefore compromising standards and indoor comfort. This in turn creates buildings with poor thermal properties i.e. buildings that allow high levels of solar gain into the building fabric, subsequently increasing discomfort to occupants and increasing the energy use especially that meant for cooling the indoor environment. Comfort levels are usually poor, as a result of the construction or lack of ventilation in the roof. These building can't last for longer periods before they start deteriorating. As a consequence, most occupants now rely on mechanical cooling mostly, fan and air conditioning, to achieve thermal comfort.

Mechanical cooling is largely dependent on electricity in Nigeria of which the residential buildings sector consumed 53.3% of electricity generated as seen in the Federal Government of Nigeria's 2009 vision 2020 report in (Oyedepo, 2014); (Adaji et al, 2015). However, due to the lack of reliable and continuous power supply from the national grid, mechanical cooling systems in residential buildings are not really dependable to provide cooling. Also these cooling mechanisms, like air-conditioning require lots of energy to run and maintain. Hence, the continuous running of air-conditioning is not feasible and sustainable (Adaji et al, 2015). In addition to the lack of constant power supply, people tend to turn to generators as a back-up power supply for their electrical appliances especially for mechanical cooling.

The construction and building sector may also be a contributing factor to the problem of indoor heat gain. There's little or no regard to thermal comfort concerns and local climate when designing and constructing buildings. Most materials used in construction today, especially the sandcrete blocks for walling, made of sand, cement and water mix, don't have sunlight reflection and insulation qualities. Also, they don't have an effective shield or insulation between the building interior and the outdoor environment. As a result, the building through its opaque fabric, experiences high level of solar gain. This also causes thermal discomfort to occupants of these buildings given the hot climate of Nigeria (Adaji et al, 2015).

A thermal comfort study was carried out in Abuja, with a view to understanding the conditions of residents in buildings across two different residential neighbourhoods in the city, during the dry and rainy seasons. This paper tries to understand the ideal and preferred conditions of thermal comfort in low-income (in the lower half of the income spectrum) buildings in Abuja, Nigeria. Furthermore, monitoring of air temperatures and humidity was carried out to determine the maximum, minimum and average values and also the way people adjust to achieve thermal comfort in buildings located in this area in order to understand what residents are experiencing. Studies such as this could also assist the improvement and recommendations of diverse levels of tropical comfort considerations required in the standards (Djongyang et al. 2010).

2 Conditions for achieving thermal comfort in buildings

Thermal comfort can be described as satisfaction with thermal sensation felt within an indoor climate; the occupants in their indoor environment should be satisfied with their indoor climate of the time (de Dear and Brager, 2002). For people to find a building thermally comfortable, building designers should provide certain thermal comfort standards to attain or improve indoor climates. Occupants should be thermally comfortable in a building and its sustainability should be increased by reducing its energy consumption potential (Nicol and Humphreys, 2002). In ASHRAE standard 55 (1992), it describes attaining thermal comfort as when the 'indoor space environment and personal factors produce a thermal environmental condition acceptable to 80% or more of the occupants within a space' (ASHRAE 1992; de Dear and Brager, 2002). In thermal comfort quality for residential buildings; the materials used, nature of building, the variations to the building structure and installation in all situations are very important options to use when relating the influence of changes to building, which must be maintained at all times (Peeters *et al.,* 2009).

3 Thermal comfort in a Hot-humid climate

Attaining thermal comfort is crucial for health and efficiency for the people in the building. Researchers have used indoor thermal measurements such as ISO 7730 and the ASHRAE standard 55 (ASHRAE, 2004) to determine indoor thermal comfort and expression of satisfaction by that condition of mind with the thermal environment. The results and analyses from these experiments have created thermal comfort templates, definitions and standards which are used in temperate regions; after all it was developed to serve the temperate climate.

There have been many studies carried out in hot humid climates with most results showing a wide range of temperatures at which people feel comfortable (comfort or neutral temperature) measured in air-conditioned (AC) and naturally ventilated (NV) buildings as seen in Table 1 below

Table 1: Neutral temperature results from field experiments conducted in hot-humid climates

Year	Researcher	Building	Location	Neutral temperature of subjects	
1990	J.F Busch	Office	Bangkok, Thailand	24.5°C (ET) for AC buildings	28.5°C (ET) for NV buildings
1991	R.J. de Dear, K.G. Leow *et al.*	Residential and office	Singapore	24.2°C for AC buildings	28.5°C for NV buildings
1994	R.J. de Dear, M.E. Fountain	AC Office	Townsville, Australia	24.2°C for AC buildings	24.6°C for NV buildings
1998	T.H. Karyono	Office	Jakarta, Indonesia	26.7°C for AC buildings	
1998	W.T. Chan *et al.*	Office	Hong Kong	23.5°C for AC buildings	
1998	A.G. Kwok	Classroom	Hawaii, USA	26.8°C for AC buildings	27.4°C for NV buildings
2003	N.H. Wong *et al.*	Classroom	Singapore		28.8°C for NV buildings

Source: Hwang *et al.* (2006) in Akande and Adebamowo, (2010)

Furthermore, studies in sub-Saharan Africa have shown most neutral temperatures are above 26.0°C as seen in Ogbonna and Harris (2007), a study carried out on naturally ventilated buildings in Jos, Nigeria achieved an operative temperature of 26.1°C, though the neutral temperature was 25.06°C. Also a study in Lagos, Nigeria by Adebamowo, (2007) achieved a neutral temperature of 29.1°C. In Akande and Adebamowo, (2010) a study on naturally ventilated residential buildings in Bauchi, Nigeria, gave a neutral temperature of 28.4°C. In Cameroun, Djongyang and Tchinda, (2012) did a survey in an inter-tropical climate in a naturally ventilated building, the thermo neutral temperature range from this experiment was 24.7°C – 27.3°C.

From the results of studies conducted by different researchers around the world, it shows that neutral temperatures have exceeded the higher range of comfort temperature, 26.0°C prescribed by Fountain et al. (1999) and the ISO EN 7730 (1994) standard. Though the studies have proven to be important, their findings have yet to be widely recognized as a comprehensive way for naturally ventilating buildings in the tropics (Adebamowo, 2007). As a result of previous research suggestions, the wider range of comfort conditions in reality is where occupants have the sensation of feeling comfortable. Also their environment is affected by several factors like physiological adaptations (experiences, acclimatisation), psychological adaptations (expectations) and behavioural adjustment (modifications made by a person consciously or unconsciously) which could contribute to occupants adapting to changes (Adebamowo, 2007; Peeters et al., 2009).

Regarding human thermal comfort, there has been much documented material worldwide from physiological, adaptive and social hypotheses but throughout sub-Saharan Africa especially the tropic regions, there have been few literature reports on comfort of occupants and residential thermal environment. The tropics may require a different level of comfort parameter in the standard, besides the current standards are almost based on experiment across a variety of climatic zones including temperate, hot-humid and cold regions (Djongyang et al. 2010). Furthermore, there is little or no literature reported on indoor comfort for residential occupants in Abuja.

This paper is aimed at filling this gap by investigating the indoor thermal comfort for occupants and their thermal environment.

4 Study Area

The study area falls within latitudes 7º 20′ and 9º 20′ north of the Equator and longitudes 6º 45′ and 7º 39′. The area now designated the Federal Capital Territory (F.C.T.), Abuja, Nigeria's capital, falls within the Savannah Zone vegetation of the West African sub region with Patches of rain forest. As it is in the tropics Abuja experiences two weather conditions annually; the rainy season which begins in April and ends in October and the dry season which begins in October and ends in April, but within this period, there is a brief interlude of harmattan, a period when the North East Trade Wind moves in with the main feature of dust haze, intensified cool and dryness. Fortunately, the high altitudes and undulating terrain of the FCT act as moderating influence on the weather of the territory. The maximum daytime air-temperature ranges from 28°C to 35°C and a minimum night-time temperature ranging from 18°C - 23°C (World climate guide, 2014); (Abubakar, 2014).

4.1 Case Study Description

Four case studies in two locations (Lugbe and Dutse Alhaji) in Abuja were identified in order to investigate the thermal comfort of occupants with their means of ventilation (natural ventilation and air conditioning), purpose of construction (for low income group) and building type (low rise building) as their main criteria.

All the roofs of the buildings selected for this study were unventilated but had a ceiling between the roof space and the rooms. Roof overhangs were in the range of 0.6m - 0.7m. The floor to ceiling height was between 3m - 3.2m. The buildings were all ventilated using operable windows and none of the external windows had shading devices. The walling material comprises mainly sandcrete blocks, which have a dimension of 45cm x 23cm x 23cm for external walls and 45cm x 15cm x 23cm for internal partitions walls like toilets and bathrooms.

The case studies are located in low and low-middle income areas, which can be defined as an area where residents earn the minimum wage of N18,000.00 (GBP 45.00 at N400.00 = GPB 1.00) to four times the minimum wage (Ekong and Onye, 2013). Most people in this area have more than one job and tend to save over time to build or rent better houses, therefore the façade of some of these houses might look like those meant for the middle income areas, but most often, they are not usually built to the recommended standard set by the housing authorities in Abuja.

Case study 1, Lugbe (LGH1), (Figures 1, 2 and 3) is located in a low-middle income area (officially designated a low-income area) called Light Gold Estate just off the express way linking the international airport in Abuja to the city centre. It's a north facing, 3-bedroom detached bungalow, built with sandcrete blocks, has aluminium roofing and is naturally ventilated.

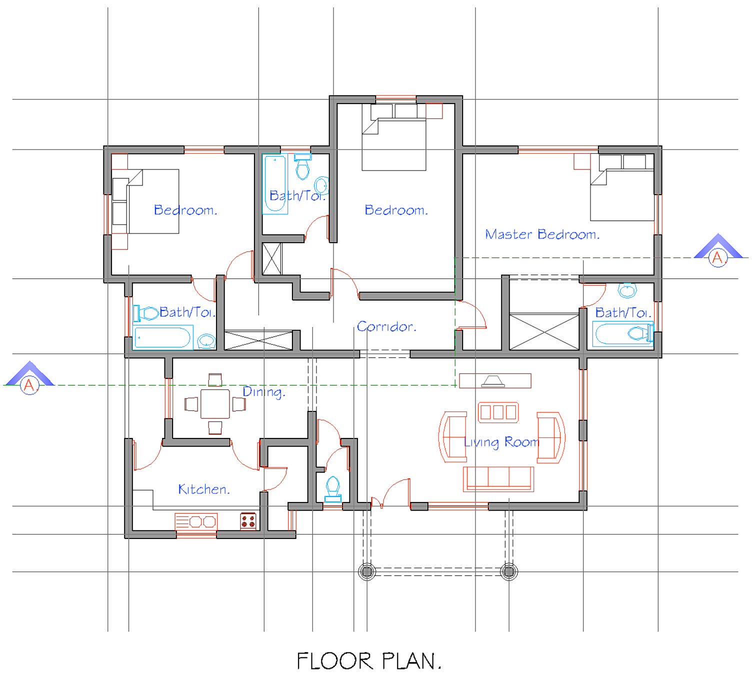


Figure 1: Floor plan of Case Study 1 in Lugbe, Abuja

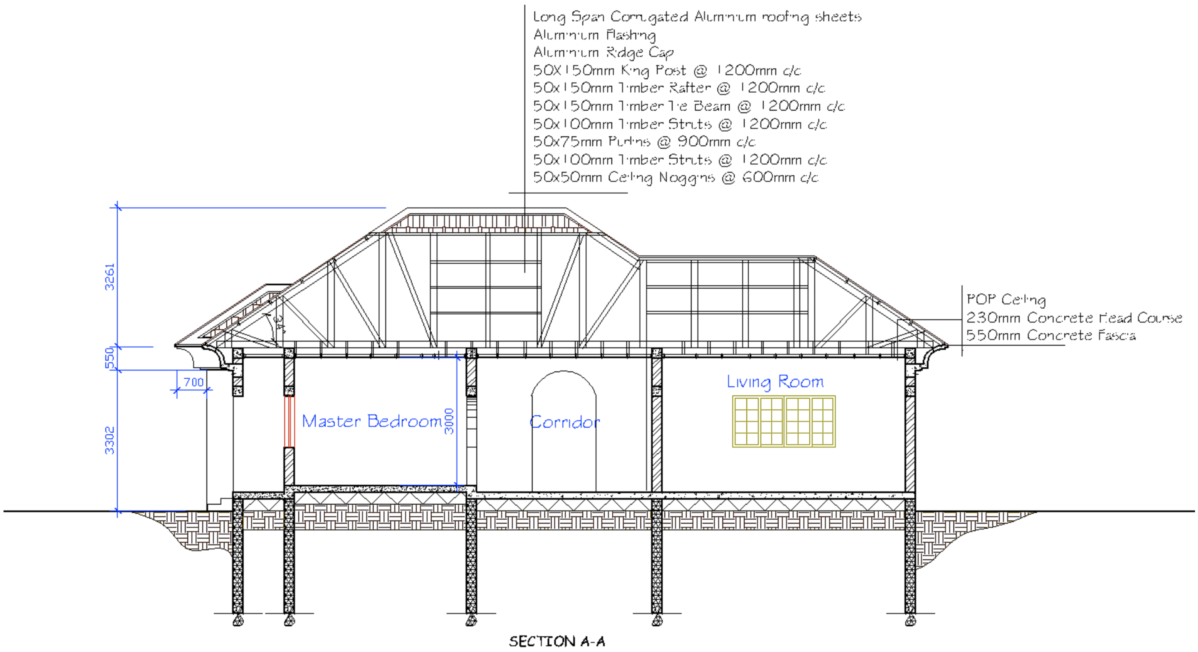


Figure 2: Section A-A of Case Study 1 in Lugbe, Abuja

Figure 3: Front view of Case Study 1

Case study 2, Lugbe (LGH2), (Figures 4 and 5) is located in a low-middle income area in Lugbe and it's in the same location as the first house only not in the same estate but north of the first case study, called Trade Moore Estate. It's an air-conditioned, north facing 2-bedroom semi-detached bungalow, built with sandcrete blocks and has aluminium roofing.

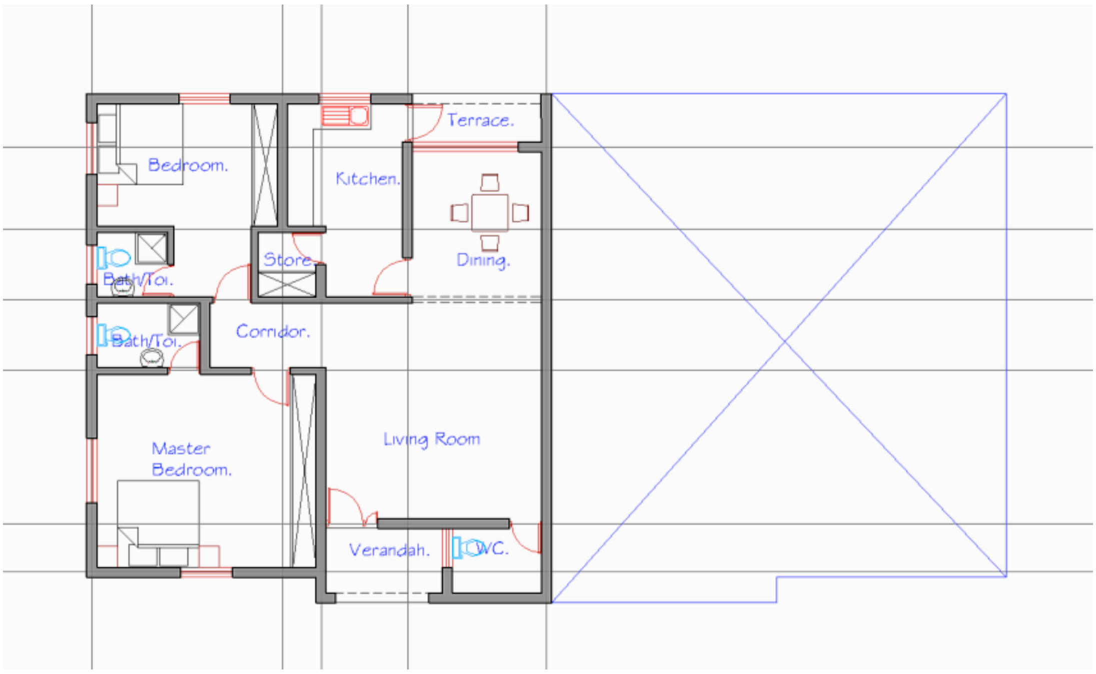


Figure 4: Floor plan for Case study 2 in Lugbe, Abuja

Figure 5: Main building, Case study 2

Case study 3 (DAH1) in Dutse Alhaji, (Figures 6, 7 and 8) is located in a low-income, high density area. The building is naturally ventilated and has a painted exterior. It is roofed with iron sheets and built with sandcrete blocks. It's in a sound state, although it needs some minor repairs. Finally, Case study 4 (DAH2) (Figures 6 and 8) is located in the same area and is a 1 bedroom flat attached to DAH1. It is air conditioned and it's also in a sound state but needs minor repairs too.

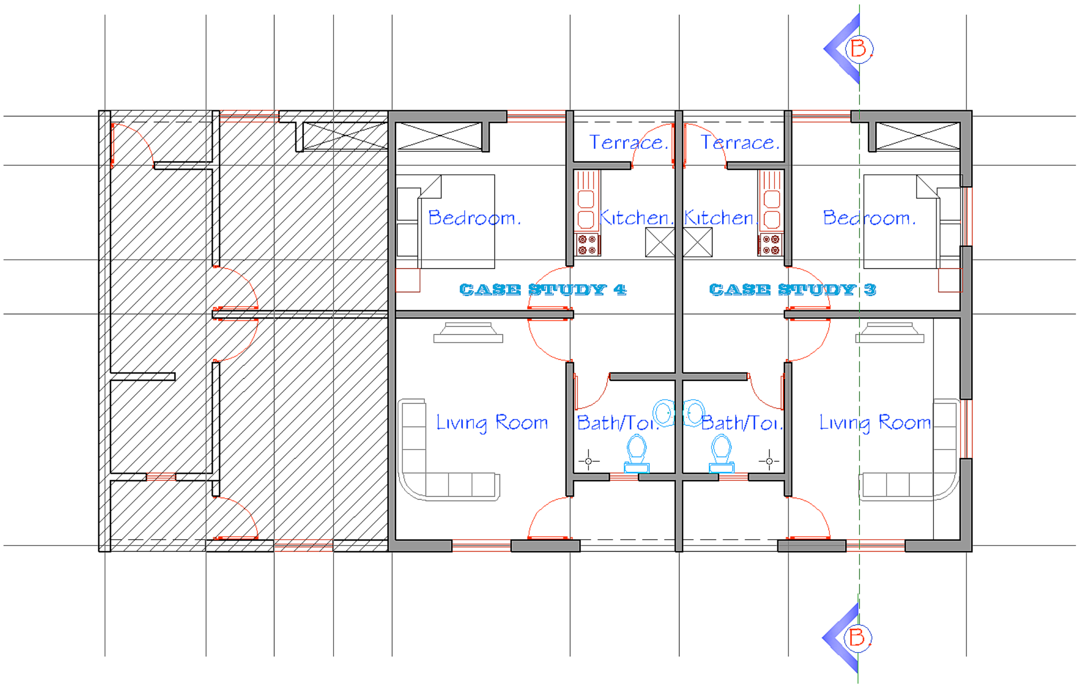


Figure 6: Floor plan for Case studies 3 and 4 in Dutse Alhaji, Abuja

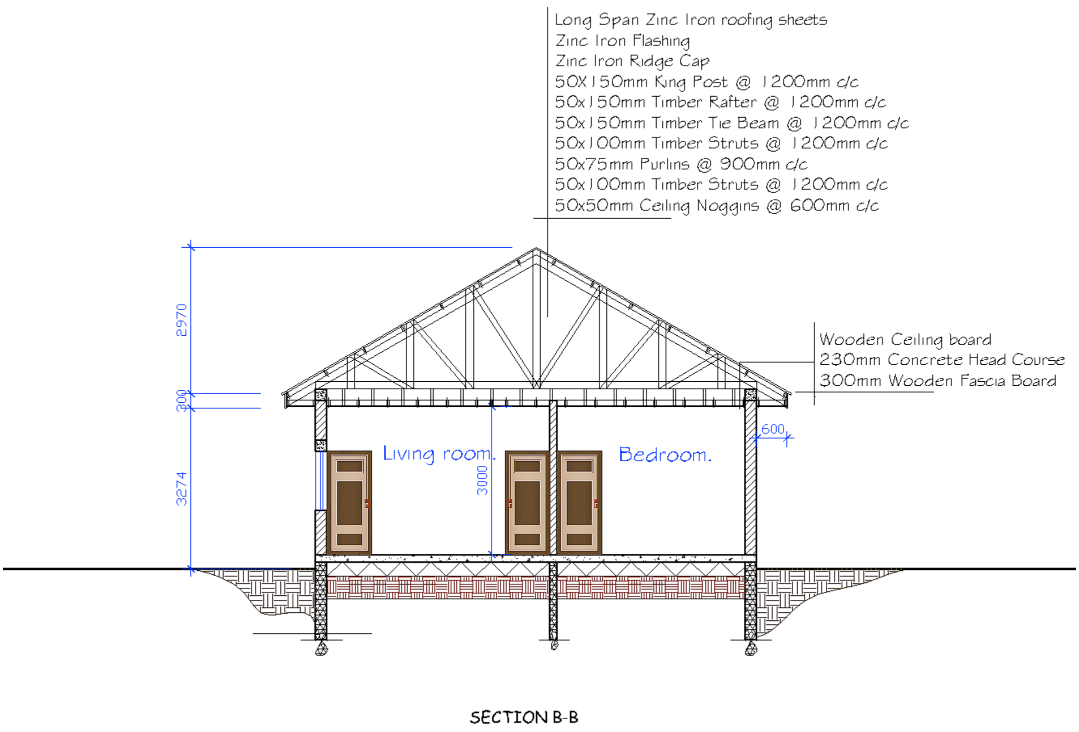


Figure 7: Section B-B of the Case Study 3 in Dutse Alhaji, Abuja

Figure 8: Main building, Case studies 3 and 4 in Dutse Alhaji, Abuja

5 Research methods and techniques used for this research

The methodology for the survey included environmental monitoring, with post-occupancy and comfort surveys. These surveys were aimed at obtaining a comprehensive understanding of occupants' thermal comfort sensation within the buildings and occupants' energy demands and use.

5.1 Post-occupancy Survey

Post-occupancy surveys help understand and compare the nature and frequency of occupants' views that cannot be measured during surveys, especially why they feel warm or hot. That's why they are critical in increasing the value of the thermal environment, (Nicol & Roaf, 2005); (Adekunle and Nikolopoulou, 2014). This survey focused on dwellings other than the case study buildings but situated in the same area. They add breadth and support the results from the individual case studies. Each questionnaire in the current study has 31 questions, requiring 8-10 minutes to complete. Questions on overall thermal comfort and thermal satisfaction in different seasons were asked for respondents to evaluate. The questionnaire was divided into three main sections: Section A, includes background information about their location, gender, age, socio-economic status, educational and occupancy status; Section B, asks about building attributes and energy consumption including house type, number of rooms in the building and duration of occupancy; Section C, considers indoor thermal conditions and looks at how residents make themselves comfortable by opening and closing windows or doors, and clothing type. Overall 109 questionnaires were distributed, 100 (92%) were returned and of these 86 (79%) were correctly completed. The questionnaires were self-administered and survey visits were conducted between 6.30am and 18.00pm (Figure 9).

Figure 9: Post occupancy survey

5.2 Comfort Survey

Thermal comfort questionnaires were issued to the occupants of the dwellings monitored. They were asked to complete the questionnaires three times per day to assess their thermal comfort state, (using the seven-point ASHRAE thermal sensation scale and a five-point preference scale). Further information on clothing insulation and activity was also collected. The comfort survey was designed as a daily diary evaluating occupants' responses to discomfort and how they achieve comfort at various times of the day (morning, afternoon and evening) for a week. These data were used to support the physical data collected at the same time.

5.3 Environmental Monitoring

The field survey was conducted during the dry and rainy seasons from 18/03/15 to 18/04/15 and 17/06/15 to 12/07/15 respectively. Air temperature and relative humidity were recorded using HOBO Temperature and Relative Humidity sensors installed on the internal walls at a height of 1.1m above the ground floor level. Four dwellings were monitored in Abuja, with two spaces representing the living area and bedroom area monitored in each case study. The outdoor environmental conditions measured were air temperature and relative humidity using Tiny Tag T/RH sensors inside a radiation shield. Data was recorded every 15 minutes (Figure 10).

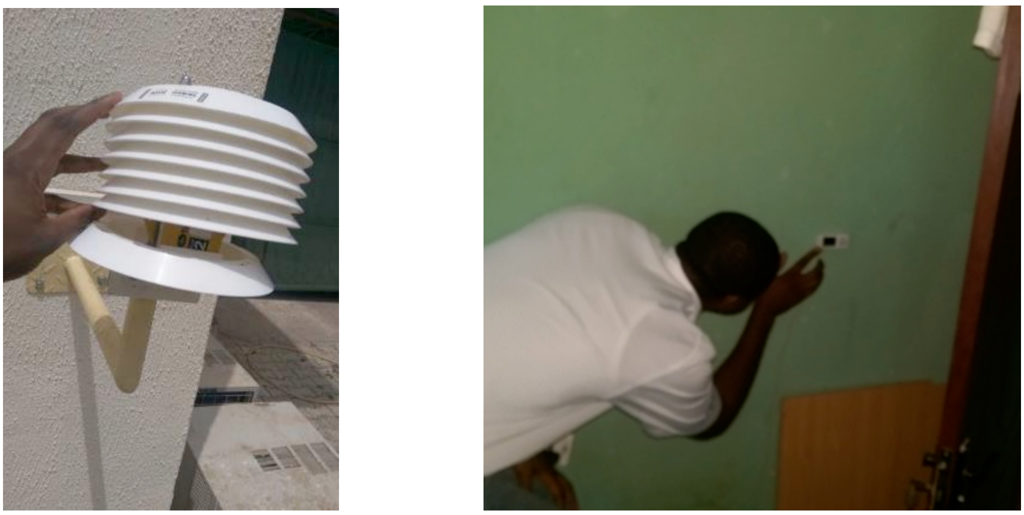


Figure 10: Installation of Tiny Tag outdoor logger and indoor Hobo T/RH sensors

6 Data analysis and Results

6.1 Analysis of Post-Occupancy Survey

Lugbe had 43 valid questionnaires returned (79% response), of which 26 (60.5%) were male and 17 female (39.5%). Most of the respondents were from the (31-45) age group, 24 (55.8%) and 17 (39.5%) from the (18-30) age group. Dutse Alhaji had 43 valid questionnaires returned (80% response), with 33 (76.7%) male and 10 (23.3%) female responses. The age response breakdown was 33 (76.7%) for the (31-45) and 10 (23.3%) from the (18-30) age group.

In the dry season, the warm part of the scale had a much greater response across all the respondents of the case studies, with 74.4% of occupants feeling ‘warm’ or ‘hot’ at Lugbe and 86.1% at Dutse Alhaji (figure 11). In contrast, in the rainy season, there was a clear shift to the ‘cool’ part of the scale for respondents in Lugbe with more than 67.0% feeling ‘cool’ or ‘slightly cool’, whilst 52.9% of respondents in Dutse Alhaji felt ‘cool’, ‘slightly cool’ or ‘neutral’ (figure 12). The mean thermal sensations for Lugbe and Dutse Alhaji (Table 2) in the dry season were around the ‘slightly warm’ and ‘warm’ while in the rainy season between ‘cold’ and ‘neutral’. The overall thermal sensation results across the two case studies show that 80.2% felt either ‘warm’ or ‘hot’ during the dry season compared to 29.1% that felt ‘slightly warm’ or ‘warm’ during the rainy season

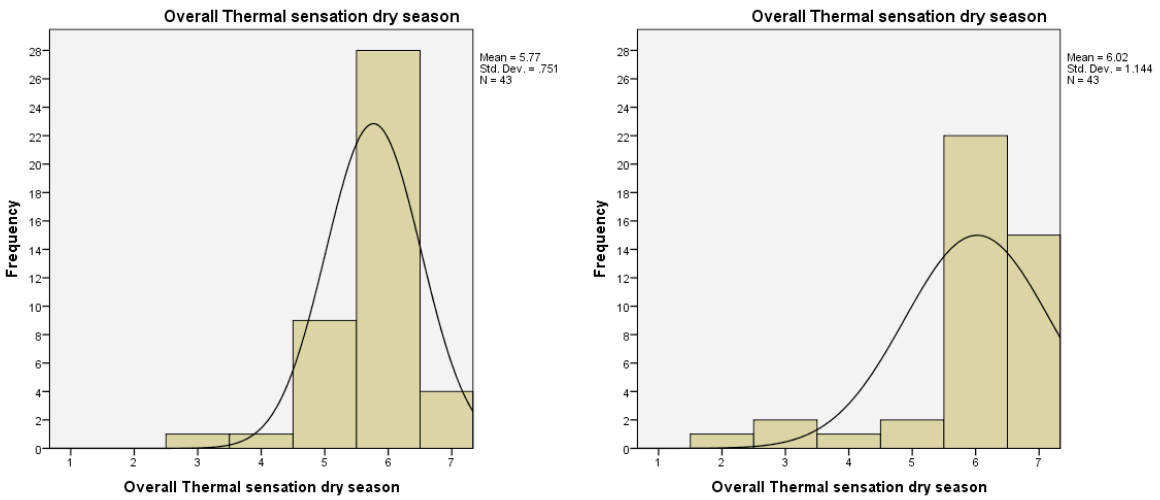


Figure 11: Distribution of overall thermal sensation votes during the dry season in Lugbe (left) and Dutse Alhaji (Right) (Scale: 1 = Cold to 7 = Hot)

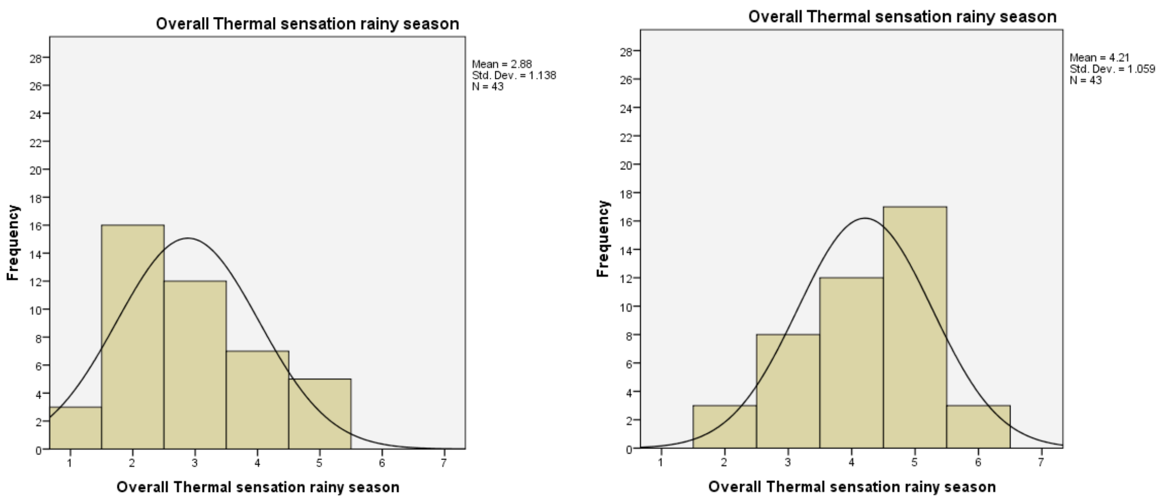
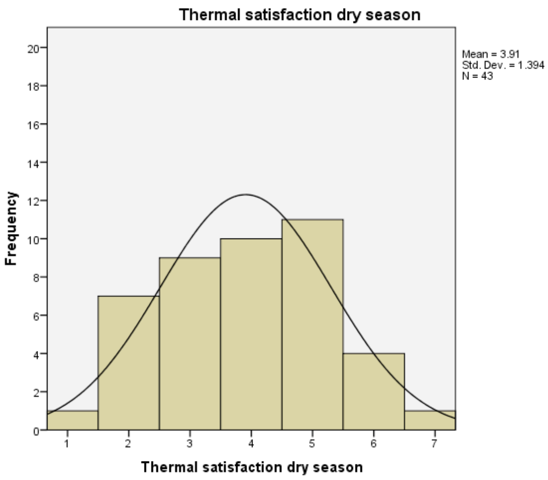


Figure 12: Distribution of overall thermal sensation votes during the rainy season in Lugbe (left) and Dutse Alhaji (right) (Scale: 1= cold to 7= hot)

Table 2: Post occupancy survey mean responses for the overall thermal sensation, thermal satisfaction, overall thermal comfort in the dry and rainy season

Case study	Overall Thermal sensation (Scale: 1= cold to 7= hot)		Thermal satisfaction (Scale: very dissatisfied to 7= very satisfied.)		Overall thermal comfort (Scale: 1 = very comfortable to 7= very comfortable)	
	Dry season	Rainy season	Dry season	Rainy season	Dry season	Rainy season
Lugbe	5.8	2.9	3.9	5.4	3.6	2.5
Dutse Alhaji	6.0	4.2	2.1	3.3	5.3	3.9

The thermal satisfaction was measured on a 7-point scale with 1 for very dissatisfied to 7 for very satisfied. In Lugbe, 37.2% were satisfied with their thermal environment compared to 90% of respondents of Dutse Alhaji that were either 'very dissatisfied', 'dissatisfied' or 'slightly dissatisfied' (Figure 13).



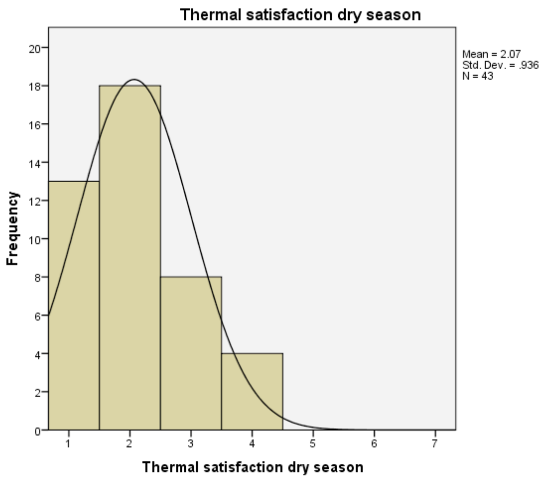


Figure 13: Distribution of thermal satisfaction votes during the rainy season in Lugbe (left) and Dutse Alhaji (right) (Scale: 1= very dissatisfied to 7= very satisfied.)

A 7-point scale (from 1 for very uncomfortable to 7 for very comfortable) was used for the overall thermal comfort. There was an almost even distribution of the comfort votes in Lugbe where 49.5% were dissatisfied, i.e. only slightly skewed towards discomfort. However, 81% of the respondents in Dutse Alhaji indicated they were uncomfortable with their thermal environment (Figure 14). These results suggest that the thermal environment has been influenced by the air-conditioning in these buildings especially in Lugbe, where 65.1% use air-conditioning in their living rooms and 58.1% in their bedroom while in Dutse Alhaji, 37.2% use air-conditioning in their living room and 30.2% in their bedroom, indicating Lugbe has more air-conditioning users compared to those in Dutse Alhaji.

For the rainy season, the respondents in Lugbe showed a substantial shift in overall thermal comfort vote towards the comfort part of the scale, with 76.7% feeling 'slightly comfortable' or 'comfortable', while 58.1% of respondents in Dutse Alhaji were 'neutral', 'slightly comfortable' or 'comfortable' (Figure 15).

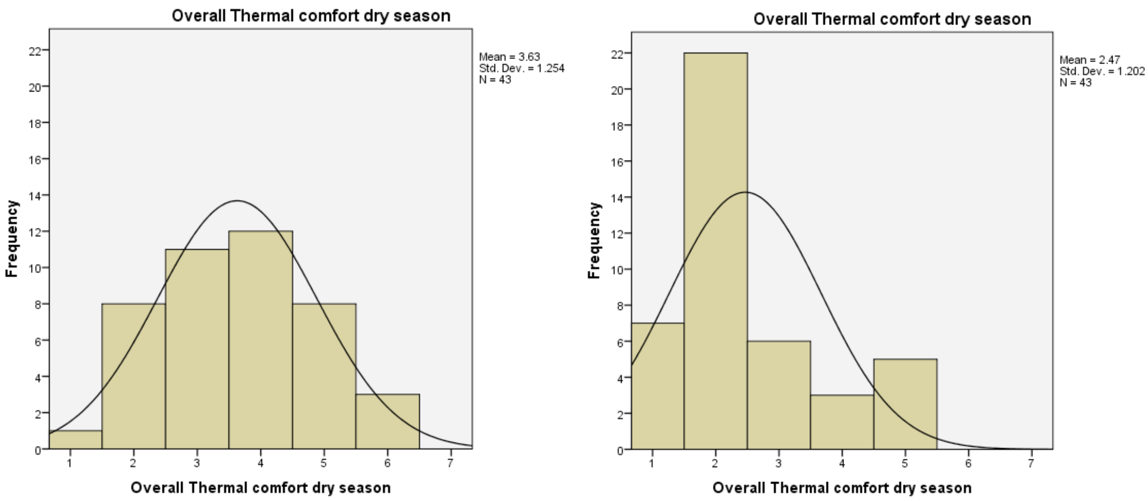


Figure 14: Distribution of overall thermal satisfaction votes during the dry season in Lugbe (left) and Dutse Alhaji (right) (Scale: 1= very uncomfortable to 7= very comfortable)

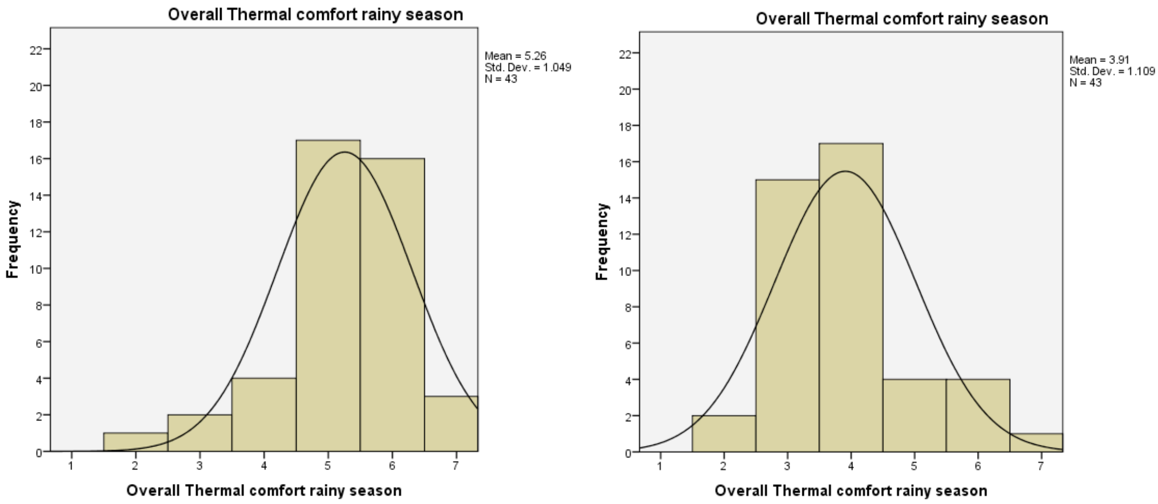


Figure 15: Distribution of overall thermal satisfaction votes during the rainy season in Lugbe (left) and Dutse Alhaji (right) (Scale: 1= very uncomfortable to 7= very comfortable)

6.2 Analysis of Comfort Survey

105 thermal comfort questionnaires were administered during the dry season and 71 were received (67.6% response), while 105 were administered during the rainy season and 55 were received, (52.4% response).

The comfort surveys (Figures 16 and 17) show most of the occupants were feeling warm with most of the distribution of votes varying from 'slightly' warm' to 'hot'. The results suggest that 50% of the time the occupants in Lugbe LGH1 felt 'warm' while 25% of the time occupants in Lugbe LGH2 felt 'warm'. Also, 77% of the time the occupants in Dutse Alhaji DAH1 felt 'warm' compared to 25% of the time in Dutse Alhaji DAH2. The 25% warm votes recorded in Lugbe LGH2 and Dutse Alhaji DAH2 can be attributed to the use of air-conditioning in these dwellings.

The majority of the residents spent 12 hours inside the house per day and most of the participants from the survey have lived in the case study buildings for over 36 months. The residents in Lugbe owned the properties they live in while the occupants in Dutse Alhaji lived in rented buildings.

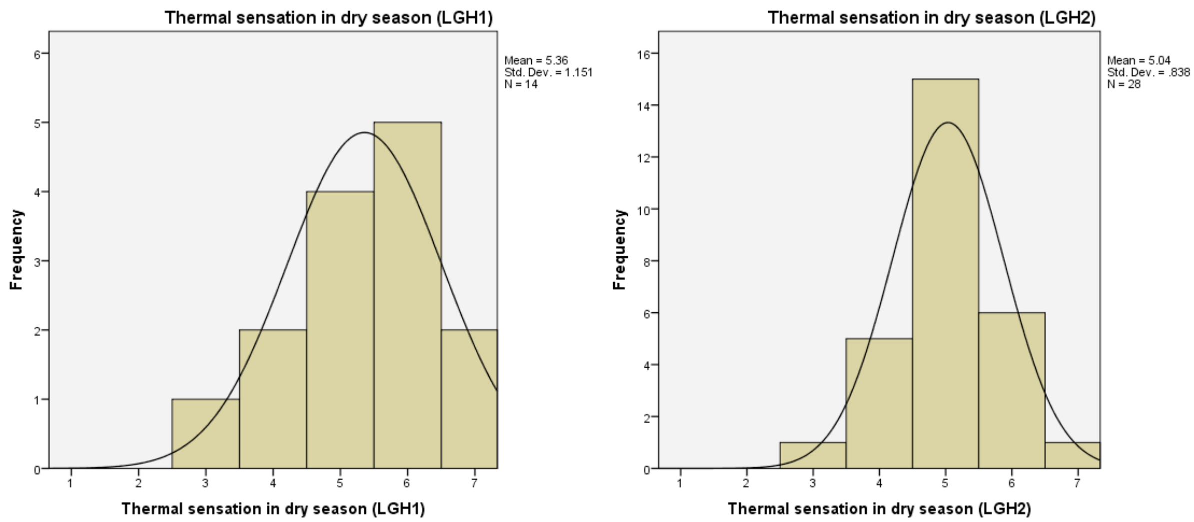


Figure 16: Distribution of overall thermal sensation votes during the dry season in Lugbe with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= cold to 7= hot)

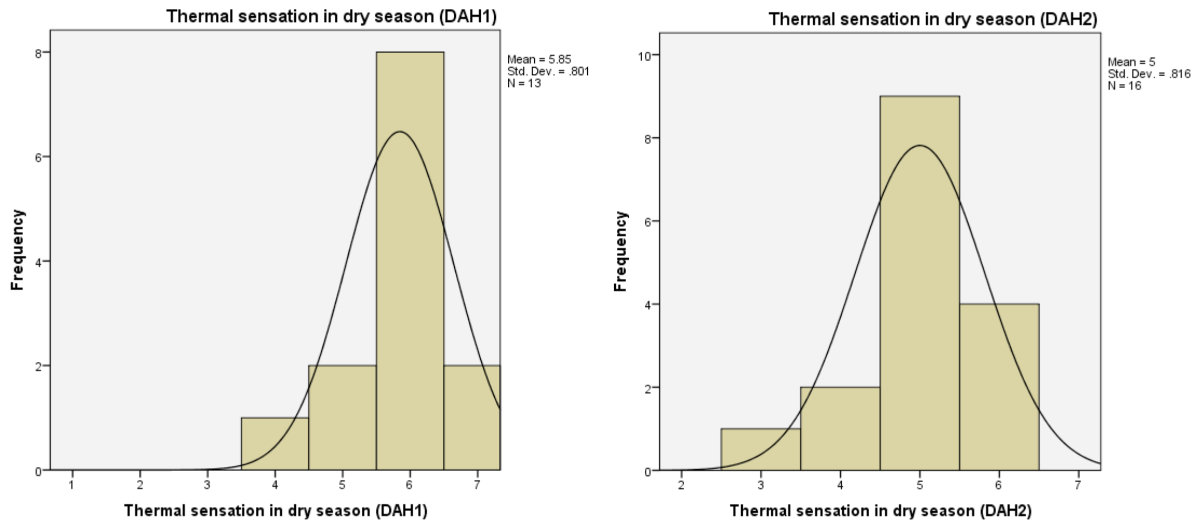


Figure 17: Distribution of overall thermal sensation votes during the dry season in Dutse Alhaji with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= cold to 7= hot)

There was a shift in the thermal sensation mean votes during the rainy season to the cool and neutral part of the scale (Figures 18 and 19). More than 67% of the time the residents in Lugbe felt either ‘slightly cool’ or ‘neutral’ or ‘slightly warm’ compared to more than 88% of the time in Dutse Alhaji that either felt ‘neutral’ or ‘slightly cool’. The results further suggest that most of the time the residents in the case studies in Dutse Alhaji felt warmer in the rainy season compared to residents in Lugbe.

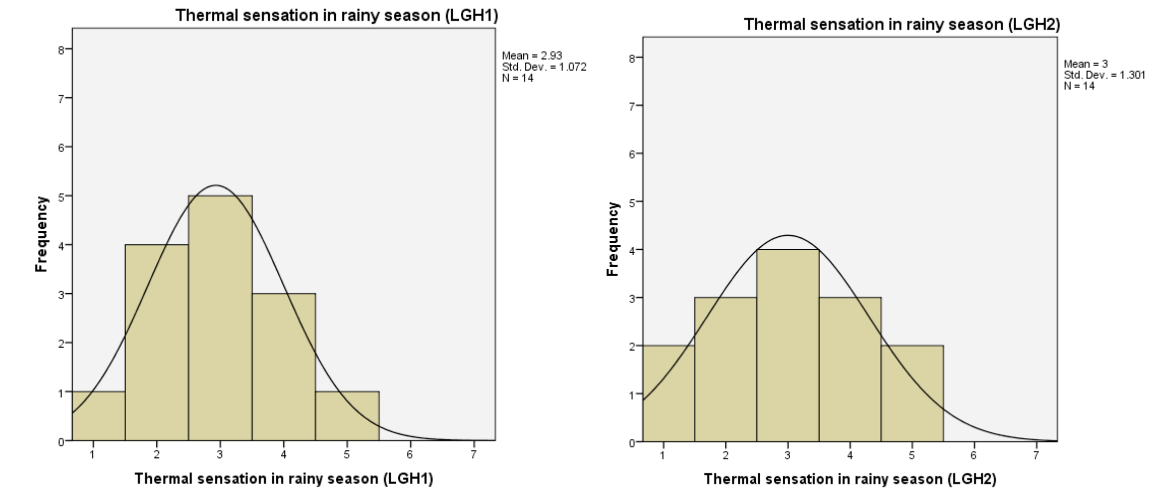


Figure 18: Distribution of overall thermal sensation votes during the rainy season in Lugbe with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= cold to 7= hot)

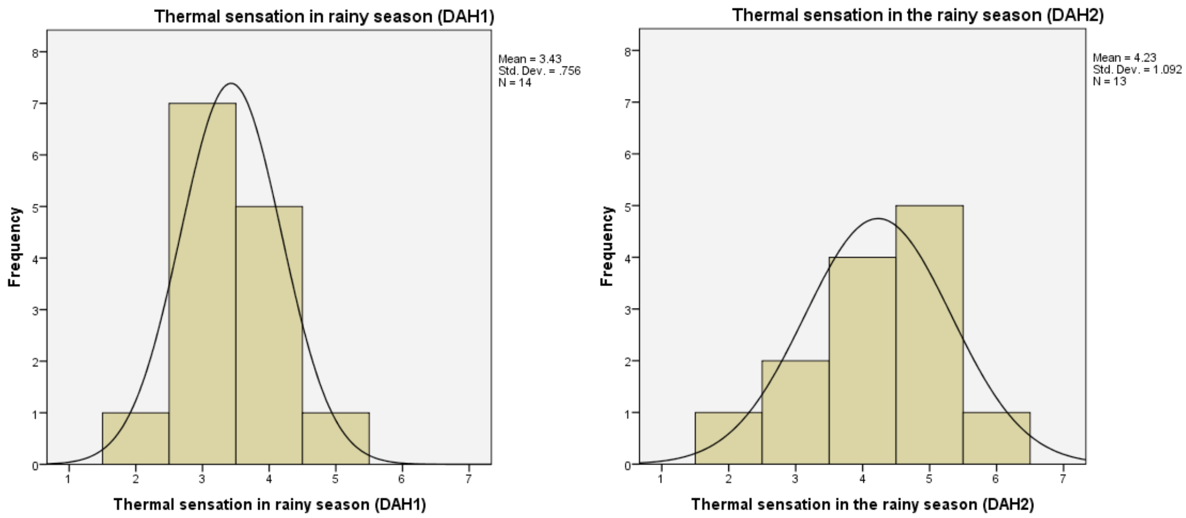


Figure 19: Distribution of overall thermal sensation votes during the rainy season in Lugbe with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= cold to 7= hot)

Table 3: Comfort survey mean responses for the thermal sensation and thermal satisfactions in the dry and rainy season

Case study	**Thermal sensation** (Scale: 1= cold to 7= hot)		**Thermal preference** (Scale: 1= much cooler to 5= much warmer)	
	Dry season	Rainy season	Dry season	Rainy season
Lugbe LGH1 (NV)	5.4	2.9	2.1	3.1
Lugbe LGH2 (AC)	5.0	3.0	2.3	4.4
Dutse Alhaji DAH1 (NV)	5.9	3.0	1.6	2.5
Dutse Alhaji DAH2 (AC)	5.0	4.0	2.3	3.2

NV: naturally ventilated building, AC: air-conditioned building

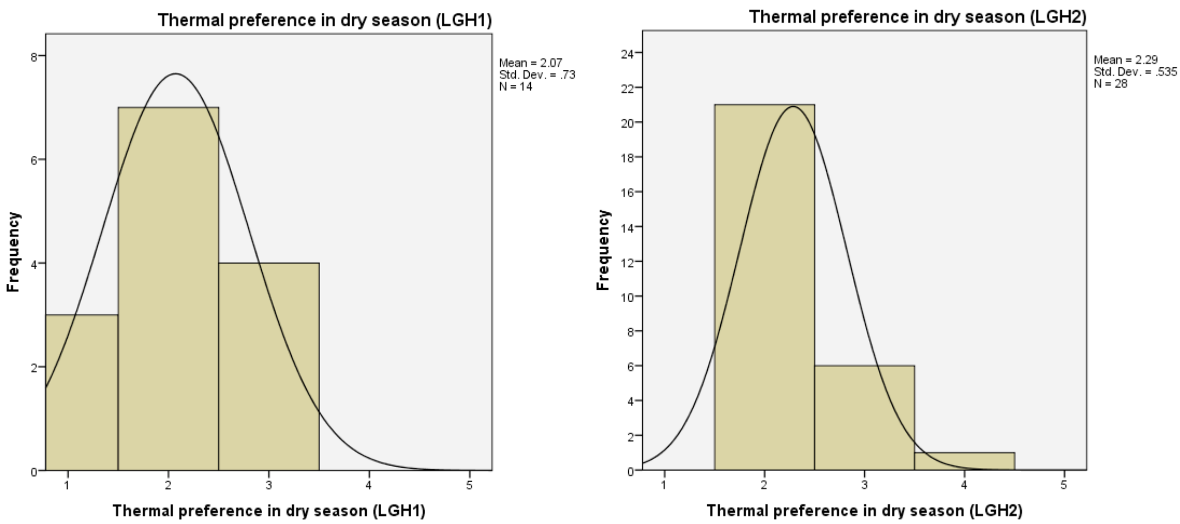


Figure 20: Distribution of overall thermal preference votes during the dry season in Lugbe with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= much cooler to 5= much warmer)

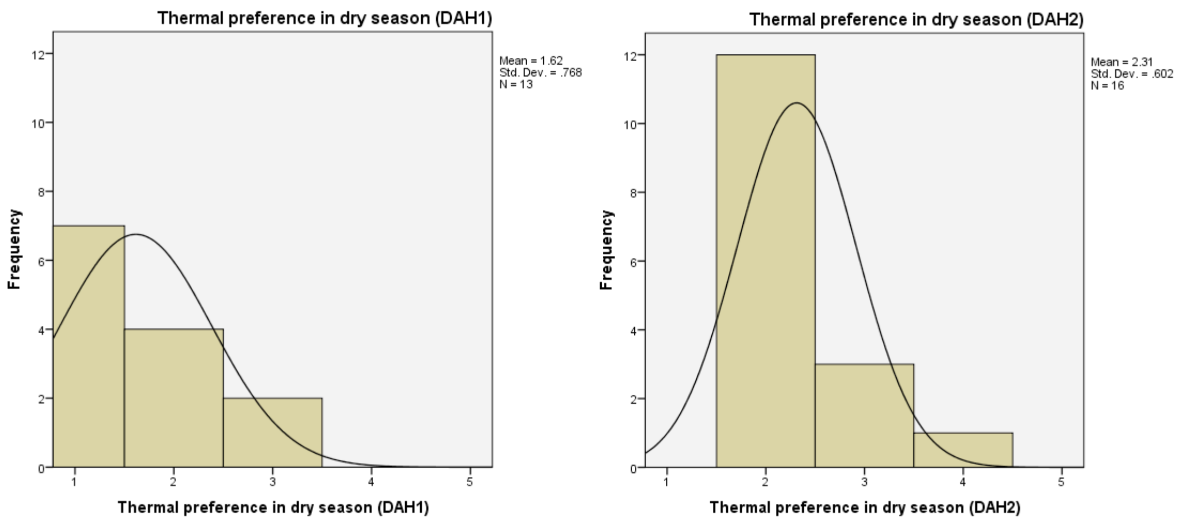


Figure 21: Distribution of overall thermal preference votes during the dry season in Dutse Alhaji with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= much cooler to 5= much warmer)

The mean distributions of occupants' responses from the dry season surveys shows they would prefer to be cooler (Figure 20-23). Also there was a drift to the 'no change' vote during the rainy season. The survey indicates that most occupants prefer their thermal environment the way it is during the rainy season (Table 3).

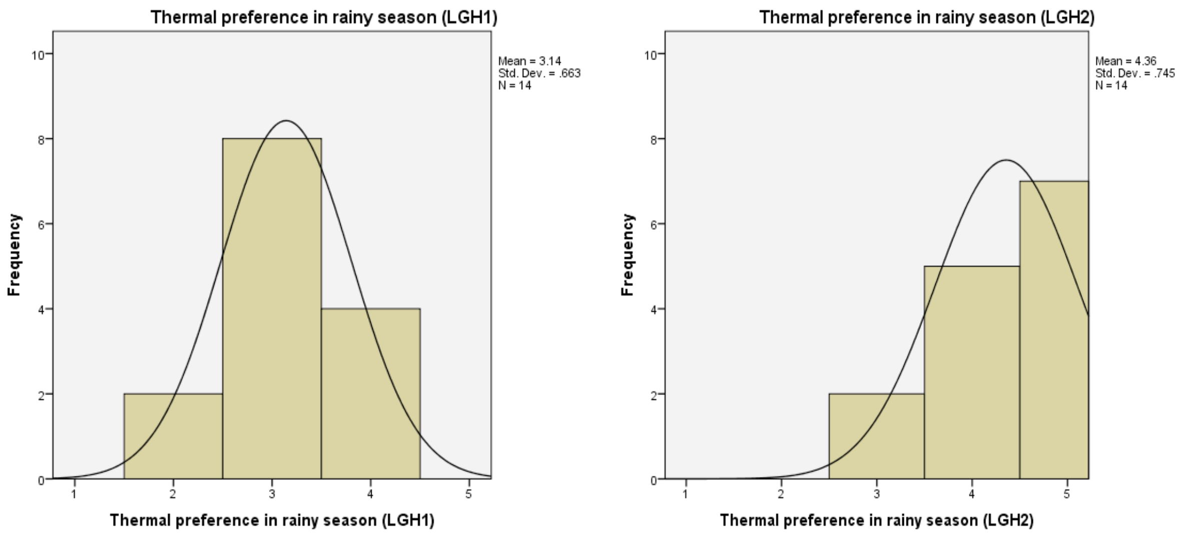


Figure 22: Distribution of overall thermal preference votes during the rainy season in Lugbe with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= much cooler to 5= much warmer)

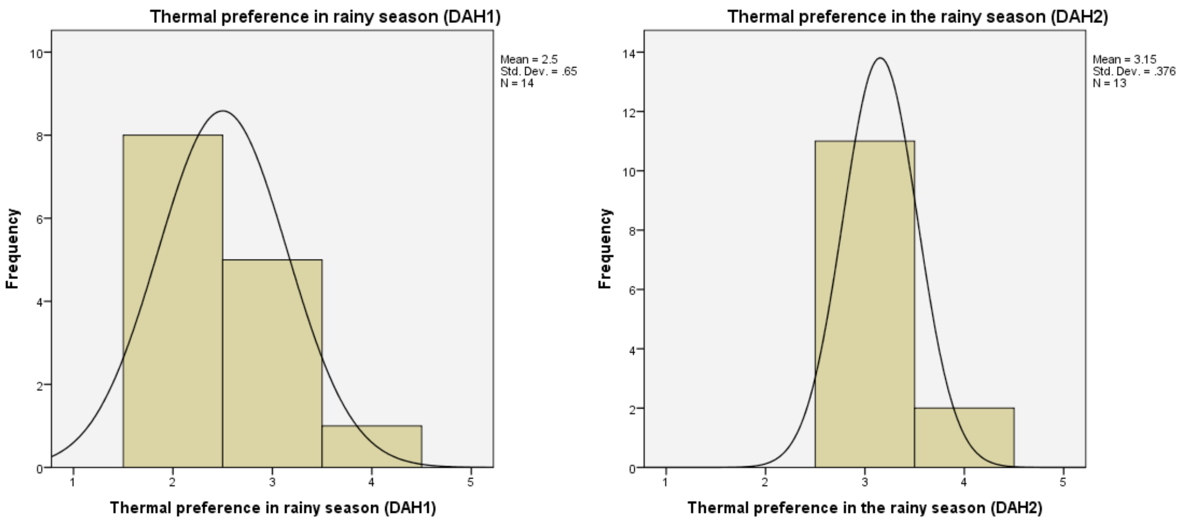


Figure 23: Distribution of overall thermal preference votes during the rainy season in Dutse Alhaji with naturally ventilated building (left) and air-conditioned building (right) (Scale: 1= much cooler to 5= much warmer)

6.3 Analysis of Environmental Survey

The outdoor temperature recorded in Lugbe during the dry season varied from 23.0ºC on 19/3 to a maximum of 41.7ºC on 21/3, with a relative humidity varying from 17.8% on 19/3 to a maximum of 93.1% on 21/3, and an average of 56% (Figure 24); while the outdoor temperature in Dutse Alhaji varied from 23.0ºC on 15/4 to a maximum of 38.0ºC on 15/4, with a relative humidity varying from 35.4% on 14/4 to a maximum of 94% on 15/4 and an average of 35.4% throughout the monitoring period (Figure 25).

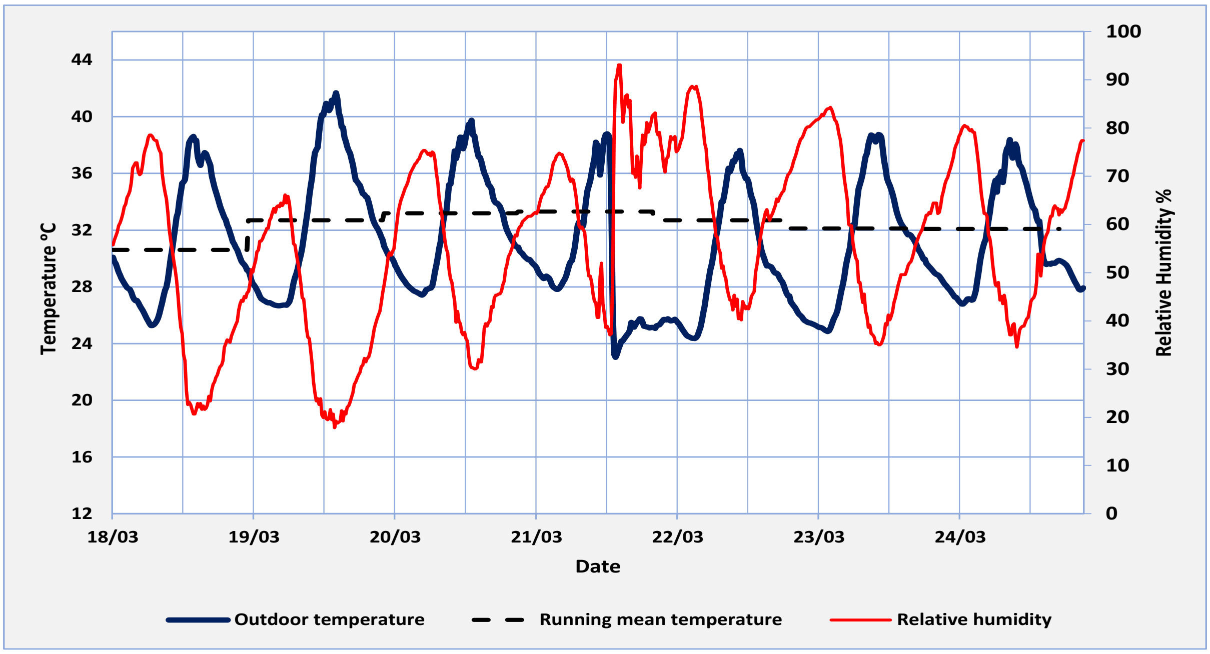


Figure 24: Outdoor temperature, running mean of daily average temperature and relative humidity during the dry season monitoring in Lugbe

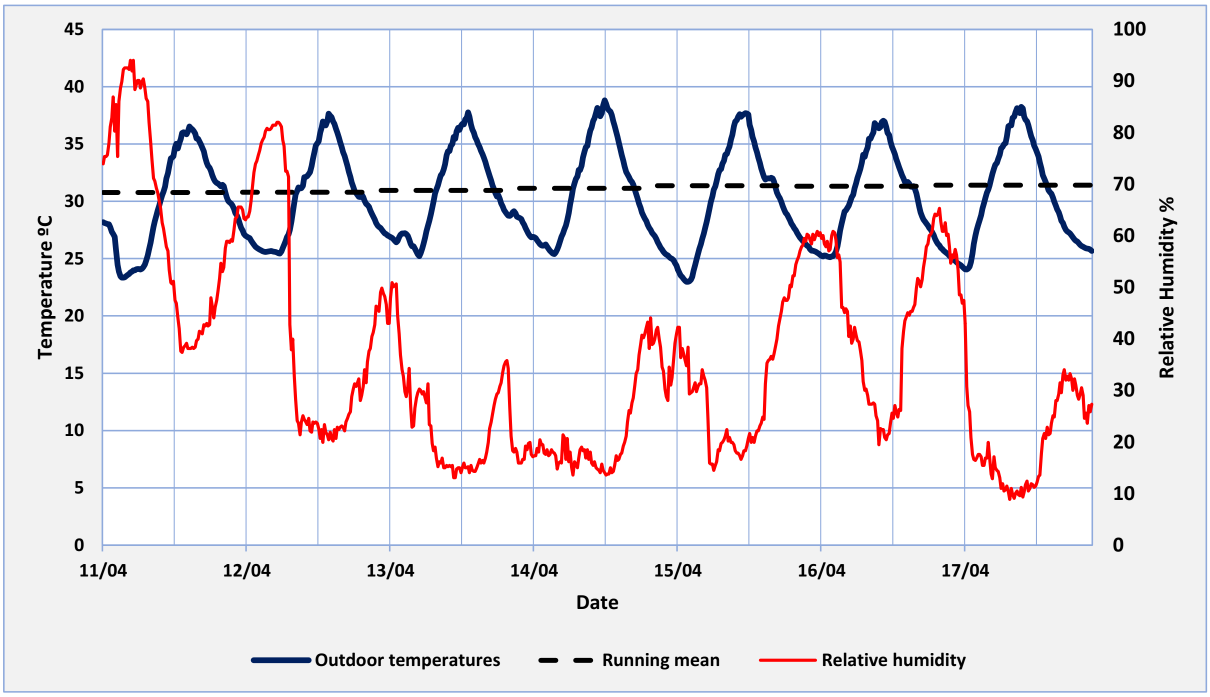


Figure 25: Outdoor temperature, running mean of daily average temperature and relative humidity during the dry season monitoring in Dutse Alhaji

The rainy season recorded an outdoor temperature that varied from 21.0°C on 17/6 to a maximum of 31.0°C on 23/6 in Lugbe, with a relative humidity varying from 55.4% on 23/6 to a maximum of 99.9% on 22/6, and an average of 81.8% (Figure 26); while the outdoor temperature in Dutse Alhaji varied from 20.5°C on 5/7 to a maximum of 32.9°C on 7/7, with a relative humidity varying from 45.9% on 11/7 to a maximum of 98.7% on 5/7 and an average of 75% throughout the monitoring period (Figure 27).

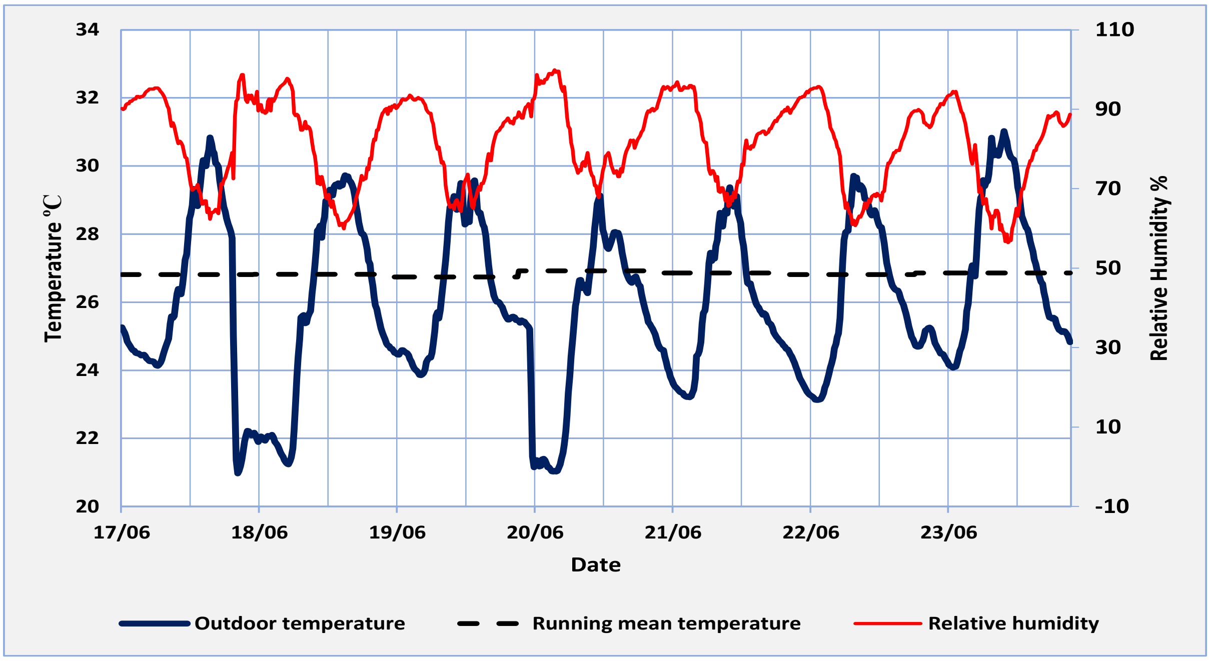


Figure 26: Outdoor temperature, running mean of daily average temperature and relative humidity during the rainy season monitoring in Lugbe

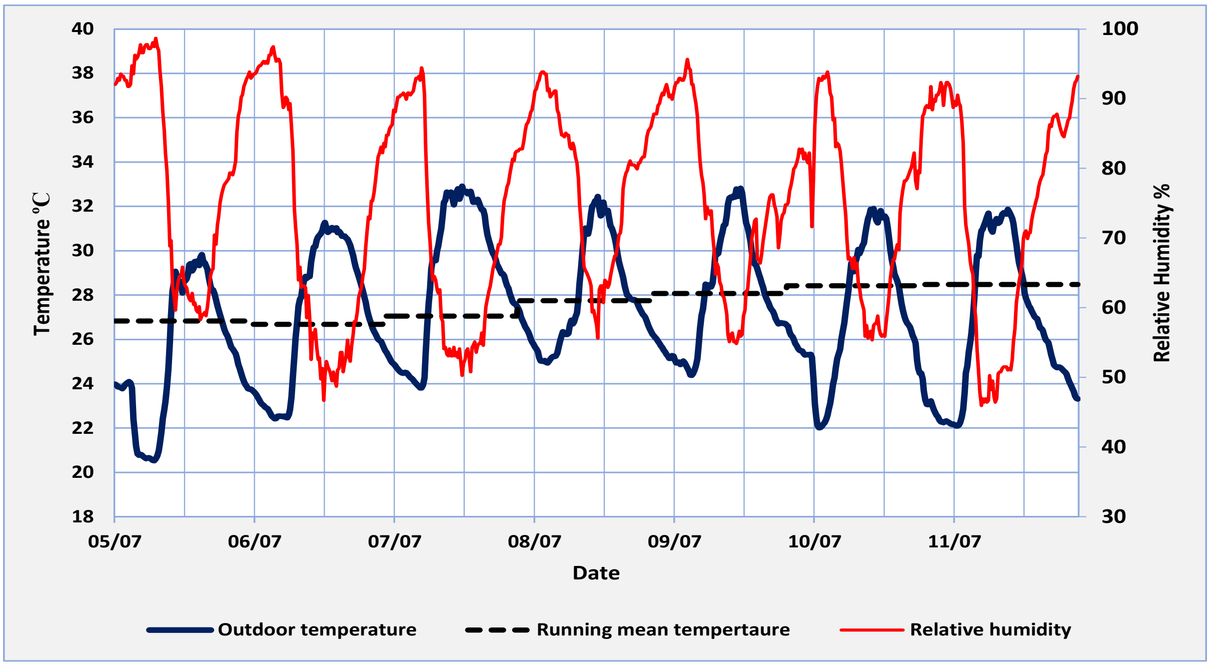


Figure 27: Outdoor temperature, running mean of daily average temperature and relative humidity during the rainy season monitoring in Dutse Alhaji

The measured outdoor temperature had a running mean temperature, $T_{rm,}$ (Figures 24-26) as defined by BSENI 15251 (BSI, 2008), varying from 30.6°C on 18/3 to a maximum of 33.3°C on 21/3 in Lugbe and 30.8°C 11/4 and a maximum of 31.4°C on 17/4 in Dutse Alhaji during the dry season monitoring. The results suggest that Lugbe had the hottest month of the year (March), with an average outdoor monthly temperature of 33.9°C and a maximum outdoor temperature of 41.7°C on 19/3.

The average indoor temperature between 08.00 and 22.00 in the monitored living areas in Lubge was 32.2°C for the living rooms and 32.1°C for the bedrooms. The living rooms recorded the hottest temperature in the building with a mean of 32.5°C and a maximum temperature of 36.2°C. The average temperature between 23.00 and 07.00 was 31.3°C for the living rooms and 31°C for the bedrooms. The living rooms were also the hottest spaces in the buildings with a mean temperature of 31.1°C (Figure 28).

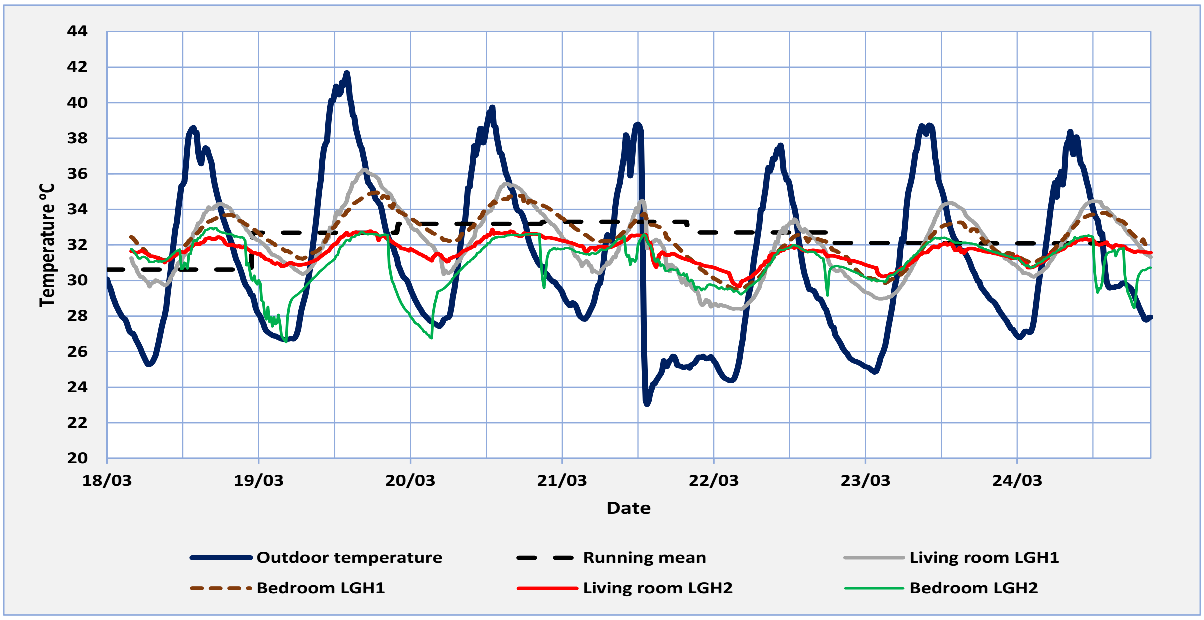


Figure 28: Living rooms and bedrooms monitored in two different buildings in Lugbe during the dry season

In Dutse Alhaji, the average indoor temperature between 08.00 and 22.00 in the monitored living areas in Dutse Alhaji was 34.4°C for the living rooms and 31.1°C for the bedrooms. The living room space recorded the hottest temperature in the building with a mean of 34.5°C and a maximum temperature of 36.8°C. The average temperature between 23.00 and 07.00 was 32.7°C for the living rooms and 31.3°C for the bedrooms. The living rooms also were the hottest spaces in the buildings with a mean temperature of 32.9°C (Figures 29).

The results indicate the living room is the hottest monitored space in the buildings and occupants in Dutse Alhaji experienced higher temperatures compared to the occupants in Lugbe.

More than 90% of the spaces monitored during the dry season in all case studies recorded temperatures above the (ISO EN7730, 1994) standard for sedentary activities which specified a 23°C and 26°C temperature range. The indoor relative humidity was 21% - 76% for Lugbe and 15% - 66% in Dutse Alhaji, which was outside the (ISO EN7730, 1994) standard range of 30% - 70% for the associated temperatures. However, the maximum relative humidity recorded in Lugbe was within the range.

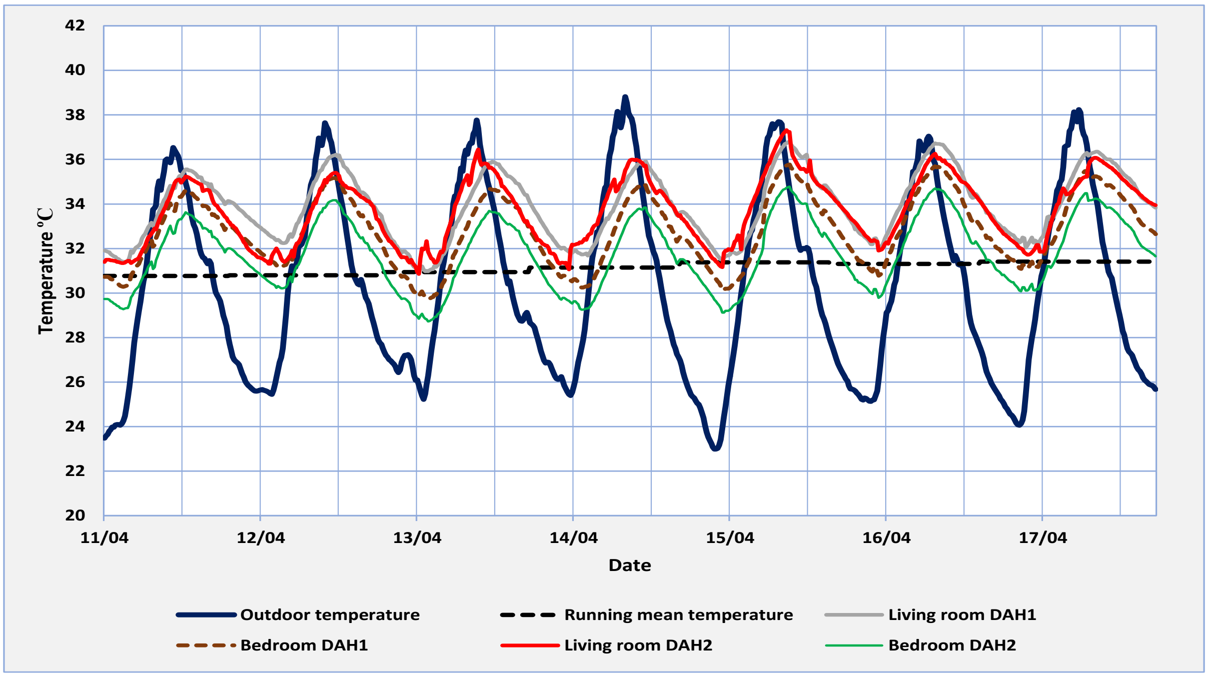


Figure 29: Living rooms and bedrooms monitored in two different buildings in Dutse Alhaji during the dry season

During the rainy season survey, the temperature range of 25°C - 30°C (Figure 30), with a relative humidity range of 29% - 91% was recorded in the living room spaces in Lugbe while a temperature range of 27°C – 35.9°C (Figure 31), with a relative humidity range of 40% - 87% was recorded in the living spaces in Dutse Alhaji.

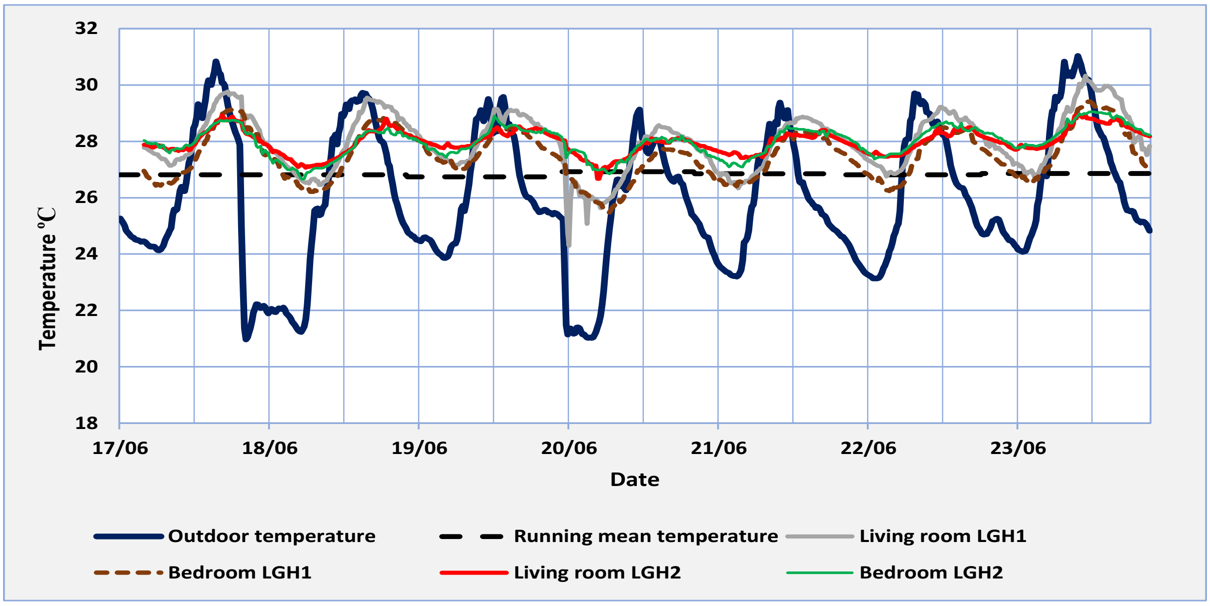


Figure 30: Living rooms and bedrooms monitored in two different buildings in Lugbe during the rainy season

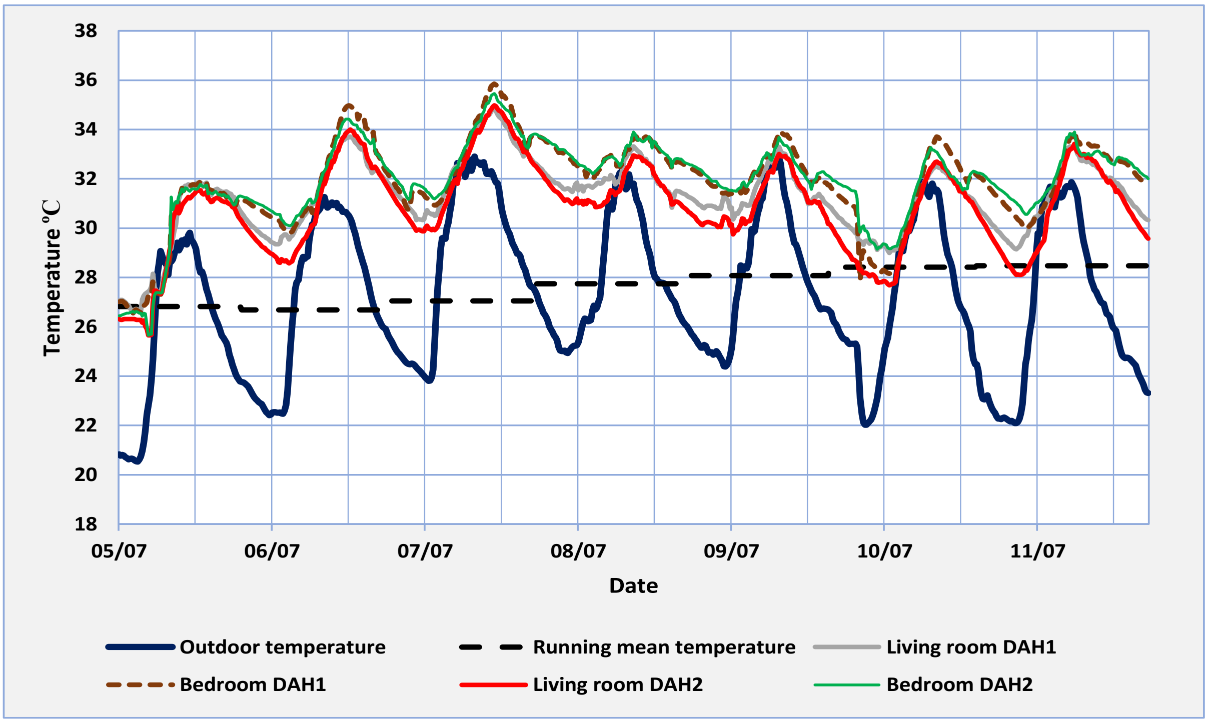


Figure 31: Living rooms and bedrooms monitored in two different buildings in Dutse Alhaji during the rainy season

7 Conclusions

The results from the post occupancy, environmental monitoring and comfort survey from different residential low-income buildings in Abuja, Nigeria were presented in this paper. Across the different locations examined during the post occupancy evaluations, 80% reported being warm and hot on the thermal sensation scale with most reporting being 'not satisfied' with their thermal indoor environment. At least 50% were uncomfortable with the thermal condition. This further suggests that occupants perceived higher indoor temperatures during the dry season.

A different perspective was provided with the comfort survey, as most of the time the monitored occupants in the naturally ventilated buildings felt hotter than the occupants in the air-conditioned buildings. More than 70% of the time the occupants in the monitored case studies felt either 'slightly warm' or 'warm' most of the time when they were indoors.

The maximum outdoor temperature and relative humidity recorded was 41.7°C and 99.9%, with the naturally ventilated buildings recording the highest and lowest temperatures of 36.8°C and 24.3°C in the living rooms in Lugbe and Dutse Alhaji. However, the difference in temperature between the air conditioned and naturally ventilated building was only about 2°C. Most of the occupants do not find their thermal conditions acceptable and more than 80% of the spaces monitored in all case studies recorded temperatures above the (ISO EN7730, 1994) standard for sedentary activities.

The results suggest that most residents in the study areas of Abuja are not satisfied with their thermal environment and there is discomfort among occupants in residential buildings. Occupants prefer to be much cooler during the dry season, therefore there is high dependence on air-conditioning to improve their thermal condition.

However, air-conditioning is not used as much as it might be because of continual power-cuts, the cost and noise of running generators and personal security issues. This is a good reason for trying to improve the construction of the dwellings so that they are made to be comfortable using more passive means. This paper has reported on four case study dwellings, but six further dwellings have since been monitored in detail and will be reported in the future.

Acknowledgements

This study was privately funded by Mr O. P. S. Adaji and supported by The Centre for Architecture and Sustainable Environment (C.A.S.E.), Kent School of Architecture, University of Kent, UK. Their dependable support made this study successful. We are grateful to the residents of the case studies, especially those that allowed us access into their homes for monitoring, and for their undue support during the period of this survey we thank them all.

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Thermal Comfort and Energy: CFD, BES and Field Study in a British Open Plan Office with Displacement Ventilation

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Abstract

Energy efficiency and thermal comfort are necessary in designing the workplace. Accurate computational modelling and analysis methods are useful to improve the design, energy consumption and user's comfort. This study compared the results of combined Computational Fluid Dynamics (CFD) and Building Energy Simulation (BES) with the contextual data collected through a Filed Study of Thermal Comfort (FSTC) regarding user comfort and energy in a workplace. The building was a six storey open plan office in Aberdeen, built in 2011, with displacement ventilation, "very good" BREEAM and "B" energy ratings. Each floor had 175 workstations, 1680m2 office area and approximately 3.5m^2 per workstation. Thermal comfort surveys and environmental measurements were applied. The results were compared with the CFD modelling of the ventilation and thermal performance, PMV and BES energy predictions. The simulation results were in good agreement to that of the field data, indicating over 70% slightly cool and 25% neutral. The combination of CFD and BES improved the accuracy of the simulation and provided important information on optimising energy and the thermal environment. This combined simulation is useful and recommended in the design phase to achieve the balance of energy and comfort in the workplace.

Keywords: Building Energy Simulation (BES), Computational Fluid Dynamics (CFD), Thermal Comfort, Energy, Workplace

1 Introduction

Various methodologies are applied to investigate thermal comfort, including experimental chambers, field studies of thermal comfort and simulation. Very few studies built a bridge between different approaches to compare the results and the accuracy of predicting thermal comfort. This study examined the use and accuracy of computer simulation in a thermal comfort study comparing it to the field data results. Computational Fluid Dynamics (CFD) and Building Energy Simulation (BES) were applied to simulate the environmental condition of an actual office building in Aberdeen, Scotland. In order to validate the results, they were compared to the collected field data regarding the actual energy use of the building and occupants' views of their thermal environment. The office had a relatively deep open plan with centrally operated displacement ventilation. A few openable windows were available for limited occupants seated around the perimeter of the building. The design of the building was awarded by the British Council for Offices. It received 'very good' BREEAM and B energy ratings.

2 Previous Related Work

Recently, Computational Fluid Dynamics (CFD) modelling is encouraged in evaluating and improving the design and thermal comfort of buildings and ventilation systems in different climatic conditions. The sophisticated nature of the CFD software allows considering various limits of design. The incompressible Navier–Stokes equations are the main basis of analysing the airflow in ventilation systems according to the motion of a viscous Newtonian fluid. Progress in numerical science and simulation as well as technological advances in computer science provided a platform for CFD to succeed (Etheridge, 2011), which in terns led to formulation of particular principles to maintain a high quality (Nielsen, 2004). For validation purposes, the CFD results are comparable to empirical results, although a degree of inconsistency is expected, due to the limits of boundary conditions of the current CFD software and the adaptive behaviour of occupants.

Energy efficiency in buildings is encouraged by many researchers (Short *et al*., 2004, Jones-Lee and Loomes, 2003). Environmental factors are considered as essential criteria in building design. In order to measure and predict the energy use of buildings, different method and software are introduces, such as Building Energy Simulation (BES). The latter is an extensive tool useful in the design phase, preparing thermal simulations and analysis of indoor environments. BES software perform under a simplified analytical method that demands input data such as properties of materials, geometric factors, climatic data, and heat transfer coefficients (Shi and Yang, 2013). For instance, Autodesk Ecotect is a commercial software used for Building Energy Simulation purposes, particularly in the design phase and environmental analysis. It includes the full range of simulation and analysis functions required to assess the performance and operation of the building design (Schueter and Thessling, 2008). The software is useful in analysis of lighting, thermal comfort and energy consumption of the building.

Yang *et al.* (2014) used the Ecotect analysis software for the planning of a residential state Ma'anshan City. Micro climatic data and energy saving methods were incorporated in the analysis. They investigated various optimisation factors, including orientation of the design, daylighting and natural ventilation. The authors concluded that the Ecotect software is useful for architects and engineers in the early stages of the building design. The results made it possible to improve the energy efficiency of the building as well as human comfort in relation to the indoor environmental factors. Shoubi *et al.* (2014) used the Ecotect software to evaluate several combinations of materials and identify alternate sustainable design solutions to reduce the energy consumption of a residential building. They established the use of the simulation software for engineers and architects to select specifications in the design phase with the least negative effect to the environment. In a study of analysing the daylighting in an industrial building, Chen *et al.* (2014) found close relationship when comparing the simulation results of Ecotect and Descktop Radiance to the collected data from the field study. The latter is the investigation of phenomena as they occur without any significant intervention of the investigators' (Fidel, 1984). Field study requires a systematic approach (Bromley, 1990) and it takes place in the natural context of the phenomena through the application of multiple sources of evidence and methods (Johansson, 2003).

The main purpose of field studies of thermal comfort is to improve comfort conditions for occupants in buildings through developing comfort prediction models using the results of the field studies (Nicol and Roaf, 2005). The respondent's view of the thermal environment is mainly subjective and therefore 'the aim is often to predict the subjective impression from a knowledge of the physical environment' (Nicol, 2004). Time and context are two important factors when capturing the occupant's natural and immediate response to the thermal environment in the context of every day life (Nicol, 2004, Nicol and Roaf, 2005). The most common methods in field studies of thermal comfort are thermal measurements and survey questionnaires. Bedford (1936) applied survey questionnaires in several factories and Nicol and Humphreys (1973) applied field studies of thermal comfort at the natural context. The ASHRAE seven-point scale thermal sensation question (ASHRAE, 2009) is widely used in thermal comfort studies, presented in Table 7. In this scale, neutral thermal sensation is considered as a thermally comfortable status (ASHRAE, 2010). Operative temperature (the mean of dry bulb and mean radiant temperature) and relative humidity are considered the main thermal factors (ASHRAE, 2013). Auliciems and Szokolay (1997) indicated air temperature as the essential factor that affects human thermal comfort. Nicol and Humphreys highlighted the essential role of the relationship between indoor and outdoor conditions on comfort, particularly in naturally ventilated buildings (Humphreys, 1977, Humphreys, 1978, Humphreys and Nicol, 1995, Nicol et al, 2012).

Various methodologies are applied to predict thermal comfort. Ctalina et al. (2009) applied a combination of CFD and experiments to evaluate the predicted mean vote thermal comfort in an experimental chamber when radiant cooling was in operation. Mainly environmental measurements were applied to calculate the PMV and mean radiant temperature in the room. Although the results of this study are useful and there are advantages in experimenting in a controlled environment, findings of experimental chambers often do not apply to the context of daily life (Nicol et al., 2012). Therefore in the present study, the results of CFD and BES were compared to the results of the real life context investigating occupants' views of the thermal environment through the application of the field studies of thermal comfort.

3 Methodologies

The building, as demonstrated in Figure 1 and Figure 2, is a six storey open plan office in Aberdeen and it won several awards including British Council for Offices. It achieved a 'very good' BREEAM and a B energy ratings. Each floor is 1680 m^2, including 175 workstations and 3.5 m^2 per person.

Figure 1: South façade and First Floor plan

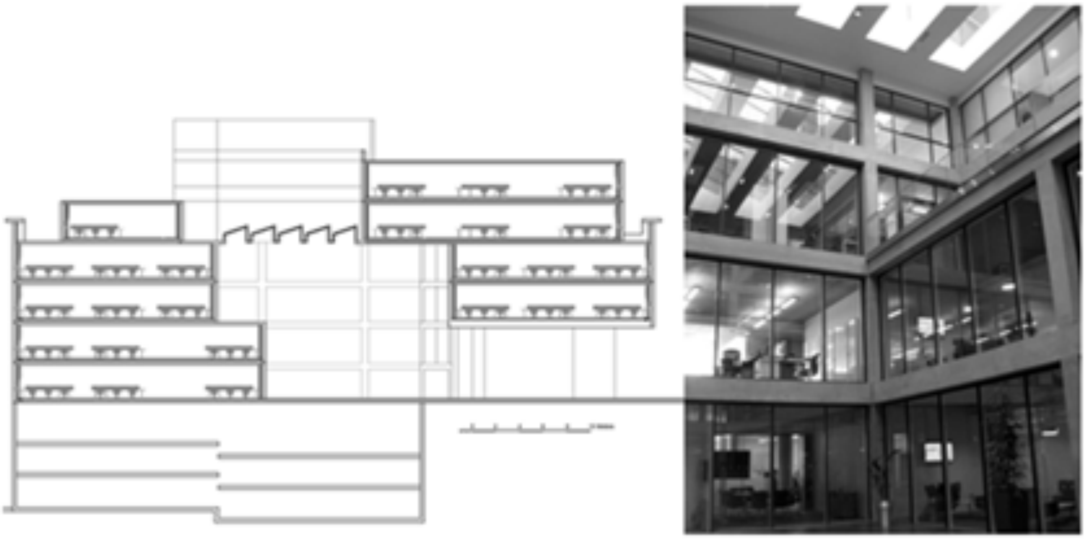

Figure 2: North-South Section and atrium

Displacement ventilation is the main system and limited small windows and blinds are provided for occupants seated around the perimeter of the building. However, as shown in Figure 3, this is a relatively deep open plan office and the majority of the occupants seated away from the windows have no means to control their immediate thermal environment.

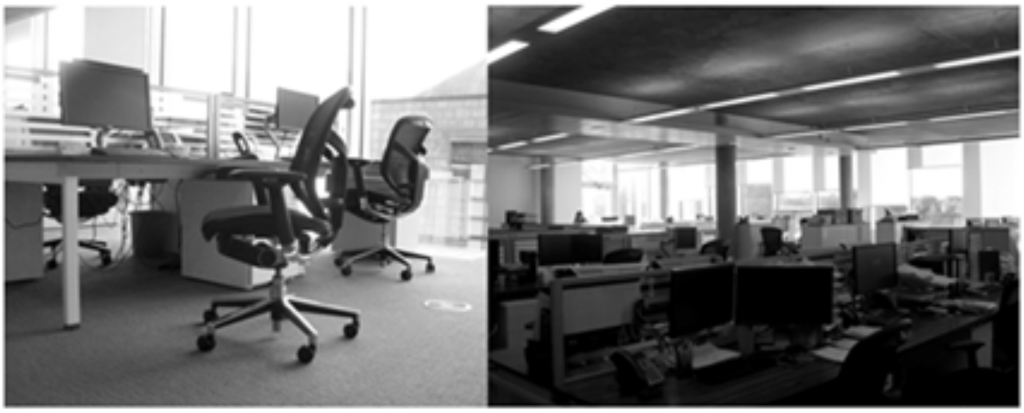

Figure 3: Open plan office, location of the vent and perimeter windows

The whole space underneath the raised floor, which is 350 mm depth, works a duct for the treated air, as illustrated in Figure 4. The displacement ventilation is centrally operated and provides 4 ach^{-1} with heat recovery. Exposed concrete works as thermal mass and internal gains are the main source of heat, although trench radiators around the perimeter of the building prevent the radiating heat loss.

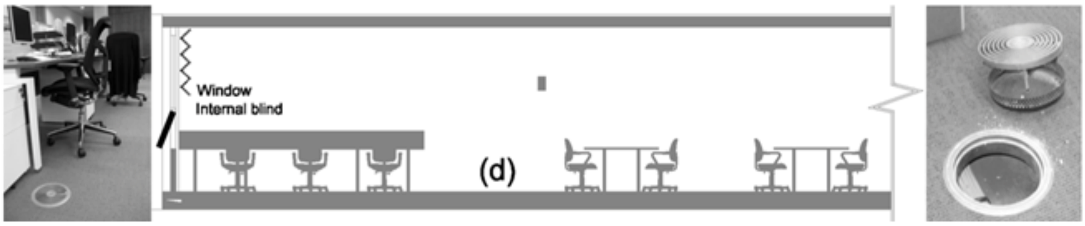

Figure 4: Displacement ventilation and personal control in the office

Figure 5 illustrates the ventilation system in the building and the use of displacement ventilation, openable window and thermal mass.

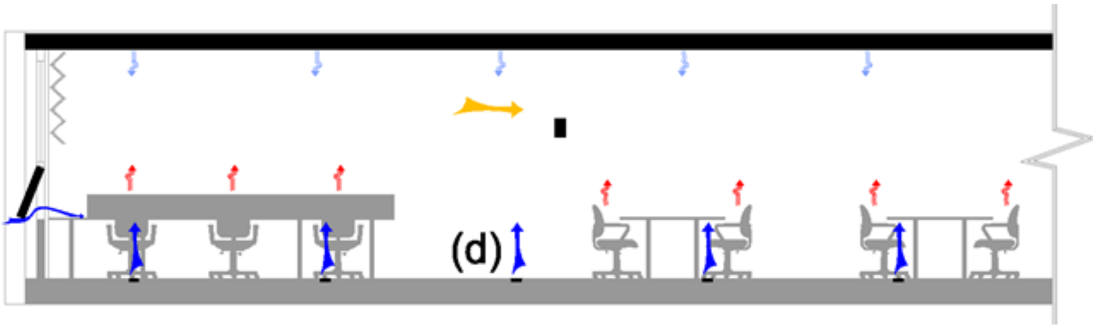

Figure 5: Summer day displacement ventilation and thermal mass

3.1 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) is a tool that uses numerical methods and algorithms to solve and analyse fluid flow problems. In building design, it can be used to predict air speed, pressure and temperature that will occur at any point throughout a predefined air volume in and around buildings with defined boundary conditions. CFD models are usually preferred for the assessment of air velocity since they can provide detailed information on the performance of mechanical or natural ventilation strategies. CFD has been implemented as the primary analysis tool in a number of studies concerning building ventilation performance.

In the present study, the CFD code from the ANSYS 14 Fluent software was employed. It used a primitive variable method involving the solution of a set of equations that described the conservation of heat, mass and momentum using the Navier–Stokes equations and the standard k-ε turbulence model. The Reynolds-Averaged Navier-Stokes (RANS) equations for mass, momentum, energy and species were solved using the commercial CFD code for the velocity and temperature field simulations. The model employed the control-volume technique and the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) velocity-pressure coupling algorithm with the second order upwind discretisation. The equation for conservation of mass, or continuity equation is as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \qquad \text{eqn. 1}$$

Where p is the static pressure and $\vec{v}$ is the velocity of the fluid. Transport of momentum in an inertial (non-accelerating) reference frame is described by:

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla \cdot (\rho\vec{v}\vec{v}) = -\nabla p + \nabla \cdot (\overline{\overline{\tau}}) + \rho\vec{g} + \vec{F} \qquad \text{eqn. 2}$$

Where $\overline{\overline{\tau}}$ is the stress tensor and $\rho\vec{g}$ is the gravitational body force. $\vec{F}$ contains the source terms that may arise from resistances and sources. The energy equation for a fluid region can be written in terms of:

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\rho h\vec{v}) = \nabla \cdot [(k + k_t)\nabla T] + S_h \qquad \text{eqn. 3}$$

Where k is the molecular conductivity, k_t is the conductivity due to turbulent transport, and S_h is the source term which includes the defined volumetric heat sources. The conservation equation for species takes the following general form:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho\vec{v}Y_i) = -\nabla \cdot \vec{J}_i + S_i \qquad \text{eqn. 4}$$

Where Yi is the local mass fraction of each species, Si is the rate of creation of addition from user defined sources. Additional transport equations were solved when the flow was turbulent. The standard *k*-epsilon transport model, which is frequently used for incompressible flows, was used to define the turbulence kinetic energy and flow dissipation rate within the model. The use of the standard *k-epsilon* transport model on building configurations was found in previous works. The turbulence kinetic energy and its rate of dissipation were obtained from the following transport equations:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k + G_b - \rho\epsilon \qquad \text{eqn. 5}$$

and

$$\frac{\partial}{\partial t}(\rho\epsilon) + \frac{\partial}{\partial x_i}(\rho\epsilon u_i) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_i}\right] + C_{1\epsilon}\frac{\epsilon}{k}(G_k + C_{3\epsilon}G_b) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} \qquad \text{eqn. 6}$$

Where: *Gk* represents the generation of turbulence kinetic energy due to the mean velocity gradients, G_b represents the generation of turbulence kinetic energy due to buoyancy. Y_M represents the contribution of fluctuating dilatation in compressible turbulence to the overall dissipation rate. C_{1e}, C_{2e}andC_{3e} are constants; $\sigma_k\sigma_k$ andσ_e are the turbulent Prandtl numbers for k and e.

The computational domain comprised of the building geometry, which was designed according to the actual specifications of the building, the outdoor and indoor domains, as illustrated in Figure 6. The outdoor airflow was simulated by setting one surface of the computational domain as velocity inlet and the surface located at the other end as pressure outlet. The building geometry was located at the middle of the domain and it produced a blockage of less than 10%. This was to ensure that the walls on the side of the domain had limited effect on the calculated airflow close to the building. Additionally, to further reduce this effect, the side and top walls of domain were set as symmetry.

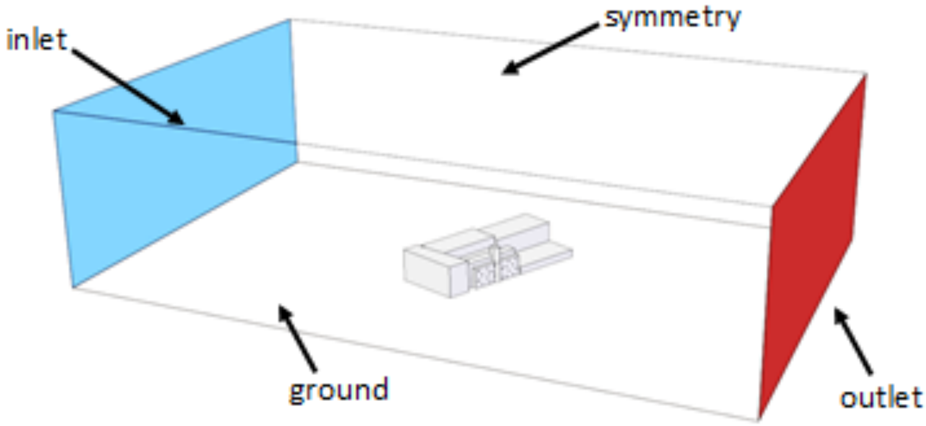

Figure 6: Computational domain

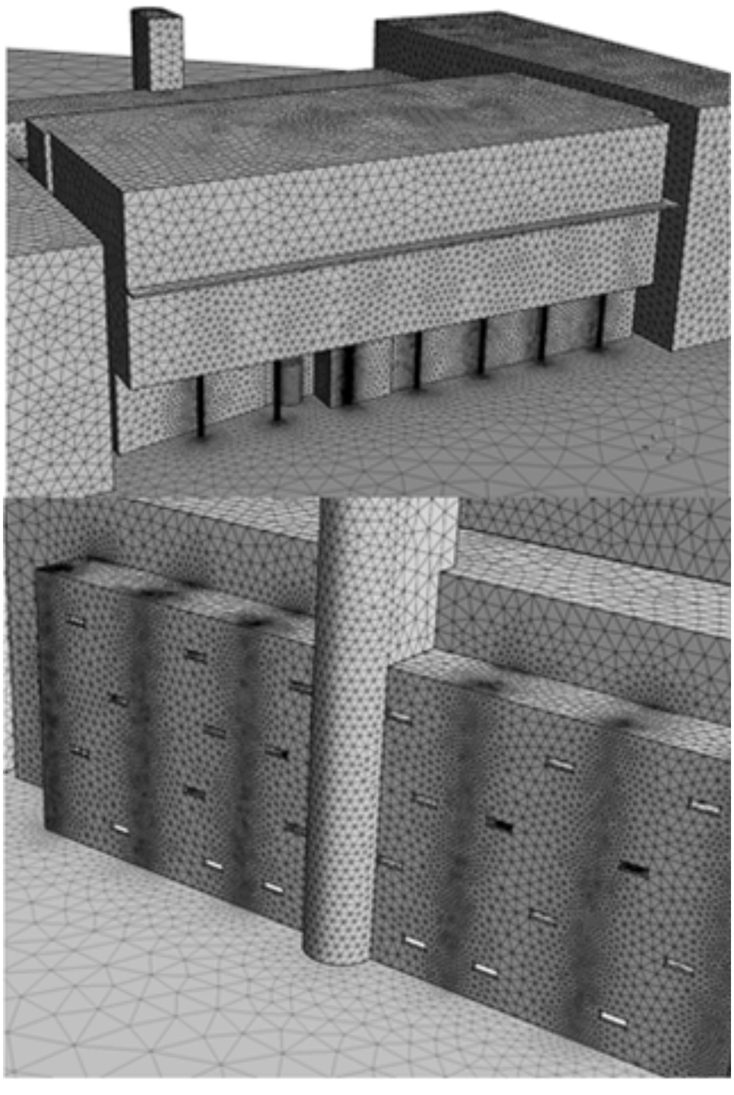

Figure 7: Mesh details (top) front view (bottom) back view

Mesh generation is one of the most important processes in a CFD simulation. The quality of the mesh plays an important role on the accuracy of results and the stability of the solution. For the investigated computational domain, patch independent CFD tetrahedron meshing technique was applied on the geometry, wherein the boundary conditions were applied on the edges and faces. The patch independent mesh algorithm for tetrahedron elements was based on the subsequent spatial subdivision algorithm, which ensured refinement of the mesh where essential, but retained larger elements where feasible, therefore allowing faster computing times. The meshed model comprised of 10.8 million elements as displayed in Figure 6. The minimum face angle was 5.67°, while the maximum edge length and element volume ratios were 9.9 and 44.6. Figure 6 and Figure 7 display the schematic of the geometry along with the meshed model.

In order to verify the accuracy of the numerical models, a grid independency test was carried out to determine the variation in results over increasing mesh sizes. Basic concepts associated with mesh refinement dealt with the refinement and evaluation of elements. Grid verification was carried out using mesh refinements (*h*-method) in order to optimise the distribution of mesh size *h* over a finite element.

The area-weighted average value of the velocity inside building façade was taken as the error indicator, as the grid was refined from 1.5 to 10.8 million elements. The grid was evaluated and refined until the posterior estimate error became insignificant between the number of elements and the posterior error indicator. The discretisation error was found to be the lowest at over ten million elements the indicated variables and the mesh was thus selected to achieve a balance between accuracy and computational time. Figure 8 displays the variation in discretisation error at increasing number of meshed elements.

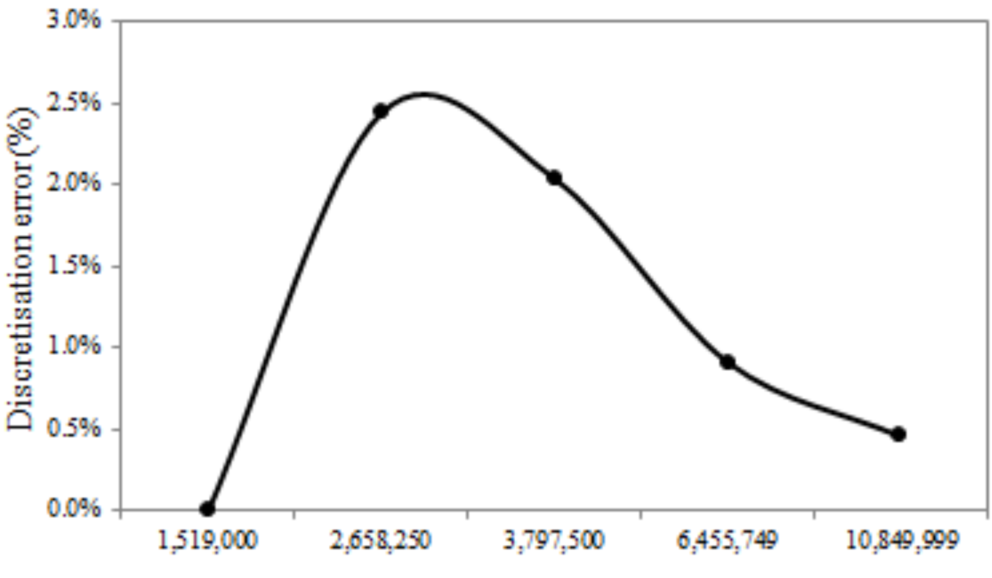

Figure 8: Mesh verification

The applied boundary conditions comprised of a reference velocity of 5m/s approaching SW to the building, as presented in Table 1. The geometry was modelled as a solid zone, while the indoor-outdoor domain was modelled as a fluid zone for the analysis. The boundary conditions were kept identical throughout the numerical investigation for all analysed models.

Table 1: Boundary conditions

Parameter	Type
Geometry	Solid zone
Enclosure	Fluid zone
Near-Wall Treatment	Standard Wall Functions
Velocity Formulation	Absolute
Solver Type	Pressure-Based
Time	Steady
Gravity	-9.81 m/s^2
Velocity Inlet	5 m/s at SW direction
Temperature Inlet	291 K
Humidity Inlet	54 %
Pressure Outlet	Atmospheric

In order to simulate the internal gain of the people, lighting and equipment, the floor surface was set as heat flux with a heat flux value of 33.7 W/m^2.

Table 2: CIBSE Guide internal gain for a typical office building

Building type	Use	Density of occupation / person·m^{-2}	Sensible heat gain / W·m^{-2}			Latent heat gain / W·m^{-2}	
			People	Lighting*	Equip't†	People	Other
Offices	General	12	6.7	8–12	15	5	—
		16	5	8–12	12	4	—
	City centre	6	13.5	8–12	25	10	—
		10	8	8–12	18	6	—
	Trading/dealing	5	16	12–15	40+	12	—
	Call centre floor	5	16	8–12	60	12	—
	Meeting/conference	3	27	10–20	5	20	—
	IT rack rooms	0	0	8–12	200	0	—

3.2 Building Energy Simulation

In this study, the Ecotect software was used as a research tool and setting regional climate conditions as a starting point, the authors simulated and analysed the building orientation, daylight in building of the commercial building. Ecotect software is an environmental analysis tool that allows designers to simulate building performance right in conceptual phase. It includes a wide array of detailed analysis functions with a highly visual and interactive display that makes analytical results can be directly presented within the context of the building model. Thus, complex concepts and extensive datasets can be communicated in surprisingly intuitive and effective ways.

The case study building is located in Aberdeen, Scotland, which is at 57° 2′ north latitude and -2° 1′″ east longitude. The Aberdeen climatic data was inserted into weather tool of Ecotect, which output the analysis results of the climate. Aberdeen has a temperate climate, and the weather changes constantly. Figure 9 and Figure 10 are respectively the distribution of annual hourly dry-bulb temperature and the distribution of annual hourly humidity generated by Ecotect Weather Tool. Figure 9 shows that Aberdeen has a typical mild summer and cold winter climate. The average annual dry-bulb temperature is about 8 °C. The coldest month is January and the average temperature is 2.8 °C, while the hottest month is August and the average temperature is 14.2 °C. The total cooling degree hours is

81 hours and the total heating degree hours is 83,149 hours. Figure 10 shows the annual humidity in Aberdeen, Scotland. The average relative annual humidity range between 60–90%. These climatic conditions are mainly outside the thermal comfort zone specifically during the winter. To ensure an acceptable indoor thermal condition, careful consideration is given to insulation in an energy-saving design.

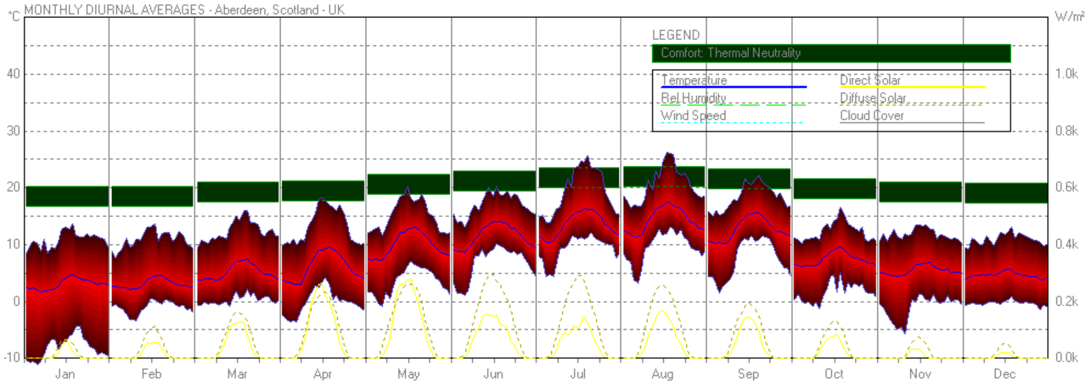

Figure 9: Distribution of hourly dry-bulb temperature.

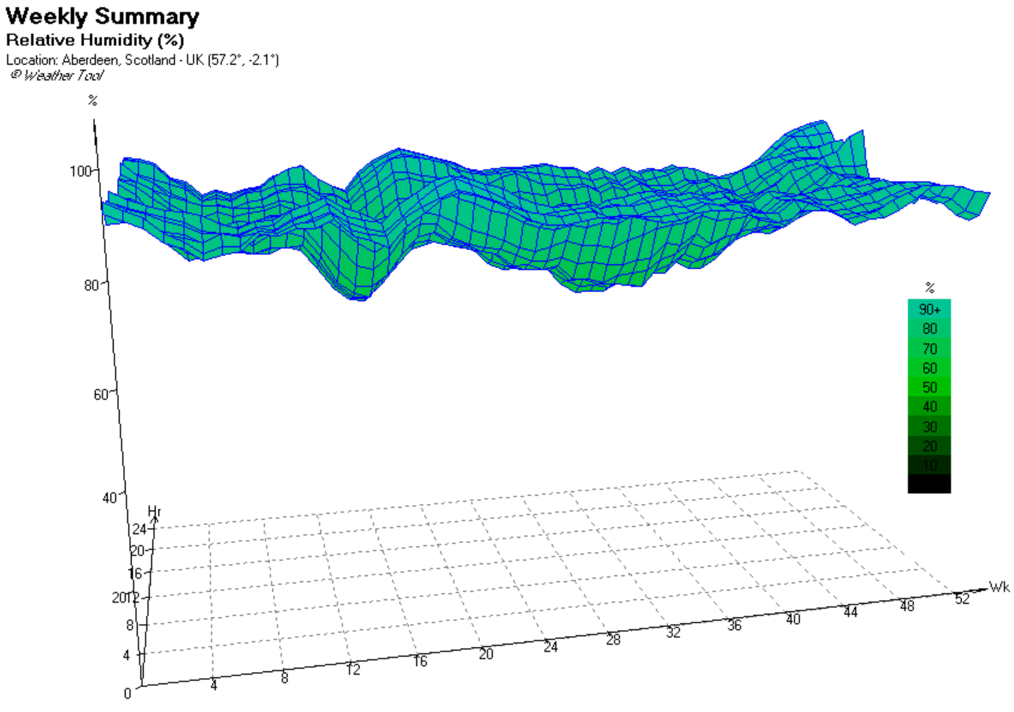

Figure 10: Distribution of relative humidity

Scotland is extremely windy, due to eastward moving Atlantic that brings strong winds continuously throughout the year. The wind prevails from south-west and north-north-west. The annual mean wind speed varies between 5 and 6m/s, as presented in Figure 11.

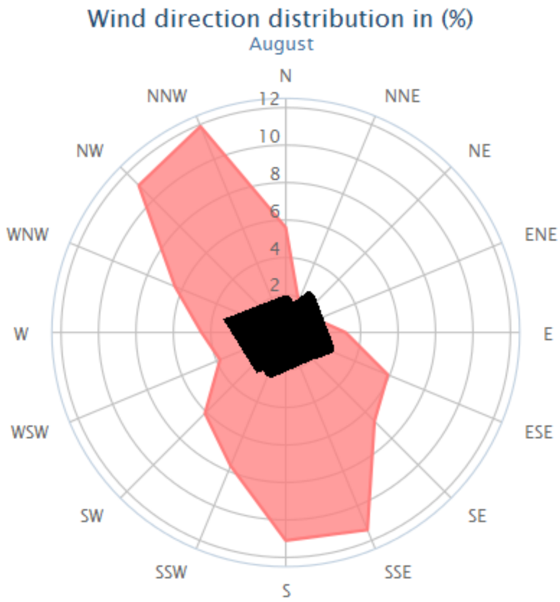

Figure 11: Distribution of wind around the building.

A full scale geometry of the building was modelled for thermal analysis using the Autodesk Ecotect software. The building consisted of three floors and each floor was divided into zones to apply different occupancy schedule and activity, internal gain profiles and infiltration rate. Figure 12 and Figure 13 show the full geometry of the building extracted from the CAD drawing.

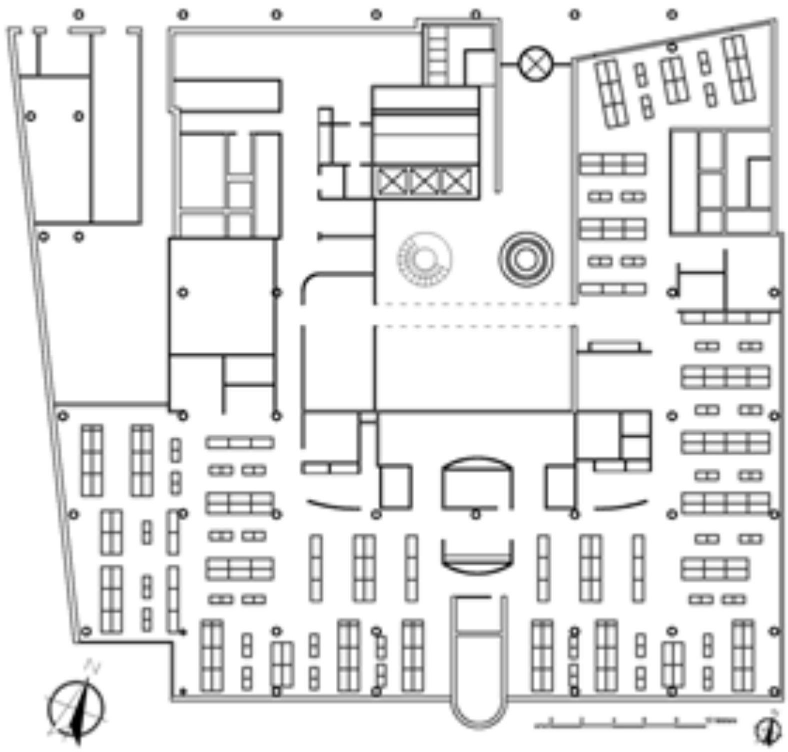

Figure 12: Floor plan of the studied building used for the Ecotect design modeller.

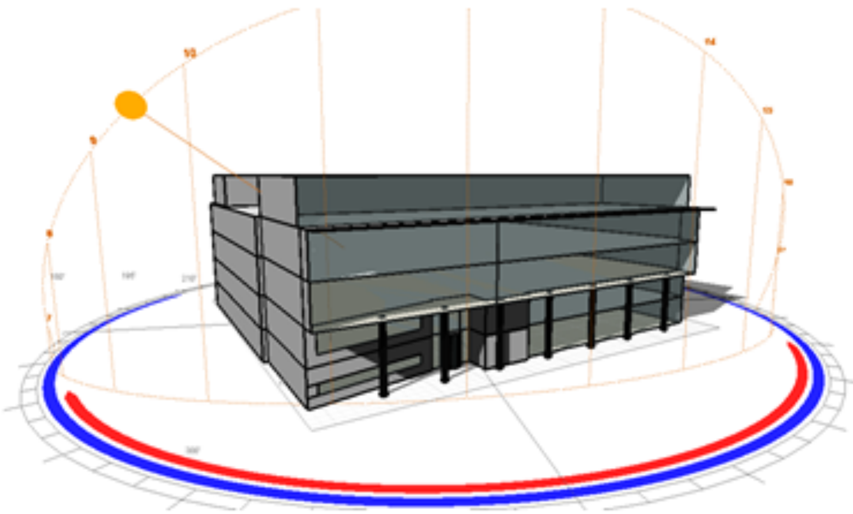

Figure 13: Ecotect thermal model showing the winter month sun path.

Table 3: Summary of building materials for the BES model

Parameter	Materials	U-Value (W/m^{2}k)
External walls	Concrete block plaster	1.80
Internal walls	Concrete block plaster	1.80
External windows	Double glazed	2.70
Flat roof	Concrete roof	0.90
Ground	Concrete slab on ground	0.88

Table 4, Table 5 and Table 6 displays the thermal properties, internal design conditions and occupancy schedules used in the modelling. The natural ventilation systems was selected to operate for 12 hours on weekdays and the comfort band was set between 22˚C - 24˚C.

Table 4: Thermal properties

Parameters	Set Values
HVAC	Mixed-Mode System
Comfort band	22˚C - 24 ˚C
Hours of operation	7.00 AM to 21:00 PM (Weekdays)

Table 5: Internal design conditions

Parameters	Set Values
Clothing	1 clo (light suit)
Lighting level	400 Lux (office)
Humidity	50 %
Air speed	0.5 m/s
Infiltration rate	4 ach (average)

Table 6: Occupants

Parameters	Set Values
Number of Occupants	167 (ground floor) 167 (first floor) 178 (second floor) 178 (third floor) 87 (fourth and fifth floor)
Occupant activity	70W - sedentary (offices) 80W - walking (halls)
Schedule	9.00 AM to 7:00 PM (Weekdays)

3.3 Field Studies of Thermal Comfort

Field studies of thermal comfort were applied in this study for the duration of a week in August 2012. Thermal comfort questionnaire, environmental measurements and follow up interviews were applied. Occupants' thermal sensation and preference were measured using survey questionnaires based on the ASHRAE seven-point scale, as presented in Table 7.

Table 7: Thermal sensation and preference questions based on the ASHRAE seven-point scale

Currently at my desk, regarding the thermal environment I feel:							
Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold	No strong opinion
+3	+2	+1	0	-1	-2	-3	
Currently at my desk, I prefer the thermal environment was:							
Much warmer	Warmer	Slightly warmer	No change	Slightly cooler	Cooler	Much cooler	No strong opinion
+3	+2	+1	0	-1	-2	-3	

Two types of thermal measurements were applied, including instant and constant measurements. The former was applied at each workstation when the occupant responded to the thermal comfort questionnaire so that occupants' responses could be compared against their thermal environmental conditions. In the constant measurements, the devices were placed at particular locations at the floor, desk and ceiling levels for the duration of the study in order to calculate the mean radiant temperature.

Table 8 shows the equipment used to measure relative humidity, dry bulb temperature and air monitoring equipment. Mean radiant temperature was calculated using surface measurements using the constant measuring method.

Table 8: Equipment for environmental measurements

Measurement	Time	Equipment details	Resolution	Accuracy	Range
Dry bulb temperature	Instant: at workstations	PCE-GA 70 air quality meter	0.1°C	±0.5°C	5 to 50°C
Relative humidity	Instant: at workstations	PCE-GA 70 air quality meter	0.1°C	±3 RH	10 to 90% RH
Carbon dioxide level	Instant: at workstations	PCE-GA 70 air quality meter	1 ppm	±50 ppm	6000 ppm
Dry bulb temperature	Constant: set in particular locations	Tiny Tag Plus 2 TGP-4500	0.01°C	0.01°C	-25 to +85°C
Relative humidity	Constant: set in particular locations	Tiny Tag Plus 2 TGP-4500	0.3% RH	±3% RH	0 to 100% RH

4 Results and Discussion

In this section, Computational Fluid Dynamics, Building Energy Simulation, and field study analysis are presented and compared.

4.1 Computational Fluid Dynamics

Using the building model, Figure 14 displays the static pressure distribution on the surfaces of the building geometry and also the surrounding buildings. In this simulation, it was assumed that the wind was from the south-east direction and had a speed of 5m/s. As observed, the positive pressure was predicted at the south-east wall of building. This was due to the force being directly perpendicular to the area of interaction. As a result, a negative pressure was created on the opposite end at the immediate downstream of the building. The maximum positive pressure was estimated at 18.5 Pa, while the maximum negative pressure was observed to be -28.0 Pa.

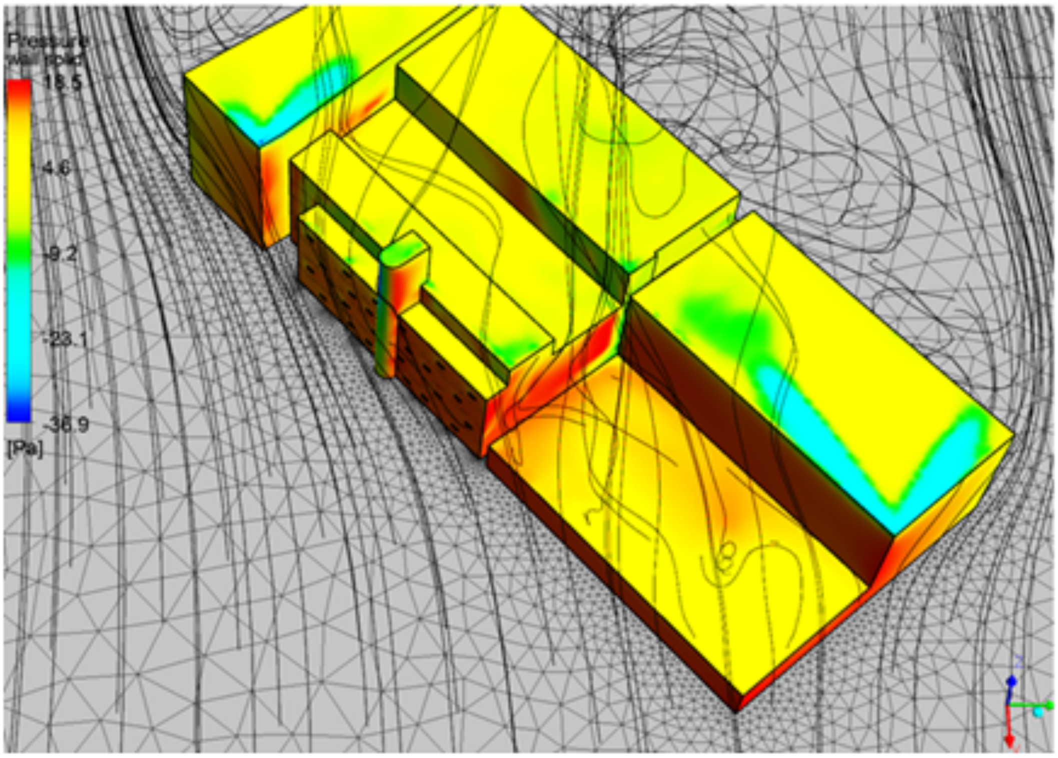

Figure 14: Surface pressure distribution around the building with wind from SE direction.

Figure 14 displays the velocity streamline around the building model. As seen in the diagram, the airflow coming from the bottom (south-east of the building) reduced speed as it approached the wall of the building and accelerated and cavitated as it moved along the roof and corner of the geometry. This created strong negative pressure at the corners and less strong negative pressure on the rest of the building walls and roof. From the streamline analysis, a large vortex was observed downstream of the airflow path. Figure 16 shows a cross-sectional contour plot of the air velocity distribution inside the building model. As observed, the highest airflow speed (up to 0.9 m/s) was calculated near the windows, where outdoor and indoor airflow are exchanged. On average, the airflow speed inside the building was between 0.1 and 0.5 m/s.

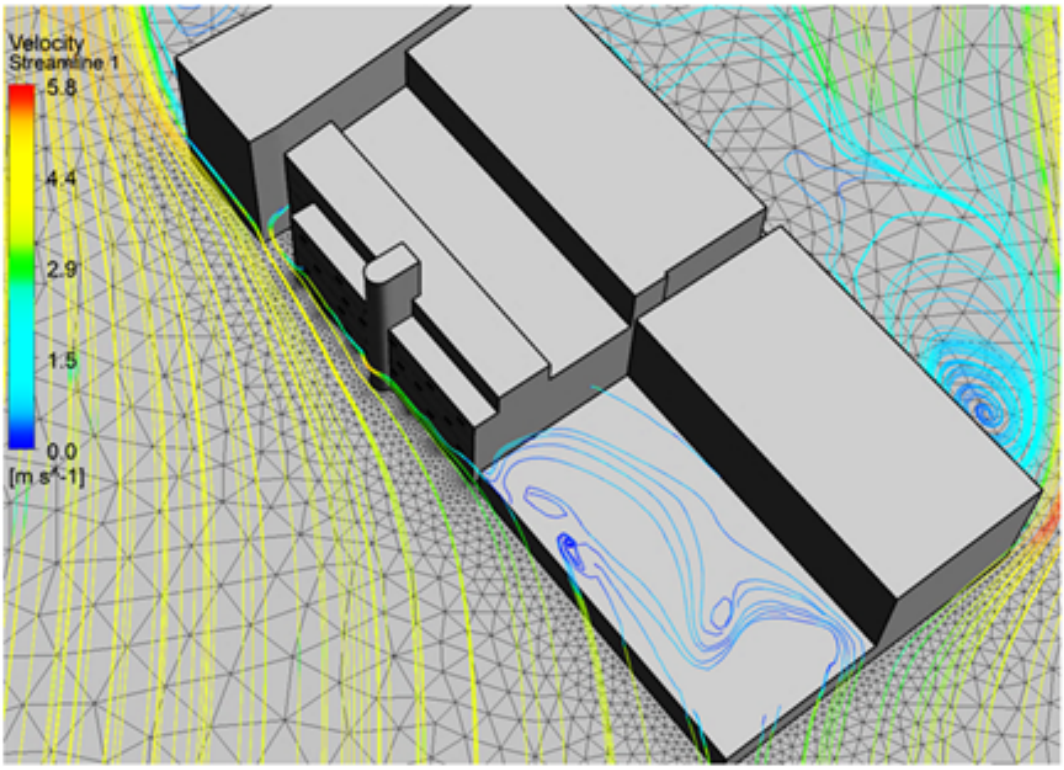

Figure 15: Velocity streamlines around the building with wind from SE direction.

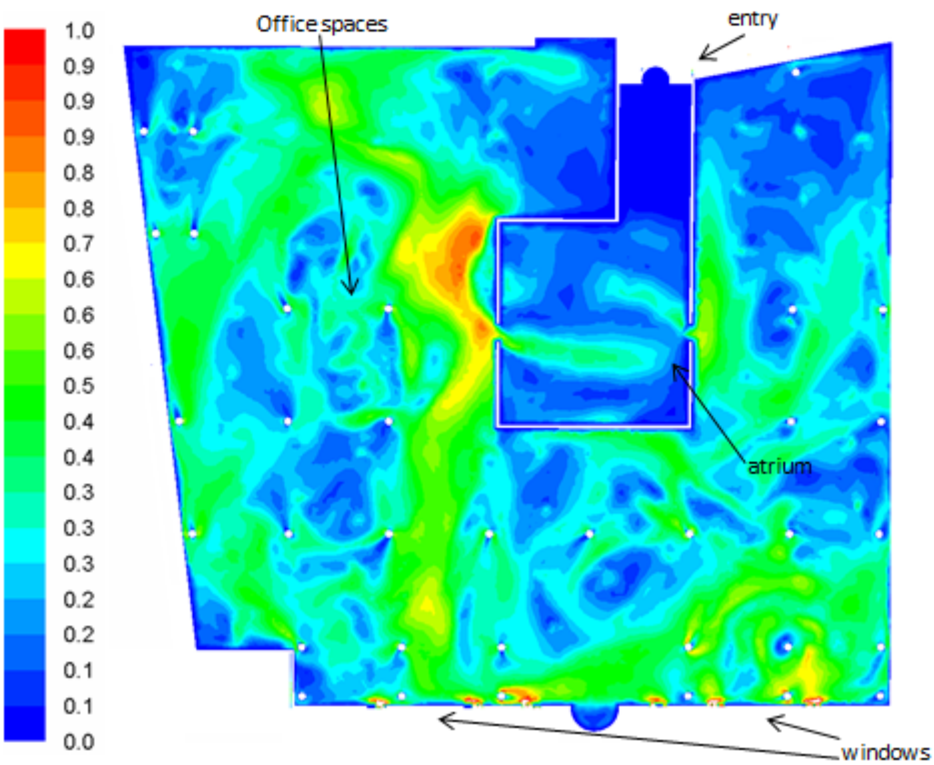

Figure 16: Indoor velocity contour of a cross-sectional plot in the ground floor

Figure 17 and Figure 18 depicts the predicted temperature distribution inside the ground floor and first floor of the building. The heat flux boundary condition was used to replicate the internal gains from the occupants, lighting and equipment. This boundary condition was applied across floor surface and was set to 33.7 W/m^2. As observed, the indoor temperature was around 18-22˚C when the outdoor temperature was at 14˚C.

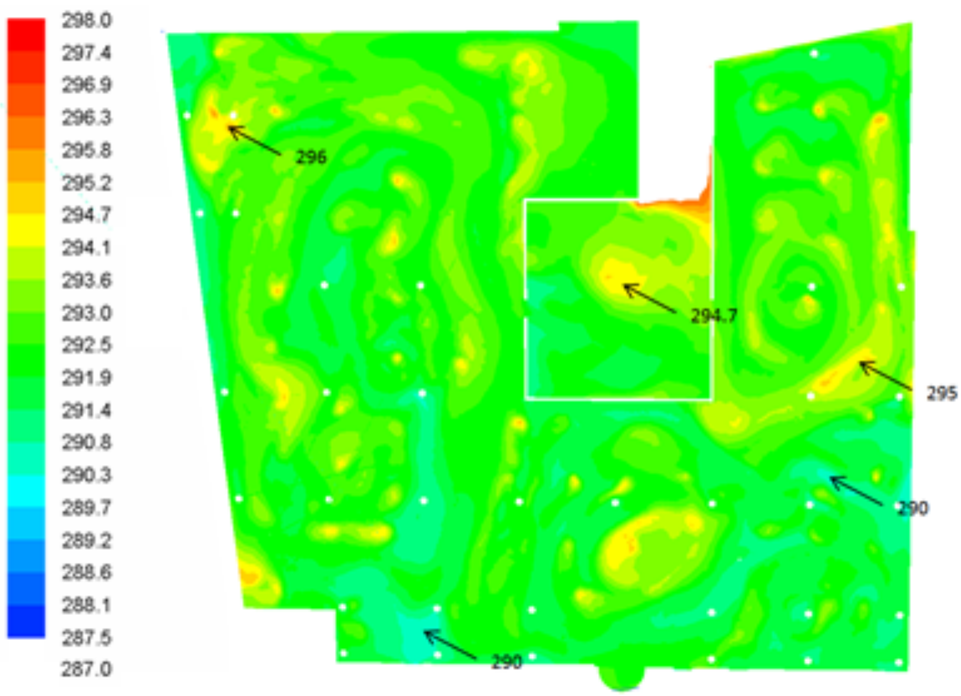

Figure 17: Indoor temperature contour of a cross-sectional plot in the ground floor

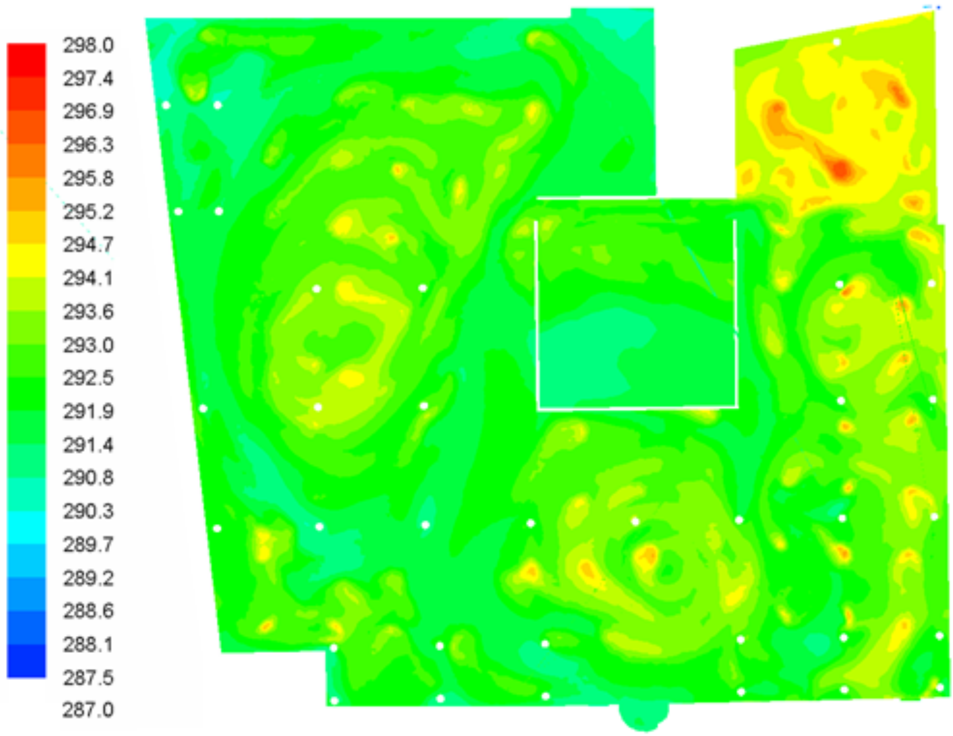

Figure 18: Indoor temperature contour of a cross-sectional plot in the first floor

4.2 Building Energy Simulation

Figure 19 shows the hourly temperature inside the first floor during a typical summer day (August 29) and winter day (January 25). On August 29, the temperature inside the ground floor was between 22–24 ˚C during occupation time when the outdoor temperature was in the range of 12.9–15.8 ˚C. On January 25, the temperature inside the ground floor was also between 22–24 ˚C during occupation time when the outdoor temperature was in the range of 0.7–5.8 ˚C, which resulted in significantly higher heating load during this month.

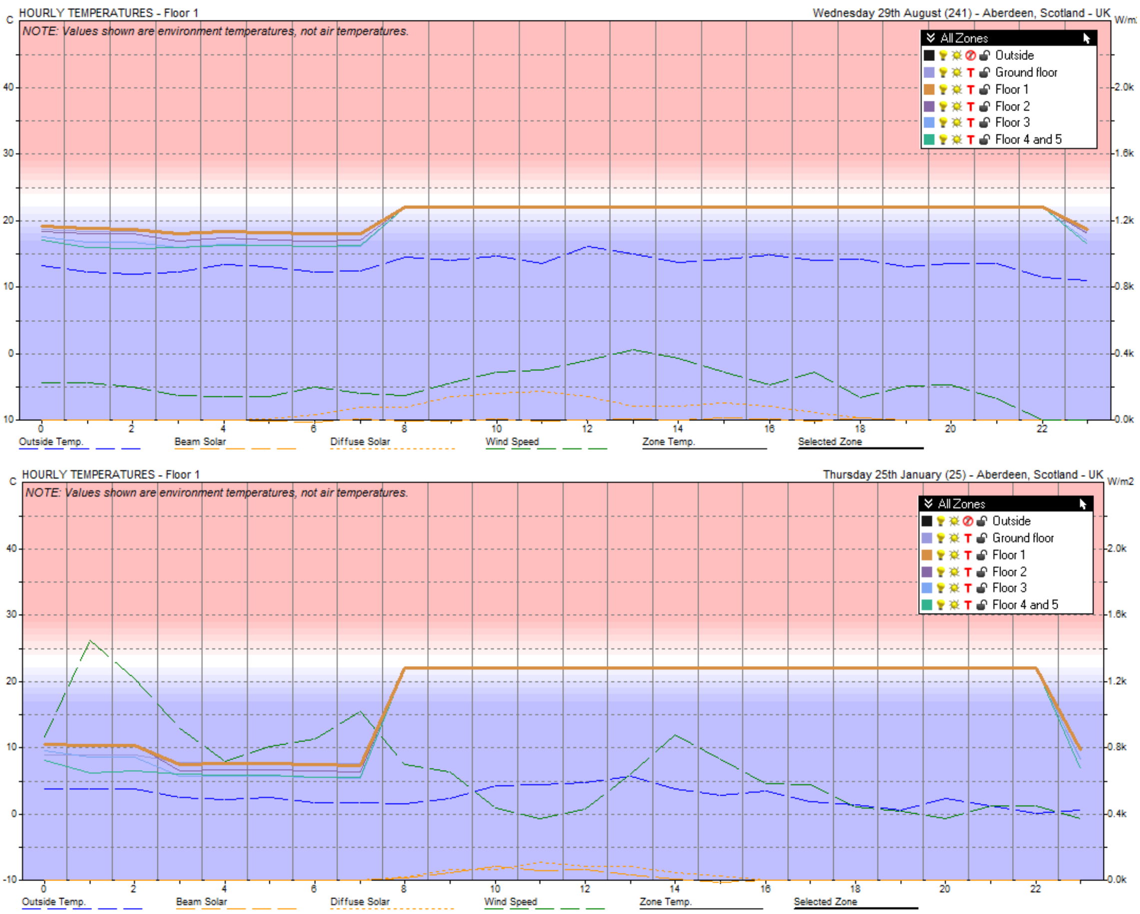

Figure 19: Heating and cooling loads of different floor during winter (top) and summer (bottom)

Figure 20 displays the monthly heating and cooling loads for each zone in the ground floor. The heating loads are displayed in red and projected above the centre line of the graph while the cooling loads were blue and projected below. Red bars indicate that heating is required and energy must be added to the space. Blue bars indicate that cooling is required and energy must be removed from the space. Each bar shows a combined cooling/heating load of the zones, which is colour coded (see graph legend). The highest monthly heating load was obtained at 235 MWh for the month of January. Table 9 summarise the results for each month.

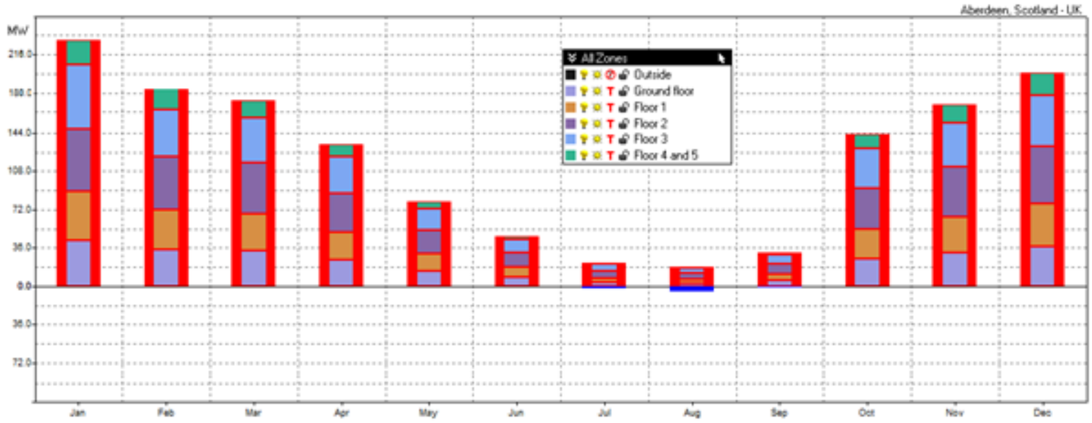

Figure 20: Heating and cooling loads of different floor

Table 9: Table Monthly heating and cooling loads

	HEATING	**COOLING**	**TOTAL**
MONTH	**(MWh)**	**(MWh)**	**(MWh)**
Jan	235.49747	0	235.49747
Feb	188.74574	0	188.74574
Mar	178.61908	0	178.61908
Apr	133.08582	0	133.08582
May	79.53194	0.07022	79.60217
Jun	47.09906	0	47.09906
Jul	22.09307	1.9878	24.08087
Aug	18.59398	4.35178	22.94576
Sep	31.90465	0.5605	32.46515
Oct	142.61882	0	142.61882
Nov	175.05411	0	175.05411
Dec	204.45195	0	204.45195
TOTAL	**1457.29578**	**6.9703**	**1464.26599**
Simulation MWh /PER m²	**0.15624**	**0.00075**	**0.15699**
Actual MWh /PER m²			**0.1594**
Simulation Error (%)			**1.51**

In order to see where the building's heating and cooling loads come from one should look at where the building is gaining and losing heat. The passive gains breakdown chart in Figure 21 shows what percentage of the gains and losses were coming from conduction, solar radiation, infiltration, and internal loads.

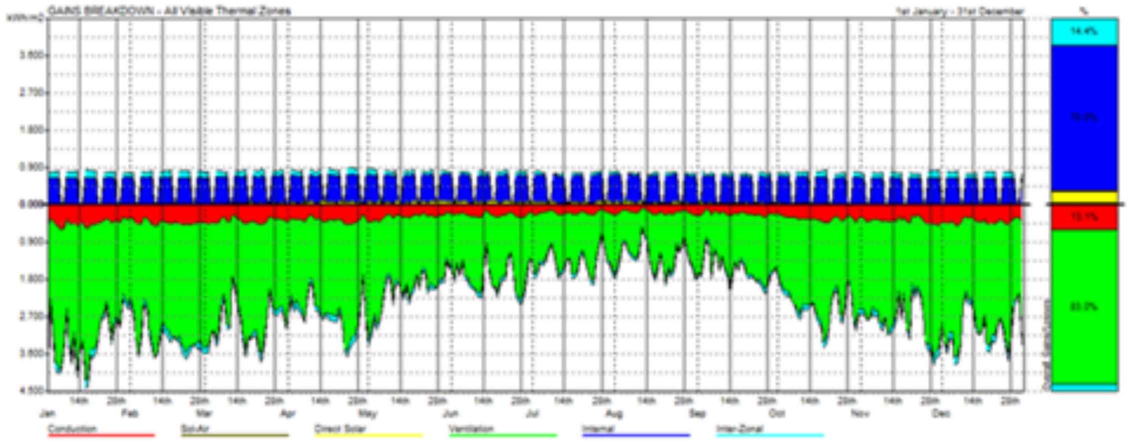

Figure 21: Passive gains breakdown

4.3 Field Studies of Thermal Comfort

The energy performance of the building was compared against the CIBSE benchmark (CIBSE, 2003), as presented in Figure 22. The energy data was provided by the building management. The energy use of the building was 200 Kwh/m^2 per year, which was within the acceptable range and much lower than the air-conditioned standard office. This was in line with the B energy rating of the building and also it indicated that the application of energy strategies and displacement ventilation was successful in reducing the energy demand of the building.

Figure 22: Energy consumption of the building against the (CIBSE, 2003) benchmark, KWh/m^2 per year

Thermal performance of the building was compared against the ASHRAE Standard 55-2013, as presented in Figure 23. This was based on the environmental measurements at workstations and each dot in Figure 23 represents the thermal condition of a particular workstation. This analysis showed that although thermal conditions were within the acceptable range, the majority of them fall into the winter conditions estimating a slightly cool thermal environment.

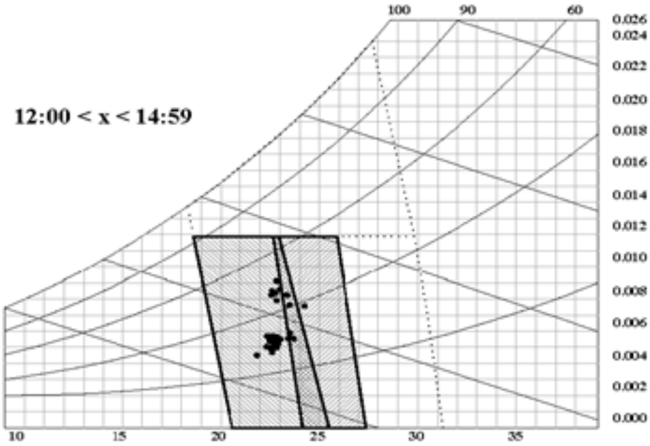

Figure 23: Thermal performance of the measured workstations according to the ASHRAE Standard 55-2013

This was in agreement with the results of simulation, which was discussed in section 4.1. The results of simulation showed indoor temperatures between 18-22˚C, which was similar to the collected data from the site, as presented in Figure 23.

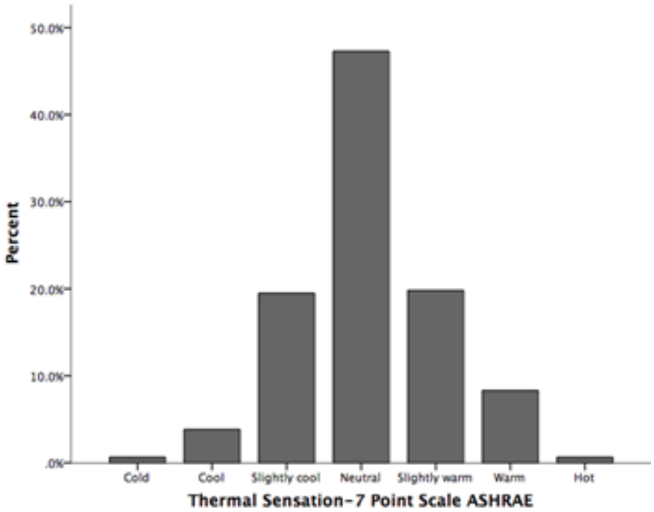

Figure 24: Occupants' response based on the ASHRAE seven point scale thermal sensation

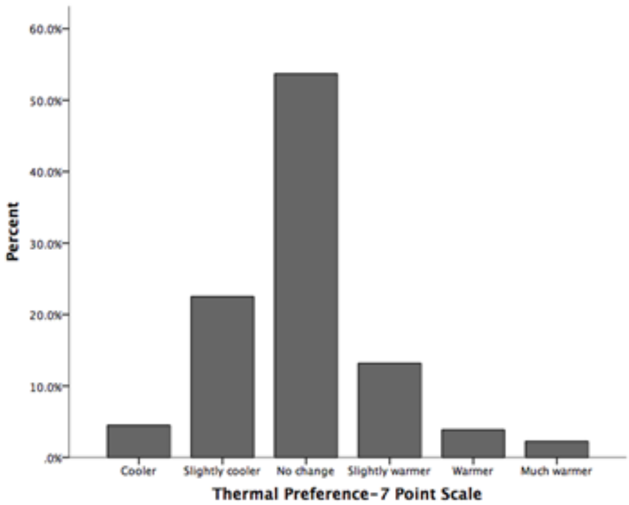

Figure 25: Occupants' response based on the ASHRAE seven point scale thermal preference

Figure 26 illustrates the boxplot of thermal sensation, thermal preference and the expected response. It shows that majority of responses are within the expected range, although some responses closely follow the expected response and some fall out of it. This disagreement is stronger in the two ends of the spectrum, particularly participants who felt cold, wanted no change to warmer conditions, while they were expected to want much warmer temperatures.

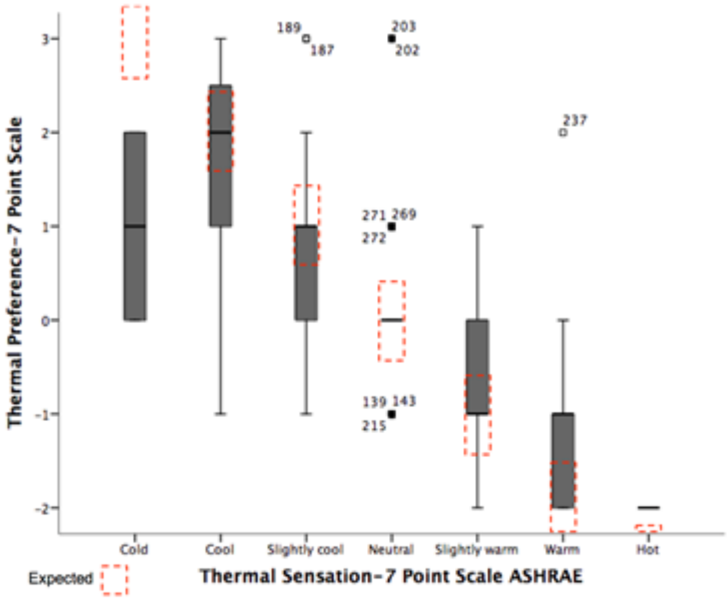

Figure 26: Boxplot of thermal sensation and preference of occupants based on the ASHRAE seven point scale

Based on the thermal measurements, the PMV was analysed, as presented in Figure 27. It showed that over 70% of the occupants were expected to feel slightly cool, while only 25% of them were expected to feel comfortably neutral. These findings agreed with the findings of the simulation, as similar thermal conditions were found.

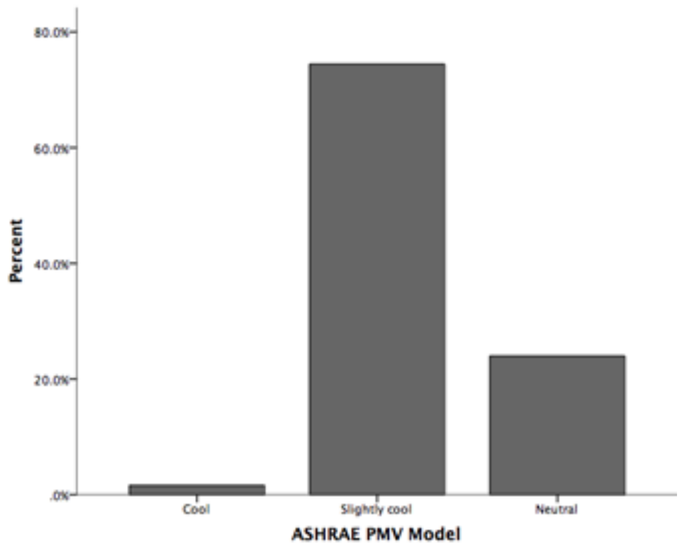

Figure 27: Calculated PMV model based on the environmental measurements of the building

5 Conclusion

The results indicated that the annual energy consumptions of the BES simulations agreed with the results of the field data. The simulation showed annual energy consumption of 0.157 MWh/m^2, which was only 1.51% lower than the actual consumption of 0.159 MWh/m^2. Furthermore, the CFD simulation showed temperatures between 19-24˚C, which was close to the temperature measurements. The PMV model based on the field data showed that 35% of the occupants were expected to feel neutral and the majority of the occupants were expected to feel slightly cool, as these temperatures fell in the winter section of thermal comfort zone. 35% of the occupants reported to have a neutral thermal sensation. The CFD simulation also showed that most of the office had sufficient airflow movement ranging from 0.1 m/s – 0.5 m/s, which also agreed with the field data.

Natural ventilation has the potential to improve the energy efficiency of buildings by reducing reliance on air-conditioning. To effectively design buildings with natural ventilation, evaluation tools are needed that are able to assess its performance. This study used Computational Fluid Dynamics (CFD), Building Energy Simulation (BES) and field study to evaluate the performance of an open plan office in in which natural ventilation was in operation. Through the integration of CFD and BES simulations, this work evaluates the quality of the thermal environment of an open plan office. Because of the complementary nature of BES and CFD results, an integration of both methods can eliminate many assumptions of the simulation, which increases the accuracy. The BES requires detailed information on the airflow and thermal conditions of the surrounding of the building. These can be computed in the CFD simulation to improve the accuracy of the prediction of the indoor thermal environment. The results indicate that BES and CFD can play an important role to improve the design of the building to achieve this balance. They provide important information to optimise the energy efficiency and the quality of the thermal environment.

Acknowledgement

The authors gratefully acknowledge the contribution of the architects, management and occupants of the case study building.

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SESSION 5

Smart Comfort and Controls

Invited Chairs: Bjarne Olesen and Ryozo Ooka

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Effectiveness of operable windows in office environments

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Abstract
A field study was conducted between November 2011 and March 2012 in nine modern office buildings in the Netherlands. One of the objectives was to objectify (under given weather conditions) how much control can be exercised by office workers over their indoor climate with operable windows.
To evaluate the effectiveness of the operable windows, dynamic experiments were conducted. The experiments started with the opening of windows by the research team. Next, response times and step responses were assessed in terms of air temperature changes and CO_2 concentration alterations. For the cases studied, as far as temperature effects are concerned: the study revealed that the step response on average was -2.2 K; the average halftime value was 8 minutes; and the temperature on average changed with -0.18 K per minute after windows were opened. As far as effects on CO_2 concentrations are concerned: step response on average was -390 ppm; the average halftime value was 7 minutes; and the CO_2 concentration on average changed with -37 ppm per minute after windows were opened. An average maximum outdoor temperature of 7.9 ^{o}C and an average wind speed of 4 m/s were measured during the study. With some limitations, the outcomes can be used to quantify how effective operable windows can be - under non-summer conditions - to office building users that periodically want to fine-tune their indoor climate.

Keywords: personal control, adjustability, occupant behavior

1 Introduction
Several studies have shown that having or not having control over one's indoor climate affects how that indoor climate is perceived (Bell et al, 2002; Boerstra et al. (2013). There is growing evidence that human responses to sensory stimuli such as suboptimal temperatures modify when those exposed have control over these stimuli, i.e. when building users have adaptive opportunities (Brager & DeDear, 1998).

In this context Rohles (2007) mentions that personal preferences differ a lot, therefore the ability of an individual to control his or her environment does have a considerable effect on satisfaction with the surroundings. Bordass, Leaman & Ruyssevelt (2001) found that building occupants are most comfortable, healthy and productive in buildings that have (that perceive to have) effective operable windows and effective temperature controls. Nicol & Humphreys (1973), Paciuk (1990) & Hellwig (2015) arrived at similar conclusions.

Modern Dutch office buildings typically have several control options. Especially operable windows and adjustable thermostats are quite common. A lot is still unclear about control over indoor climate in Dutch offices and the added value of especially operable windows. An important unanswered question is: How effective are operable windows? Both in terms of thermal comfort and indoor air quality adjustability.

A field study was designed to explore the effectiveness of adjustable thermostats and operable windows in an office building context. The results related to the effectiveness of adjustable thermostats have been presented previously, see Boerstra, Loomans & Hensen (2013). In this paper the operable windows related results are presented. Here the central objective was to objectify (under given weather conditions) how much control can be exercised by office workers over their indoor climate with operable windows.

2 Methods

The field study was carried out in nine office buildings located in 7 different cities in the Netherlands.

The buildings were selected based on the following criteria:

- State-of-the art office work environment (relatively modern office concept);
- Well maintained building and HVAC systems;
- Gross net floor surface at least 2000 m^2 (around 22000 ft^2);

Easy access for the research team to the workspaces (and the office workers).

The selected buildings were used by either governmental institutions or commercial organizations. The buildings were equipped with different types of HVAC systems ranging from traditional to more innovative systems such as slab heating/cooling systems.

Note that Dutch office buildings differ in an important way to average office buildings in North-America and Asia: they normally have more options for control. Eight of the nine buildings studied had operable windows and seven buildings offered possibilities for manual temperature control in winter at room level.

The buildings were visited at different times from November 2011 till March 2012. Average maximum outside temperatures during the measurement days varied from +5 to +17 °C, with one exception (in that case the daily maximum was - 3°C).

Inside the buildings relevant building and HVAC system characteristics were mapped with the use of a checklist. For example, an inventory was made of the type of heating systems installed in the buildings and of the ways these heating systems could be controlled by the building occupants. A more detailed description of the nine buildings can be found in Annex 1.

In each building several effect measurements were performed (on average 6 per building). These measurements involved temperature and CO_2 measurement that lasted half an hour or more (up to 3 hours) and that were done during and after the research team had opened a window.

The measurements allowed us to objectify the available level of control that occupants had over the indoor climate. That is, given the weather conditions at the time of measurements, the floor plans, the characteristics of the operable windows etcetera. The measurement outcomes were used to quantify the indoor climate effectiveness of the operable windows.

The window effectiveness measurement procedure consisted of 4 steps:

Step 1 'Room selection':

Upon arrival in each building a walk through survey was conducted. Indicative measurements with handheld devices of the actual room conditions (especially air temperature, relative humidity and CO_2 concentration) were used to identify suitable rooms to perform an intervention experiment in. Rooms that were not in use during the measurement day or rooms with unusual high or low (start) temperature were discarded. Selected rooms were expected not to have substantial changes in terms of heat loads and internal CO_2 production during the first 2-3 hours after the window had been opened.

Step 2. ‘Start intervention’:
Next the measurement equipment was installed in the selected rooms. For the measurements a calibrated Brüel & Kjær 1213 climate analyzer was used and several calibrated CaTeC klimabox 5000 logging devices. The latter allowed to log (changes in) air temperature, humidity and CO_2 concentration. The measurement equipment was placed as close as possible to one of the workstations in the room, typically at a distance of 2 to 3 m from the façade. The equipment was put at table height (around 0.7 to 0.9 m above floor level). As far as thermal comfort effects are concerned: the main focus was on (changes in) air temperature, At the start and end of each intervention (see below) control measurements (with the Brüel & Kjær 1213) were made to check for any unusual changes in radiant temperature and relative humidity during the experiment.

Step 3. ‘End intervention’:
At intervals of about 30 minutes, handheld devices were used to determine whether and how air temperature and CO_2 concentration had changed since t_0 (the time at which the window was opened). During these inspection rounds it was also assured that no major changes in terms of ‘loading’ of the rooms had taken place. As soon as a new steady state had been reached in a room the intervention was stopped (windows were closed again) (at t_{end}) after which the measurement data were retrieved for further analyses.

Step 4. ‘Measurement data analysis’:
Each intervention was quantified in terms of step response and response time. These terms are graphically explained in Figure 1. This is an example for temperature effect only; a similar approach is used when objectifying the CO_2 concentration effect. The step response here is defined as the difference between the measured value (air temperature in this example) at the new steady state conditions and the value at t_0. The response time is defined as the time interval between t_0 and the time t_{end} at which the new steady state has been reached. Also the concept of half-life is explained in Figure 1. Half-life ($t_{½}$) is the time interval after which the measured value (in this case air temperature) is equal to $T(t_0)$ plus 0.5·times the step response. Half-life is a general concept that is also used in other fields (chemistry, physics, biology, etc.) to describe any phenomenon which follows an exponential change in time. The prime indicator that is calculated is the indoor climate effectiveness of the windows expressed in Kelvin per minute or (in the case of the CO_2 measurements) ppm per minute. This refers to (an approximation of) the average rate at which the temperature and CO_2 concentration change during the time interval t_0 to $t_{½}$. The indoor climate effectiveness of the windows is then calculated by dividing (0.5·times the step response) (in K or ppm) with ($t_{½}$ -t_0) (in minutes).

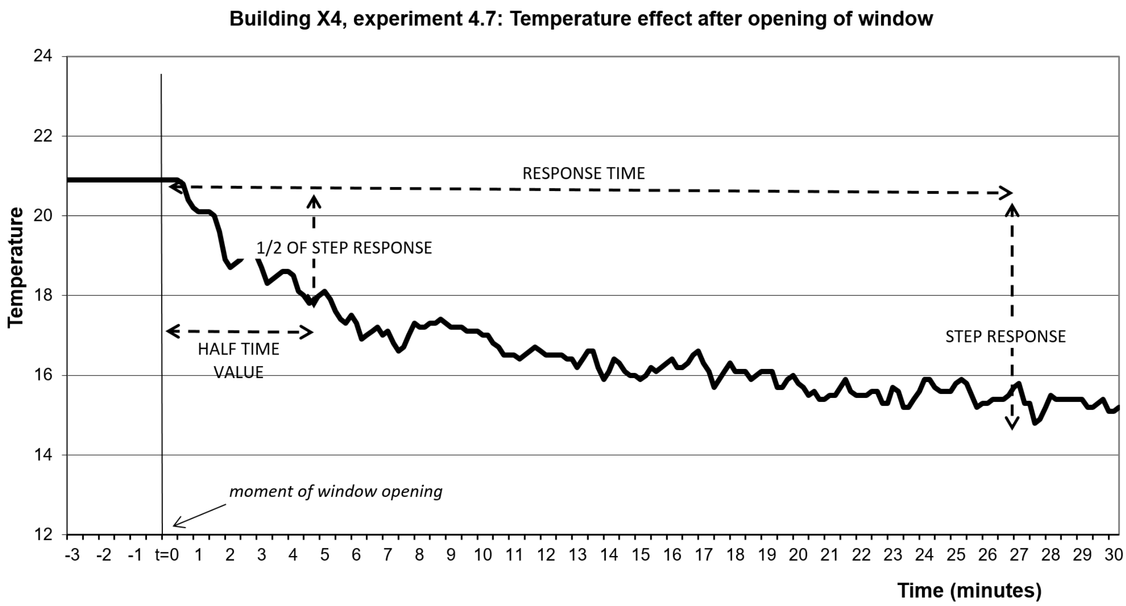
3 Results

Two examples of the window effectiveness measurement outcomes are presented graphically in the Figures 1 and 2. Figure 1 presents the results of a ‘temperature effect experiment’: an operable window was opened and the effect on air temperature was measured). Figure 2 presents the results of an ‘CO_2 concentration effect experiment’: an operable window was opened and the effect on CO_2 concentration was measured.

The results for all temperature measurements are summarized in Table 1. The results of all CO_2 concentration measurements are summarized in Table 2. These tables also included average weather conditions for that day.

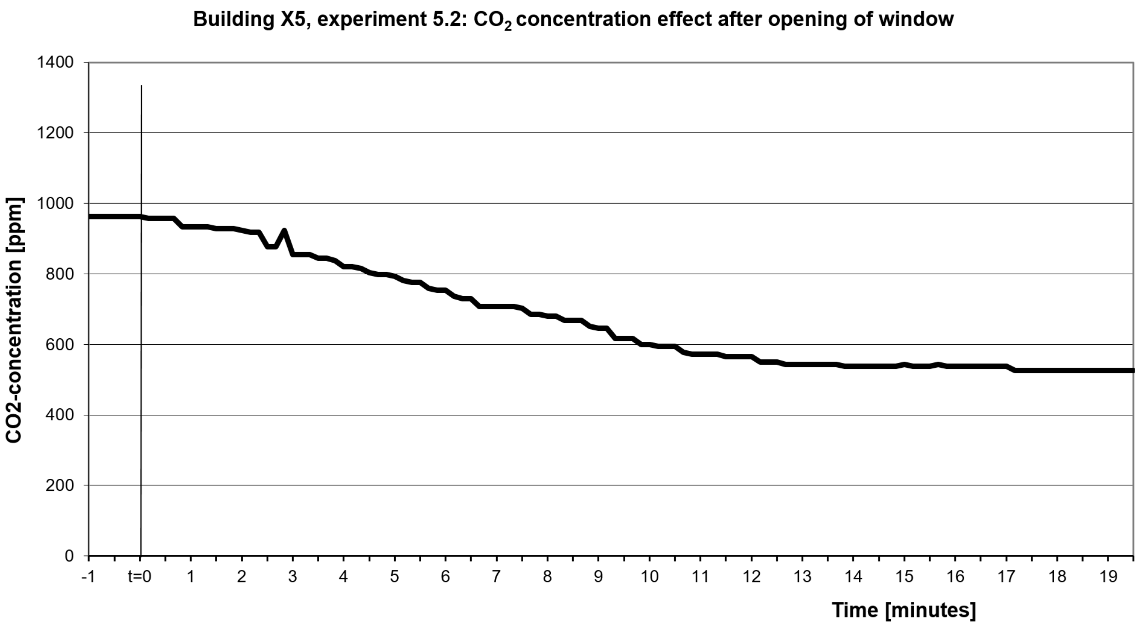
The two tables show that large differences between buildings were found. In some spaces window opening resulted in no significant effect on inside air temperature while in other buildings temperature decreases of 3 to 4 K were measured before steady state was reached. Window effectiveness in this case varied from 0 K/minute to -0.38 K/minute. The latter meaning that after windows were opened the air temperature decreased with nearly 0.4 K per minute. Note that this was measured in an office building with relatively large operable windows during rather cold outside weather. The values as obtained for the halftime value indicate for all buildings that the average response takes place within the order of minutes. That is, given the momentary outdoor conditions.

Also the CO_2 concentration measurements showed quite a bit of variation. In some spaces CO_2 concentration went down less than 100 ppm after a window was opened, in other spaces this was more than 700 ppm. Window effectiveness for CO_2 effect varied from 12 ppm/minute to more than 120 ppm /minute. The latter meaning that after windows were opened the CO_2 concentration dropped with a 'speed' of more than 120 ppm per minute. Note that this was measured in an office building with very large operable windows. Also for CO_2 concentration response times turned out to be in the order of minutes.



Date: 16-12-2011	Start time:	12:35:02	Step response: - 6.1 K	Halftime value: 5 minutes	Wind speed: 7 m/s
Space no.: A358	Floor surface: 23 m²		Response time: 27 minutes	Outside temp. (max): 4.8 °C	Wind direction: N

Figure 1. Example nr. 1 of a window effectiveness measurement outcome. During this specific experiment the focus was on air temperature effect. The figure includes an explanation of the concepts response time, step response and half-life. Note that below the figure additional information is presented such as the date of the experiment and the maximum outside temperature of that day according to the KNMI (Dutch Meteorological institute).



Date: 16-01-2012	Start time: 15:24:00	Step response: -436 ppm	Halftime value: 6 minutes	Wind speed: 4 m/s
Space no.: B2.22	Floor surface: 27 m²	Response time: 17 minutes	Outside temp. (max): 4.4 °C	Wind direction: NW

Figure 2. Example nr. 2 of a window effectiveness measurement outcome. During this experiment the focus was on CO_2 concentration effect.

Table 1. Effect of window opening on air temperature

Building	*# of experi-ments*	*AVG step response (min - max) [K]*	*AVG response time (min - max) [minutes]*	*AVG halftime value (min - max) [minutes]*	*AVG window effec-tiveness** [K/ minute]*	*Outside temp (day max) [°C]*	*Outside wind speed [m/s]*
X1	5*	-2.2 (0 ; -4.8)	38 (15 ; 85)	11 (2 ; 25)	-0.10	+17	5
X2	2*	0	-	-	0	+9	4
X3	3*	-0.1 (0 ; -0.2)	18	5	-0.01	+10	4
X4	6	-4.4 (-2.5 ; -8.7)	42 (26 ; 75)	13 (2 ; 30)	-0.17	+6	7
X5	8	-3.8 (-0.5 ; -9.6)	21 (11 ; 24)	5 (1 ; 10)	-0.38	+7	3
X6	2	-1.5 (-1.3 ; -1.6)	20 (13 ; 26)	5 (3 ; 6)	-0.15	-3	2
X7	4	-1.7 (-0.2 ; -2.5)	19 (10 ; 30)	4 (3 ; 5)	-0.21	+10	4
X8	2	-2.8 (-0.8 ; -6.8)	32 (15 ; 60)	13 (4 ; 21)	-0.11	+5	7
X9	5	-3.7 (-0.2 ; -6.2)	32 (10 ; 60)	6 (1 ; 16)	-0.31	+10	3
All combined	**37**	**-2.2**	**28**	**8**	**-0.18**	**-**	**-**

** In building X1, X2 and X3 respectively 1 time out of 5, 2 times out of 2 and 2 times out of 3 no temperature effect were measured after opening a window.*

*** Calculated with the following formula: window effectiveness = (1/2 * step response) / (halftime value)*

4 Discussion

The central objective was to objectify (under non-summer weather conditions) how much control can be exercised by office workers over their indoor climate with operable windows.

Due to practical circumstances it was not possible to quantify the window effectiveness in the 9 buildings under comparable weather conditions. So the outcomes cannot really be used to compare the buildings with each other. Instead the overall results should be seen as an indication of what the indoor climate effects of 'the Dutch operable office window' are when the window is opened under non-summer conditions. The halftime values as obtained indicate that the response from opening a window in any of the investigated office buildings is in the order of minutes.

The effectiveness of operable windows is not just dependent upon momentary weather conditions. Also aspects like office layout and characteristics of the operable parts have an impact. So the results of this study can only be seen as a first quantitative overview for the IEQ effectiveness of operable windows in offices. Nevertheless, with some limitations, the outcomes can be used to quantify how effective operable windows can be - under non-summer conditions - to office building users that periodically want to fine-tune their indoor climate.

Table 2. Effect of window opening on CO_2 concentration

Building	***# experi ments***	***AVG step response (min - max) [ppm]***	***AVG response time (min - max) [minutes]***	***AVG halftime value (min - max) [minutes]***	***AVG window effec-tiveness [ppm/ minute]***	***Outside temp (day max) [°C]***	***Outside wind speed [m/s]***
X1	1	-190	60	5	-19	+17	5
X2	3	-310 (-70 ; -770)	52 (27 ; 90)	13 (5 ; 25)	-12	+9	4
X3*	-	-	-	-	-	+10	4
X4	2	-290 (-280 ; -300)	58 (45 ; 70)	10 (6 ; 15)	-15	+6	7
X5	2	-350 (-260 ; -440)	25 (17 ; 32)	5 (4 ; 6)	-35	+7	3
X6	2	-750 (-640 ; - 850)	26 (20 ; 31)	3 (2 ; 4)	-125	-3	2
X7	2	-450 (-370 ; -540)	26 (22 ; 29)	6 (3 ; 8)	-38	+10	4
X8	2	-380 (-220 ; -530)	23 (21 ; 24)	10 (6 ; 14)	-19	+5	7
X9*	-	-	-	-	-	+10	3
All combined	**14**	**-390**	**39**	**7**	**-37**	**-**	**-**

* *No CO_2 measurements in relation to window opening effect were performed in the buildings X3 and X9*
** *Calculated with the following formula: window effectiveness = (1/2 * step response) / (halftime value)*

The results show that operable windows can be very effective and that window opening in an office building under certain circumstances can result in quite fast changes in air temperature and CO_2 concentration. The field study revealed that the temperature step response on average was -2.2 K. The average halftime value was 8 minutes and the temperature on average changed with -0.18 K per minute after windows were opened. As far as effects on CO_2 concentrations are concerned: step response on average was -390 ppm. The average CO_2 halftime value was 7 minutes; and the CO_2 concentration on average changed with -37 ppm per minute after windows were opened.

A remark concerning the air temperature effects measured: thermal comfort is not just affected by air temperature (air temperature adjustments) but also by air velocity (air velocity changes). Separate measurements have shown (not further presented in this paper) that in most of the spaces that were investigated also air velocity at work stations went up after windows were opened; often with 0.15 m/s or more. When estimating the effectiveness of the operable windows of this study in terms of overall thermal comfort adjustability one should also take air velocity effects into account and look beyond just the air temperature increases measured.

One limitation of this field study is that it was done in late autumn and winter. So the study does not offer inside in the effectiveness of operable windows (especially in terms of air temperature effects) when outside temperatures are high (20 °C and more). To estimate how the use of operable windows in summer affects indoor air temperature (thermal comfort) and CO_2 concentration, an additional study should be done during the summer months.

Another limitation is related to the definition of 'window effectiveness' that has been used in the context of this paper. For now the following formula has been used: window effectiveness = (1/2 * step response) / (halftime value). A future version of that formula also could include contextual aspects like e.g. momentary wind speed, wind direction, outside CO_2 concentration and/or outside temperature (or even better: the difference between the inside and outside CO_2 concentration / temperature at the start of the intervention).

Comparison of the results of this study to those of other field studies is not straightforward, partly because this type of study is quite rare. The authors are not aware of any other field studies that used window effectiveness measurements similar to the ones described in this paper. Haldi and Robinson (2007) studied personal control over indoor climate in eight Swiss office buildings under summer conditions, so these results could not be compared. In addition, Haldi and Robinson did not perform comparable temperature and CO_2 effect measurements as the ones described in this paper.

The operable window effects described in this paper can be compared to the adjustable thermostat effects that are described in Boerstra, Loomans & Hensen (2013). The latter were the outcomes of thermostat effectiveness measurements that were performed during the same period in the same 9 office buildings. In the best buildings (with the most effective, fastest adjustable thermostats) thermostat effectiveness at best was 0.02 to 0.03 K/minute. While temperature effectiveness for the operable windows (under non-summer conditions) turned out to be 0.18 K/minute on average. So one could state that windows were a factor 6 'faster' than adjustable thermostats. This is of course only relevant when occupants want to *lower* their room temperature. *Increasing* air temperature, during the heating season, in an office building, by opening of closing a window is not feasible.

5 Conclusions

The field study in the 9 office buildings showed that the average Dutch office worker can exercise a considerable amount of control over his/her indoor climate through the use of operable windows. The results imply that under non-summer conditions inside air temperature can be decreased (on average) with 0.18 K per minute. And the CO_2 concentration can be decreased (on average) with 37 ppm per minute when windows are opened. Halftime values for all investigated buildings for both parameters were, on average, less than 10 minutes.

With some limitations, the outcomes can be used to quantify how effective operable windows can be - under non-summer conditions - to office building users that periodically want to fine-tune their indoor climate.

Acknowledgements

The authors would like to thank Patrick Creemers and Richard Claessen for their assistance during the field study and their help with the analysis of the data. At the time of the field study Patrick and Richard were Master students of the unit Building Physics & Services of the Eindhoven University of Technology in the Netherlands.

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Annex 1. Characteristics of the nine office buildings

Aspect	**Building**				
	X1	**X2**	**X3**	**X4**	**X5**
Type of organization	Housing corporation	Main office HVAC product manufacturer	Departmental building government	Town hall	Main office construction company
Year of construction / latest major renovation	1948 / 2000	2006 / -	1967 / 1998	2003 / -	1986
Floor surface	5,000 m^2 (54,000 ft^2)	7,300 m^2 (79,000 ft^2)	33,000 m^2 (355,000 ft^2)	6,400 m^2 (69,000 ft^2)	4,100 m^2 (44,000 ft^2)
Office layout	mainly enclosed spaces, some office landscape	mainly office landscape	enclosed spaces (mainly 1, 2 and 4 person offices)	enclosed spaces (mainly 1, 2, 4 and 6 person offices)	mostly 1 person rooms
Number of floors	3	3	21	5	4
Average floor depth	25 m (82 ft)	15 m (49 ft)	23 m (75 ft)	15 m (49 ft)	13 m (42 ft)
Number of workstations	150	520	1400	220	65
Percentage of glazing	±20%	±70%	±40%	±50 & 80%	±20%
U-value glass	1.1 m^2K/W	0.7 m^2K/W	ca. 2 m^2K/W	1.6 m^2K/W	ca. 3 m^2K/W
Ventilation system	mechanical supply and exhaust system with central heat recovery (twin coil)	mechanical supply and exhaust (CAV) with heat recovery via enthalpy wheel	mechanical supply and exhaust with central recirculation	mechanical supply and exhaust (CAV), steam humidification central heat recovery via Resolair units	mechanical air supply and exhaust with heat recovery via enthalpy wheel
Heating system	after heater in above ceiling VAV induction-unit connected to district heating system	heating via 4 pipe climate ceiling connected to geothermal heating / cooling storage system and heat pump	after heater in DID induction unit connected to district heating system	radiators and convectors connected to district heating system	radiators connected to natural gas heaters
Cooling system	local cooling via VAV induction-units	local cooling via climate ceiling (see above) and central precooling of ventilation air	after cooler in DID induction unit	central precooling of the supply air	some central precooling of the supply air
Temperature control winter	wall thermostat	indirect via desktop computers connected to building management system	wall thermostat with on-off presence knob	adjustable thermostatic valves on radiators and convectors	adjustable thermostatic valves on radiator
Temperature control summer	wall thermostat	see above	wall thermostat with on-off presence knob	none	none
Ventilation control	operable windows (medium size)	operable windows (medium size)	operable window (medium)	partially operable windows (medium)	operable windows (medium, zigzag double sliding)

Annex 1. Characteristics of the nine office buildings (continued)

Aspect	Building			
	X6	**X7**	**X8**	**X9**
Type of organization	Main office façade building product manufacturer	Head quarter consumer organization (building I)	Head quarter consumer organization (building II)	Tax office government
Year of construction / latest renovation	2010 / -	1971 / 1990	1958 / 2005	2011 / -
Floor surface	2,000 m^2 (22,000 ft^2)	11,600 m^2 (125,000 ft^2)	11,200 m^2 (121,000 ft^2)	46,600 m^2 (502,000 ft^2)
Office layout	mainly office landscape	partly enclosed spaces, partly office landscape	mainly office landscape	partly enclosed spaces, partly office landscape
Number of floors	3	8	8	25
Average floor depth	16 m (52 ft)	15 m (49 ft)	15 m (49 ft)	23 m (75 ft)
Number of workstations	35	680	450	2600
Percentage of glazing	±90%	±50%	±60%	±70%
U-value glass	1.1 m^2K/W.	ca. 3.5 m^2K/W	1.2 W/m^2K	1.1 W/m^2K.
Ventilation system	air supply via double, folding façade and operable windows, mechanical exhaust in kitchen, toilet etc	natural supply via large and small operable windows, no mechanical exhaust	mechanical supply and exhaust , humidification of the ventilation air and heat recovery via twin coil	mechanical supply and exhaust system (VAV) with under floor supply
Heating system	slab heating connected to geothermal installation with heat pump	radiators connected to natural gas heaters	radiators and ventilator convectors connected to natural gas heaters and central preheating of the ventilation air	slab heating with additional convectors connected to central heat / cold storage in the soil with heat pump and central preheating of the supply air
Cooling system	slab cooling (see above)	None	ventilator convectors connected to cooling machines and central precooling of the supply air	slab cooling (see above) and central precooling of the supply air
Temperature control winter	None	adjustable non-thermostatic valves on radiators	adjustable thermostatic valves on radiators and ventilator convectors	adjustable thermostatic valves on convectors; sometimes also wall thermostats
Temperature control summer	None	None	adjustable thermostatic valves on ventilator convectors	None
Ventilation control	operable windows (large, in double folding façade)	operable windows (small and large combined)	operable windows (large)	operable windows (medium)

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Impacts of Variations in Air Conditioning System Set-Point Temperature on Room Conditions and Perceived Thermal Comfort

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Abstract

This paper describes research carried out to investigate specific features of the operation of air-conditioning systems of University buildings in Hong Kong. Changes in thermostat set points were introduced so as to investigate the impact on conditions experienced and also to determine spatial variations within the rooms. Measurements of environmental conditions were made at 5 minute intervals over a total investigation period of 6 days. Concurrently with the environmental measurements occupant surveys took place, the subjects being a group of postgraduate students. Some 912 sets of survey data were accumulated and this was used in conjunction with environmental data to compare actual and predicted sensation votes. Comparisons of sensation votes and preference votes were also carried out. Main findings were: that a significant degree of temperature variation occurred across the rooms despite the sets of controllers being used in conjunction with each other to effect changes; that the relationship between actual and predicted sensation votes exhibited a degree of variation between days even with the same occupants and that occupants tended to vote over a wider range than was predicted; and that there was a clear (as expected) inverse relationship between actual sensation and preference voting.

Keywords: thermal comfort; temperature variation; air-conditioning; controls; Hong Kong

1 Introduction

In certain climates air-conditioning systems have become almost ubiquitous; sometimes because of necessity and sometimes because of occupant expectation. The energy consumption associated with use of air-conditioning is a feature of both modern life and modern buildings, and the resulting peak demand requirements can have substantial impacts on electricity supply systems. There is also concern that occupied and space conditioned spaces may exhibit issues with negative reaction from occupants when operated outwith suitable ranges – for instance: too warm in winter; and too cold in winter (see for example Mendell and Mirer, 2009). Further, in order to deal with present and impending problems of global climate change, any steps available to reduce carbon dioxide-generating energy use should be taken. The question then remains how to minimise the demand for air-conditioning whilst maintaining the required degree of comfort. Part of dealing with this conundrum is to understand better how air-conditioning systems are used in practice and how they perform when perturbations are introduced; evidence suggests this is less than optimal (Sekhar, 2016).

As a result of these concerns, studies have been undertaken to elicit information on how well systems perform when variable influences exist, such as shifting of thermostat set-points. These studies can also help to answer questions about occupant perception and reaction to changes in air-conditioned conditions. Several studies of this topic have been carried out (such as Boerstra, Loomans and Hensen, 2013) though none in detail for this particular building situation. In the longer term, understanding of this issue could also help determine how different, perhaps 'smart' systems could be used to enhance air-conditioning control (see Cheng and Lee, 2014).

This paper reports results of recent field studies carried out in Hong Kong. The subjects of the studies were University students, most newly arrived in Hong Kong from different parts of China. No single previous climatic background was predominant amongst the group. This student course group has been investigated in previous years but for different purposes and results presented at the NCEUB Windsor Conference (Pitts, 2014).

The buildings of Hong Kong are largely air-conditioned and during the periods of study in the later summer, external conditions generally require substantial use of air-conditioning to achieve comfort. The rooms used in this study were located in buildings completed in the last 6 years and both had won awards for sustainability.

A particular reason for choosing a location such as Hong Kong is both the number of thermal comfort studies performed there over the years (see for example Mui and Chan, 2003) and also because there has been evidence to suggest cooling systems are operated at lower temperatures than might be expected to cope with a combination of occupant expectation and the higher clothing insulation levels often worn (Chan et al, 1998).

The aims of the study were several-fold:

a. To examine how changes in the thermostat settings in the rooms impacted upon conditions produced in the rooms and potential variations in thermal conditions between different points within the rooms.
b. To determine the comfort reactions of the student groups over several days given a situation in which the conditions set by the thermostats were changed.
c. To examine if the students exhibited any degree of tolerance to environmental conditions which might be outside their normal comfort envelope.
d. To compare between days and between rooms to check if any patterns of reaction were evident.

2 Locations Studied

The two rooms investigated were both lecture rooms and both had similar furniture: moveable bench style desks and plastic chairs with no padding. The buildings used were adjacent, separated only by a University campus service road. Both had similar air-conditioning systems with thermostatic controllers placed in groups on one wall of each room – significantly perhaps the walls for the thermostats were those opposite to the windows. The air-conditioning air supply and extracts were integrated into the ceilings with supply air adjacent to the light fittings and spread evenly across the whole of each space. Solar heat gain was minimised during the course of the study by drawing down fabric blinds on the windows – in one case this consisted of a double set of screens to minimise influence.

Room 1 had approximate dimensions of 10m. x 7m.; room 2 was larger at approximately 8m. x 12m. Each room had standard fluorescent type lighting systems. Floor to ceiling heights was approximately 2.8m. Some windows were openable but all remained closed during the course of the surveys as external temperatures exceeded 30°C with very high humidities.

Figure 1 shows a panoramic photo of one of the rooms in which the surveys were carried out.

Figure 1. View of Room 1.

3 Environmental Surveys

The well-known Hobo data loggers were used to monitor temperature and humidity in the rooms being surveyed. These devices use simple measurement transducers which can lead to variations between individual sensor measured values. In order to check for calibration purposes, all devices to be used were placed in an isothermal location and left to reach equilibrium at two different temperatures before and during the tests. The variations in measured values over periods of several hours was evaluated and though variations did exist – typically of 0.1°C for test periods (though occasionally larger), there was no discernible pattern and no specific logger which seemed to be measuring temperatures at an offset to the mean. For measurement of relative humidity larger variations could be expected due to the nature of the measurement transducers and it was decided that a check was required for variations of larger than ±2% r.h. (representing up to 4% variation between sensors); however agreement was surprisingly consistent between readings from the loggers under the same conditions as mentioned above. In calibration tests for the 2014 study only one logger consistently produced values more than 2% different to the average value (which was corrected for in the analysis) and in 2015 all loggers appeared to register within 2% of the average so no adjustments were made.

Thermal conditions were measured at 10 points in 2014 and 7 points in 2015 in each of the spaces. Temperature and humidity data were collected at 5 minute intervals using a rectangular grid distribution across each room: in 2014 a 3 x 3 grid spread of data loggers was used with an additional measurement point at the front of the room; in 2015 a 3 x 2 spread of loggers was used again with an additional logger at the front of the lecture room.

It was not possible to measure mean radiant temperature or air velocity at the individual points however the air movement (caused principally by the air-conditioning system) was established to be fairly uniform by spot checks. Mean radiant temperature could not be measured continuously but spot readings suggested it could be estimated as the air temperature plus 1°C. The lack of continuous measurement of these two parameters is an area which could be prescribed for further study should sufficient equipment is made available in the future.

4 Occupant Surveys

The study was carried out with two different groups of students: one in 2014 and one in 2015. Each year two rooms were surveyed on sequential days when occupied by those students whilst undertaking classroom activities. Though some of the activity consisted of sitting listening to lectures there was a substantial amount of task activity meaning movement between locations and slightly elevated metabolic rates. In each room three days worth of surveys were completed (one in 2014, two in 2015) giving a total of six days of data. There were more females (typically 75%) in each group than males but these data were not collected as part of each individual survey. The majority of students surveyed were between 22 and 25 years of age. There was no obligation to complete the survey and some of the individual surveys produced fewer sets of results as students were either preoccupied with other tasks or simply chose not to take part.

The survey process utilised was that each day the groups of students would be invited to respond on several occasions to the comfort survey questionnaire. At each time point the questionnaire asked them to provide the following details:

1. Clothing information from which to estimate clo values;
2. Their position within the room so as to determine the most appropriate set of environmental measurements to be used;
3. Information on activity level just prior to the completion of the survey, from which to estimate metabolic rate;
4. Sensation vote on ASHRAE 7-point scale;
5. Preference vote on 5-point scale;

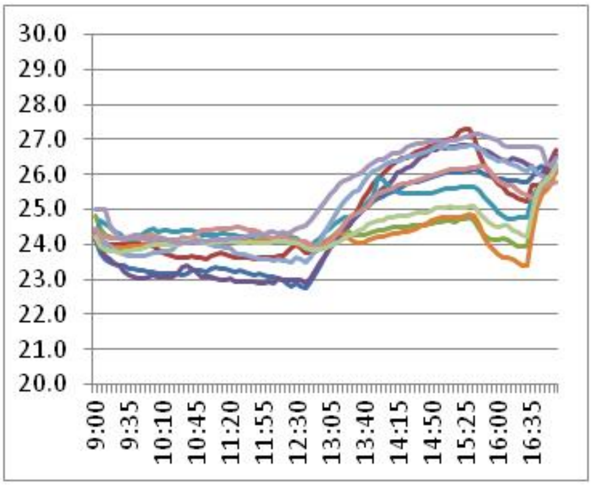
Several surveys were carried out each day numbering between 4 and 7 per day, with 23 to 41 students completing each survey depending on the year, class size and other factors (mentioned above). In total 912 timed survey response sets were collected.

5 Variation of Control Settings and Impact on Thermal Environment

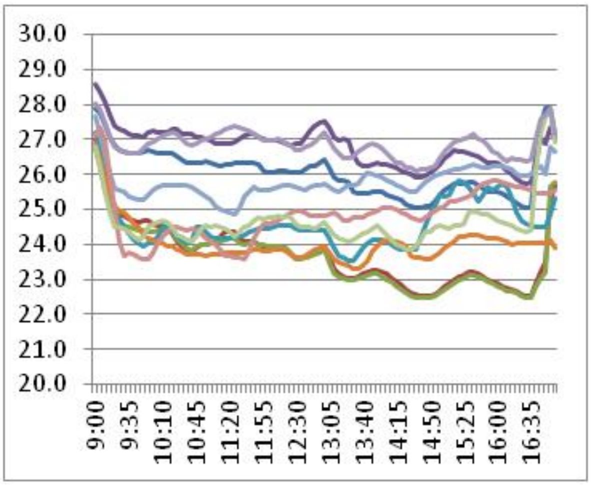
The control thermostats in the University rooms were available for staff and students alike to modify in response to conditions. The systems were also programmed only to operate at times that the rooms were expected to be occupied.

Each or the survey rooms had a number of thermostat/controllers – in each case they were positioned in groups (typically of 3) adjacent to each other. In 2014 neither the lowest or highest temperature that could be set was limited – at least in terms of the control setting – however in practice tests before carrying out the assessment it was observed that the actual conditions could not reach the more extreme values. In 2015 it was observed that for some of the controllers the temperature settings available were limited to between 23.5°C and 27.5°C. This is in line with University's Energy Policy for controlling working areas in summer to 25.5°C ±2°C. The settings used on each day were defined by an attempt to create a degree of variation in order to examine reactions.

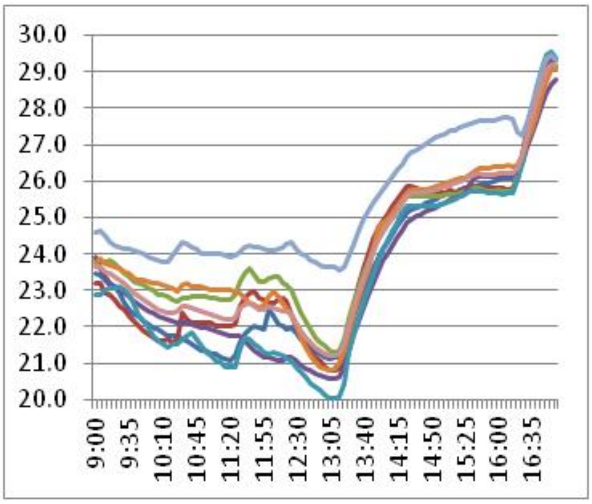
In 2014 on day 1 temperatures were set low in the morning (22°C) and high in the afternoon (26°C); and on day 2 the opposite was attempted. In 2015 on day 3 temperatures were initially set to 23.5°C but then for a short period the limits were overridden to create low temperatures just before lunchtime. In the afternoon temperatures were once again set to 26°C.



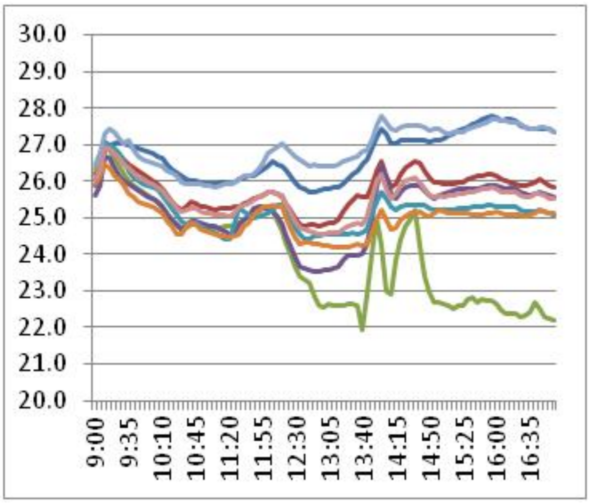
Room 1 Day 1 2014



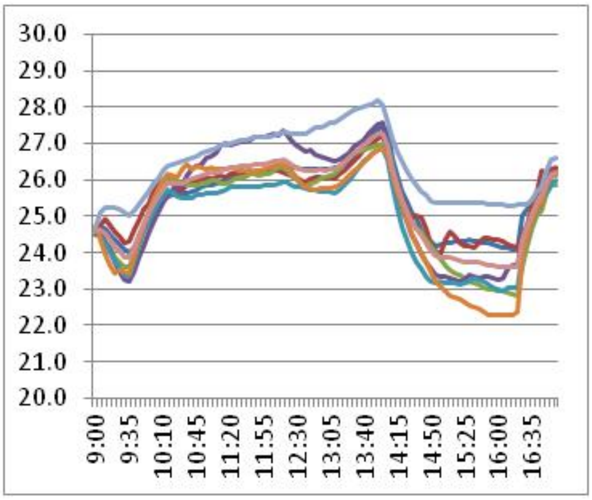
Room 2 Day 2 2014



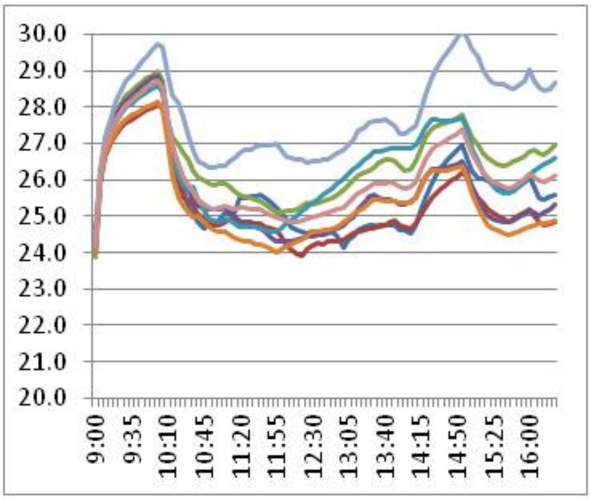
Room 1 Day 3 2015



Room 2 Day 4 2015



Room 1 Day 5 2015



Room 2 Day 6 2015

Figure 2. Temperature measurements (°C) vs. time of day at each measurement point in each room (shown as different coloured lines) – results for each survey day shown separately

On day 4 temperatures were initially set high at 27.5°C but then reduced to 25°C in the morning. At lunchtime the set point temperature was reduced to 23.5°C but then later in the afternoon back to 25°C. On day 5 a sequence of 23.5°C then up to 26°C before a short period at 27.5°C later returning to 23.5°C. Finally on day 6 the system was run at the maximum possible temperature overridden to 28.5°C for a short period before being reduced to 25°C then in the afternoon being increased to 26°C. The resulting measurements at the various locations are shown in Figure 2.

From Figure 2 one might infer several things:

a. That in both room cases (though more pronounced in Room 2) the conditions varied significantly across the range of measurement points even with the same set point being specified.
b. That room 1 seemed to have a more consistent performance that room 2.
c. That the systems seemed to operate more effectively in producing some desired temperatures as compared to others.

An inference from this might be that air conditioning control systems do not always produced the desired conditions. Another notable feature was the availability of controls within the space but with minimal instruction on how to operate. Perhaps it is assumed that knowledge of how to use is intuitive but it was not explicit which controls affected which parts of the room, hence the choice to vary all in unison. The only evident information was the details of the University Policy to operate systems within certain limits to control energy use.

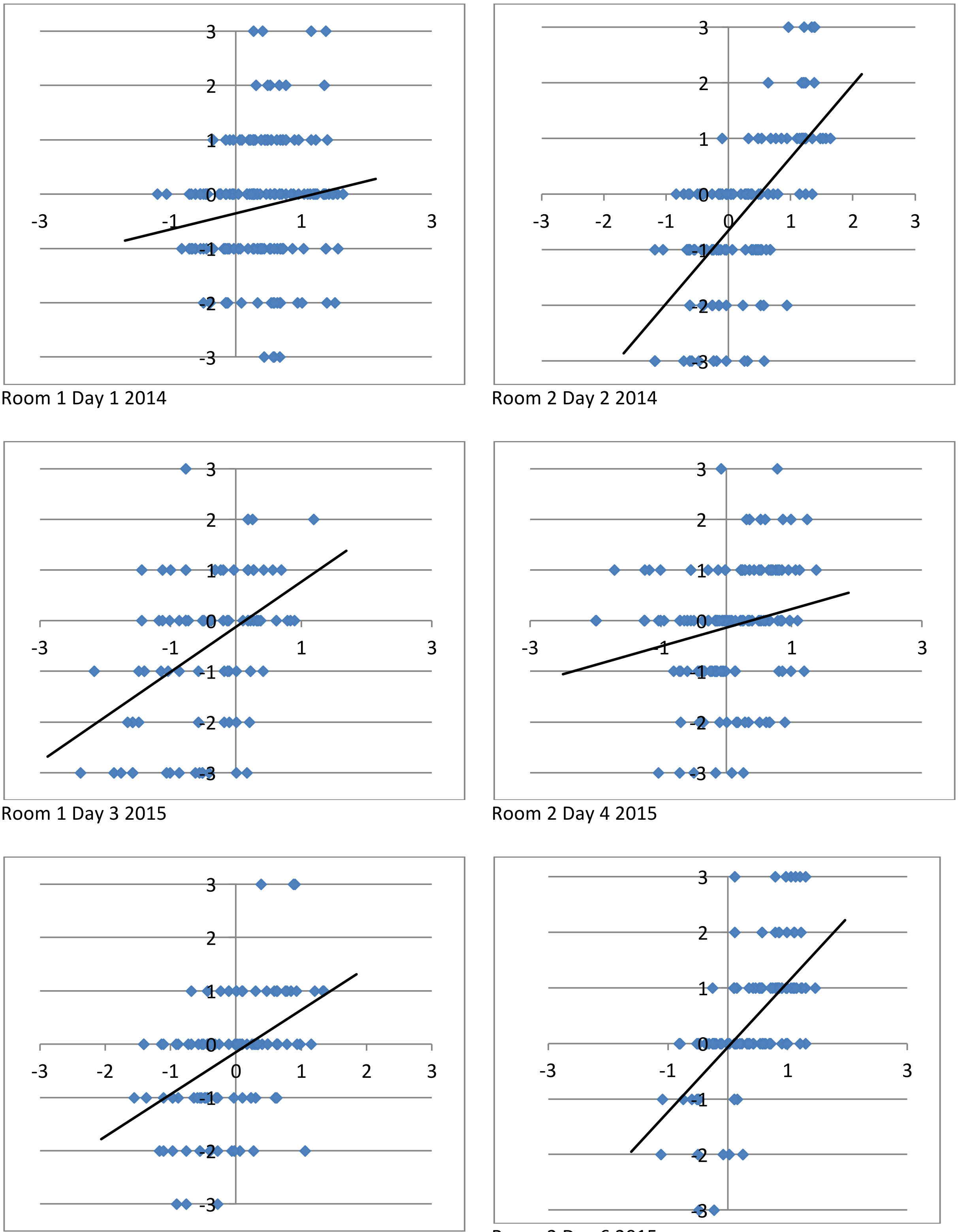
6 Sensation: Comparison of Actual and Predicted Votes

Actual sensation votes were collected for the 912 surveys and compared with predicted sensation votes based on the measurements of environmental and personal variables. The predictions used the standard algorithms first developed by Fanger (1973) and reported widely in many other publications using the seven-point scale.

Figure 3 presents 6 charts, one for each day of the study and Figure 4 shows the combined data for all six days. From visual observation it appears that in all cases actual sensation votes recorded by the occupants had values over a wider range than the predicted values, perhaps indicating the occupants were more sensitive to the changing environmental conditions. This is at variance with some other studies which have suggested a rather ‘flatter’ response, i.e. that sensation votes were not as great as predicted.

The occupants did adapt by adding and removing clothing and there was certainly the opportunity to move around the rooms in order to adapt to conditions, however this does not seem to have been utilised to a great extent. The only observable (but not recorded) reason for this was the desire to sit in friendship or tasks groups.

Standard linear regression analysis was performed and shown on charts for the individual days and for the whole set of data is summarised in table 1. These analyses show considerable variation in both relationship between the variables and in R^2 value. More detailed studies are suggested by this in order to consider if unexpected variations are being introduced.



Room 1 Day 1 2014 | Room 2 Day 2 2014 | Room 1 Day 3 2015 | Room 2 Day 4 2015 | Room 1 Day 5 2015 | Room 2 Day 6 2015

Figure 3. Occupant Sensation: Predicted Vote (horizontal axis) vs. Actual Vote (vertical axis) for each day/room (superimposed lines show least square-regression analyses)

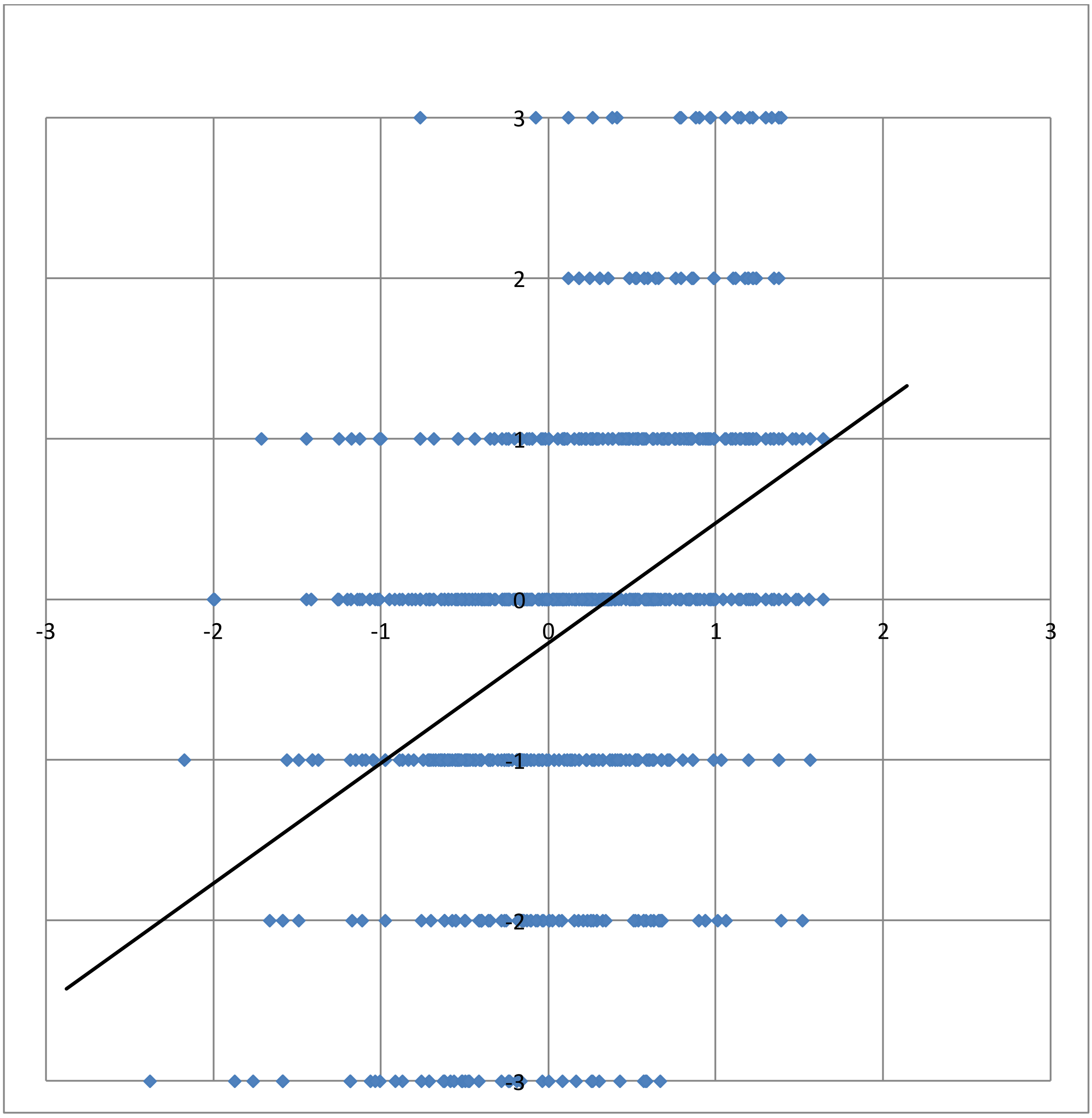


Figure 4. Occupant Sensation: Predicted Vote (horizontal axis) vs. Actual Vote (vertical axis) for all measurement days (superimposed line shows least square-regression analyses)

Table 1. Linear regression analysis for predicted vs actual sensation vote shown in graphs of figure 3 and 4

Survey day	Linear regression	R^2 value
Room 1 day 1 2014	y = 0.2947x – 0.351	0.024
Room 2 day 2 2014	y = 1.3111x – 0.6534	0.4287
Room 1 day 3 2015	y = 0.8894x – 0.1246	0.201
Room 2 day 4 2015	y = 0.3661x – 0.1388	0.042
Room 1 day 5 2015	y = 0.7919x – 0.152	0.2077
Room 2 day 6 2015	y = 1.1665x -0.0695	0.3603
All days	y = 0.7483x – 0.2723	0.169

7 Sensation and Preference

The thermal sensation felt by occupants is one of the key drivers to take action: either to adjust thermal controls for HVAC or to take adaptive actions such as changing position or clothing level. The survey recorded data on a five point preference scale (much cooler, cooler, stay the same, warmer, much warmer). This was then correlated against the seven-point sensation scale. The results are shown in Figure 5 for each day in turn.

Considering the wide variation in sensation relationships exhibited in figure 3, the preference analysis reveals more consistent relationships.

Table 2. Linear regression analysis for preference votes vs. actual sensation votes shown in graphs of figure 5

Survey day	Linear regression	R^2 value
Room 1 day 1 2014	y = -0.4462x – 0.0715	0.5207
Room 2 day 2 2014	y = -0.4320x – 0.0218	0.4929
Room 1 day 3 2015	y = -0.4413x + 0.0922	0.5461
Room 2 day 4 2015	y = -0.5334x – 0.0997	0.6859
Room 1 day 5 2015	y = -0.5007x – 0.0293	0.7042
Room 2 day 6 2015	y = -0.4601x – 0.1447	0.6108

8 Adaptation

Some adaptation by the occupants was evident in terms of clothing adjustments. These are not analysed in detail here but can be summarised as a fraction of the participants on each day that surveys were undertaken. The following data are taken from the self-reported surveys:

Day 1, 10 students adjusted their clothing level out of a total of 41 = 24%
Day 2, 11 students adjusted their clothing level out of a total of 37 = 30%
Day 3, 5 students adjusted their clothing level out of a total of 28 = 18%
Day 4, 9 students adjusted their clothing level out of a total of 29 = 31%
Day 5, 4 students adjusted their clothing level out of a total of 24 = 17%
Day 6, 7 students adjusted their clothing level out of a total of 23 = 30%

It should be noted that there were limits to the adaptation that was possible – simply because of factors such as social norms and modesty with regard to clothing levels. Nevertheless the data do show some reaction to changing conditions. A more complete and accurate piece of research could be suggested to analyse this issue in more depth.

9 Discussion

The thermal sensation felt by occupants is one of the key drivers to take action: either to adjust controls or to adapt their immediate environment. Understanding the strength of that driving force is therefore very important as a route to optimising air-conditioning and the associated energy use.

Understanding the ways in which people make such choices is also important to make design choices for the future concerning novel technologies and novel means to achieve comfort or reduce discomfort. Research work in the field is already developing (Leephakpreeda, 2012).

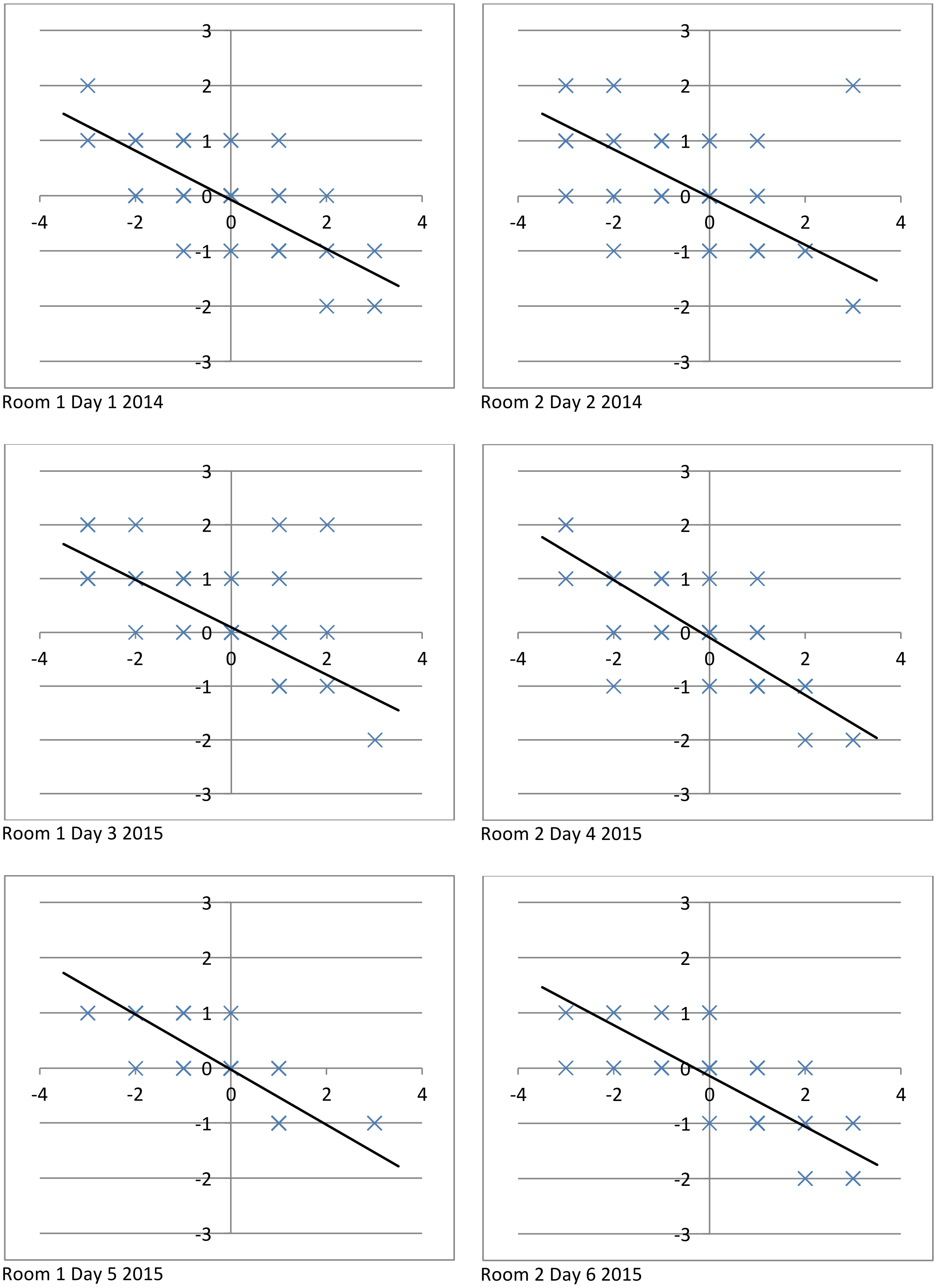


Figure 5. Occupant Preference (vertical axis) vs. Sensation (horizontal axis) votes from Occupant Surveys (lines show least square-regression analyses)

The results presented here indicate a number of areas in which variations occur which had not been anticipated. Firstly in terms of the conditions created and experienced across the space of the rooms investigated. The changing of the thermostat settings introduced in some cases much wider variation between points and also potentially some instability in the room being able to maintain specific conditions.
Secondly the reactions of the occupants to the experienced conditions were somewhat different to what had been expected. Variations occurred between members of the same group on consecutive days in their sensation votes, meaning perhaps there is less confidence is specifying any specific set of conditions to achieve comfort because of the individual impacts. The interlinked impact of choices about clothing level is incorporated within the analysis however the reasons for choices were not recorded.
Clearly this modest study produces more questions than it answers, but in so doing helps to identify some key areas that require research. The nature of the analyses which show differences between actual and expected performance contribute to the continuing debate about performance gaps between energy consumption predictions and actual performance.

10 Conclusions and Recommendations

The main conclusions are:

1. Temperatures set by controllers for air conditioning systems were not clearly met in the rooms to which they were attached.
2. Modification of temperature settings for temperature controllers in closed air-conditioned rooms tended to produce uneven temperature or inconsistent temperature distributions in these rooms – sufficient to create marked variations in thermal comfort sensation experienced.
3. Occupants of rooms exhibited variable correlations between actual sensed conditions and those predicted using the PMV methodology.

The thermal sensation felt by occupants is one of the key drivers to take action: to change HVAC system setting to move location; to adjust clothing; or to manipulate local environment in some other way. Several areas are therefore suggested for further research:

a. Further studies of room environments into which perturbations of control system operation have been introduced;
b. Research into interactions between air temperature and room air distribution and how this could be affected by use of non-standard or unexpected set-points
c. More detailed studies of occupants should be initiated which go beyond the basic comfort survey in order to understand better their reactions and understanding of comfort and also about how they would wish to access and use control systems.
d. Contribution of the system performance issues in these circumstances can also be investigated in relation to identifying the impacts in variations of building systems functioning.

Acknowledgement
Thanks are due for the cooperation in carrying out this study to students and staff of the Chinese University of Hong Kong

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Process Control of Personalized Heating

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Abstract

Personalized conditioning systems represent one of promising solutions for two major problems in current indoor environment – high energy consumption and unsatisfactory thermal comfort. As personalized conditioning focuses on a small space around a single person, it can better and more effectively satisfy the individual needs for thermal comfort than a traditional HVAC system. Personalized conditioning systems that have been tested rely mostly on control by user interaction, i.e. the users have to decide on the level of cooling or heating. This can lead to decreased comfort or increased energy consumption due to incorrect use of the system. This paper presents a novel method of process control of personalized heating based on human thermophysiology. The new control method is compared with user interaction and fixed setting of personalized heating system consisting of heated chair and heated desk and floor mats.
Different control strategies for personalized heating were tested with 13 human subjects in a climate chamber under operative temperature of 18 °C for 90 minutes. The test subjects evaluated their thermal comfort every 15 minutes via a computer based questionnaire. As skin temperature of the hands was previously identified as a good predictor of cool discomfort under uniform conditions, it was tested in this study as a control signal for personalized heating.
Thermal comfort and energy use with personalized heating are compared in the results section. Personalized heating improved thermal comfort in all test cases. No significant difference was observed between user interaction, fixed setting, and automatic control.

Keywords: Control, Human subjects, Personalized heating, Thermal comfort, Thermophysiology

1 Introduction

The building sector nowadays accounts for 40% of the primary energy consumption in EU and US (Pérez-Lombard et al. 2008). Most of this energy is spent on providing a comfortable indoor environment by heating, ventilation and air conditioning (HVAC). Current standards for designing the indoor environment such as ISO EN 15251 (2007) prescribe controlling the indoor environment in a narrow range in order to ensure thermal comfort. However, narrowing range of indoor air temperatures is energy demanding and does not lead to higher thermal satisfaction (Arens et al. 2010).

Especially in the office environment Personalized Conditioning System (PCS) is one of the promising ways how to improve thermal comfort and meanwhile reduce energy consumption. PCS brings ventilation, heating, and cooling closer to the user and allows to adjust the microenvironment to suit individual needs. Meanwhile, energy is deployed only at the place of actual need and the background environment can be controlled in more relaxed manner. This way, energy can be saved due to higher effectiveness of the whole conditioning system.

A number of PCS have been recently developed and tested. Much more attention has been paid to personalized ventilation and cooling rather than to personalized heating (Veselý & Zeiler 2014). Nevertheless, some studies have already proven that personalized heating can improve thermal comfort (Melikov & Knudsen 2007; Watanabe et al. 2010; Zhang et al. 2010; Pasut et al. 2014) and also has potential to reduce the overall heating demand (Zhang et al. 2010; Foda & Sirén 2012; Verhaart et al. 2015).

Most of the researched PCS were controlled solely by user interaction, which can potentially lead to problems with thermal comfort, such as overshoots or delayed reactions, as well as worse energy performance due to inefficient operation. As the hand and finger skin temperature relates to thermal comfort in cool environment, it seems to be a promising control signal for an automated control. The study investigates such an automation of the control process and tests it alongside with user interaction.

2 Methods

2.1 Personalized Heating System

The tested personalized heating system consists of a heated chair, a heated desk mat, and a heated floor mat (Figure 1). The effectiveness of these heaters was tested in another yet unpublished study (Veselý et al. 2016). The maximum power of the heaters is as follows, heated chair: 36 W, heated desk mat: 80 W, and heated floor mat: 100 W.

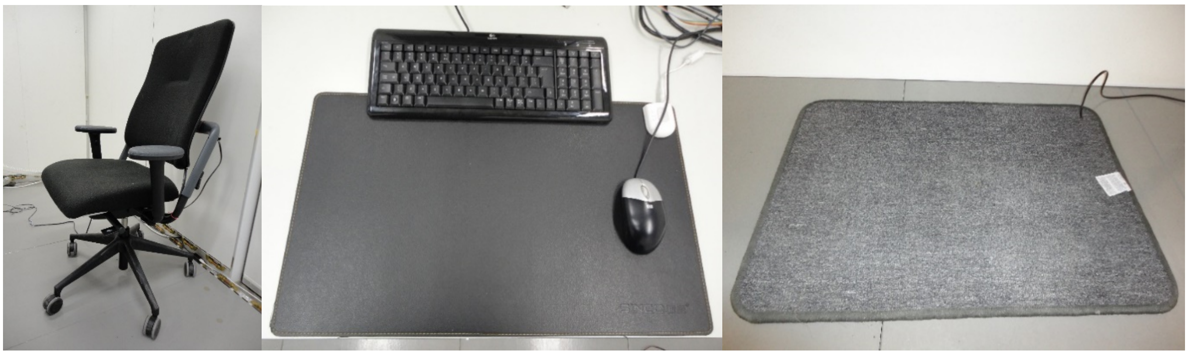

Figure 1 Heated chair (left), heated desk mat (middle) and heated floor mat (right)

Personalized heating system in some of the test cases was user controlled (Figure 2) and the settings were logged with an interval of 2 seconds.

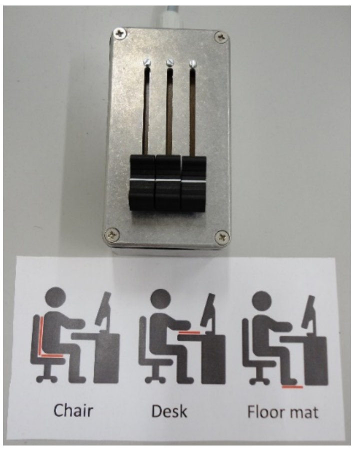

Figure 2 User control over personalized heating system

2.2 Climate Chamber and Environmental Conditions

Experiments were conducted in a climate chamber of Unit of Building Physics and Services, Eindhoven University of Technology, The Netherlands. The climate chamber is a well thermally insulated room of dimensions 3.6 x 5.7 x 2.7 m^3. It allows for a precise control of the indoor environment, namely air movement, air temperature, and temperatures of all surrounding surfaces.

During this experimental phase the climate chamber was set to maintain both air and mean radiant temperature at 18 °C. As mixing ventilation was used the air movement in the occupied zone was negligible and can be assumed of up to 0.15 m/s. The subjects performed an office work resulting in metabolic rate of 1.2 met and they were instructed to wear clothing ensemble with insulation of 0.7 clo (common winter indoor clothing). These background conditions result in PMV of -1.5 and corresponding PPD of 50 %.

Two user desks (Figure 3) were set up in the climate chamber. Both user desks were equipped with a computer screen, a keyboard, and a mouse. The test subjects connected their laptops to the provided equipment at the beginning of each session.

Figure 3 One of the two user desks in the climate chamber

2.3 Subjects

Thirteen healthy university students (seven males and six females) volunteered as test subjects. Their anthropological data are listed in Table 1.

Table 1 Anthropological data of the 13 test subjects

	Height [m]	Weight [kg]	Body mass index	Age [years]
Mean	1.79	81.1	25.1	24.9
Standard Deviation	0.12	26.8	5.8	3.2

2.4 Procedure

Four test cases as shown in Table 2 were tested and all test subjects experienced all test cases. The same personalized heating system was used in all test cases except for the reference. The test cases 'Fixed' and 'Auto' were based on results of a pretest with 9 test subjects. In test case 'Fixed' the average setting from the end of the pretest session was set for the entire test. The 'Auto' case was based on correlation of the settings of each heater with the hand skin temperature. The settings are presented in the results chapter.

Table 2 Test cases

Test case code	Description
Ref	Reference case (i.e. no personalized heating applied)
User ctrl	User controlled personalized heating
Fixed	Fixed settings based on average settings from the pretests
Auto	Automatic control based on hand skin temperature

Each session comprised 30 minutes of warm accustomization (i.e. just outside of the climate chamber) and 90 minutes of exposure. During the accustomization period the skin temperature loggers were attached. During the exposure the subjects performed ordinary office work on a computer. The subjects were asked to fill in a questionnaire regarding their thermal comfort every 15 minutes within the exposure.

2.5 Measurements – Subjective Evaluation

During the experimental sessions the subjects evaluated their thermal comfort via a java-based app (sample screenshots shown in Figure 4). This app includes questions regarding the subjects' clothing, thermal sensation, thermal comfort, and wellbeing. Thermal sensation and comfort questions are asked as overall and in particular for neck, head, arms, hands, legs, and feet. An ASHRAE 7-point scale is used for evaluation of thermal sensation and a comfort scale (from clearly comfortable to clearly uncomfortable with separation of just comfortable/just uncomfortable in the middle) for thermal comfort.

Figure 4 Thermal comfort questionnaire app

2.6 Measurements – Environmental Data

The thermal environment in the climate chamber was continuously monitored during all experimental sessions. This includes measurements of air speed and air temperature at the heights of 0.1, 0.7, and 1.1 m (standard heights for a sitting person) as well as the relative humidity and globe temperature in the occupied zone of the room. All environmental data were logged with an interval of one minute and measured in compliance with ISO 7726 (ISO 1998).

2.7 Measurements – Physiology

In order to investigate the effect of personalized heating on human physiology skin temperature was measured on 14 locations on the body by iButtons (van Marken Lichtenbelt et al. 2006) as shown in Figure 5. Digital thermometer DS18B20 was used to measure the hand temperature (location "I" in Figure 5) additionally to iButton. This allowed for real-time reading of the temperature that can be used in a control loop.

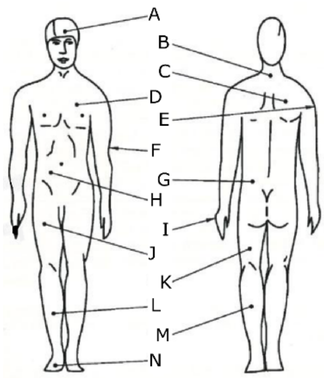

Figure 5 Positions of iButtons

3 Results

3.1 Settings of personalized heating system

A pretest with 9 test subjects was used to extrapolate settings of the personalized heating for test cases 'Fixed' and 'Auto'. The pretest followed the same procedure as the normal test and test subjects controlled the personalized heating by user interaction. An average setting from the end of the pretest was used as a fixed setting for the whole exposure of test case 'Fixed'. These settings were as follows, heated chair set at 50 % of its max power, heated desk mat at 65 % of its max power, and heated desk mat at 70 % of its max power.

Proportional control based on hand skin temperature was used in test case 'Auto'. The control equation was derived from linear correlation of the hand skin temperature and the user controlled power of the heaters in the pretest (heated desk mat shown in Figure 6). This correlation resulted in R^2 values of 0.62 for the heated chair, 0.90 for the heated mat, and 0.86 for the heated floor mat. The derived control curves are shown in Figure 7.

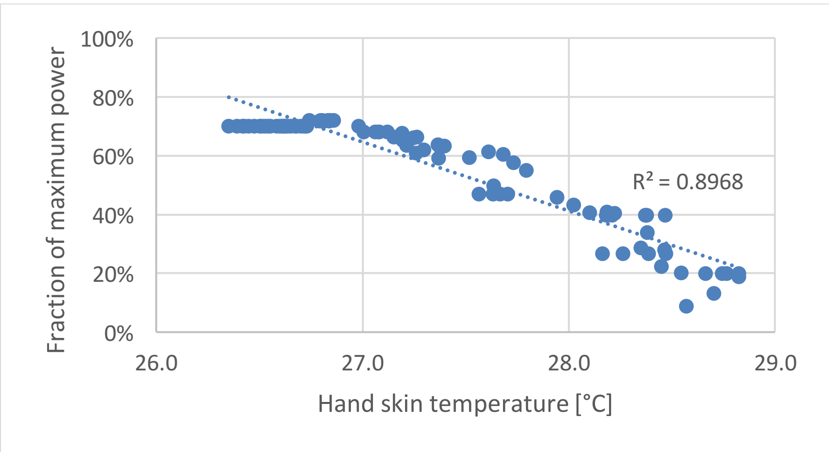

Figure 6 User control over heated desk mat in the pretest, average of 9 test subjects

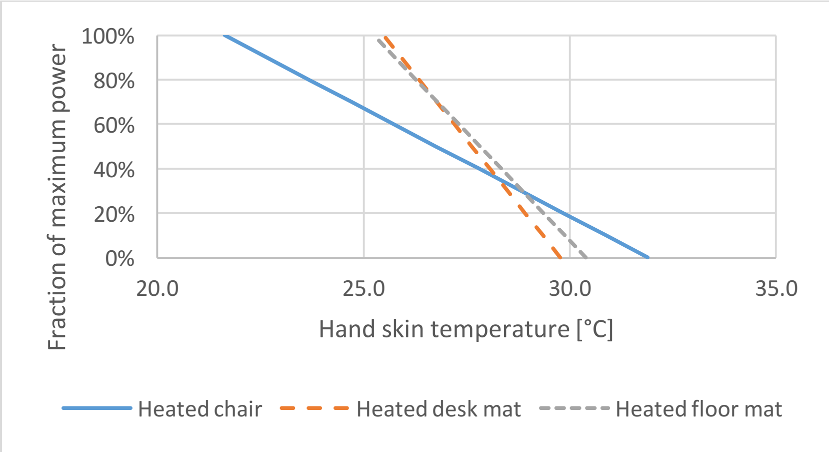

Figure 7 Proportional control of the heaters used in test case 'Auto'

3.2 Thermal sensation and comfort

The average overall thermal sensation over the whole exposure is shown in Figure 8. At the beginning of the exposure the test subjects felt about neutral because of the accustomization right outside of the climate chamber. In the 'Ref' case thermal sensation dropped under slightly cool at the end, while in other test cases it was maintained above neutral by personalized heating system.

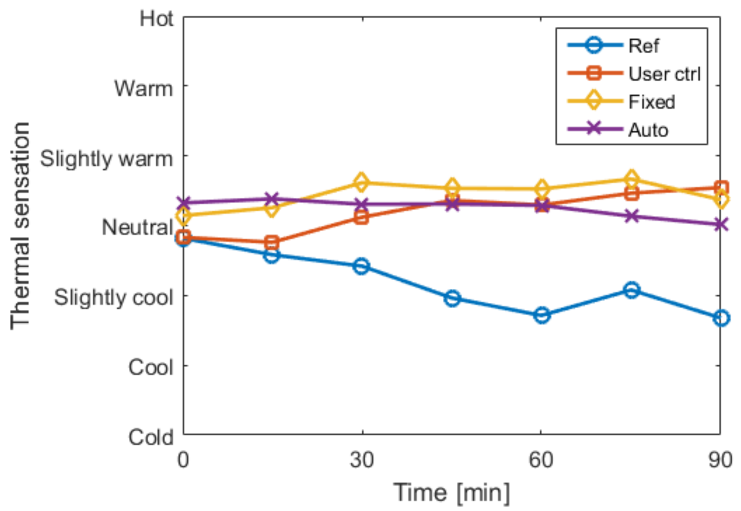

Figure 8 Overall thermal sensation (average of all 13 test subjects)

Figure 9 shows the thermal sensation and comfort at the end of exposure. The difference between the 'Ref' case and the other cases is significant ($p < 0.05$) for both, thermal sensation and comfort. The response to 'Fixed' seems to be more scattered than for 'User ctrl' and 'Auto'. However, no significant difference was found among these three test cases.

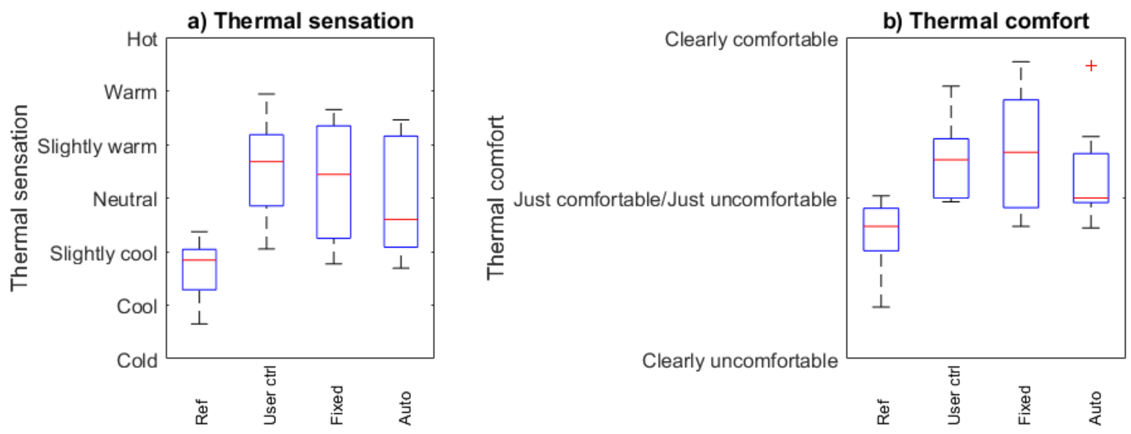

Figure 9 Thermal sensation (a) and comfort (b) at the end of exposure (boxplots of all 13 test subjects)

Figure 9 shows the thermal sensation and comfort at the end of exposure. The difference between the 'Ref' case and the other cases is significant ($p < 0.05$) for both, thermal sensation and comfort. The response to 'Fixed' seems to be more scattered than for 'User ctrl' and 'Auto'. However, no significant difference was found among these three test cases.

3.3 Energy consumption

Figure 10 depicts the energy consumption of the personalized heating system under the different control modes. The lowest energy consumption was observed in the test case 'User ctrl'.

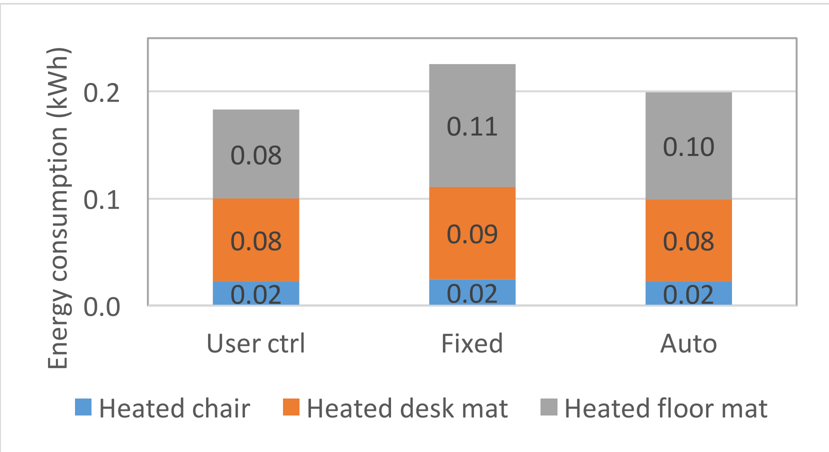

Figure 10 Energy consumption of personalized heating averaged per person over the whole exposure (90 minutes)

4 Discussion

The finger and hand skin temperature was previously identified as a good predictor of cool discomfort (Wang et al. 2007). It could be expected that the moment of cool discomfort is the moment when people turn on or increase the power of personalized heating when available. Wang et al. (2007) reported that approx. 30 °C of fingertip temperature seems to be a threshold for a risk of cool discomfort. This is in line with our observation on the relation of hand skin temperature and the setting of personalized heating. The test subjects tended to turn on the system at hand skin temperature of about 30 °C and then increase the power as the hand temperature was decreasing.

As expected personalized heating clearly improved thermal comfort. However, no significant difference was observed between the three tested modes of control. Zhang et al. (2010) reported that the user interaction is in some cases a preferred option over fixed setting, but this happens only in more extreme thermal conditions, which can explain why we did not observe a similar trend.

The energy consumption of the presented personalized heating system was the lowest when user controlled. However, this was probably influenced by rather short exposure and the fact that most of the test were gradually increasing the heating power within a first third of the test in order to find a comfortable setting. It also has to be noted that the fixed setting, which appears to perform the worst from energy perspective, would benefit from presumably lower cost of the system and its maintenance.

The test subjects were also asked for general comments on personalized heating control. Some claimed that they preferred user interaction because they want to be in charge, while others prefer automatic control because they want to focus just on their work. This implies that a flexible system combining user interaction with automatic control might be needed. One of the possible options for such a combination is shifting the set points of the automatic control via user interaction. This is recommended for further research.

5 Conclusions

The presented personalized heating system significantly improved thermal comfort. No significant difference in terms of thermal comfort was observed between three modes of control of personalized heating, i.e. between user interaction, fixed setting and automatic control.

User controlled personalized heating used slightly less energy than the other two modes. The following issues are recommended for further investigation:

- Uniformity of the thermal environment, when personalized heating is applied.
- Possible individualizing of the automatic control of personalized heating.
- Possible combination of user interaction and automatic control of personalized heating.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
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Thermal comfort of displacement ventilation in environments with different mean room temperatures

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Abstract
The evaluation and prediction of local thermal comfort is becoming increasingly important. Therefore, a highly modular test chamber, the Aachen Comfort Cube (ACCu), was built in order to evaluate the thermal comfort in indoor environments by test subjects. The thermal environment in the cube can be mapped to different situations with variable surface temperatures and a variable air distribution system.
Test trials are used to investigate different temperature gradients between ankle and head in displacement ventilation configurations. Environments with three different mean room temperatures of 20 °C, 23 °C and 26 °C are investigated. At a mean room temperature of 20 °C and 26 °C a vertical temperature gradient of $\Delta T/\Delta y$ = 8 K/m is examined and at 23 °C vertical temperature gradients of $\Delta T/\Delta y$ = 1, 4.5, 6, 8 and 12 K/m are tested. The evaluation of trial results shows that mean room temperatures of 20 °C and 23 °C are more acceptable than 26 °C with a vertical gradient of $\Delta T/\Delta y$ = 8 K/m. The results of the different vertical temperature gradients of 23 °C are even better than the predicted thermal comfort in literature data from ASHRAE Standard 55. The percentage of dissatisfied persons rises with higher vertical air temperature difference nearly linearly.

Keywords: thermal comfort, thermal sensation, displacement ventilation

1 Introduction
Air conditioning of rooms and buildings is getting more important throughout the world. There are different concepts of ventilation systems, mainly based on mixed or displacement ventilation configurations. In a concept of mixed ventilation air is supplied to a room with high mean velocity and generates high turbulence levels in order to reach a uniform mixing of the air.

In contrast, in a displacement ventilation concept, cool air is supplied to the room close to the floor at a low velocity level. The warm air rises to the top and temperature stratification occurs in the room. Since the 1980s displacement ventilations concepts are used for air conditioning in environments with high thermal loads (Skistad et al, 2004).

The thermal comfort of a user describes the feeling of being satisfied with the thermal environment (ANSI/ASHRAE Standard 55, 2013). Several local external parameters, for example radiation temperature asymmetry, air temperature and air speed have an influence on the test persons. In concepts of displacement ventilation the effect and the limit of vertical air temperature gradients between the head and the ankle level have an important influence on the global and local thermal comfort.

In order to predict the thermal comfort in environments with different vertical temperature gradients, a 33 node comfort model (33NCM), which can estimate the local and global thermal comfort was developed previously. The body of the human is divided into 16 segments and every segment has a skin and a core layer. These different body parts are connected with a central virtual blood node. All major heat transport processes between the nodes are simulated and balanced (Streblow, 2011). In order to improve the models accuracy, different test scenarios of displacement ventilation are investigated and presented in this paper.

2 Method

2.1 Aachen Comfort Cube

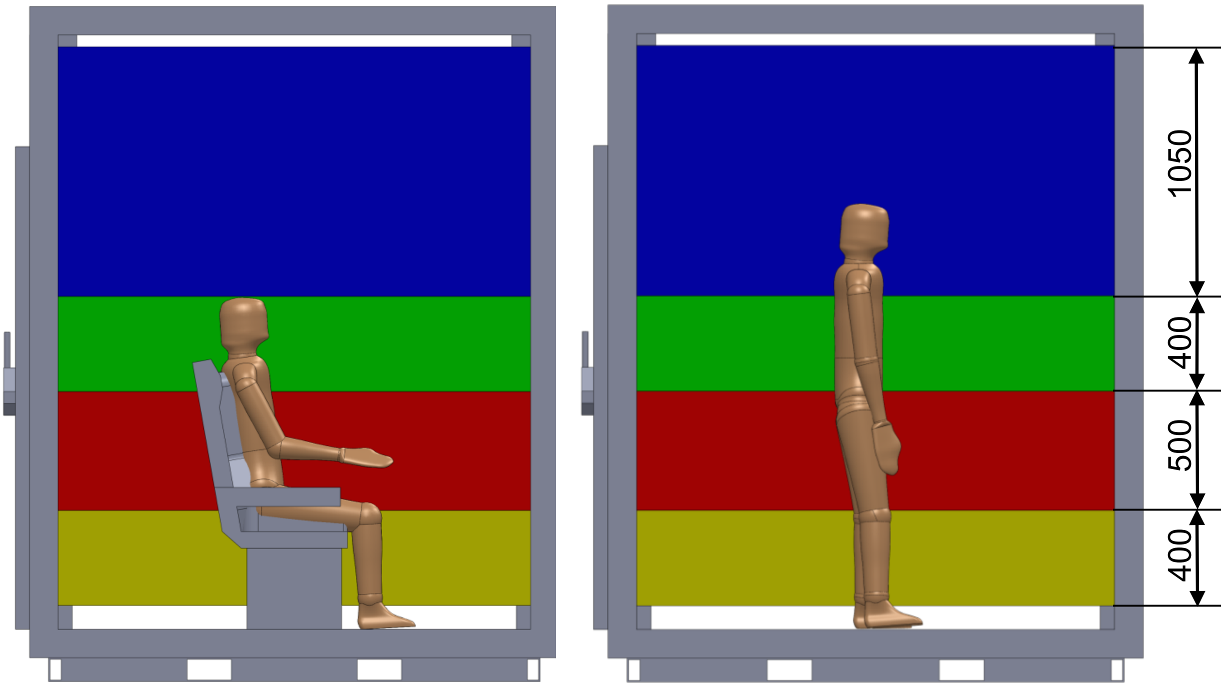

Figure 1. Test subject standing and sitting in the comfort cube [dimensions in mm].

A highly modular comfort cube was built and can be mapped with different ventilation situations where all surface temperatures and the air distribution system can be varied. The comfort cube has a floor area of 2 m x 2 m and a height of 2.5 m. Three of the surrounding side walls are divided into four surface segments. The first and the third segment are 400 mm high, the second is 500 mm and the fourth segment is 1050 mm high. A test subject can stand and sit in the comfort cube (figure 1) (Möhlenkamp et al, 2013).

Each surface segment can be set to a temperature between 15 °C and 40 °C, including the ceiling and the ground segments. In every surface segment capillary tube mats are installed. Warm or cold water can flow through the capillary tube mats and heat up or cool down each surface segment separately. The warm water for the surface segments is heated up by instantaneous water heaters.

Displacement ventilation concepts are implemented by horizontal ventilation slots above the floor. The supply air temperature can be set between 15 °C to 40 °C. In the test cases, a volume flow of 200 m^3/h is used (corresponding air change rate 20 1/h).

2.2 Measurements

The air temperature is measured at four different heights (0.1 m; 0.6 m; 1.1 m; 1.7 m) and at four positions at each corner with Pt100 temperature sensors with an accuracy of ±(1/10·(0.30 °C+0.005·T) (DIN EN 60751, 2008). Additionally, the globe temperature is recorded in order to investigate the influence of the radiation with Pt100 sensors. In figure 2 the positions of the temperature sensors are printed. At the positions A, B, C, D the air temperatures and at the positon G the globe temperature are measured. The velocities are measured at the positons V_1 and V_2 at four different heights (0.1 m; 0.6 m; 1.1 m; 1.7 m) in a benchmark case with heat dummies and without real test persons.

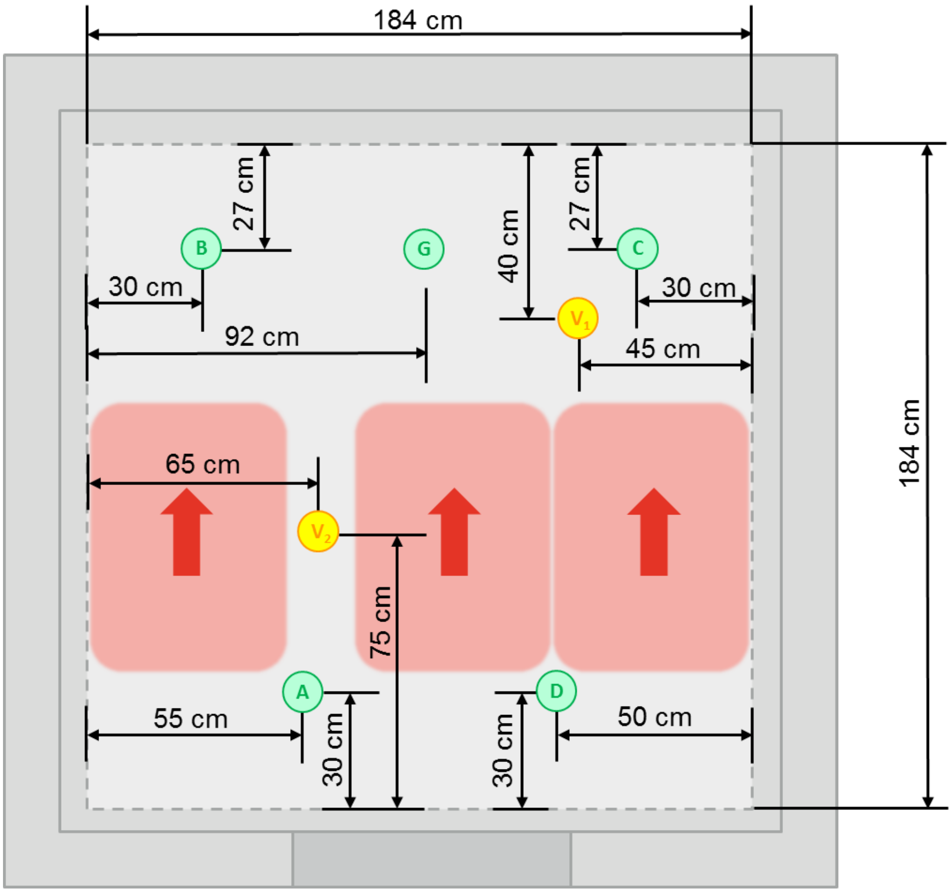

Figure 2. Sensor positions at the Aachen Comfort Cube (ACCu).

In figure 2 the positons of the test persons are shown in the red boxes. The temperature gradients of the test cases are measured between 0.1 m and 1.1 m. Three test persons can evaluate the thermal comfort at the same time.

In order to minimize the influence of radiation, the side walls are covered with styrodur® elements. Hence, the wall temperature measured with the help of infrared thermography is nearly the same as the air temperature at this level (figure 3).

The air velocities are measured with omnidirectional air velocity probes. At the feet, the air velocity at position V_1 at a height of 0.1 m near the outlet is between 0.17–0.20 m/s. For the heights of 0.6 m, 1.1 m and 1.7 m the air velocities are between 0.04–0.08 m/s. The velocities at the position V_2 at the heights of 0.1 m, 0.6 m and 1.1 m are also between 0.04–0.08 m/s (Möhlenkamp et al, 2014, 2015).

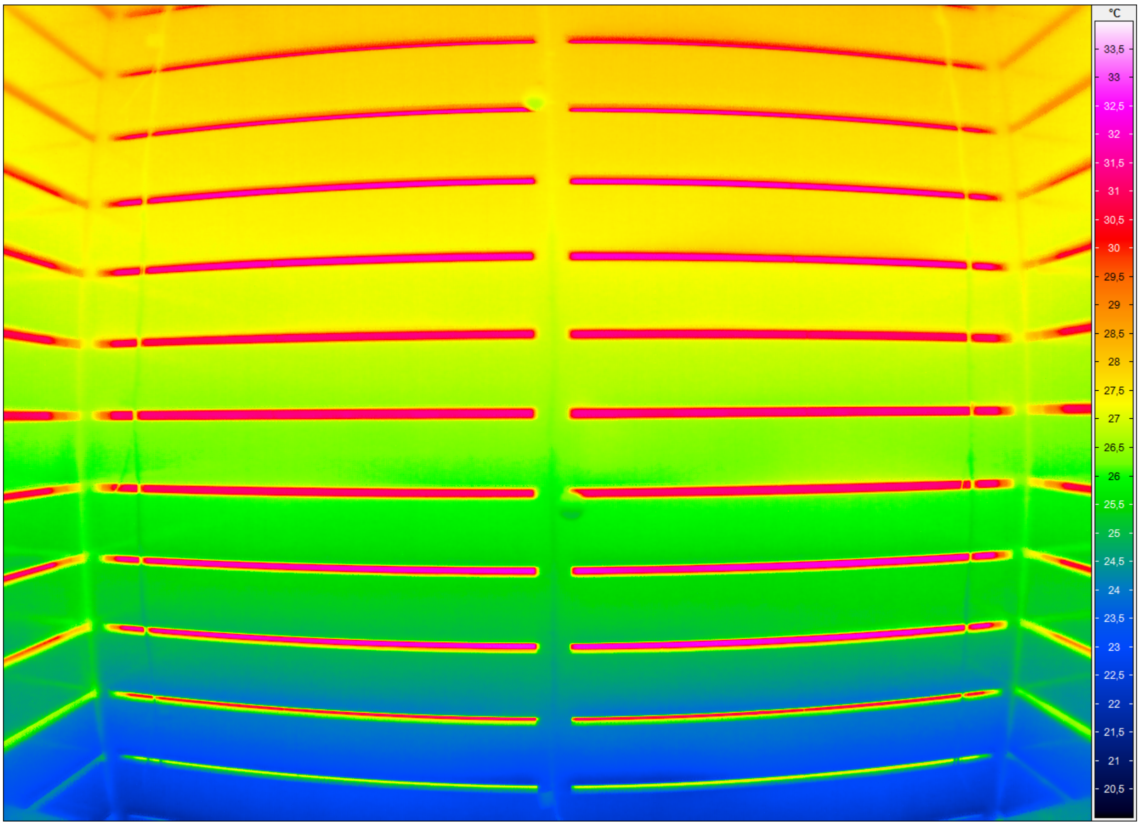

Figure 3. Thermographic image of installed insulation.

In figure 4 the measured temperature stratification of the different test cases is shown. In every test case the air temperature in the height of 0.6 m is nearly 23 °C.

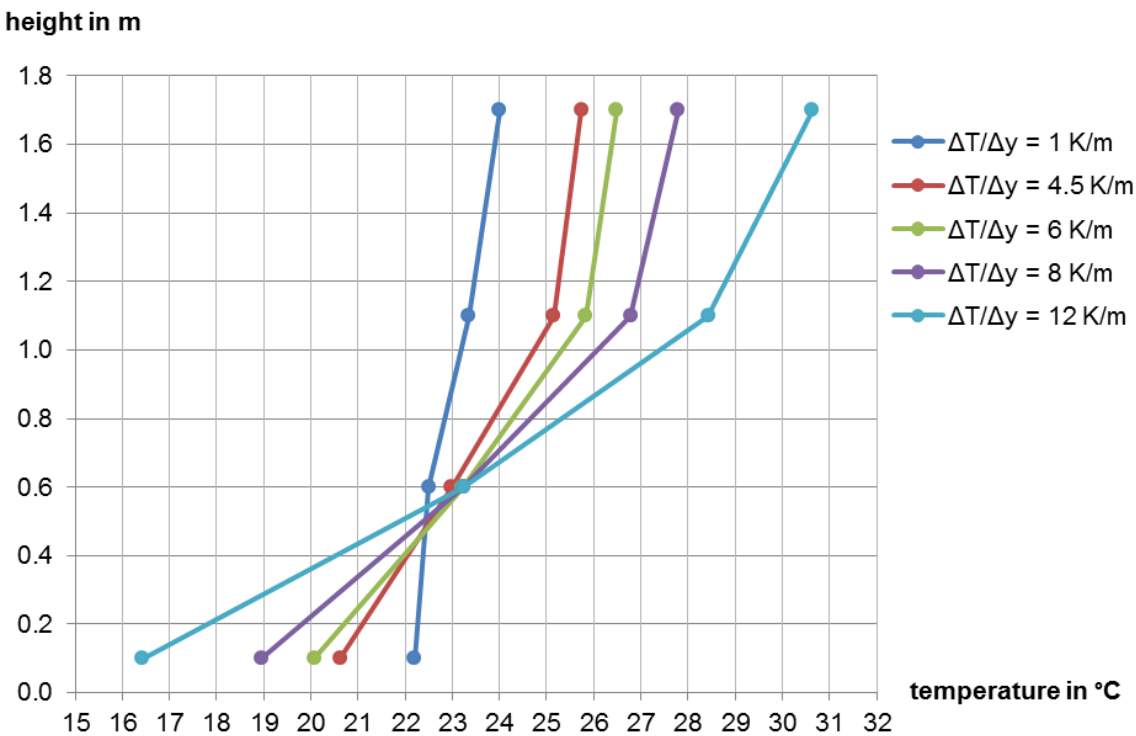

Figure 4. Temperature stratification of the different test cases.

2.3 Questionnaires

The thermal comfort of different configurations is evaluated by test subjects in a sitting position. The questionnaires were presented in German language. During the test period, subjects completed the questionnaire, consisting of questions about the thermal sensation the thermal comfort and the thermal preference for the overall sensation and the local sensation considering single body parts.

The thermal sensation scale is based on the 7-point ASHRAE scale ranging from “cold” to “hot”. The neutral state is queried in deviating form with “neither cool nor warm”. The thermal comfort scale is represented between “very uncomfortable” and “very comfortable” based on the scale from Zhang (Zhang, 2003).

Different mean room temperatures of 20 °C, 23 °C and 26 °C are tested. At a mean room temperature of 20 °C and 26 °C vertical air temperature gradients of $\Delta T/\Delta y$ = 8 K/m are tested. Additionally a room temperature of 23 °C with vertical air temperature gradients of $\Delta T/\Delta y$ = 1, 4.5, 6, 8 and 12 K/m are evaluated by test subjects. After at least 20 minutes of constant conditions in the ACCu the test persons fill out the questionnaires.

The number of test subjects depends on the test case and is between 42 and 126. The test subjects have no dress regulations. The mean value of the clothing factor is about 0.7 clo (0.4 clo–1.6 clo) including the clothing factor of the seat.

3 Results

3.1 Environments with a mean room temperature of 23 °C

In all cases the mean room temperature is 23 °C and is determined from the average of supply air and exhaust air temperature (table 1).

Table 1. Supply and exhaust air temperature of different test cases.

ΔT/Δy	1 K/m	4.5 K/m	6 K/m	8 K/m	12 K/m
supply air temp.	*22.1* °C	*20.1* °C	*19.5* °C	*18* °C	*14.8* °C
exhaust air temp.	*23.6±0.3* °C	*25.9±0.5* °C	*26.9±0.5* °C	*28.1±0.3* °C	*31.5±0.1* °C

The presented evaluation is based on the answers for thermal sensation (figure 5) and thermal comfort (figure 6) for a mean value of all test persons. In all figures the mean value is printed. First of all, the $\Delta T/\Delta y$ = 1 K/m configuration shows the best evaluation for thermal sensation and thermal comfort. With higher temperature gradients the feet area is rated worse. The evaluation at the feet area increases from “neither cool nor warm” for the $\Delta T/\Delta y$ = 1 K/m configuration to “slightly cool” for a gradient of $\Delta T/\Delta y$ = 12 K/m. For the head area the evaluation of thermal sensation rises from “neither cool nor warm” to “slightly warm”.

In the $\Delta T/\Delta y$ = 1 K/m configuration the thermal comfort at the feet area is between “just uncomfortable” and “just comfortable” and decreases to “just uncomfortable” for the $\Delta T/\Delta y$ = 12 K/m configuration. Also the thermal comfort at the head area decreases from between “just comfortable” and “comfortable” to “just comfortable”. Overall, the part of the dissatisfied test persons increases between the $\Delta T/\Delta y$ = 1 K/m and the $\Delta T/\Delta y$ = 12 K/m configuration.

To sum up, the most critical point for local thermal comfort is the head and feet area. These body parts will be considered in the following chapter.

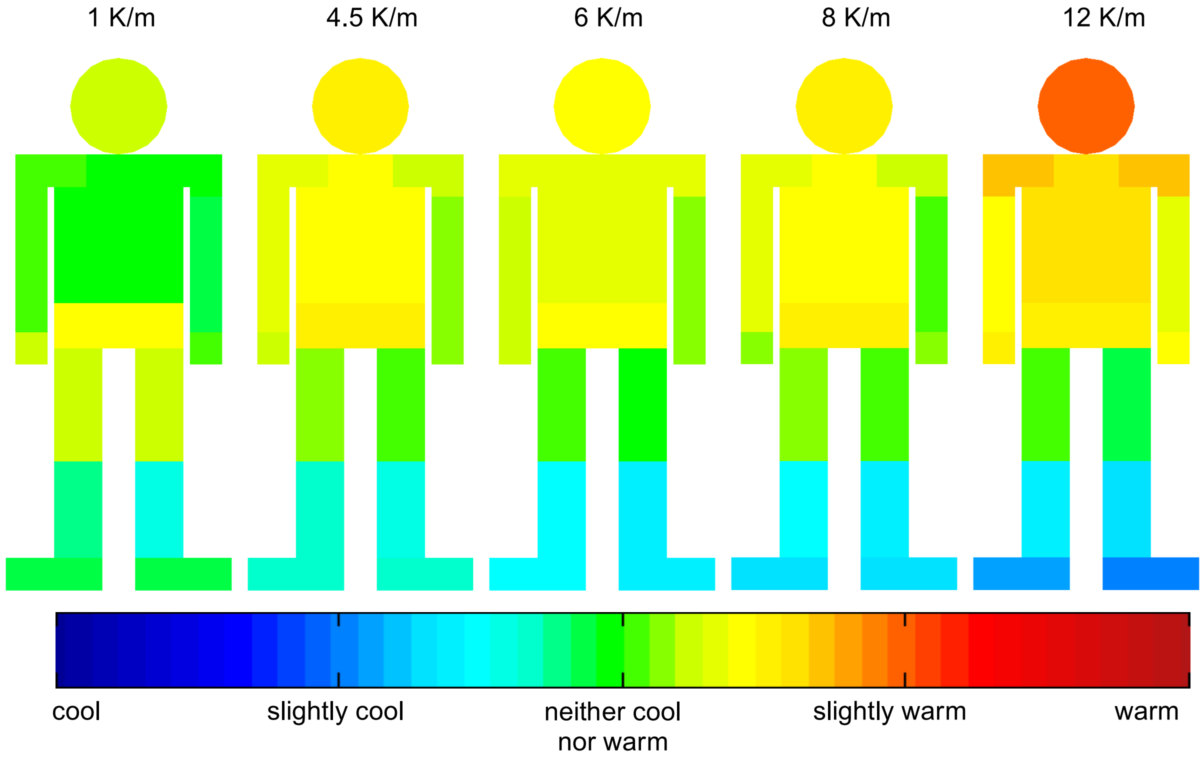

Figure 5. Thermal sensation with a gradient of ΔT/Δy = 1 K/m, ΔT/Δy = 4.5 K/m, ΔT/Δy = 6 K/m, ΔT/Δy = 8 K/m and ΔT/Δy = 12 K/m.

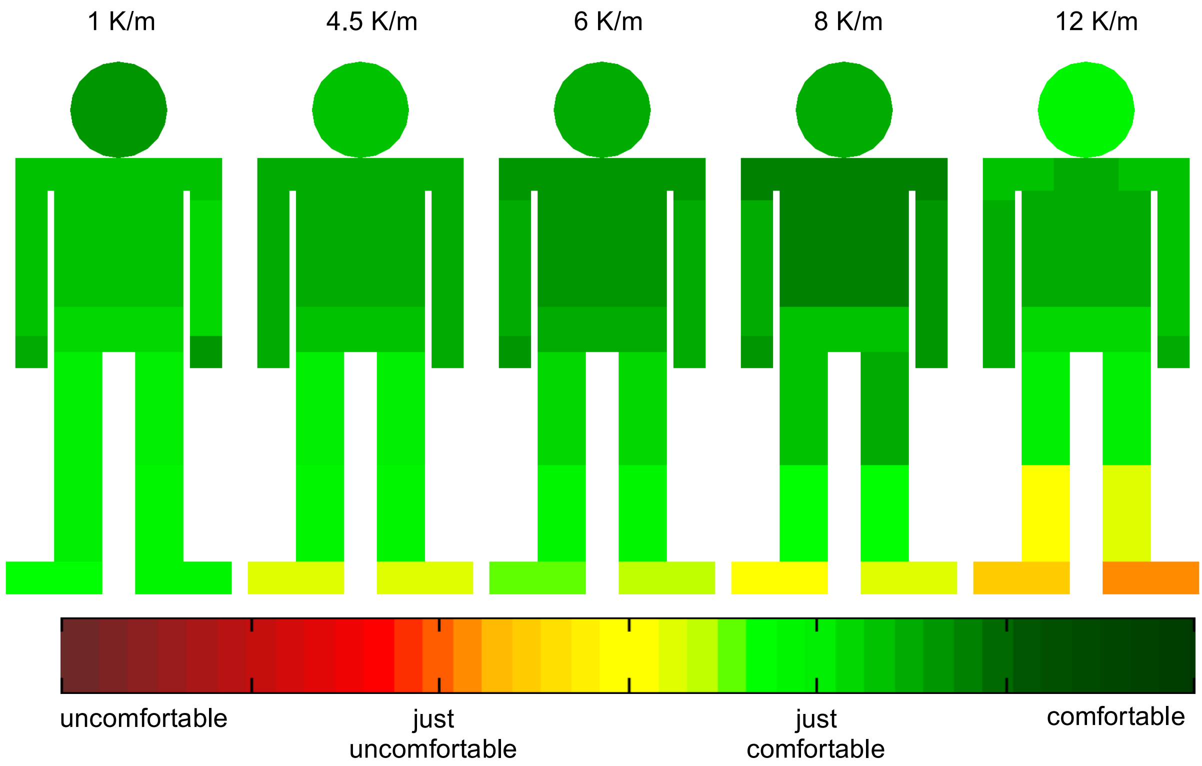

Figure 6. Comfort sensation with a gradient of ΔT/Δy = 1 K/m, ΔT/Δy = 4.5 K/m, ΔT/Δy = 6 K/m, ΔT/Δy = 8 K/m and ΔT/Δy = 12 K/m.

3.2 Comparison with ASHRAE Standard 55

In the following section literature data from ASHRAE Standard 55 is compared to the results of the own experimental data (ISO 7730, 2006; ANSI/ASHRAE Standard 55, 2013). The experimental data of the ASHRAE Standard is based on the studies by Olesen (Olesen et al, 1979). In the 1970s, Olesen conducted some experiments addressing the impact of the vertical air temperature gradients on thermal comfort. In his study each subject can prefer his room temperature level and it is changed according to their wishes for different temperature gradients. The mean room temperature is between 23.9±0.8 °C and 24.5±1.2 ℃.

In contrast, the presented results in this paper are based on experiments with a constant room temperature of 23 °C (height 0.6 m). Therefore, the percentage of dissatisfied persons regarding head and feet level is calculated from the answers of the test persons.

In figure 7 the percentage of dissatisfied persons (PD) is printed over the temperature gradient (K/m). All answers between "very uncomfortable" and "just uncomfortable" are summed up to the PD-Index. The answers from the questionnaire are shown for the overall thermal comfort (orange), the head (blue), the left foot (red) and the right foot (green). The literature data from ASHRAE Standard 55 are printed in black (Möhlenkamp et al, 2015).

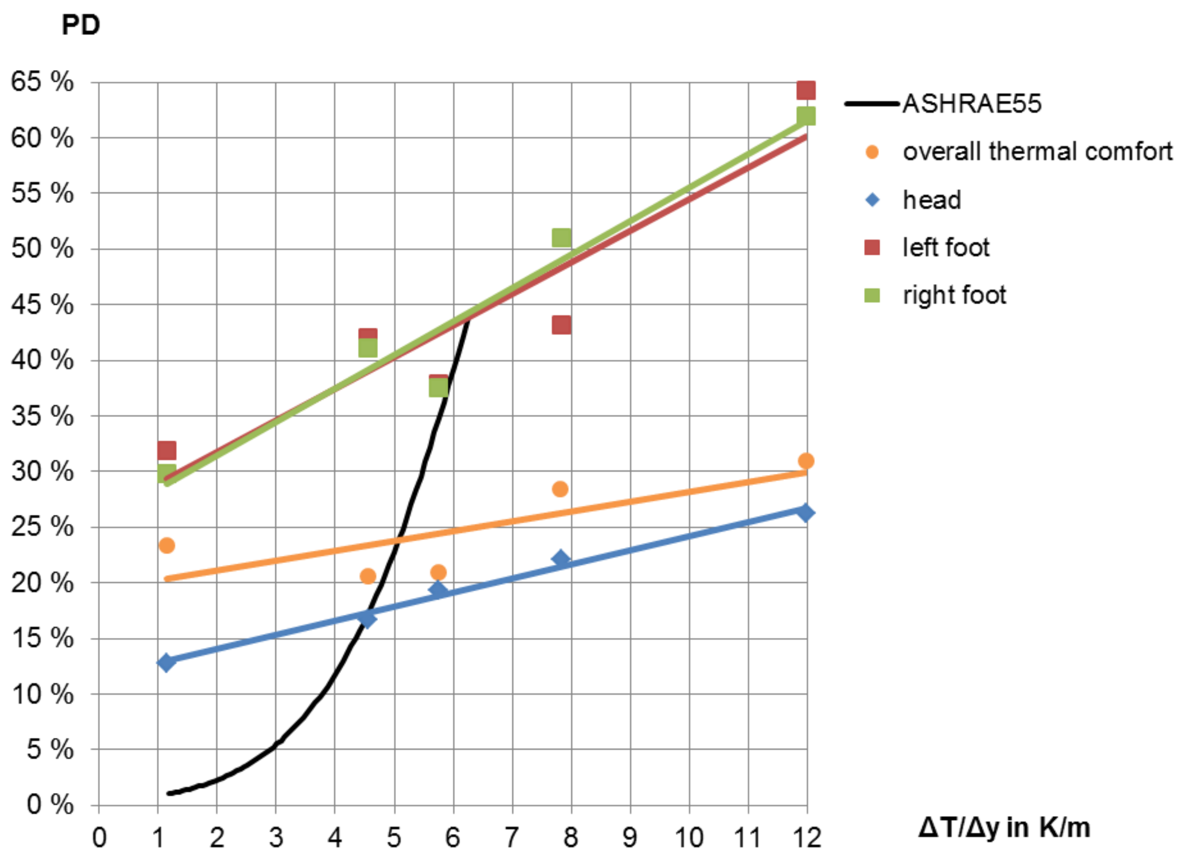

Figure 7. Percentage of dissatisfied persons depending on the temperature gradient.

For all body parts and the overall thermal comfort the percentage of dissatisfied persons rises nearly linearly with higher vertical air temperature gradients.

The results of the overall thermal comfort are found between the evaluation of the head and feet level. However, the feet area is the most critical point as here are the most complains about the thermal comfort. Nevertheless, the influence of the feet area is not as big as the head area, because the overall thermal comfort is close to the evaluation of the head level.

In the literature data from ASHRAE Standard 55 the percentage of dissatisfied grows exponentially in contrast to the experimental data (Möhlenkamp et al, 2014, 2015). One reason for the difference might be a different room temperature in the test cases from Olesen. Also, the influence of radiation is not known in the experiments of Olesen.

3.3 Environments with a mean room temperature of 20 °C and 26 °C

Additionally, a room temperature of 20 °C and 26 °C with a vertical air temperature gradient of $\Delta T/\Delta y = 8$ K/m are tested with subject tests. In table 2 the supply air and exhaust air temperatures for the different test cases are shown.

Table 2: Supply and exhaust air temperature of a room temperature of 20 °C and 26 °C

	T_m = 20 °C	T_m = 26 °C
ΔT/Δy	8 K/m	8 K/m
supply air temp.	*14.9 °C*	*21.5 °C*
exhaust air temp.	*25.2±0.2 °C*	*31.3±0.5 °C*

In figure 8 the vertical air temperature gradients for three room temperatures 20 °C, 23 °C and 26 °C are printed. Nominal room air temperatures are measured at a height of 0.6 m. The data for the room air temperatures of 23 °C are adopted from the previous investigations. The vertical air temperature gradient is evaluated between 0.1 m and 1.1 m.

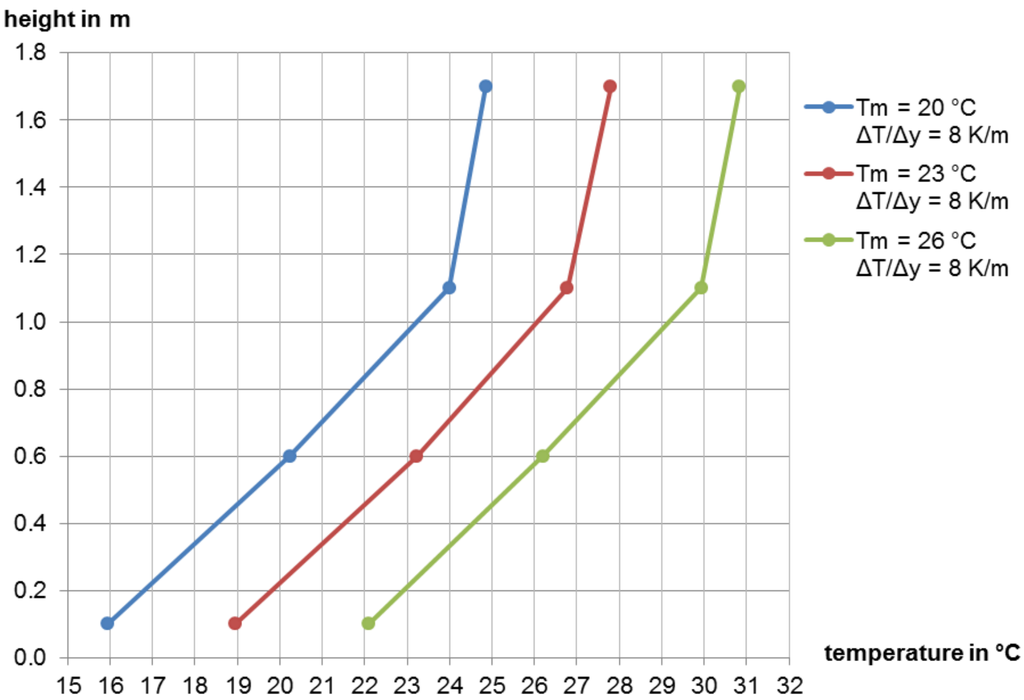

Figure 8. Temperature stratification for different room temperatures.

In figure 9 the evaluation for the thermal sensation is shown on the left side, for the thermal comfort on the right side. For a room air temperature of 20 °C the head and torso area is evaluated with "neither cool nor warm". The feet area is rated with "slightly cool". Comparable results for the head and torso area is given for a room air temperature of 23 °C. The feet area is rated better with a mean voting between "slightly cool" and "neither cool nor warm". In contrast, for a room temperature of 26 °C the thermal sensation is evaluated for all body parts between "slightly warm" and "warm". So there are major changes of the evaluations between 23 °C and 26 °C then between 20 °C and 23 °C.

The evaluation of the thermal comfort shows the same effect. The head and torso area is voted between "just comfortable" and "comfortable" for a room air temperature of 20 °C and 23 °C. For 20 °C the feet area is evaluated with "just uncomfortable", for 23 °C with between "just uncomfortable" and "just comfortable". The evaluation for a room air temperature of 26 °C is for all body parts between "just uncomfortable" and "just comfortable". Room temperatures of 20 °C at the head and torso area are as comfortable for subjects as room temperature of 23 °C. A room temperature of 26 °C implies a significant deterioration for the test subjects. Therefore it makes sense to tolerate lower room temperature instead of higher values. In rooms with displacement ventilation concepts, control strategies should be implemented according to these results (Möhlenkamp et al, 2015).

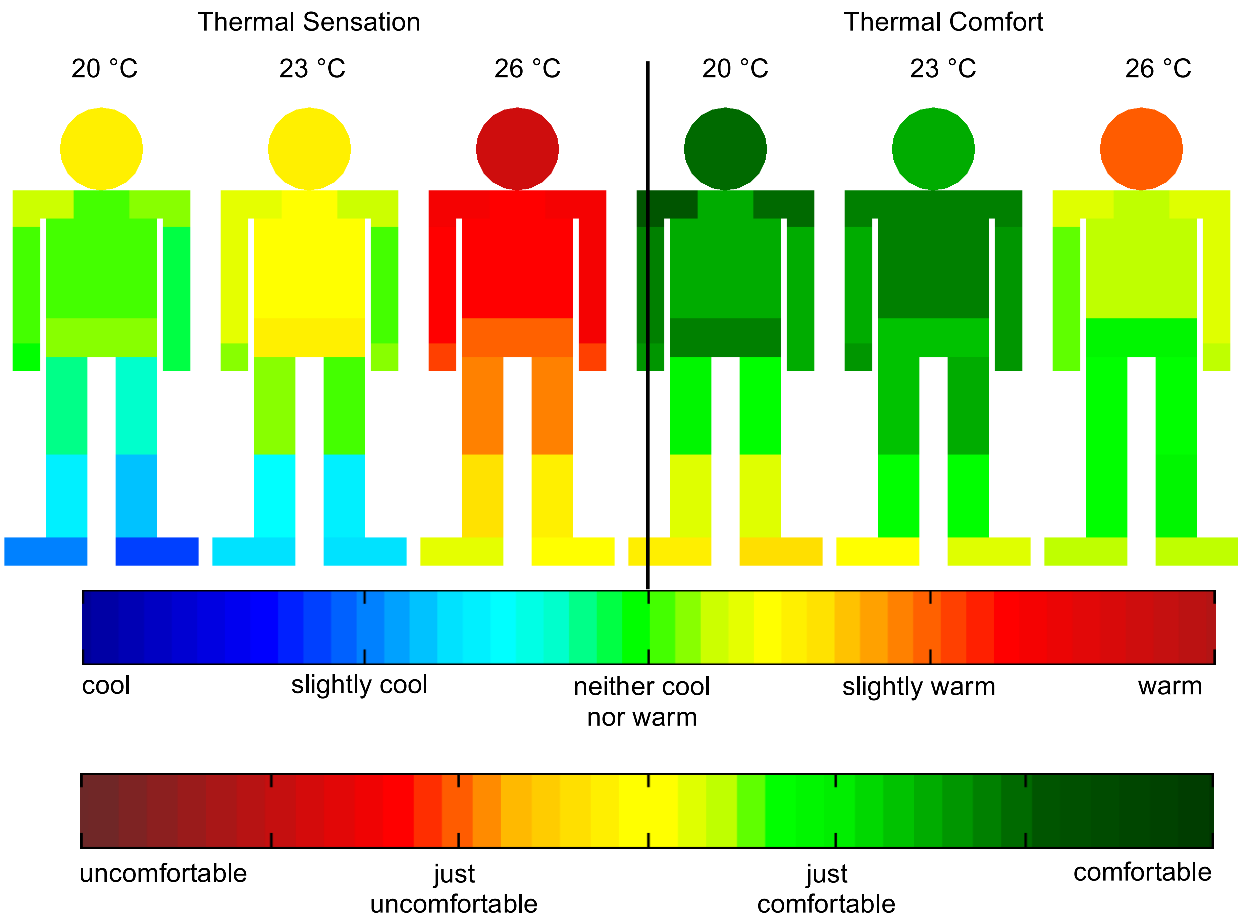

Figure 9. Thermal sensation and thermal comfort for a vertical air temperature difference of $\Delta T/\Delta y$ = 8 K/m and a room temperature of 20 °C, 23 °C and 26 °C.

4 Conclusion and Outlook

In this study the thermal comfort of displacement ventilation in environments with different mean temperatures and different vertical air temperature gradients between head (1.1 m) and ankle (0.1 m) are investigated. Test subjects cannot prefer and change their mean room temperature. Test campaigns with a room temperature of 20 °C, 23 °C and 26 °C are evaluated with different vertical air temperature gradients.

For a room temperature of 23 °C the percentage of dissatisfied persons rises with higher temperature gradients ($\Delta T/\Delta y$ = 1 K/m up to $\Delta T/\Delta y$ = 12 K/m) nearly linearly. For higher vertical air temperature gradients the results are better than the predicted thermal comfort in literature data. To sum up, higher vertical air temperature gradients can be tolerated in displacement ventilation concepts than recommended in the literature and regulations.

Additionally, room temperatures of 20 °C and 26 °C with an vertical air temperature gradient of $\Delta T/\Delta y$ = 8 K/m are tested. One results of this comparison is that test subjects tolerate this temperature gradient with lower room temperature more easily than with higher air room temperature.

In order to transfer the results to real ventilation environments, further investigations with room temperatures of 20 °C and 26 °C and different vertical temperature gradients have to be evaluated by test subjects.

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Occupant-Centered Building Operation Strategies for Balancing Thermal Comfort and Energy Efficiency in Warm and Humid Climates

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Abstract
Through detailed monitoring and analysis of how occupants use energy in buildings, insight into energy efficient operation and control methods can be developed alongside human comfort indicators. Maintaining human thermal and visual comfort in passively ventilated and conditioned homes is a multi-sensory experience and requires a dynamic interaction between the occupant and the building. Five 60-hour operation experiments were carried out by the research team in a community design research lab during the Midwest summer of the United States. The goal of these experiments was to keep the buildings operational temperature within the adaptive comfort zone provided by ASHRAE 55 (ASHRAE, 2013) and thus minimize the need for active system use. The researchers kept a detailed operation log recording the time stamps of different operations in the lab. A trained energy simulation model is used to predict cooling energy consumption without these operations. Comparing to measurement in the house, the energy impact of different operations are quantified as an additional indicator. In conclusion this paper presents a series of experimentally validated operational control strategies for a hybrid designed lab located in a climate with warm and humid summers. Weather dependent operation strategies and their energy efficiency are provided to enhance the relationship between people and buildings. This approach leads to more energy efficient behaviours as well as more responsive systems of control.

Keywords: occupants behaviour, building operation, passive strategy, energy saving.

1 Lab Context and Components

The Iowa NSF EPSCoR community design research lab is located in Iowa, USA and occupied all year round by staff, who operate and maintain the building as a nature activity center. The building's mechanical systems and enclosure must be able to mitigate the harsh cold winters as well as hot and humid summers associated with the ASHRAE Climate Zone 5. The hybrid lab is designed to not only weather those extremes but capitalizes on solar energy and passive ventilation opportunities that produce and conserve energy. Converting solar radiation into usable energy through the use of a photovoltaic array as well as a sunspace, which captures radiation in the form of heat to offset active heating system costs within the lab, are just a few ways in which this building utilizes its renewable energy resources.

The lab (Figure 1) has a series of operable components which allow for flexibility through the seasons. Lower windows near work spaces allow for cross ventilation through the corresponding upper clerestories during passive ventilation opportunities. The lab's shed roof stratifies the convective air flows in the space, separating rising heat from the occupants and inducing air flow through the space when both the inlets and outlets are open during warm weather seasons. Exterior sliding louvers located over the southern and eastern windows allow for solar heat gain mitigation through those surfaces with the option of withdrawing them completely during overcast days.

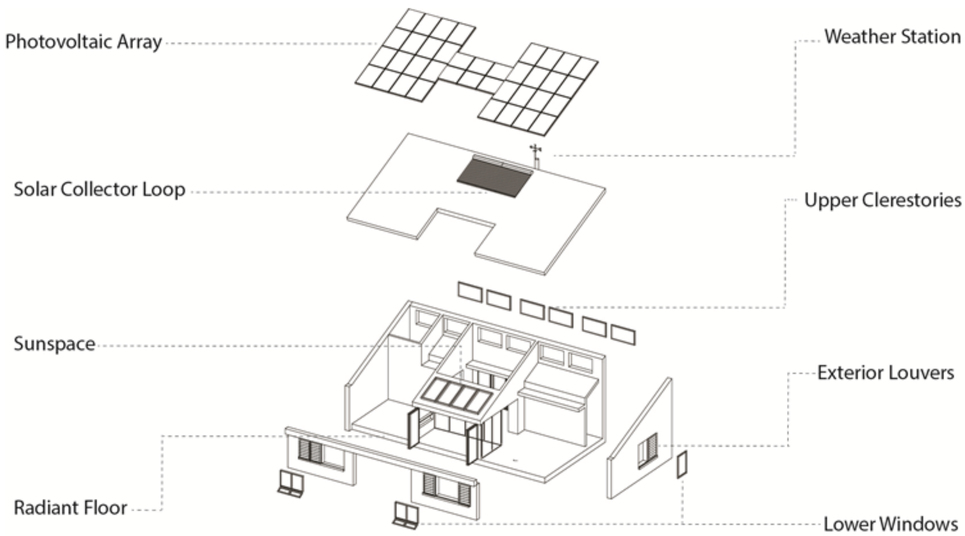

Figure 1 Lab Components and Overview

The operable louvers control light levels in the space alongside reducing cooling loads during high temperature days with strong solar radiation. The lab's sunspace provides passive heating opportunities during cold seasons but must be flushed out during hot summer days. This is done through closing all interior sunspace components and opening the exterior doors to allow for heat to escape. The solar collector loop on the roof works adjacent to the photovoltaic system in harvesting the sun's thermal energy for use within the lab. The loop utilizes readily available solar energy for use in the lab's radiant floor heating system and offsets energy costs normally generated through electrical, natural gas, water, or forced air heating systems.

A Data Acquisition System (DAS) has been monitoring the indoor and outdoor environment, mechanical and electrical system for over 4 years. A data driven HVAC system control is fed by real time measurements. Recently a dashboard displaying the key data needed for operation and the website terminal of HVAC system control was launched in the house to better visualize the house performance and ease the occupants' control decisions. The lab's combination of sensors used to measure interior and exterior variables are distributed evenly throughout the interior of the house as well as located within the weather station on the roof. Supplying a constant stream of data to the lab's data acquisition unit provides direct feedback to the occupants as well as historical reference for future performance monitoring.

2 Research Question

The house had originally been designed as a residence. After the house being transformed into an office for naturalist and visitor center of Honey Creek Resort State Park in Iowa, the occupants' interaction with the house changed from the original design intention. In spite of the flexibility of operating the house with multiple passive strategies, the house operations often relied more on active HVAC system control for the majority of the time. In addition due to some maintenance issues of the building envelope and security concerns, the stack and cross ventilation and sunspace operations were difficult to operate during a daily routine and thus were abandoned by the house occupants. These altered usages of the house could reverse the energy saving of passive operation to increased energy consumption (He, et al, 2014). To develop an ideal house performance as designed, a researcher was operating the house for five time periods during the summer of 2015.

3 Research Method

During a series of five controlled experiments a researcher occupied the lab for a period of 60 hours to monitor and operate the buildings components. Monitoring of interior and exterior environmental variables as well as climatic conditions allowed for informed manipulation of the building's envelope to capitalize on passive ventilation opportunities and reduce solar heat gain. A series of factors were monitored in relation to the internal and external environments through a building data visualization interface which communicates real time data to the occupant. This information facilitates informed decision making at any current point in time based on real time data of interior conditions as well as forecasted weather information. The factors monitored during the experiments were as follows:

- Dry Bulb Air Temperature (Interior/Exterior)
- Relative Humidity (Interior/Exterior)
- Wind Speed / Direction (Exterior)
- Solar Orientation / Radiation (Exterior)
- Local Weather Conditions (Exterior)

Outdoor Air temperature, relative humidity, and wind speed play key roles in creating interior conditions which accommodate human comfort during passive ventilation opportunities. Temperature is often the only variable used in determining comfort for interior conditions, occupants often view temperature as how the AC and comfort are controlled in spaces. Adding more variables, including outdoor relative humidity, wind speed and solar radiation levels can help the researcher to make a better informed decision of predicting passive ventilation opportunities.

The ability to predict passive ventilation opportunities as well as the interior conditions they produce can help to reduce active system use and in turn produce energy saving alternatives. During the experiment time frames these five factors were monitored and logged hourly in an excel log to be referenced alongside the data points collected from the lab's sensors. These processes allow the researcher to monitor the environmental conditions before and after changes are made to the adjustable envelope components.

Operation of the building components can be broken down into a series of tasks completed at different times throughout the day in correlation with solar orientation and weather conditions. During passive ventilation, windows are opened to induce air flow through the space. During unfavourable conditions the windows are closed and the air conditioning unit is used to supplement the space's interior conditions. The building's operable components are as follows:

- Opening the lower south windows
- Opening lower east window
- Opening clerestory windows
- Louvers on south windows
- Louvers on east window
- Sunspace Open

During the experiment time frame operations were completed in accordance with three factors: mitigate solar radiation, respond to weather conditions, and facilitate passive ventilation. Following the sun's orientation across the sky the lab's louvers were used when direct heat gain could be mitigated to reduce the building's cooling load by sliding the louvers over the windows and reflecting radiation back out into the environment. Weather conditions were constantly changing and as a response operations were completed throughout the day in order to prevent water infiltration or excessive cooling from storm fronts. During rain events the lab's openings were all closed disallowing passive ventilation and preventing the introduction of humidity into the space. The lab's lower and upper windows were opened during comfortable conditions to facilitate passive ventilation as a means of reducing energy use by the lab's active systems.

A detailed log was used to record operations completed throughout the day as well as the resulting interior conditions of the space. Alongside this data, local weather and the number of occupants was also recorded. This record was then used to correlate the operation logs with the resultant energy loads on the building's mechanical systems to provide insight into the energy saved during passive ventilation.

Local weather conditions played an important role in implementing operation strategies given that during rain events passive ventilation is only possible if water does not infiltrate the envelope. In order to ensure the safety of the equipment and enclosure passive ventilation was not utilized during major rain events or other inclement weather. The log in Table 1 shows how the exterior weather conditions were recorded alongside environmental variables and a timestamp.

Table 1: Experiment Log Example

Date	Start Time	End Time	Description	# of occupants	Interior Temperature	Exterior Temperature	Interior Humidity	Exterior Humidity	Weather
27-Jun	5:16 PM	7:36 PM	Drove to honey creek						
	8:02 PM	8:04 PM	Check weather	9	23.4	26.6	55.9	50.3	Clear Skies
	8:06 PM	8:09 PM	Open lower windows	9					
	8:09 PM	8:17 PM	Opened all clerestories	2					
	8:18 PM	8:18 PM	Opened 1 north door	2					
	8:24 PM	9:20 PM	Began placing Hobologgers	2					
	8:40 PM	8:41 PM	Radiation shield fans on	2					
	9:20 PM	9:24 PM	Check Weather	2	22.6	20.8	66.6	82.6	Clear
	9:27 PM	9:27 PM	Closed north door	2					
	10:02 PM	10:07 PM	took quick shower	1					
28-Jun	7:27 AM	7:38 AM	Shut all clerestories	1					
	7:39 AM	7:39 AM	Shut east window, Left lower southeast/west windows open	1					
	7:39 AM	7:52 AM	Took shower	1					
	7:54 AM	7:54 AM	Check Weather	2	21.2	17.5	66.1	97.6	Thunderstorm
	8:41 AM	8:43 AM	Closed East louvers	3					
	8:48 AM	8:57 AM	Cooked eggs with ham on stove	1					
	8:59 AM	9:10 AM	ate breakfast	1					
	9:12 AM	1:44 PM	Worked on operation modes	2					
	9:23 AM	9:48 PM	began raining outside	2					
	10:07 AM	10:08 AM	Checked Weather	2	22.3	18.9	71.6	93	Cloudy, rainy
	10:14 AM	10:14 AM	Opened exterior sunspace door	2					
	11:19 AM	11:21 AM	opened central clerestories	3					
	12:09 PM	12:11 PM	Checked Weather	2	23.1	23.2	62.2	77.2	partly cloudy
	1:28 PM	1:42 PM	turned stovetop on	1					
	1:44 PM	1:57 PM	ate lunch	1					
	1:58 PM	2:11 PM	fixed east louvers	2					
	2:11 PM	2:24 PM	Measure each skylight for covering	2					
	2:28 PM	2:29 PM	opened east kitchen window and removed louvers	2					
	2:30 PM	2:33 PM	opened bathroom, bedroom, and kitchen clerestories	2					
	2:34 PM	2:36 PM	Checked weather	2	25.2	26.6	62.1	63.5	partly cloudy
	2:45 PM	4:40 PM	worked on building operations	1					
	4:40 PM	4:42 PM	Checked Weather	2	27.3	27.8	54	58.7	Clear skies
	4:44 PM	5:19 PM	Worked on Qualtrics	1					
	5:19 PM	5:19 PM	shut exterior sunspace door	1					
	5:20 PM	5:47 PM	went for a run	1					
	6:18 PM	7:15 PM	worked on building operations	1					
	7:16 PM	7:16 PM	Opened exterior sunspace door	1					
	7:17 PM	7:19 PM	Checked weather	1	26.9	25.1	55.5	73.4	Partly cloudy
	7:24 PM	10:28 PM	Worked on operations	1					
	8:38 PM	8:42 PM	Checked Weather	1	26	23.1	63.6	80.2	Partly cloudy, lightly sprinkling
	9:21 PM	9:21 PM	Shut exterior sunspace door	1					
	10:28 PM	10:30 PM	checked weather	1	24.3	19.9	54.9	90.5	Partly Cloudy
	10:30 PM	10:37 PM	Got ready for bed						
29-Jun	7:36 AM	7:50 AM	Woke up, took shower	1					
	7:55 AM	7:57 AM	Closed east window and louvers	1					
	7:57 AM	7:59 AM	Checked weather	1	21.2	20.1	60.8	88.2	Clear Skies
	7:59 AM	8:01 AM	Opened exterior sunspace doors	1					
	8:03 AM	8:41 AM	Worked on Building operations	2					
	8:41 AM	8:48 AM	Cooked breakfast on stove	2					
	8:48 AM	8:56 AM	Ate Breakfast	2					

Note: The temperature unit logged in Table 1 is in Celsius.

4 Data Analysis

Data from the experiments show that opportunities for passive ventilation largely occur over night when temperature and humidity levels are relatively low or tolerable. During mid-day when the sun's rays are overhead and temperature rises, the building's openings are closed and interior conditions are maintained at comfortable conditions until the active air conditioning system is prompted to take over by a rise in interior temperature. This strategy allows for nightly flushing out of heat in the building's materials, lengthening the period of time during the day for comfortable passive ventilation and reducing energy usage by active systems.

High solar radiation is correlated with high temperature and low humidity levels during the day while at night solar radiation drops to zero and humidity begins to rise again. This shows that while night time flushing may remove latent heat, there is a possibility of humidity levels rising above tolerable levels inside the building.

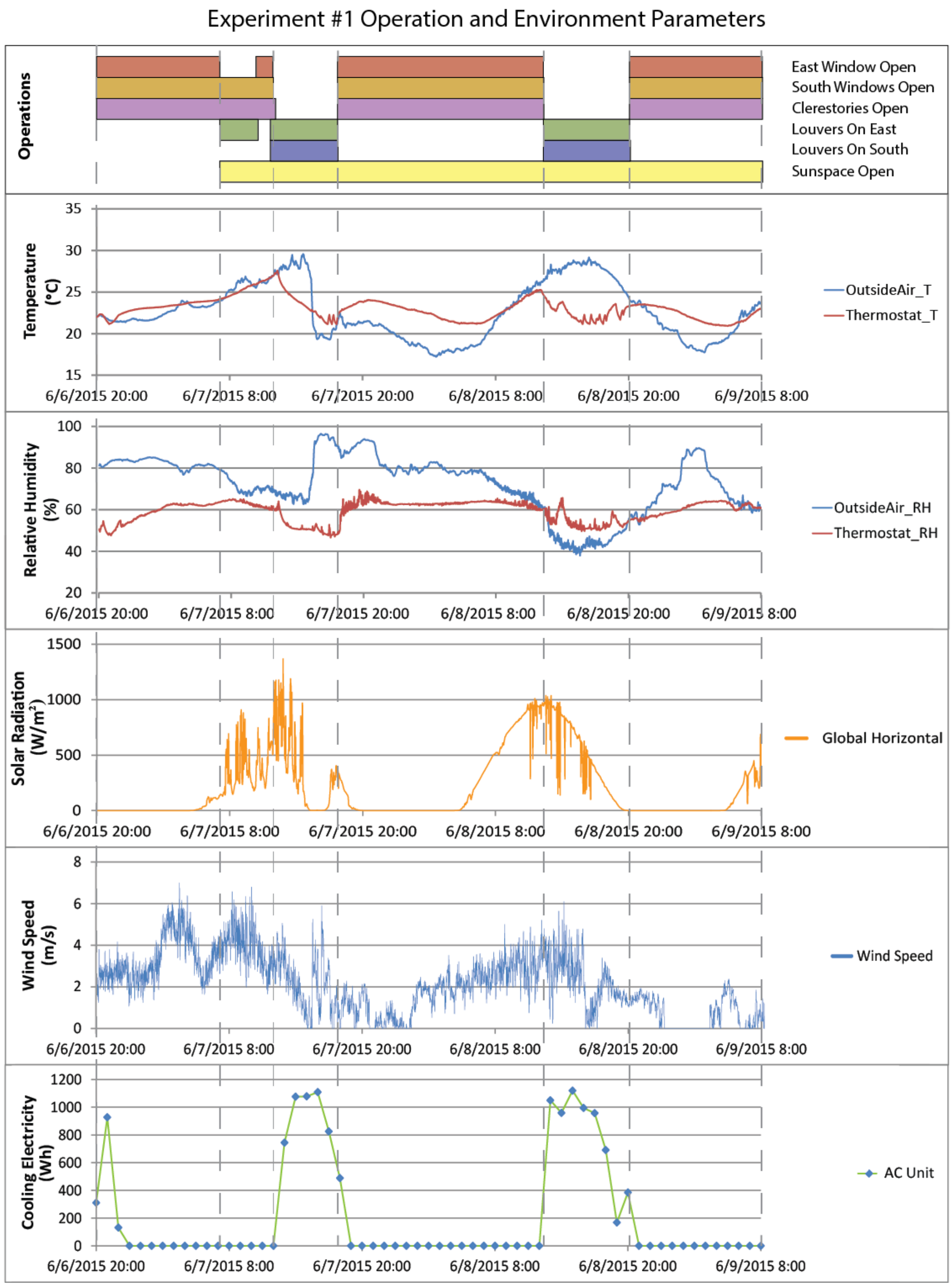

Figure 2: Experiment 1 Operation and Environment Parameters

Experiment one took place from 8pm on June 6, 2015 through 8am on June 9, 2015. Weather throughout the experiment timeframe featured no rain events alongside high solar radiation exposure and variable wind speed. The operation strategy outlined at the top of the graph (Fig. 2) shows frequent passive ventilation was used for the majority time of the experiment. During peak solar radiation exposure louvers were placed over the windows to prevent heat gain only to be removed again later in the day when passive ventilation was again possible. Conditions as they were recorded by the occupant report that the interior grew too hot (27°C/ 60% RH) during midday operations and had to be supplemented with active systems. This can be seen in the bottom graph in Fig.2 when looking at the AC consumption as correlated with interior temperature and humidity.

Experiment #2 Operation and Environment Parameters

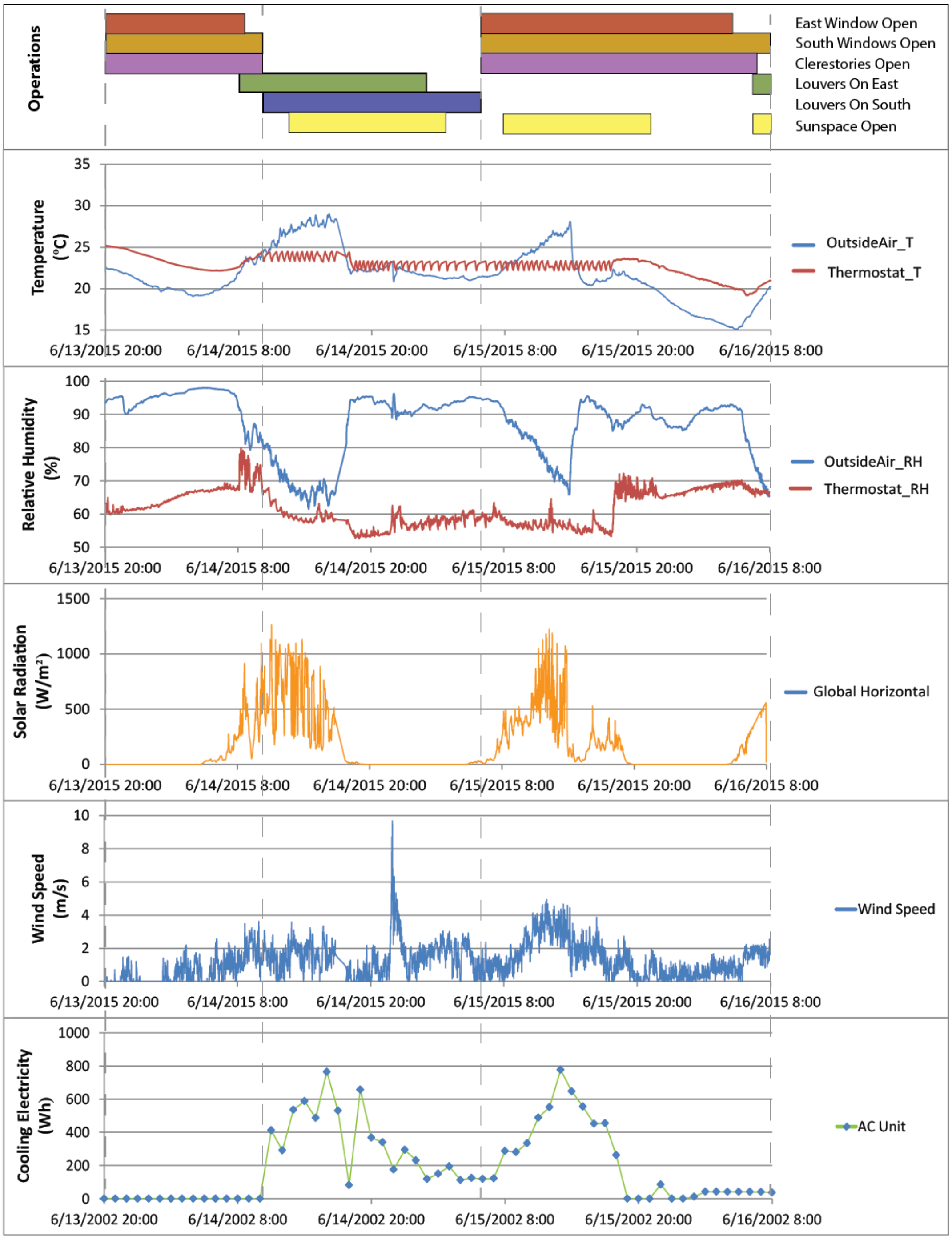

Figure 3: Experiment 2 Operation and Environment Parameters

Experiment two took place from 8pm on June 13, 2015 through 8am on June 16, 2015. Weather during the experiment consisted of overcast skies and intermittent rain. The operation strategy that was implemented shows passive ventilation at the beginning and end with high AC use during the second day (Fig. 3). The rain event occurred around 10am through midnight on June 14th. The operation strategy shows that windows were left open during the third day (June 15th) of the experiment while the AC was running, a missed operation not planned. Comfort conditions on the interior as reported by the researcher were tolerable with high humidity, rising from 69% to 80% before the rain.

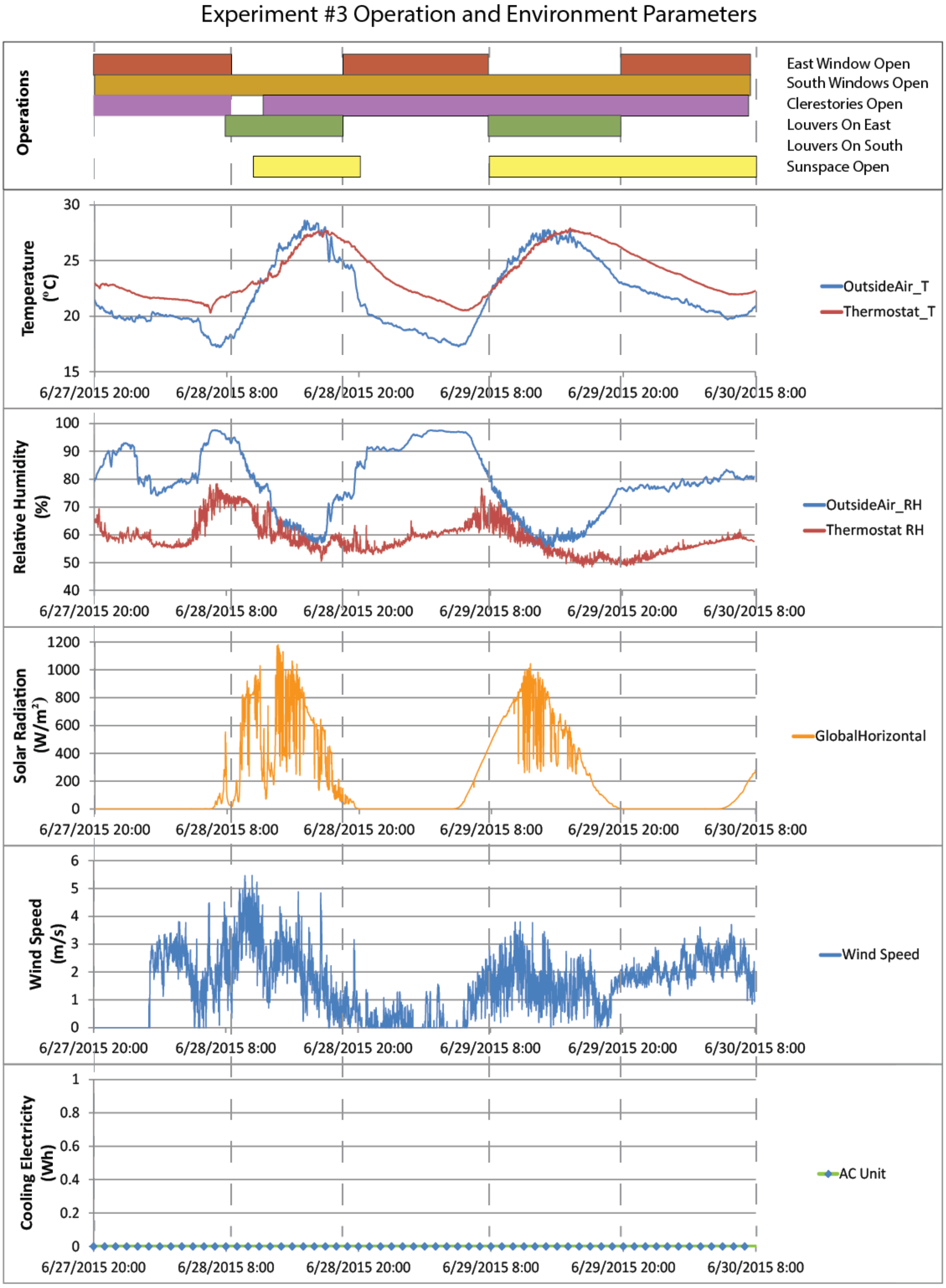

Figure 4: Experiment 3 Operation and Environment Parameters

Experiment three took place from 8pm on June 27, 2015 through 8am on June 30, 2015. Weather during the experiment consisted of no rain events with moderate wind speed allowing for passive ventilation with no AC consumption for the entirety of the time (Fig. 4). Windows remained open for the entire experiment to allow for natural ventilation. The strong solar gain was mitigated with the opening of the sun space to release heat to the outside and applying louvers during high solar radiation time periods. Comfort as reported by the researcher was variable but tolerable during the passive ventilation timeframe. Occupying the space without AC required some tolerance of minor discomfort for short periods of time but was compensated by the cooling energy saving.

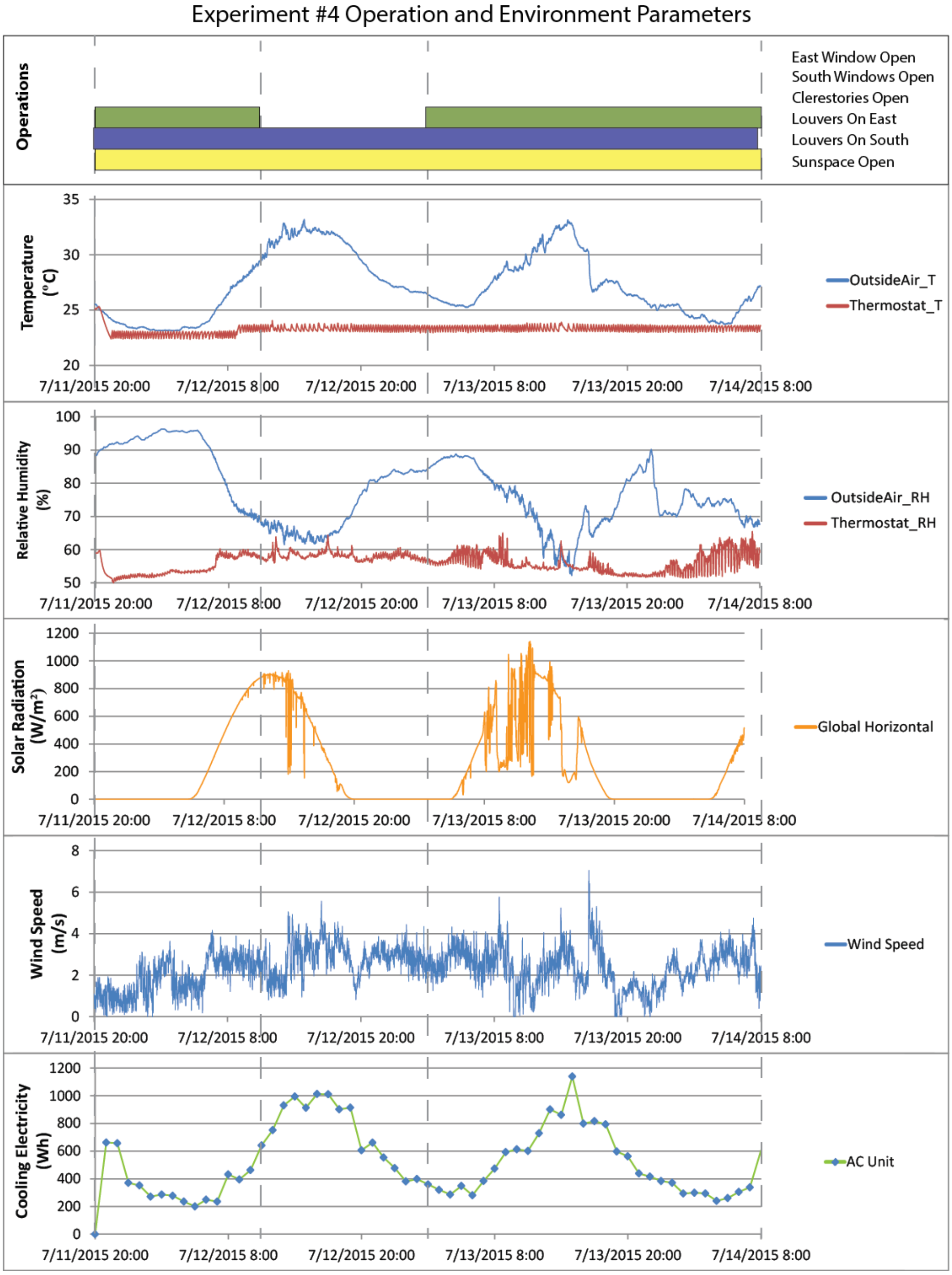

Figure 5: Experiment 4 Operation and Environment Parameters

Experiment four took place from 8pm on July 11, 2015 through 8am on July 14, 2015. Weather during the experiment consisted of clear skies with no rain events coupled with high solar radiation and temperatures for the entire duration. The operation strategy implemented during this the experiment did not include any opening of the windows for passive ventilation due to high temperatures and humidity levels outside. Outdoor condition could bring a tolerable indoor environment between 1am and 6am on July 14 through natural ventilation, when outside temperature dropped below 25ºC, RH remained around 75% and wind speed was around 3m/s. But checking live data and opening window cannot be implemented due to the sleeping schedule of the researcher. Heat gain was reduced with the constant flushing of the sunspace as well as through use of louvers over the windows. Comfort as reported by the researcher was considered satisfactory given that use of the mechanical cooling system was relied upon for the duration of the experiment.

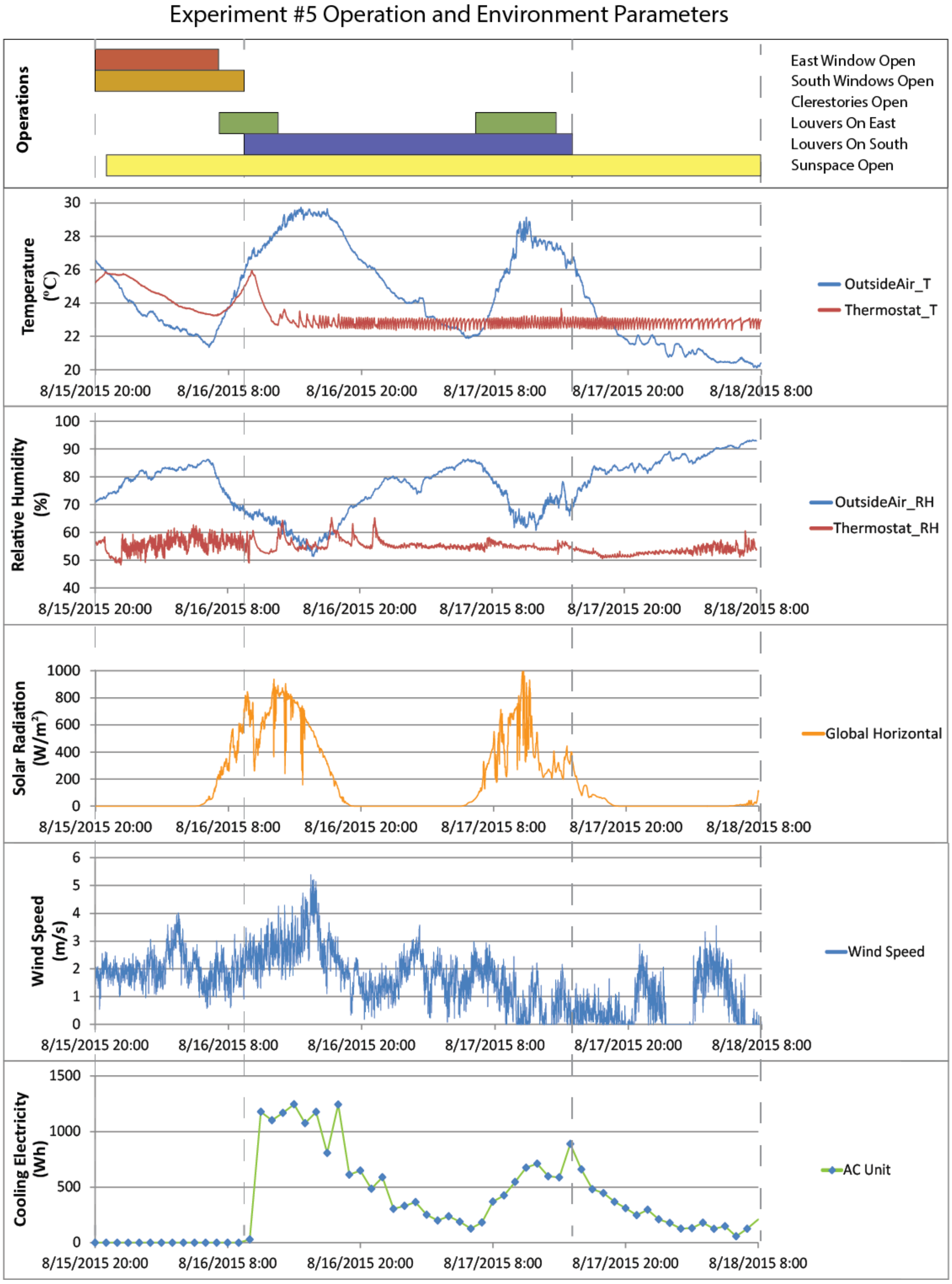

Figure 6: Experiment 5 Operation and Environment Parameters

Experiment 5 took place from 8pm on August 15, 2015 through 8am on August 18, 2015. The weather during the experiment consisted of a mixture of clear, sunny skies, high temperatures, and a rain event (August 17th night). The operation strategy implemented took advantage of passive ventilation early in the experiment at night of August 15th before switching to the mechanical cooling system. The reliance of mechanical cooling is due to subsequent high humidity and temperatures, as well as the rain. There were so few natural ventilation opportunities between 8pm and midnight on August 16 that the researcher skipped it. Solar heat gain was reduced through the continuously flushing of the sunspace as well as placing louvers over the windows during periods of high solar radiation. Comfort as reported by the researcher was described as pleasant with much of the interior environment controlled by the mechanical cooling system for the majority of the experiment.

Figure 2 to Figure 6 show the relationship between the five environmental factors during the experiment timeframes. These charts were utilized to determine when passive ventilation was feasible comparing factors other than solar radiation and climate data. Temperature, relative humidity, and wind speed work together dynamically to produce comfortable interior and exterior environments.

The adaptive thermal comfort model was utilized after the experiment time frame to determine the operation strategies effectiveness and compliance to ASHRAE-55 (ASHRAE, 2013). The input variables include: dry bulb indoor air temperature, mean radiant temperature, prevailing outdoor mean air temperature and indoor air speed. The dry bulb indoor air temperature is averaged hourly based on measurement inside the house. Mean radiant temperature is assumed to be the same as the dry bulb indoor air temperature, because when the natural ventilation operations are in place, the solar radiation level is always low enough to avoid additional solar heat gain from the unshaded windows. And the surrounding surfaces of wall and furniture are close to dry bulb air temperature (Nicol et al., 2012). Prevailing outdoor mean air temperature is a simple arithmetic average of the outdoor air temperature in seven sequential days prior to the day in question (ASHRAE 55, 2013). And the indoor air speed is an arbitrary selection of 0.3m/s for all the plots because it's the lowest air speed available with the plotting tool (Tyler et al., 2013) and the researcher did not report obvious feeling of air movement around body from natural ventilation. Fig. 7 includes the comfort plots when only natural ventilation was implemented for cooling and the researcher was lightly clothed and sitting and working on computers. Thus the adaptive comfort during sleeping time and AC running period is not included. By implementing this analysis across all of the experiment time frames a percentage of compliant to non-compliant operation times is developed as shown in Table 2.

Compliance with ASHRAE standard 55 during the experiments was maintained at 92% or above for the entire duration of the occupied times passively ventilating. Analysis of the individual experiments shows that experiment 4 does not occur on the plot due to reliance on the mechanical systems. Experiment 2 features the only plotted data point outside of the compliant area. Further analysis of the log shows that during this experiment night time natural ventilation was used and during that timeframe conditions became too warm resulting in noncompliant conditions. Analysis of the experiment's data charts shows that the lab's mechanical AC and ventilation system turned on for 100 % of experiment 4 and 80% of experiment 5 due to high temperatures and humidity levels. Examples of this can be found in figure 5, where cooling set point was set to 22.8 ºC during the experiments. Strategies during these time periods of mechanical ventilation focus on mitigating the solar heat gain through transparent surfaces to reduce the amount of cooling load on the building while also opening the sunspace exterior doors to ensure heat does not build up in the space.

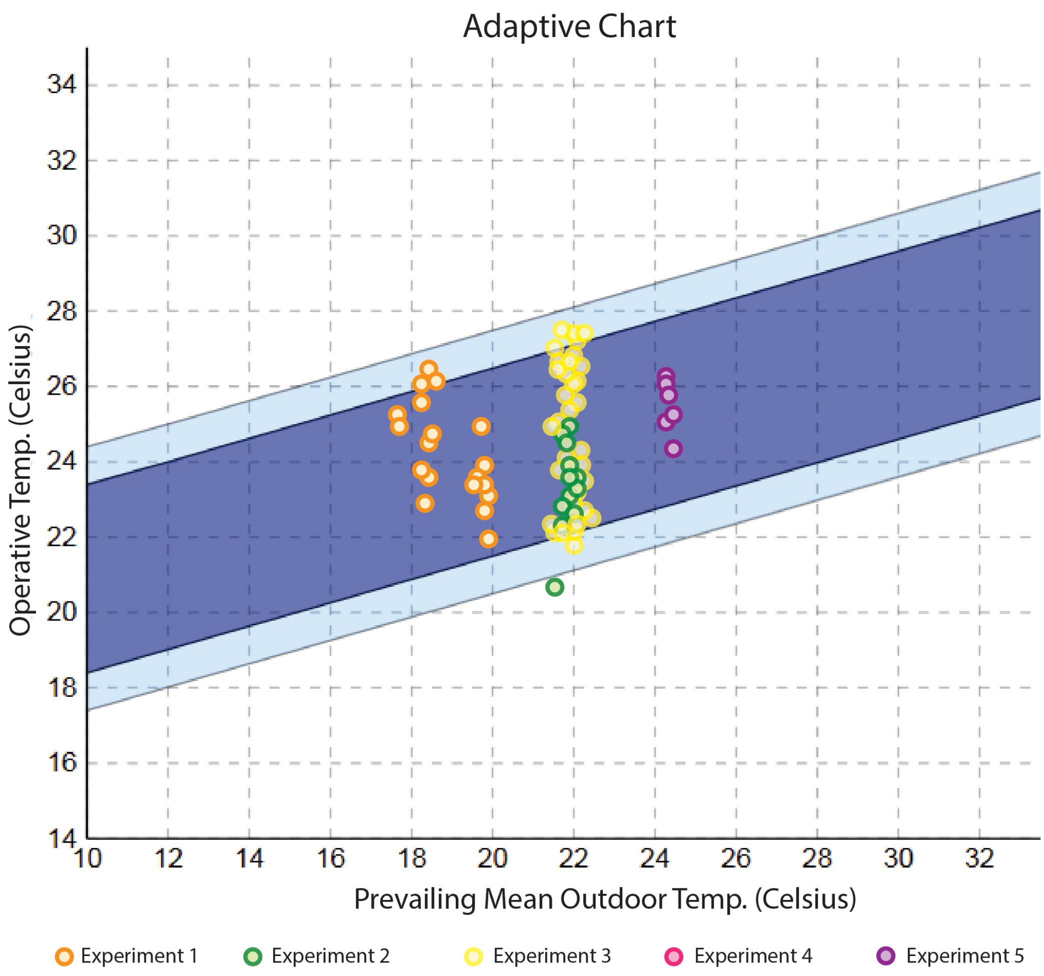

Figure 7: Adaptive Comfort Chart. Hourly average values during experiment timeframes (Tyler, 2013).

Table 2: Adaptive Chart Experiment Compliance Comparison

Experiment	90% - 100% Compliant	80% Compliant	Not Compliant
1	84%	16%	0%
2	92%	0%	8%
3	81%	19%	0%
4	NA	NA	NA
5	100%	0%	0%

5 Energy Simulation

An energy model was trained to predict the energy savings from experiment operations. DesignBuilder V4.5 was used as the simulation interface with EnergyPlus V8.3 as the simulation engine.

Since the experiments were carried out from June to August, 2015, the measurement data in the same three months are selected to train the energy model. 92 days of AC unit performance data from June 1 to August 31, 2015 are divided into 3 groups: stable AC control for 52 days, unstable AC control for 35 days and unreliable measurement for 5 days.

During the stable AC control period, the AC schedule is set to be: occupied mode is on from 7:01am to 7:00pm, and the cooling set point is 22.8°C; Unoccupied mode is from 7:01pm to 7:00am of the second day, and the cooling set point is 26.7°C. In the unstable AC control period, the AC set point ranges from 21.7°C to 23.3°C with irregular occupied timestamps and occupancy loads. All the experiments happen in the unstable AC control period, when the researcher could override the default cooling control and adjust it for energy saving and comfort purpose. And during the unreliable measurement period, due to system maintenance a lot of data was either missing from the records or showed extreme outliers, making the measurement not suitable for this research application.

To develop a prediction tool, first the data from stable AC control period is used to train the AC cooling simulation model. After getting a satisfied result from the model training, the occupancy schedule of experiments is updated in the building energy model according to experiment logs, for the occupancy of the building is changed during experiment from an office schedule to a mix usage of residence and office. The simulation result of this updated model gives AC cooling consumption that could have been used without passive strategy intervene. The difference between simulated and measured AC consumption is considered to be a result of the passive strategy operation.

The total daily AC cooling consumption from trained energy model results in a Normalized Mean Bias Error (NMBE) at 6.45% and Coefficient of Variance of Root Mean Square Error (CVRMSE) at 28.30%. These two statistic indices indicate a reliable model for small house energy consumption prediction.

Table 3: The Impact of Passive Strategy Operated during Experiment

Experiment	**Day**	**Simulated Cooling without operation =S (Wh)**	**Measured Cooling with operation =M (Wh)**	**Simulation without Error SE= S/(1+NMBE) (Wh)**	**Simulation Standard Deviation SSD= SE*CVRMSE (Wh)**	**Possibility of Yielding Cooling Saving from Experiment Operation**
#1	1	7434	5321	6984	1976	80%
	2	6707	6323	6301	1783	49.5%
#2	3	8448	5759	7936	2246	83.3%
	4	4265	6121	4007	1134	3.1%
#3	5	5216	0	4900	1387	100%
	6	7699	0	7233	2047	100%
#4	7	15498	13799	14559	4120	57.3%
	8	15589	13472	14644	4144	61.1%
#5	9	12561	11994	11800	3339	47.7%
	10	10898	9550	10238	2897	59.4%

All the five experiments approximately start from Saturday night 8pm to Tuesday morning 7am for a 60 hour time period. In the following comparison between simulation and measurement, the 24 hour period from Sunday 00:01 to Sunday 24:00 is considered as Experiment Day #1, Monday 00:01 to Monday 24:00 is considered as Day #2, and so on.

Among all the 10 experiment days (Table 3), Day #4 is most likely not yielding any energy saving from the passive operations, and then followed by Day #2 and Day #9 where the possibility of saving energy through operation is slightly lower than 50%. The reasons are analyzed based on the logs and DAS measurements as followings.

For Day #4, it was raining during the night of Experiment Day #3 and the researcher lowered the cooling set point by 1.2ºC around 7pm (Fig. 3). Both the exterior high humidity and interior lower cooling set point result in a continuous AC cooling consumption overnight. And during day time, the researcher missed to close the windows while AC was still running. These operations are not yielding any energy saving. It could even cause a higher energy consumption for the total value of a whole day. And when compared with the simulation prediction, the energy saving possibility is found to be very low from these operations.

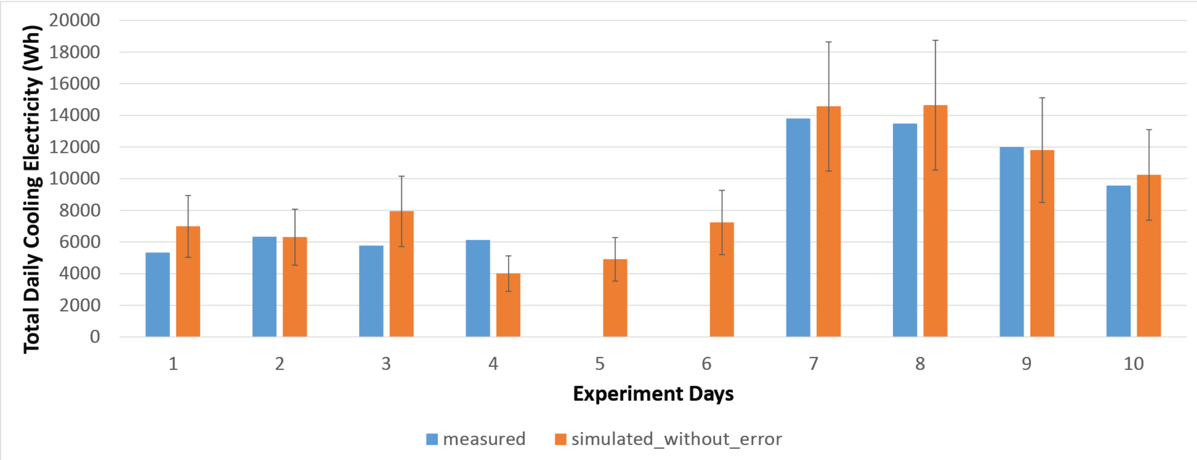

Figure 8: Comparison between Simulation and Measurement Results with NMBE and CVRMSE of the Trained Model

On experiment Day #2 (Fig. 2), the researcher utilized natural ventilation in the morning when outside humidity was between 60% to 80%. The highly humid air stayed in the house until AC was turned on around noon to start cooling both the dry air and moisture from a condition of 24.7ºC/62% RH to 21.2ºC/53% RH. During the AC cooling period, a hot water shower was taken in the house and added extra heat and moisture to the cooling load.

Before 11am on Day #9 (Fig. 6), the AC was turned off and windows were opened to bring in the exterior air around 22.8ºC/ 70% RH. The log reports from the previous night till morning natural ventilation bringing a very humid and uncomfortable environment inside (outdoor RH above 80% and indoor RH between 50%-60%). And thus when the indoor air temperature rose to 26ºC and the researcher started AC around 11am, a lot of extra energy need to spend on cooling down the humid warm air.

The most successful cases which have high possibility of energy savings are on day #1, 3, 5, 6. On Day #1 although the RH was high as well, there was a sudden outdoor air temperature drop to about 20ºC around 3pm (Fig. 2), and AC load was immediately decreased at that time. In addition, nobody was showering when AC was on.

On experiment Day #3 (Fig. 3), although the humid air was brought in through natural ventilation, both the indoor and outdoor air temperature was below cooling set point when windows were open. The air humidity adds thermal mass to slow the speed of indoor air temperature increase. On Day #5 and #6 (Fig. 4) the AC was not turned on at all and the researcher managed to keep the condition within comfort range during the whole experiment #3.

Comparing different operation strategies together, it appears that the energy savings impact of shading and sunspace configuration is not as obvious as natural ventilation. On experiment Day #7, #8 and #10 (Fig. 5 and 6), when AC system was constantly on without natural ventilation, operations of changing the shading and sunspace opening configuration result in a possibility of energy savings at about 60%.

Summarizing the results of all experiments suggests that outdoor air humidity should be considered in conjunction with outdoor air temperature and indoor cooling set point to decide when to utilize natural ventilation. During a typical humid summer day when natural ventilation and mechanical cooling might alternate in rapid sequence, natural ventilation should be discontinued before the exterior air temperature reaches the indoor cooling set point to achieve maximum energy savings. If warmer humid air is brought into the house, it's possible, that natural ventilation will result in some energy increase instead of cooling saving.

6 Conclusion and Future Work

Through detailed monitoring of environmental conditions and buildings components, operation strategies are developed for reducing energy costs and maintain human comfort. Metrics of this nature allow for performance benchmarking while also providing direct feedback to users in regards to how their behaviours affect energy usage. Real time data collection and feedback to occupants allows for informed decision making that reduces energy consumption by prompting changes in behaviour before an individual becomes physically uncomfortable. Developing models to better measure and predict these variables leads to improved building interfaces and energy efficient operation strategies for building users.

The understanding of passive operation strategies is improved through this experimental process. For a warm and humid climate, implementing natural ventilation could bring in moisture as well, which results in either cooling energy savings or increases, depending on the relation of the temperature difference between exterior humid air and indoor cooling set point.

The high variability of factors relating to local weather and interior conditions coupled with the effort needed to monitor and operate the building have aided in the understanding of building operation strategies. An use of programmed monitoring and mechanically operated openings could make improvement through removing operation errors caused by occupants, and yielding additional energy saving by allowing for a longer operation period during times of sleep. Implementation of these technological components must be done with additional investigation on the potential energy saving through smart control alongside the extra energy consumed by using a mechanical system for smart control.

Other passive strategies of operating shading and spatial configuration are promising methods to save cooling energy, but for a limited operation length and unstable outdoor weather condition, the result is not as obvious as natural ventilation. To quantify the amount of energy saving by the passive strategies, it is necessary to improve the model accuracy and precision for a better prediction.

Acknowledgement
Special thanks to the Iowa naturalist Hannah Wiltamuth, Jacob Ahee for supporting the experiments at their office; Mike Wassmer from LiveToZero Llc for providing the data collection support and HVAC control interface; Karthik Abbineni for helping filtering measurement data. This material is based upon work supported by the National Science Foundation Grant Number EPSC-1101284. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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Implementation of an experimental setup for the analysis of transient thermal comfort in buildings with dynamic heating operation

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Abstract
Prior research indicated that charging the buildings thermal mass by increasing the heat flow above the current heating demand at given times can be efficiently used as a measure of demand side management (DSM). In combination with electricity driven heating systems such DSM can support matching the heat demand with the growing yet fluctuating renewable electricity generation. For this purpose, the set point temperatures within a building need to be dynamically adjusted resulting in transient non-linear temperature changes. Still, it is crucial to ensure the residents thermal comfort to enable acceptability of the suggested load shifting approach. However, the effects of such non-linear temperature drifts upon the thermal comfort are unknown.
Therefore, this paper presents the implementation of an experimental setup for the analysis of transient thermal comfort in buildings. Therein, a complex building model with a very detailed representation of building physics and heating systems is used to generate realistic thermal boundary conditions (i.e. air- and surface temperatures) for climate chamber experiments. Thus, the proposed setup allows the emulation of different heating systems and the resulting dynamic temperature scenarios with non-linear temperature drifts in a climate chamber. Further, the suggested experimental procedure allows evaluating the influence of different metabolic activity levels and thermal preconditions upon the subject's perception of analysed scenarios.

Keywords: transient thermal comfort, comfort under non-uniform conditions, climate chamber experiment, dynamic temperature control, role of comfort in smart buildings

1 Motivation

In 2015, renewable energies accounted for almost one third of the gross electricity production in Germany (AGEB, 2015). According to the German government, this share of renewable energy generation should be doubled (to approx. 60 %) by 2035 (EEG, 2014). To manage the resulting volatility of such strongly increasing renewable energy generation and to meet the challenge of matching electricity production and demand, consumption flexibility within the electric grid is needed. Residential and commercial buildings, account for up to 30 % of Germany's final energy consumption, with space heating of residential buildings alone representing 18 % of the final energy demand (AGEB, 2015). Therefore, employing electricity powered heating systems (e.g. heat pumps) and managing them through Demand Response (DR) measures can be a suitable and cost-effective source of consumption flexibility in the future (Harb et al., 2014; Müller et al., 2015; Wolisz et al., 2016). Besides of the conventional thermal energy storages and batteries the structural thermal storage capacity of a building can be effectively used to store energy in a building. Thereby, the buildings thermal mass is charged by increasing the heat flow above the current heating demand. Depending on the building and the associated heating system, this allows reducing or even totally eliminating the buildings heating demand for some upcoming hours (Wolisz et. al, 2015a; Reynders 2013 (B&E); Reynders 2015 (BS 2015)). In order to increase the storage capacity of the structural thermal mass of a building (e.g. walls) different dynamic heating operations are performed. Often the set point temperatures within the building are adjusted for this purpose. Thus, a wider permissible set point temperature range with higher and lower set points than under regular building operation is favourable. Still, it is crucial to ensure the resident's thermal comfort to enable acceptability of the suggested load shifting approach. Consequently, temperature boundaries ensuring thermal comfort of occupants under fluctuating thermal conditions resulting from the dynamic heating operation are required. However, the effects of such a discontinuous heating operation upon the thermal comfort are unknown. Moreover, every heat emission system has a different ratio of radiative and convective heat transfer and vastly varying thermal response times. Thus, as of today no clear statements about the resulting thermal perception by the human body can be made. This paper presents the implementation of an experimental setup and the associated approach for the analysis of thermal comfort under transient conditions in buildings with dynamic heating system operation.

2 Literature Review

Thermal comfort is defined as "the condition of mind that expresses satisfaction with the thermal environment" (ASHRAE 55, 2013). Over the last decades, a lot of research for thermal comfort assessment was performed (Fanger, 1970; Mishra et al., 2013; de Dear et al., 2013; Rupp et al., 2015). Generally, two distinct approaches for thermal comfort evaluation are applied. The first method is the PMV-PPD (Predicted Mean Vote - Predicted Percentage of Dissatisfied) approach introduced by Fanger (1970) and the second approach is the adaptive thermal comfort model described in detail by Nicol & Humphreys (1998; 2002). The PMV-PPD approach is based on a steady-state heat balance model of the human body incorporating personal physiological parameters (e.g. metabolisms, clothing) and environmental parameters such as air temperature, relative humidity, mean radiant temperature and air velocity.

The PMV index is deployed to predict the mean thermal sensation of a large group of persons, while the PPD index gives a prediction of the percentage of people that are dissatisfied with the thermal environment (ASHRAE 55, 2013). In contrast to the PMV-PPD heat balance model, the adaptive thermal comfort approach takes into account the ability of people to interact with their thermal environment in such ways that they can restore their thermal comfort when discomfort occurs.

In addition to the PMV-PPD model, the adaptive comfort model also considers non-physiological aspects such as behavioural adjustments (e.g. opening windows, the use of fans) and psychological expectations (Brager and de Dear, 1998). Thus, occupants are regarded as active users in the thermal environment as opposed to a passive role within the PMV-PPD model. PMV and PPD indices were the basis for the widely used international standards ISO 7730 (2005) and ASHRAE 55 (2013) to evaluate thermal comfort. The adaptive model is included in the ASHRAE standard 55 (2013) and in the DIN EN 15251 (2007) as an optional method for assessing thermal comfort in naturally ventilated buildings. These standards are mainly applied for steady-state and uniform thermal environments and even though there are studies stating that PMV indicates plausible results also under transient non-uniform conditions (Kolarik et al., 2007), this is not the broad consensus (Zhang et al., 2008).

In the past, the vast majority of studies on human thermal comfort have been carried out under steady and uniform conditions, yet there has been an increasing number of studies regarding non-uniform and dynamic conditions over the last twenty years (Hensen, 1990; de Dear, 2013). Recommendations for operative temperature drifts or ramps can be found in the standards ISO 7730 and ASHRAE 55. It is suggested that the temperature should not change more than 2 K (ISO 7730) respectively 2.2 K (ASHRAE 55) during a one-hour period. Furthermore, the standard EN 15251 suggests maximum operative temperature ranges from 18 °C to 25 °C for winter conditions. Kolarik and Toftum (2009, 2010) investigated the influence of increasing and decreasing moderate temperature ramps on thermal comfort under experimental winter conditions using climate chambers. Temperature scopes were from 17.8 to 25 °C with ramps of 0.6 and 1.2 K/h and exposure times between 4 and 8 hours. The total number of recruited subjects ranged from 25 to 29, consisting of female and male college students aged between 20 and 27 years. Subjects were exposed to different experimental winter conditions for up to 3 times over successive weeks; during experiments standardized office tasks were carried out. In contrast to the experiments by Kolarik et al. (2009), subjects within the experiments of Toftum et al. (2010) were allowed to adapt their clothing insulation during the experiments. However, no difference in thermal responses was observed between the experiments with fixed or adjustable clothing insulation. Moreover, slow temperature drifts of 0.6 K/h showed no significant influence on thermal comfort as in agreement with previous studies (Hensen, 1990). A similar study was performed by Schellen et al. (2010) who analysed the differences between young adults and elderly in thermal comfort sensation in response to moderate temperature ramps. Eight young male adults (age 22-25) and eight older male adults (age 67-73) were exposed to a temperature drift from 17 to 25 °C and back to 17 °C with a temperature gradient of 2 K/h over the course of 8 hours. Subjects wore standardized clothing (1.0 clo) and also had to perform office tasks. Experiments indicated that the thermal sensation of the elderly was 0.5 scale points lower on the 7-point thermal sensation rating scale (ISO 7730) in comparison with their younger counterparts.

A variety of other studies addressed step changes as transient thermal condition. Most of the studies were performed in climate chambers with focus on summer conditions, thus step changes under steady conditions from hot to neutral temperatures and vice versa (i.e. air conditioned rooms or buildings) (Liu et al., 2013).

Only a small minority of the studies had their focus on step changes under winter conditions from cold to neutral temperatures, as for instance entering or leaving a building. Du et al. (2014) examined temperature step-changes from cool to neutral and back to cool. The neutral temperature was 22 °C and the cool temperatures were 12, 15 and 17 °C. For their experimental setup two differently conditioned climate chambers with constant temperatures were used. Subjects were 30 minutes in the cold environment before moving to the neutral environment for 60 minutes. Subsequently, returning to the cold environment for another 30 minutes. Twenty subjects (10 female and 10 male) aged between 20 and 30 years took part in the experiments. Uniform clothing (1.17 clo) was worn and only sedentary activities like reading or resting were performed.

However, none of the studies found, involved scenarios where occupants entered a room from a natural or cold environment to be faced with unusually warm or cold conditions, which are corrected towards the comfort temperature at a natural rate resulting from building physics. Moreover, only linear temperature drifts were used in the climate chamber experiments with temperature ranges according to the international standards. However, such drifts do not represent the changes of indoor temperatures when heating systems are turned on or off. Especially, the conditions resulting from thermal demand response can lead potentially to strong and non-linear changes of air and operative temperature, possibly even directly related to a large step change of temperature if assuming the residents are just arriving at home. Thus, even though there are quite a number of studies analysing comfort in face of step changes or transient temperature changes, none of them have evaluated the realistic non-linear thermal conditions resulting from the reaction of building physics upon extreme interactions with a realistic domestic heating system.

This paper will describe the implementation of an experimental setup for the analysis of transient thermal comfort in buildings. The proposed setup will allow the evaluation of different thermal scenarios of dynamic temperature control with a wide range of temperature set points, non-linear temperature drifts and diverse heating systems. For that purpose, a complex building model, developed in Dymola/ Modelica (Modelica Association et al., 2015), is used to generate dynamic non-linear heating and cooling curves as boundary conditions for a climate chamber. The goal of the following experiments with subjects will be the determination of advisable transient thermal comfort conditions for dynamic heating operations.

3 Approach

3.1 Concept

Climate chamber experiments with dynamic heating operations will be conducted and evaluated based on the feedback of a possibly diverse group of subjects, which are not familiar with the concept of dynamic heating. A complex building model with a very high granularity for representation of building physics and heat transfer methods is used to generate realistic thermal boundary conditions for the climate chamber experiments, ensuring consistence with the physical thermal behaviour of a building under dynamic heating operations.

Besides of multiple experimental scenarios with varying profiles for the operative temperature set points also different activity rates of subjects will be examined. Thermal comfort assessment is based on a questionnaire, which will be completed periodically by the subjects. Furthermore, physical and physiological measurements will be performed for that purpose. The obtained data will be analysed by statistical methods to deduce the temperature boundary conditions for dynamic heating operations to be used in future building management systems.

3.2 Simulation

A climate chamber typically represents a single room where a defined thermal environment can be created by heating or cooling and regulating the room air conditions (e.g. air exchange and humidity). However, when intending to incorporate the dynamic thermal behaviour of structural components of an entire building as well as heat flows from the outside environment such as solar radiation, and accordingly their effects on a single room inside a building, the capabilities of a classical climate chamber is stretched to its limits.

Therefore, a more sophisticated chamber with detailed control of all surface temperatures is required. To generate the inputs for that chamber a complex building model taking into account the surrounding environment, structural components and physical properties is developed within the modelling and simulation environment Dymola in the modelling language Modelica. The developed model builds upon the HouseModels Library which is part of AixLib Library which is made publically available by the Institute for Energy Efficient Buildings and Indoor Climate (Fuchs et al., 2015). The HouseModels Library was validated with several test cases, for example with the case 600 of the ASHARE Standard 140. Thereby, the model produced all required outputs within the minimum and maximum specified ranges (Constantin et al., 2014).

The building model consists of several layers. The top layer defines the outer environment, with the boundary conditions that impinge on the envelop of the building such as the outside air temperature, the soil temperature, the wind velocity and the solar radiation. Since the concept of dynamic heating is generally applicable in winter, these environmental values are set to static average German winter conditions according to the test reference year (TRY) (BBSR, 2011). The building itself has supply layers consisting of a heating system, an air-handling unit and the building physics layer being composed of multiple rooms that are aggregated to individual stories and a roof. A room consists of an air volume, its space-enclosing structural components and thermal structures representing the furniture and floor covering within a room. The room’s furnishing is described in a simplified way by thermal capacities with properties of wood and metal, accounting for the assumed thermal mass and surface area of these materials in a given room (Wolisz et al., 2015b). The floor covering is integrated as an additional layer upon the floor with generic material properties representing a typical floor-heating suitable material. The space-enclosing structural components can be distinguished in heat storing components like walls, ceilings and floor-slabs and non-storing components such as windows and doors. The structural elements are described through their geometry and their physical characteristics such as heat capacity and heat transfer coefficient (U-value) dependent on the chosen construction materials. Those values are taken from the German Energy Saving Ordinance 2009, since this building standard represents a large share of the modern German building stock constructed or retrofitted between 2009 and 2016 (BMWi, 2013).

A distinctive feature of the used building model is its granularity. The heat storing structural components (e.g. walls) are also composed of multiple layers (i.e. insulation, concrete, steel etc.) and even these layers are further fragmented into few millimetre thick sub-layers.

Such an accurate building physics representation allows detailed insight into the thermal behaviour and heat distribution within the structural elements, enabling precise description and evaluation of the current condition of each individual building layer. In this study, the precision of the model enables us to extract the precise surface temperatures of walls, floors and ceilings required as boundary conditions of the climate chamber.

Further, each structural component is connected to all adjoining rooms or the outer environment via heat and mass flows as well as radiation, depending on the individual components properties. Thus, these thermal connections describe the underlying physical heat transfer equations and the resulting thermal flows of the building. The mass flow connectors characterize the physical interaction of the air volumes within the house, determined by an air exchange rate. Heat and mass flows from the heating system are either connected directly to the affected layers of the structural elements (i.e. floor heating, concrete core activation) or to the convective and radiative energy exchange within the room (i.e. radiators). Having simulated these surface and air temperatures and the resulting operative temperature for any chosen room, it is possible to transfer dynamic profiles for all thermal boundary conditions resulting from the complex thermal behaviour of the building to our climate chamber. Consequently, also the non-linear thermal conditions resulting from dynamic heating operations can be precisely emulated in the climate chamber.

3.3 Scenarios

The following scenarios addresses possible dynamic heating operations, which can be performed in Central-European winter climate conditions. Four main scenarios S1 to S4 with different thermal profiles are defined and will be performed and evaluated with test subjects in the climate chamber. The first two scenarios S1 and S2 cover the case that occupants are returning home in winter, while the heating system is either charging or discharging the thermal mass of the building. In both cases the heating system will react immediately after detecting the occupancy change seeking to reach the defined neutral comfort temperature as quickly as possible.

The main research question in scenario S1 is the maximum operative temperature that is still acceptable without comfort loss for a homecoming person taking into account the corresponding natural cool-down gradient towards the neutral temperature. Exactly the opposed research question is the focus of the scenario S2. Here, it is to be found which lowest operative temperature is acceptable for an occupant returning home in winter, again taking into account the associated fastest possible heat-up towards the neutral temperature resulting from building physics and the evaluated heating system.

Additionally, it will be analysed if the thermal condition in the building is perceived differently depending on the way the occupants return to the building. In particular, the metabolic activity and the thermal conditions while returning home might affect the thermal sensation. Therefore, the subjects will be preconditioned before entering the climate chamber in two different ways representing exemplary people returning home by feet, as a high activity level, and residents coming home by car, as low activity level. Accordingly, it will be also evaluated if the activity level of the residents after returning home has an impact upon the perception of the thermal conditions within the building.

Therefore, again two different tasks for the subjects are defined, representing exemplary for the low activity level occupants resting on the couch (e.g. reading or watching TV) and for the high activity level occupants performing housework (e.g. cooking or cleaning). This results in four possible constellations of metabolic activity for scenarios S1 and S2 (high → high, high → low, low → high, low → low).

The third and fourth scenario (S3 and S4) cover the cases that occupants are at home in winter while the heating system begins either charging or discharging the thermal mass of the building. In these cases, the main research question is the maximum, respectively minimum operative temperature that can be reached without compromising the comfort of the occupants when starting charging/ discharging at a neutral temperature and taking into account the corresponding natural heating/ cool-down gradients within a 2.5-hour period. Thus in these scenarios the subjects will enter the climate chamber directly and instead of the preconditioning there will be a phase of acclimatization to the natural condition before any temperature changes. As in scenarios S1 and S2, the subjects will perform differentiated tasks in order to represent different activity levels at home.

Table 3.1: Overview of all scenarios and sub-scenarios

Heating Scenario		Phase 1	Phase 2	Sub-Scenarios
S1	**residents are**	not at home	at home	two different activity levels before and two after occupancy change
	subjects in	preconditioning	climate chamber	
	heating system	on	off	radiators (comparison with floor heating/ radiative panels possible)
	temperature	increased	decreasing	starting temperature and resulting temperature gradient
S2	**residents are**	not at home	at home	two different activity levels before and two after occupancy change
	subjects in	preconditioning	climate chamber	
	heating system	off	on	radiators (comparison with floor heating/ radiative panels possible)
	temperature	decreased	increasing	starting temperature and resulting temperature gradient
S3	**residents are**	at home	at home	two different activity levels
	subjects in	climate chamber	climate chamber	
	heating system	on	on	radiators (comparison with floor heating/ radiative panels possible)
	temperature	neutral	increasing	end temperature and resulting temperature gradient
S4	**residents are**	at home	at home	two different activity levels
	subjects in			
	heating system	on	off	-
	temperature	neutral	decreasing	end temperature and resulting temperature gradient
$S0_{1/2}$	**residents are**	not at home	at home	two different activity levels before and two after occupancy change
$S0_{1/2}$	**subjects in**	preconditioning	climate chamber	
$S0_{3/4}$	**residents are**	at home	at home	two different activity levels
$S0_{3/4}$	**subjects in**	climate chamber	climate chamber	
S0	**heating system**	on	on	radiators (comparison with floor heating/ radiative panels possible)
	temperature	neutral	neutral	-

For the scenarios, involving a heating system (all besides S4) the boundary conditions of the climate chamber as well as the heating behaviour will be evaluated assuming a radiator-based heating system in the first place. Radiators are chosen since this is by far the most common heating system and the system with the most critical impact upon the air and the operative temperature when performing dynamic heating operations (Wolisz et al., 2016). Nevertheless, the climate chamber is capable of emulating also floor heating and radiative wall or ceiling mounted panels. Therefore, some scenarios will be repeated with boundary conditions resulting from other heating systems to take into account the different temperature gradients and the different shares of convective/ radiative heat transfer of these systems. This will allow complementing the results with a sensitivity analysis concerning the choice of the heating system.

Finally, two reference scenario $S0_{1/2}$ and $S0_{3/4}$ will be performed. In these cases, the subjects will be either preconditioned (as in S1 and S2) or directly brought into the climate chamber (as in S3 and S4) also performing different activities, however they will be exposed constantly to the neutral temperature in the climate chamber. This is required to have a benchmark for the comfort perception in our test environment and can also be used to compensate effects like the changing comfort perception over time (compare Toftum et al., 2010). Table 3.1 presents all planed scenarios and sub-scenario for this analysis.

3.4 Subjects

A possibly equally distributed group of female and male subjects in different age groups would be the most favourable composition for the experiments. However, often experiments performed at technical universities are confronted with a majority of available subjects being male college students between 20 and 30 years of age. Especially if a high number of subjects is required and equal distribution between genders and age groups becomes hard to realize. Still, past studies have shown that the differences in comfort perception between young, elderly, male and female subjects is rather limited within the observed temperature range close to the natural temperature (Fanger, 1970; Collins et al., 1980; Schellen et al. (2010); Karjalainen, 2012). Also, the results of these studies allow to consider the indicated offsets between the types of subjects in the evaluation. Nevertheless, at least some scenarios will be performed with representative groups of young, elderly, male and female subjects, thus allowing to get some additional insight on the sensitivity of subject groups upon outcomes in this study.

Subjects should not be familiar with the concept of dynamic heating in buildings, should have no expectations about the thermal conditions they will be exposed to und should not talk with other subjects about the faced thermal conditions and the resulting comfort perception. Therefore, subjects will get only very basic information about the experiment and can participate only once. As in reality the subjects will have freedom of choosing the clothing, as well in the precondition phase as in the climate chamber. Therefore, the subjects will be asked to bring all personal clothing they would normally wear in winter conditions outside and at home. Some additional clothing for personal comfort (e.g. slippers, blanket etc.) will be available in the climate chamber. Moreover, the subjects will be asked to avoid intense physical activity (i.e. strenuous exercise), excessive eating or drinking (especially caffeine, alcohol, very hot or cold meals or beverages) within few hours before the experiment to ensure validity of experimental data. Further, subjects should be generally healthy and not take any medications, which might alter cardiovascular or thermoregulatory responses to temperature changes (Schellen et al., 2010). Subjects will receive a financial compensation for participating in this study, which is fixed and not correlated in any manner with their responses.

3.5 Questionnaire

An online-based questionnaire will be used for the experiments. During the preconditioning phase (S1/ S2) or the acclimatization phase (S3/ S4) the subjects will be introduced to questionnaire and asked to insert some basic personal characteristics such as their gender, age, height and weight. Furthermore, subjects have to specify the clothing they are wearing. For this purpose, subjects can mark multiple clothing items that are listed in the form. Afterwards, the subjects will be asked regularly to complete the online-based questionnaire including a seven-point thermal sensation scale, a six-point thermal comfort scale, a five-point thermal preference scale and a two-point thermal acceptability scale according to DIN EN ISO 10551 (2002). Additionally, at the beginning of every questioning the subjects are asked to measure their heart frequency with a finger attachable heart rate monitor and indicate the measured value in the questionnaire. Finally, the subjects have to state whether they changed their clothing since the last answered questionnaire and if this is the case, they have to mark which clothing items they changed.

The questionnaire will be repeated approx. every 15-20 minutes during the total experiment. In the final questionnaire at the end of the experiment subjects are going to further evaluate the thermal sensation, comfort, preference and acceptability over the entire period of the experiment as well as the air quality and their subjective well-being. Also, subjects will be confronted with the concept of dynamic heating and asked for their emotions towards such a heating operation based upon their experience. Finally, the subjects will answer some generic questions, which are not related with the experiment at all to analyse whether the thermal conditions and the potential discomfort they were exposed to impacts the general attitude of the subjects.

4 Experimental Setup

4.1 Climate chamber design

The experiments will be carried out in a climate chamber with 16 m² floor space and 48 m³ air volume (4 m x 4 m x 3 m, L x W x H) which is located at the test facility of the E.ON Energy Research Center at the RWTH Aachen University. Each wall of the climate chamber including the floor and ceiling consists of four metal sheet coated polyurethane hard foam segments with integrated capillary tube mats. The temperature of every lateral surface can be individually controlled via a software user interface. Further, this software can integrate dynamic temperature profiles for each surface and log all surface temperatures as well as up to 34 additional temperature measurements. Moreover, a powerful air-handling unit provides the room with the required air temperature and ventilation flow rate. A schematic drawing and a real picture of the climate chamber is given in figure 4.1.

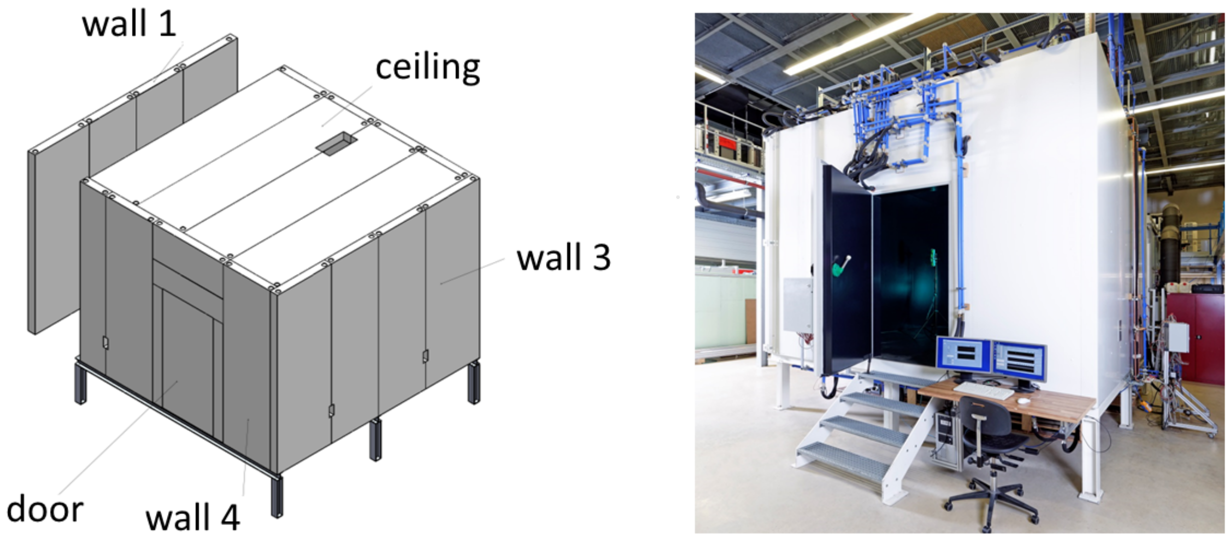

Figure 4.1: Schematic and real depiction of the climate chamber

In this analysis, the climate chamber represents the thermal conditions in a ground floor room with two outer walls and two inner walls situated in a two story single family house, as given in figure 4.2 on the left. In this experimental setup, the climate chamber will be equipped with residential furniture (a sofa, a coffee table, a desk, two chairs and shelfs), as well as a carpet and wall cladding with similar properties to a typical wallpaper. In this way, the interior should create a natural atmosphere reducing the subject's awareness of being in a climate chamber.

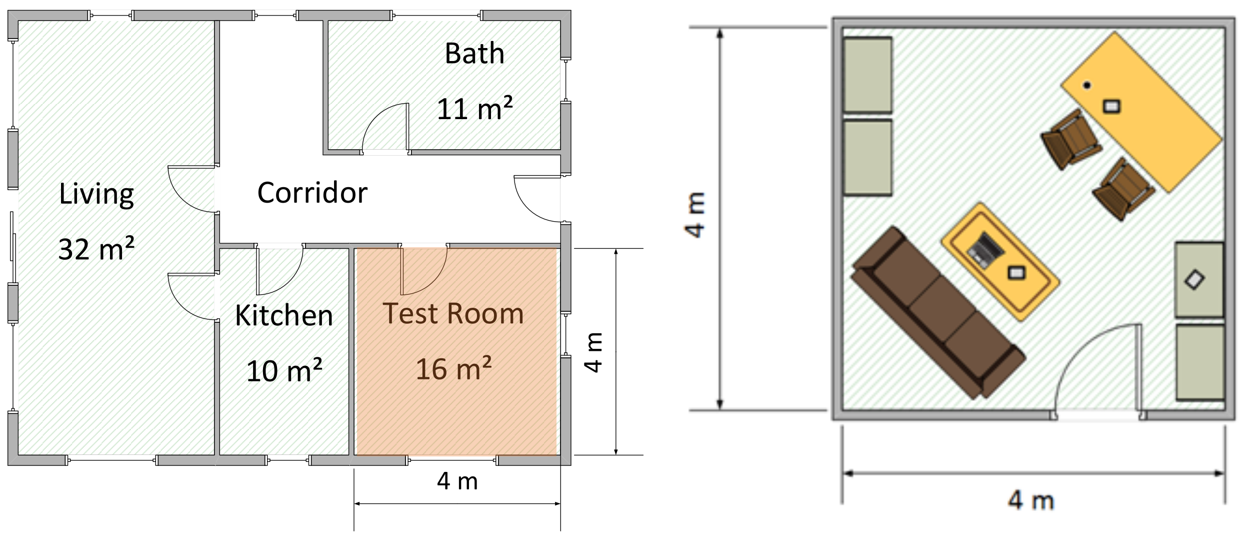

Figure 4.2: Location of the analysed room in the simulated building (left); layout of the implemented room in the climate chamber (right)

The internal layout of the climate chamber is depicted in figure 4.2 on the right. Preconditioning of the subjects is performed in two additional climate chambers. A small one, with very precise wall and air temperature control is equipped with car seats and will be operated in a way representing the thermal conditions of the residents driving home in winter climate (figure 4.3 on the left). The second preconditioning chamber is an air-cooled container placed outside of the building and controlled to keep the air temperature between 1 and 3 °C (figure 4.3 on the right). This container is equipped with two step-machines enabling the subjects to emulate walking home in cold winter conditions independently of the real ambient conditions.

Figure 4.3: The climate chambers used for preconditioning, driving home (left) walking home (right)

4.2 Measurements

Besides of the subjective classifications regarding the thermal comfort, which are obtained through the questionnaire, additional physiological and physical measurements are performed. The metabolic rates of each subject will be determined according to DIN EN ISO 8996 (2005) based on the measured heart rates and the age of the subjects indicated within the questionnaire. The clothing insulation (i.e. heat resistance) that subjects are wearing will be ascertained according to DIN EN ISO 9920 (2009). Furthermore, it is intended to measure body and skin temperatures of the subjects in some selected scenarios. Monitoring the thermal conditions in the climate chamber is based on resistance thermometers being used to continuously measure surface, air and operative temperatures in the climate chamber. To capture the vertical distribution of the air temperature in the climate chamber, it is measured at the heights of 10, 60, 110 and 170 cm at four different positions in the chamber (DIN EN ISO 7726, 2002). The operative temperature will be measured at the height of 170 cm at five positions in the climate chamber. Surface temperatures will be measured at two points on each wall, the floor and the ceiling. Air humidity and CO_2 concentration is continuously measured in the climate chamber and both preconditioning rooms. Furthermore, air exchange (i.e. ventilation) will be constantly measured and controlled in the test chamber.

4.3 Experimental implementation

Once the subjects arrive, they will receive a general introduction regarding the experimental procedure and the use of the questionnaire. All subjects will be provided with a heart rate monitor, tablet computer for the questionnaire and a randomly selected coloured card describing their activity levels in the experiment. If subjects should not feel comfortable with the electronic questionnaire a paper-based version can be provided as well. Every tablet or paper-based questionnaire will be also marked with the coloured label that represents one of the four activity scenarios. According to the assigned activity level for S1 and S2, two subjects will take a seat for approx. 15-20 minutes in the climate chamber simulating the conditions of driving home by car. Simultaneously, the other two subjects will be walking on the step machine in the air-cooled container to simulate walking home. After the preconditioning, all four subjects will go directly into the climate chamber for 150 minutes. In S3 and S4 the subjects will enter the main climate chamber directly after the introduction to the experiment and stay there for 180 minutes. To ensure good air quality in the climate chamber a fresh air flow of approx. 50-60 m^3/h and an possibly imperceptible air speed of less than 0.15 m/s will be supplied to the climate chamber at temperatures resulting from the simulation. Subjects of all scenarios will perform different activities within the climate chamber according to their coloured activity scenario cards. Hence, two subjects will follow sedentary activities on the couch, while the other two subjects will execute activities representing light housework or cooking. An acoustic signal will signalize regularly the time to answer the questionnaire. The whole experiment will be supervised and controlled from outside the climate chamber using the control software and if necessary allowing interaction with the subjects through a camera, a microphone and speaker inside the chamber.

As soon as the experiment starts, subjects are expected not to leave the climate chamber, unless any special circumstances occur. For all scenarios the neutral operative temperature in the room will be 21 °C. In the reference scenarios S0 this will be the temperature that is maintained constantly in the climate chamber. Based on the performed dynamic buildings simulations the possible operative starting temperatures for scenario S1 will be in range of 23 to 27 °C and 15 to 19 °C for scenario S2. For scenario S3 and S4 the starting point of the operative temperature is the neutral temperature of 21 °C and the possible end temperatures range between 23 to 25 °C for S3 and 19 to 20 °C in S4. The temperature gradients of the operative temperatures are determined by the thermal building physics and the underlying heating supply system modelled within the simulation. Thus assuming practicable operation schemes for the dynamic heating this gradient is the limiting factor for the operative temperatures which can be reached. Table 4.1 summarizes the possible temperature ranges for this analysis, while in figure 4.4 an exemplary outcome of the simulation for scenario S1 is given indicating the resulting temperature gradients that will be reproduced in the climate chamber.

Table 4.1: Operative temperature ranges which can be analysed in the scenarios

Heating Scenario	Starting Temperature in °C	End Temperature in °C	Direction of temperature change	Exposure Time in h
S1	23 - 27	21	decreasing	2.5
S2	15 - 19	21	increasing	2.5
S3	21	23 - 25	increasing	2.5
S4	21	19 - 20	decreasing	2.5
S0	21	21	constant	2.5

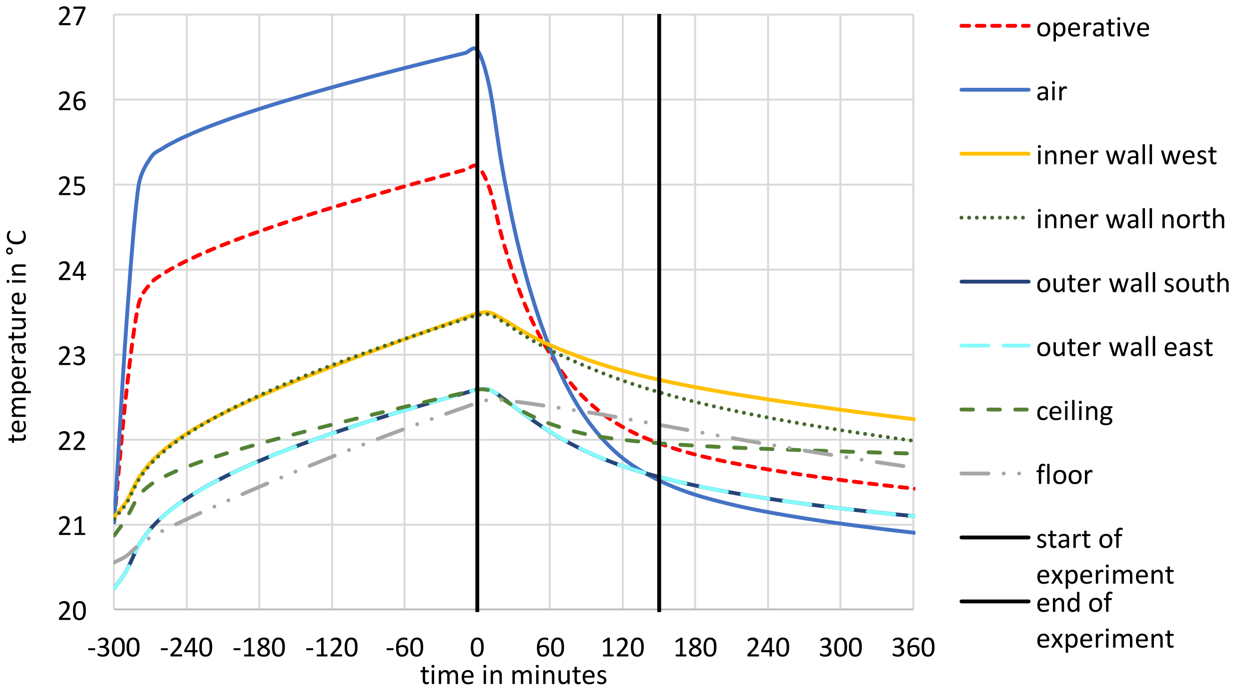

Figure 4.4: Exemplary input temperature profiles for the climate chamber, simulated for scenario S1

5 Next steps

The outcomes of the very high number of scenarios and sub-scenarios suggested in this approach have the potential to draw a clear picture about the impact of dynamic temperature control in residential buildings upon thermal comfort. However, if all possible scenarios have to be performed with a significant number of subjects the required total subject number could easily exceed 1000 and the required testing time and required budget would become prohibitive. Therefore, experiments will not be performed in a strict order but all scenarios will be tested with a limited number of subjects and test cases indicating high consistency in subjects comfort perception will be continued with a significant number of subjects. Furthermore, it will be evaluated if the different activity schemes before and after the occupancy change have a significant impact upon thermal comfort perception. In case that this hypothesis would be rejected at an early stage, these sub-scenarios would not be further evaluated. Generally it will be observed whether the subjects comfort perception in different repetitions of one experimental setup is consistent (e.g. Friedman Test or similar). Further, the outcomes of similar scenarios with different thermal profiles will be evaluated to detect significant differences (e.g. Kruskal-Wallis Test, Mann-Whitney U Test or similar). Similarly, it will be tested if there are significant differences in comfort perception as compared to the reference scenarios. Further analysis will be performed for some selected scenarios, which will be used for sensitivity analysis taking into account specifically controlled groups of subjects (i.e. age and gender) and alternative heating methods.

Once the evaluation is completed, it is intended to include the found outcomes into a building management software that is being developed at the E.ON Energy Research Center. This model predictive software performs an optimisation of the dynamic heating schedule in a building with respect to the required thermal energy, the costs of that energy and the thermal comfort. The developed control algorithm will adapt in a self-learning manner to the building physics dependant thermal behaviour of any building. The results of this analysis should improve the potential and quality of the algorithm by further specifying the operative temperature boundaries which can be exploited by the algorithm dynamically with respect to the different conditions being tested in the experimental scenarios.

Furthermore the results will be integrated into the 33 node comfort model (33 NCM) developed at the E.ON Energy Research Center (Streblow, 2010). So far the model development is based on own static experimental data and a further validation with data from literature with limited data on dynamic thermal comfort evaluation as summarized in the literature review (Ogata et al. 2015). With this new experimental data the model will be extended in its usability under dynamic thermal boundary conditions and can be used for the evaluation of further heating concepts. This new data has the unique advantage of very well defined boundary conditions combined with the logging of physiological and psychological human evaluation.

Acknowledgments

The authors gratefully acknowledge that the presented experimental approach was developed in cooperation with Masayuki Ogata from the Department of Architecture at the Waseda University, Tokio, Japan, chaired by Prof. Shin-Ichi Tanabe.

Grateful acknowledgement is also made for the financial support by the German Institute for Economic Research (DIW) and the European Union's Horizon 2020 research and innovation programme (grant agreement No. 646116).

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SESSION 6

Comfort and Climate

Invited Chairs: Philomena Bluyssen and Jens Pfafferot

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
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A comparative winter study on thermal comfort in several climate regions in China

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Abstract
The article introduces a comparative winter thermal comfort field study in four cities representing different climate zones in China, which are Harbin for SC (Severe Cold), Beijing for C (Cold), and Shanghai for HSCW (Hot Summer & Cold Winter) zones. Measurements of environment parameters and subjective investigations using questionnaires were conducted in teaching buildings on campus. Totally 740 valid questionnaires were collected for analysis. Due to the huge difference of outdoor temperatures and the different conditions of indoor space heating between climatic zones, several distinctive features were found. Although it was warmer outdoors, the indoor temperature in Shanghai was much lower than Harbin and Beijing, due to the lack of space heating. The clothing level of Shanghai occupants was similar to Harbin and lower than Beijing. When the indoor environment was colder than neutral, the mean TSV values in Shanghai were higher than Beijing, revealing people in Shanghai had better adaptation to cold environment. Results show the indoor temperature in Harbin was sometimes overheated, and people in Harbin had been used to the warm environment during winter.

Keywords: thermal comfort; thermal adaptation; winter; space heating; over-heating

Nomenclature

t_a	air temperature
RH	relative humidity
t_g	globe temperature
v_a	air velocity
$\overline{t_r}$	mean radiant temperature
t_{op}	operative temperature
I_{cl}	clothing insulation
$t_{out,d}$	daily mean outdoor temperature
t_n	neutral temperature
t_c	comfort temperature
TSV	Thermal sensation vote
PMV	predicted mean vote
PPD	predicted percentage of dissatisfied
HVAC	heating, ventilating, and air conditioning

1 Introduction

Indoor thermal comfort in cold climates is an important topic, since it determines how much heating people need indoors, which further relates with issues such as energy consumption and air pollution nowadays. In China, due to the different climate features between climate zones, the situations for winter are complicated. According to the national standard *Thermal Design Code for Civil Building (MOHURD, 1993)*, five climate zones are defined as Severe Cold (SC), Cold (C), Hot Summer & Cold Winter (HSCW), Hot Summer & Warm Winter (HSWW), and Mild (M) zones. Despite the M zone, all the other four zones have obvious temperature variations during the year. Temperature differences between climate zones in winter are much more significant than they are in summer. In the hottest month (July), temperature in HSWW is no more than 10^{o}C higher than it is in SC. However in the coldest month (January), SC is nearly 35^{o}C colder than HSWW.

Having the huge outdoor temperature difference between climate zones, the existence of difference between space heating modes makes the issue more complicated. Among these climate zones, only urban buildings in SC and C zones have district heating. A few people in the HSCW, HSWW, and M zones might use individual heating devices, although in fact they are not widely and continuously utilized. Regarding both the outdoor and indoor differences, it is worthy to know: Are the zones in the north “really colder” than those in the south? And, how do the local people evaluate their indoor thermal comfort in winter?

2 Methodology

2.1 Time and place

The study was conducted in three cities, which are Harbin (SC), Beijing (C), and Shanghai (HSCW). Field studies were taken place from December to February. The target buildings were all teaching buildings on campus. During the study period, buildings in Shanghai weren’t supplied with space heating, while in Harbin and Beijing they had district space heating indoors. The district heating did not have terminal control, which means the occupants were not able to adjust the indoor temperature by themselves.

2.2 Instruments and questionnaire

The field measurements were conducted once a week. Multiple instruments were involved, including AM-101 PMV and PPD indices meter, WSZY-1A Self-recording thermometer & hygrometer, FB-1 Self-recording anemometer, and HWZY-1 Self-recording globe thermometer. The AM-101 PMV and PPD indices meter, which was used in the Beijing study, recorded t_a, $\overline{t_r}$, RH and v_a. In Harbin and Shanghai investigations, the WSZY-1A, FB-1 and HWZY-1 were used as a combination. The measuring range and accuracy of the above instruments is shown in Table 1. During field measurements, the sensors were placed no more than 1m far from the occupants, and at a height of 0.6m from the floor.

Table 1. Measuring range and accuracy of the instruments used in this study

Instrument	Variables	Range	Accuracy
AM-101 PMV and PPD indices meter	t_a	15~35°C	±0.5°C
	t_g	15~35°C	±0.5°C
	$\overline{t_r}$	15~35°C	±0.5°C
	RH	20~80%	±3%
	v_a	0~1m/s	±0.1m/s
		1~5m/s	±0.5m/s
WSZY-1A Self-recording thermometer & hygrometer	t_a	-40~100°C	±0.5°C
	RH	0~100%	±3%
FB-1 Self-recording anemometer	v_a	0~10m/s	≤ ±5% of measured value
HWZY-1 Self-recording globe thermometer	t_g	-50~100°C	±0.4°C

1. Please choose the clothes you are currently wearing:

Coats or jackets: ☐down jacket/coat; ☐cotton-lined jacket/coat; ☐windbreaker; ☐athletic jacket; ☐suit jacket;

Upper clothes: ☐sweater; ☐wool vest; ☐undershirt; ☐long-sleeved shirt; ☐short-sleeved shirt;

Lower clothes: ☐long pants; ☐wool trousers; ☐sweat pants; ☐cotton-padded trousers; ☐long underwear; ☐shorts; ☐skirt; ☐dress;

Shoes and socks: ☐socks; ☐stockings; ☐shoes; ☐cotton slippers; ☐sandals;

Others: ☐please specify:___________

2. Your current thermal sensation is:

cold cool slightly cool neutral slightly warm warm hot

-3 -2 -1 0 +1 +2 +3

3. You want the indoor temperature to be:

-1 lower 0 maintained +1 higher

4. Is the current indoor thermal environment acceptable?

Unacceptable Just unacceptable Just acceptable Acceptable

-1 -0 +0 +1

Fig. 1. Questionnaire used in this study

The environment parameters were being recorded when people in the classrooms were doing individual studies or having a break between classes. Meanwhile, those occupants were investigated by using questionnaires. In this study, we mainly asked the occupants about their clothes they were wearing, and their thermal sensation, thermal preference, and thermal acceptance (Fig. 1).

2.3 Investigated occupants

The gender and age distributions of the investigated occupants are shown in Table 2. There are totally 740 valid feedback questionnaires, which show the amounts of males and females are not discrepant much from each other. The mean ages of Harbin, Beijing and Shanghai occupants were close to 21.5. All the participants in the investigations had lived in their cities for at least one year, thus they could be considered to have adapted to the local climates well.

Table 2. Distributions of gender and age of the investigated occupants

	Amount of occupants		Age		
	Males	Females	Min.	Max.	Mean
Harbin	101	105	20	23	21.2
Beijing	155	149	17	37	21.3
Shanghai	111	119	18	23	21.7

3 Results

3.1 Environment parameters

The distributions of indoor and outdoor environment parameters are shown in Table 3 and Table 4. In Beijing, the t_a, $\overline{t_r}$, RH and v_a were all measured by instruments. In Harbin and Shanghai, $\overline{t_r}$ was calculated by using t_a, t_g and v_a according to *ISO 7726* (ISO, 1998). The t_{op} in Harbin, Beijing and Shanghai was simplified as an average value of t_a and $\overline{t_r}$ according to the conditions introduced in *ASHRAE Standard 55* (ASHRAE, 2013).

Table 3. The variation of the measured indoor environment parameters in the three cities

Environment parameters	Harbin			Beijing			Shanghai		
	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
t_a (°C)	21.1	26.4	23.9	17.8	25.5	21.3	14.9	18.5	16.4
$\overline{t_r}$ (°C)	21.4	28.2	24.8	16.3	24.8	20.0	14.6	20.4	16.5
RH (%)	18.4	35.1	25.9	18.1	47.6	30.0	39.4	73.1	56.9
v_a (m/s)	0.01	0.06	0.027	0.00	0.25	0.13	0.02	0.08	0.04
t_{op} (°C)	21.3	27.1	24.3	16.3	25.1	20.7	14.8	19.4	16.5

Table 4. The outdoor temperature range of the three cities during the investigation periods

	Min.	Max.	Mean
Harbin	-18.4	2.0	-8.9
Beijing	-2.0	10.4	3.6
Shanghai	5.0	14.5	7.9

During the period when the study was conducted, Harbin experienced the coldest weather among the three cities. The lowest $t_{out,d}$ in Harbin reached -18.4^{o}C, while the $t_{out,d}$ in Shanghai never fell below 0^{o}C. However, the indoor temperature in Shanghai was the lowest, due to the lack of space heating indoors. Harbin and Beijing had apparently higher indoor temperatures than Shanghai did. The *RH* was low in Harbin and Beijing, and was moderate in Shanghai. The v_a in all three cities were very low, which was not sensible and might not have influence on thermal comfort.

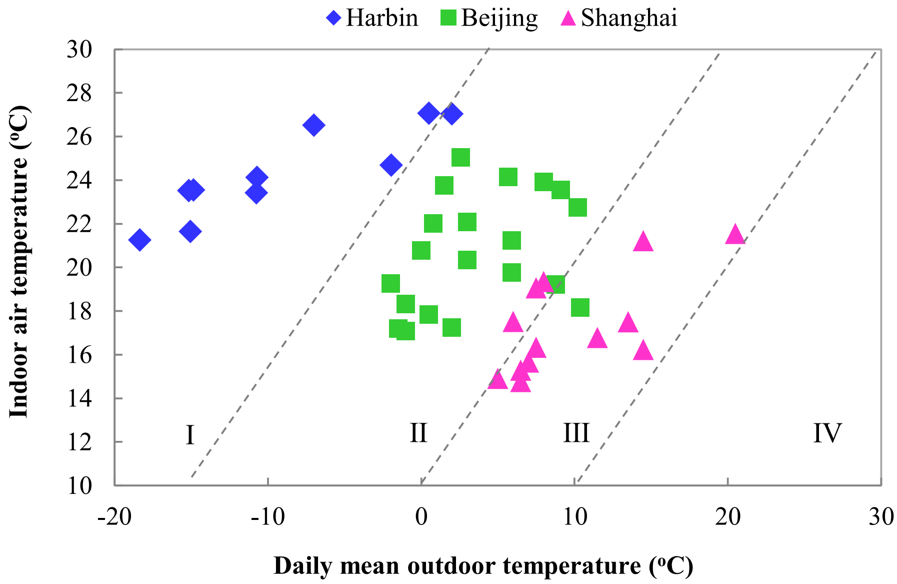


Fig. 2. Relationship between indoor air temperature and daily mean outdoor temperature

Fig. 2 presents the measured indoor and outdoor temperatures of each city. According to the distribution of data dots, the chart could be divided into four areas:

Area I: $t_{op} \geq t_{out,d} + 25$

Area II: $t_{out,d} + 10 \leq t_{op} < t_{out,d} + 25$

Area III: $t_{out,d} \leq t_{op} < t_{out,d} + 10$

Area IV: $t_{op} < t_{out,d}$

It is obvious on Fig. 6 that no data dot is in Area IV, which means t_{op} was always higher than $t_{out,d}$ on the day when a measurement was conducted. Furthermore, it is easy to find that most data from Harbin fall into Area I, while the Beijing data are mostly in Area II and the data from Shanghai fit Area III. If considering a situation that the $t_{out,d}$ is the same in these three cities, then it is very likely that the t_{op} in Beijing would be lower than Harbin, meanwhile higher than Shanghai. Having this difference between the three cities, it is interesting to explore how people evaluated and reacted to their thermal conditions

3.2 Clothing condition

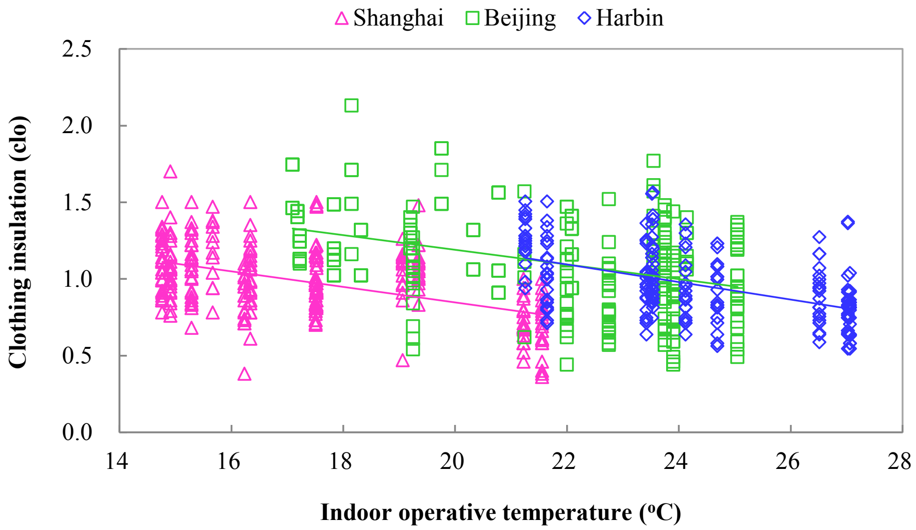


Fig. 3. Relationship between occupants' clothing insulation and indoor operative temperature

$$I_{cl,Shanghai} = -0.0507t_{op} + 1.8605 \quad (1)$$
$$I_{cl,Beijing} = -0.0477t_{op} + 2.1442 \quad (2)$$
$$I_{cl,Harbin} = -0.0573t_{op} + 2.3547 \quad (3)$$

Fig. 3 and Eqs. (1) - (3) present how indoor t_{op} influences occupants' clothing amount. The regression results of Harbin and Beijing almost overlap with each other. The mean values of I_{cl} in the three cities were 0.96clo (Harbin), 1.1clo (Beijing), and 0.99clo (Shanghai). People in Shanghai wore similar amount of clothes as people in Harbin did, although the mean t_{op} in Shanghai was 8°C lower than Harbin. Within the same temperature range of 17~22°C, the I_{cl} in Shanghai was about 0.3clo lower than it was in Beijing regarding a same temperature level.

3.3 Thermal comfort

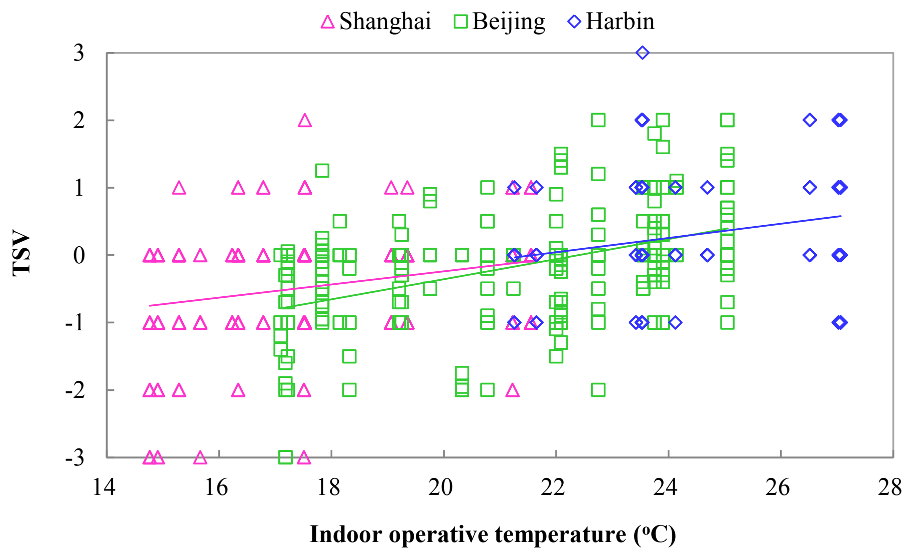


Fig. 4. Relationship between TSV and indoor operative temperature

The relationship between TSV and indoor t_{op} is presented in Fig. 4. By using Eqs. (4) - (6), the t_n could be calculated, which were 22.45°C (Shanghai), 22.39°C (Beijing), and 21.58°C (Harbin) respectively. The slope of Eq. (5) is greater than those of Eqs. (4) and (6), which shows the Beijing occupants were more sensitive to the temperature changing than occupants in Harbin and Shanghai. When the temperature was lower than neutral, the mean TSV values in Shanghai were a little bit higher than Beijing, even though people in Shanghai wore few clothes than people did in Beijing.

$$TSV_{Shanghai} = 0.0973t_{op} - 2.185 \quad (4)$$

$$TSV_{Beijing} = 0.149t_{op} - 3.3359 \quad (5)$$

$$TSV_{Harbin} = 0.1059t_{op} - 2.285 \quad (6)$$

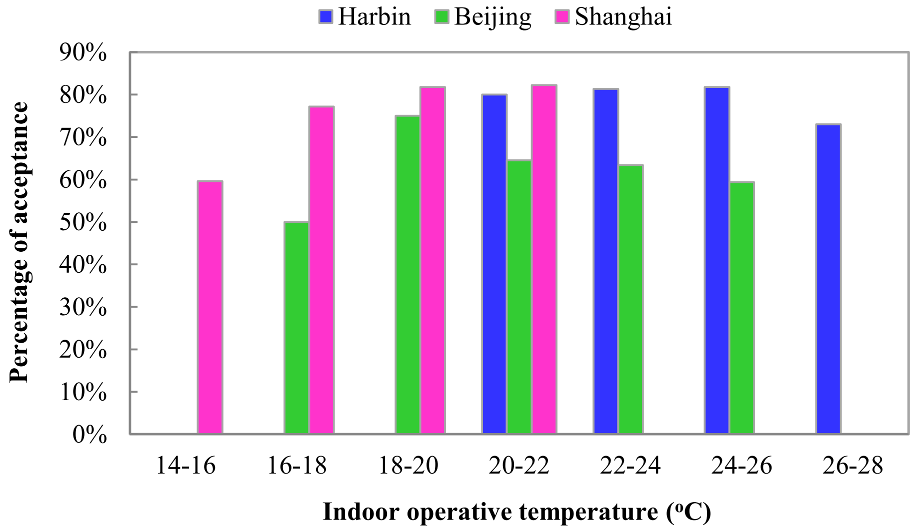


Fig. 5. Percentage of thermal acceptance in the three cities

Regarding the thermal acceptance votes, we consider all the votes which fall between “+0” and “+1” as acceptable. Fig. 5 shows the percentage of thermal acceptance in the three cities. In Harbin, the percentage was always over 70%, and reached 80% when temperature was between 20°C and 26°C. In Shanghai, although there was no space heating, the percentage of acceptance was close to, or even exceeded 80% in the temperature range of 16~22°C. Obviously, people in Shanghai adapted well to cold environment in winter. The percentage of acceptance in Beijing was lower than those in Harbin and in Shanghai. People in Beijing were neither as adapted to cold environment as people in Shanghai, nor as adapted to warm environment as people in Harbin.

According to the thermal preference votes, a higher percentage of people in Beijing than in Shanghai hoped the indoor environment to be warmer, when indoor temperature was lower than neutral. When indoor temperature was higher than neutral, the percentage of people who would like to maintain the thermal condition was higher in Harbin than in Beijing, showing people in Harbin were more used to the warm indoor environment during winter.

4 Discussion: The warmer, the better?

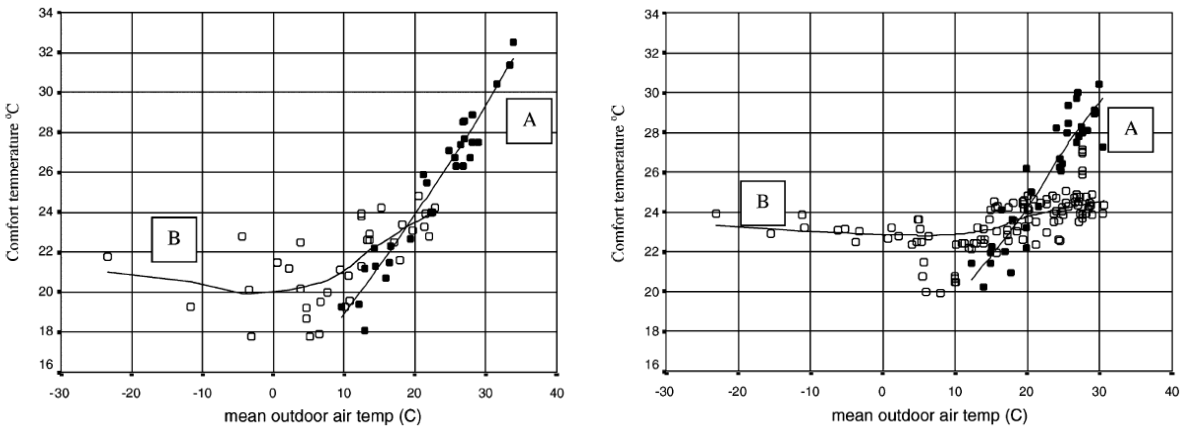
It is always arguable that how "warm" is enough for winter. In this study, it appears that the coldest city (Harbin) enjoyed the warmest indoor environment, meanwhile the warmest city (Shanghai) seemed not be warm enough indoors.

Regarding considerations from aspects such as comfort, health, cost, and feasibility of technologies, people may hold different opinions towards the above issue. The indoor environment should indeed be kept warm during winter to meet a basic thermal comfort demand. However, the problem is if "comfort" has been "over provided" in some cases. Take Harbin, one of the studied cities in this paper, as an example. Wang et al (2003, 2006, 2011, 2012) found the winter indoor temperature in Harbin had been consecutively increasing during the past 20 years. As Table 5 shows, in 1990 the mean level of measured indoor t_a was 17.47°C, which then rose to 20.1°C in the year 2000, and further reached 22.8°C in 2010. While the t_a increased by more than 5°C during the 20 years, the t_n in 2010 was also nearly 5°C higher than it was 20 years ago.

Table 5. Changing of indoor thermal conditions during the past 20 years (Wang et al, 2003, 2006, 2011, 2012)

Year	t_a (°C)	t_n (°C)	I_{cl} (clo)
1990	17.47	17.69	1.74
2000	20.1	-	1.37
2009	21.6	20.4	0.88
2010	22.8	22.6	1.04

This was not just accidently happened in China. Nicol and Humphreys (2002) presented a comparison using the data collected from various field studies, as shown in Fig. 6. The chart on the left side shows the field results in 1970s, and the right one presents data in 1990s. If comparing these two charts, it could be easily found the regression lines for free running buildings (A) stay almost the same, however for HVAC buildings, the distributions of data dots and regression lines (B) differ a lot between the two charts. In 1990s, the mean level of indoor t_c during the cold season was 2°C higher than it was in 1970s, and even tended to be as high as the t_c in summer.



(a) (b)

Fig. 6. Relationship between indoor comfort temperature and mean outdoor air temperature ((a)-1970s, (b)-1990s)

While the indoor temperature increased, people do not have to wear heavy clothes during winter, which brings them comfort and convenience. However, Yu et al (2013) announced that constantly staying in a warm heated environment might weaken people's thermoregulatory, so that might cause discomfort or even health problem when experiencing a cold stress. The over relying on heating prevents people from exercising their acclimatization to cold environment, which they should have inherited through generations. It is necessary to arouse some vigilance on this trend.

5 Conclusions

The authors conducted a comparative thermal comfort field study during winter. Having analyzed the field data from Harbin, Beijing and Shanghai, some conclusions could be drawn as follows.

(1) Among the three cities, Harbin was the coldest and Shanghai was the warmest during the study period. The mean level of $t_{out,d}$ in Harbin was almost 17^{o}C lower than that in Shanghai. However, due to the lack of space heating, the indoor temperature in Shanghai was much lower than those in Harbin and Beijing, where buildings had district heating supplied indoors.

(2) The mean values of I_{cl} in the three cities were 0.96clo (Harbin), 1.1clo (Beijing), and 0.99clo (Shanghai). People in Shanghai wore similar amount of clothes as people in Harbin did, although the indoor temperature in Shanghai was much lower than Harbin.

(3) When the indoor environment was colder than neutral, the mean TSV values in Shanghai were higher than Beijing, even though people in Beijing wore more clothes. The t_n in the three cities were 22.45^{o}C (Shanghai), 22.39^{o}C (Beijing), and 21.58^{o}C (Harbin) respectively.

(4) In Harbin, the percentage of acceptance was always over 70%, and reached 80% when temperature was between 20^{o}C and 26^{o}C. In Shanghai, people showed strong adaptation to cold environment with their percentage of acceptance close to, or even exceeded 80% in the temperature range of 16~22^{o}C. The percentage of acceptance in Beijing was lower than those in Harbin and in Shanghai.

Acknowledgements

This study was supported by Beijing Natural Science Foundation (8154049), and National Science & Technology Support Program of China during the Twelfth Five-year Plan Period (2013BAJ15B01). The authors would sincerely thank Professor Zhaojun Wang at Harbin Institute of Technology, and Professor Xiang Zhou at Tongji University for their great supports in conducting the field study.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Seasonal influence on the dynamics of thermal sensation during transition from indoors to outdoors

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Abstract

We investigate acclimatization effects on outdoor thermal perception. Steady-state conditions were ensured by a prolonged stay of participants (N=16) in a test chamber prior to the subjects' exposure to outdoors, i.e. after five consecutive hours under nearly thermal comfort conditions indoors. After that, subjects walked in a controlled pace around the external precincts of the facility and were asked to vote on their thermal sensation and preference according to a standard questionnaire: a) immediately, b) 15 minutes and c) 30 minutes after they left the controlled indoor environment. Altogether 36 sessions were performed with varying outdoor conditions over winter, spring, and summer 2015. We evaluate the effects of exposure time on the subjects' thermal perception against predictions of the outdoor thermal conditions in terms of UTCI (Universal Thermal Climate Index) and the derived DTS (Dynamic Thermal Sensation). ANOVA results showed that UTCI conditions remained unchanged throughout the 30-min exposure time outdoors, but differed between seasons, whereas the subjects' thermal perception votes differed both between seasons and the times of votes. Reduced thermal sensitivity was noticed in winter and spring at the first vote, resulting in greater prediction bias (underestimation), which was attenuated at higher temperatures and during longer exposure times. An initial overshooting at the first vote towards cool response occurred at moderate temperatures in summer, increasing bias (overestimation), which was also attenuated with increasing temperature and time of exposure.

Keywords: thermal sensation, transition, outdoors

1 Introduction

The paper is concerned with the "time spent in the thermal environment" question when conducting outdoor comfort studies. Short-term acclimatization plays an important role on the perceived thermal sensation, with a longer exposure of a person to the thermal environment leading to more accurate perceptions of it.

Skin temperature strongly affects how one perceives the thermal environment. Höppe (2002) shows through computer modelling of the skin temperature that in the cold at least three hours would be needed for steady state to occur in the heat exchange between skin and air temperature; in warm conditions, steady state is reached more quickly but nevertheless only after approximately half an hour.

According to the physiological concept of Alliesthesia (Cabanac, 1971) "a given stimulus will arouse either pleasure or displeasure according to the internal state of the stimulated subject", thus stepping from thermal homogeneity to transient outdoor conditions should create immediate responses that would then diminish with time of exposure. When a subject experiences for a long time a thermally static environment, „with no opportunity for the body to interpret the ‘usefulness’ of a stimulus for thermoregulation“, there is a greater chance that he will more effectively experience thermal pleasure or displeasure under sudden transient conditions. De Dear (2011) pointed to the relevance of the alliesthesia concept to the planning of transitional spaces and tested this hypothesis in a climate-chamber study with participants exposed to step-up and step-down temperature changes (De Dear et al., 1993). Results described the more immediate effect in step-up than in step-down changes on reported thermal sensation; the authors suggested the accuracy in thermally perceiving a given thermal environment to be closely related to cutaneous thermoreceptors.

In this context, the “time spent…” question or the time needed for short-term acclimatization gains in importance.

As for long-term acclimatization, the adaptive comfort concept (ASHRAE, 2004) (ASHRAE Standard 55) is based on changes in thermal preference over different seasons, with increased tolerance towards heat in summer and towards cold in winter. In a field study in Israel, Pearlmutter et al. (2014) observed how expectations to seasonal changes in weather conditions affect the seasonal acclimatization factor.

In this paper we test the short and long-term acclimatization effects from subjective responses to outdoor conditions of participants who took part of a controlled field experiment over three seasons in a temperate climate (Karlsruhe, Germany).

2 Methods

The study was carried out in and outside a climate chamber located at the Karlsruhe Institute of Technology. The Laboratory for Occupant Behaviour, Satisfaction, Thermal Comfort and Environmental Research (LOBSTER) climate chamber is composed of two adjacent 24 m² offices (Figure 1). It was designed as a semi-controllable environment with operable windows where two office spaces, each provided with two workstations would closely resemble a conventional work environment. Glazings have triple-paned windows and a window-to-wall ratio of approximately 75%.

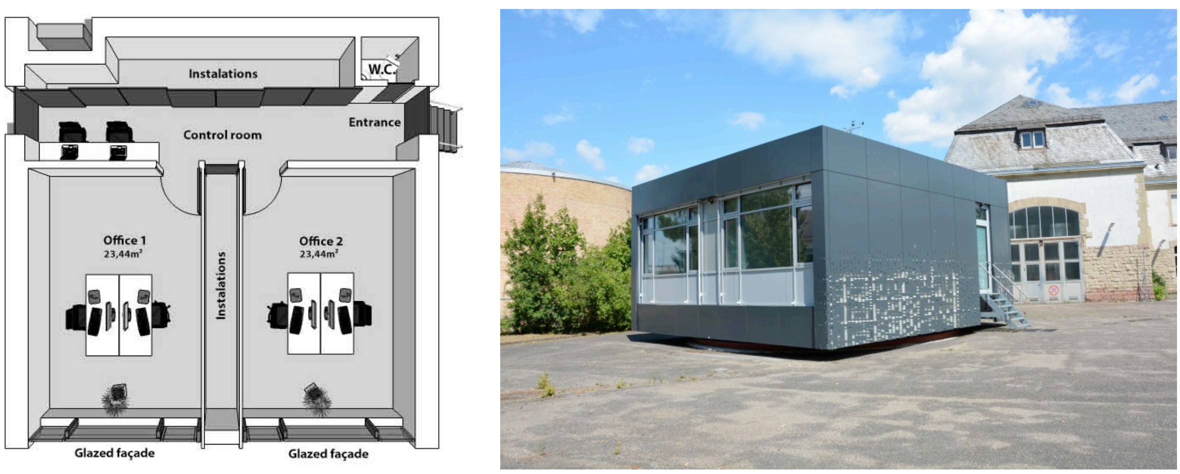

Figure 1. Floor plan and the LOBSTER test facility in summer (July 2015).

16 German males with an average height of 1.80m (SD 0.06m), weight of 80kg (SD 8.9kg), and 24.9 years old (SD 3.6) stayed for a period of 5 hours inside the chamber under

controlled thermal conditions, after which they were lead to the outdoor environment for 30 minutes. All wore sneakers, t-shirt and jeans inside the offices while outdoors they wore such ensemble underneath a standard fleece pullover and jacket (or not, depending on the season, though this was a group decision). From the clothing insulation tables (ISO 9920, 2007) the insulative value of the applied clothing was estimated to be around 0.7 clo inside and outside, in summer between 0.7 and 1.05 clo, in spring 1.3 clo and in winter 1.65 clo.

While in the office, metabolic rate corresponded to a seated position, reading and doing light work; in the open, participants were asked to walk around the climate chamber at a regular pace close to 4 km/h, so that similar conditions to the ones predicted by the human biometeorological index UTCI were met. Estimated indoor metabolic rate was 70 W/m² or 1.2 Met (ISO 7730, 1994), outdoors 135 W/m² or 2.3 Met (Bröde et al., 2012a).

Conditions monitored indoors and outdoors were the relevant thermal comfort variables air temperature, humidity and speed and the mean radiant temperature, the latter calculated according to ISO 7726 (1998). For that, two Ahlborn comfortmeters ALMEMO 2690 were used, one in each office, which were continuously monitored by the researchers who would promote slight changes in the air-conditioning system in order to ensure quasi steady-state thermal conditions within the lower and upper limits of the thermal comfort zone, given by the PMV index. During the 5-hour period in the chamber other aspects regarding indoor comfort were evaluated in a parallel study (not discussed in this paper).

Food intake and beverages were standardized for all participants, only still water and neutral, sugarless biscuits and fruits were provided during the 5-hours sessions.

After the 5-hour acclimatization period in the climate chamber, subjects were invited to leave the test facility and walk to a hand-made weather station consisting of two HOBO U12-011 dataloggers, one of which was placed within a plastic 15 mm globe painted grey for recording globe temperature; and the other logger hung on a string inside a 50 cm-long PVC tube for preventing direct solar radiation while allowing natural ventilation to the logger. Spot measurements of wind speed were taken using a hand-held anemometer (Testo 416 Mini-Vane anemometer), which had been attached to the tripod. Back-up data from the roof-top Thies weather station, located at 6m from ground level on the roof of the climate chamber were also used. Measurements on soil were close to the respondents, air temperature and humidity sensors at 1.30 m, globe thermometer at 1.2 m and anemometer at approximately 1.6 m.

A standard comfort questionnaire was given to the subjects at three different time stamps: immediately after leaving the test chamber; after 15 min of light walk around the LOBSTER facility; and after further 15 min walking outside. In this paper, we focus on reported thermal sensation according to the German version of the 7-point perceptual judgment scale with a neutral point (ISO 10551, 1995). Groups of four were tested each day and for three consecutive days per season, so that each individual would repeat two times the experimental procedure, hence a total of 9 days per subject.

Indoors, the PMV (ISO 7730, 1994) thermal comfort index was used for the thermal evaluation of the offices. Indoor thermal conditions were real-time monitored with the Ahlborn comfortmeters and post-processed in the UC Berkeley Thermal Comfort Program WinComf batch-version 1.01 (1994-1995) for assessing PMV data.

Outdoors, thermal conditions were post-processed with the non-steady state Universal Thermal Climate Index (UTCI), which is based on a multi-node model of human thermoregulation (Fiala et al., 2012) using the approach of equivalent temperature. For a direct comparison to the reported thermal sensation votes, the UTCI-Fiala model also predicts thermal sensation (Bröde et al., 2012b; Fiala et al., 2003), termed 'Dynamic Thermal Sensation' (DTS).

Monitored data were analysed by applying mixed-model ANOVA (Littell et al., 1996) and by means of locally estimated smoothing splines (LOESS) (Zuur et al., 2009). Results include thermal votes reported in three different time stamps over three days within three seasons (Table 1). In total, 48 sessions are evaluated in this paper, encompassing a total of 417 thermal votes.

Table 1. Breakdown of experimental sessions.

Season	Period
winter	January 12 through February 6
spring	April 13 through May 8
summer	June 22 through July 17

3 Results

Outdoor conditions measured over the three seasons are varied, including mild days in winter, unexpected warm days in spring and heatwave episodes in summer. ANOVA results (Table 2) showed that the climatic conditions as assessed by UTCI (Figure 2) remained stable during the 30 min exposure time, but differed between seasons.

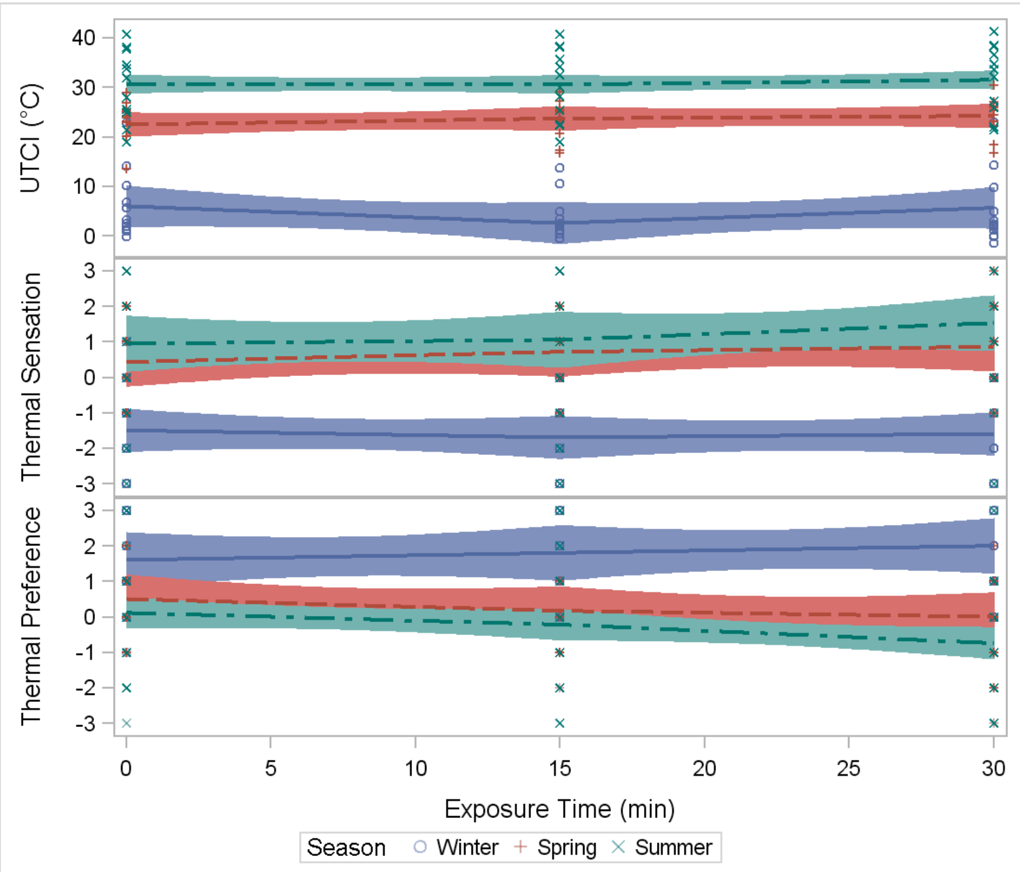

Figure 2. UTCI, thermal sensation & preference related to season and exposure time. Individual data and smoothing function (LOESS) with 95% CI for time effect.

Table 2. ANOVA results with numerator (NumDF) and denominator degrees of freedom (DenDF), F- and P-values for UTCI, thermal sensation (TS) and thermal preference (TP) depending on season and exposure time.

			UTCI		TS		TP	
Effect	Num DF	Den DF	F Value	P-Value	F Value	P-Value	F Value	P-Value
Season	2	33	56.19	<.0001	65.92	<.0001	61.37	<.0001
Exposure Time	2	33	1.85	0.1739	7.47	0.0023	3.26	0.0524
Exposure Time*Season	4	33	3.49	0.0175	2.53	0.0497	4.29	0.0042

Furthermore thermal sensation and preference both differed between seasons and exposure times (Figure 2, Table 2). The statistically significant interaction effects (Exposure Time*season) indicate that time courses were modified by season, with e.g. a slight increase of thermal sensation votes with time in spring and summer compared to a slight decrease in winter.

The sensitivity of thermal sensation on UTCI related to season and exposure time is analysed by LOESS in Figure 3. The curves' shape depended on season and exposure time and the non-monotonous LOESS curves shown in Figure 3 for winter and spring just after transition (at time stamp 1 or at 0 min) resembled the linear shape found in summer at later times. There was also a pronounced initial overshooting response in summer with cooler reported thermal sensation at identical UTCI (~20°C) compared to spring and winter.

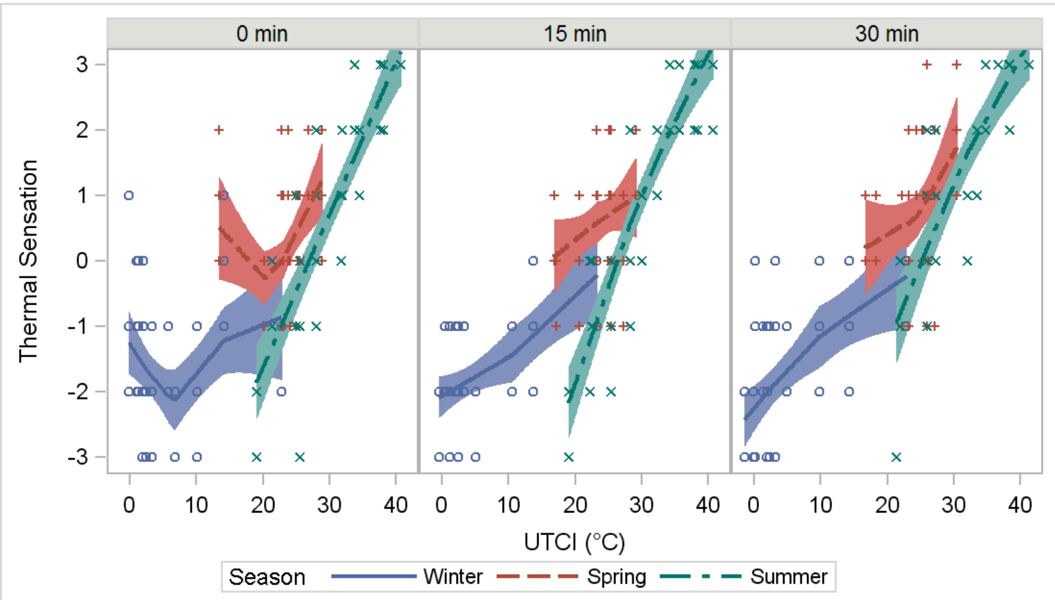

Figure 3. Sensitivity of thermal sensation on UTCI related to season and exposure time analysed by LOESS smoothing functions with 95% CI.

Figure 4 shows the mean prediction error (bias) of DTS (Dynamic Thermal Sensation) for the three UTCI ranges, as a function of season and exposure times. The reduced thermal sensitivity in winter and spring at 0 min (cf. Fig. 3) result in greater bias (underestimation), which were attenuated at higher temperatures and during longer exposure times. In addition, the initial overshooting cool responses in summer increased bias (overestimation), which was also attenuated with temperature and time of exposure (Table 3).

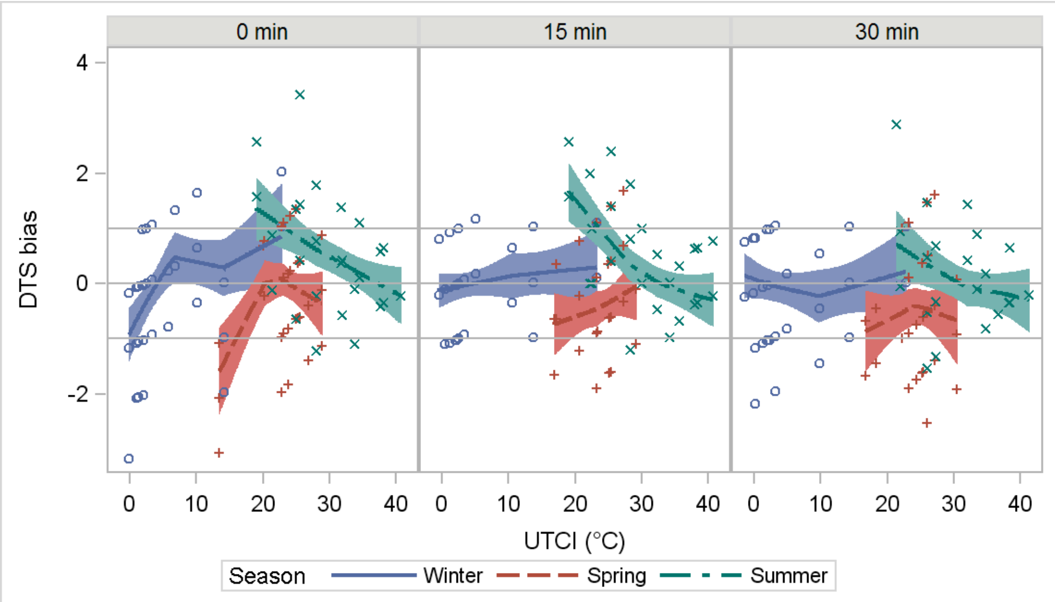

Figure 4. Mean prediction error (bias) of DTS (Dynamic Thermal Sensation) related to UTCI values for different seasons and exposure times analysed by LOESS smoothing functions with 95% CI.

Table 3 illustrates the time course of bias and root-mean-squared prediction error (rmse) for the different seasons showing that bias and rmse were reduced after 15 min in winter and after 30 min in summer, respectively, whereas for spring there was not much change in rmse and even a slightly increased bias.

Table 3. Mean prediction error (bias) and root-mean-squared error (rmse) of DTS (Dynamic Thermal Sensation) related to season and exposure time.

Season	*bias*			*rmse*		
	0 min	*15 min*	*30 min*	*0 min*	*15 min*	*30 min*
Winter	-0.12	0.00	-0.02	1.10	0.71	0.89
Spring	-0.19	-0.43	-0.52	1.03	0.94	1.12
Summer	0.45	0.31	0.03	1.03	1.07	0.94
Total	0.04	-0.05	-0.18	1.05	0.92	0.99

4 Discussion and Conclusion

In this study, we compare TSV against predicted thermal sensation (DTS) with the non-steady state index UTCI. Results suggest that the longer exposure time will reduce prediction errors and therefore lead to more consistent thermal votes' estimates. A longer exposure proved to be advantageous in the three seasons evaluated, which could be regarded as a necessary condition for validating thermal votes in outdoor comfort surveys.

From previous research on transient indoor conditions (De Dear et al., 1993) which have indicated that, when moving from indoors to outdoors during winter time, the initial thermal sensation responses could be biased against cooler TSV, our results support the recommendation to consider only thermal responses for respondents with longer occupancy in the outdoor environment. In view of the strong need to standardize procedures in outdoor comfort surveying (Johansson et al., 2014), the main contribution of the study is to set a minimum of 30 minutes as the suggested permanency in the outdoor environment in the case of field studies.

The consideration (for evaluation purposes) of thermal votes reported in a shorter timeframe from the last indoor exposure –whatever thermal history the subject might have experienced prior to the questionnaire survey, could lead to significant errors in calibrating existing comfort indices or in proposing comfort ranges for a given population.

Acknowledgements
We acknowledge the Brazilian research funding agency CAPES, the European Union 7th Framework Programme (FP7/2007-2013) grant agreement no. PIRG08-GA-2010-277061 and the Fachgebiet Bauphysik & Technischer Ausbau/Karlsruher Institut für Technologie (fbta/KIT), in special Marcel Schweiker and Andreas Wagner.

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Impact of Internal Loads and Operational Strategies on Comfort and Energy Consumption: An Application in the Composite Climate of India

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Abstract

This paper assesses the impact of internal loads and operational pattern of a mixed-mode building on its thermal comfort, heating and cooling energy consumptions. The study deals with an office building with a built-up area of 1280 m^2 located in composite climate of India (29.9°N and 77.9E). The building was modelled and simulated using Energy Plus software tool. Significant internal thermal loads and operational strategies were identified based on a sensitivity study. Internal thermal mass contributed by furnishings and upholstery, volume of internal spaces and the type of lighting were found to have a significant impact on heating and cooling energy. With respect to operational patterns variable thermostat settings based on adaptive comfort criteria, dynamic window operations and the use of lighting controls were found to have a significant impact. A prototypical office space in the building was selected for detailed analysis. Parametric simulation studies were carried out and the impact of these factors on comfort and energy consumption was estimated. Based on these findings strategies for reducing the heating and cooling energy consumption were evolved. Findings from the prototype evaluation were applied to the whole building and results pertaining to improvement in comfort and reduction in energy consumption have been presented.

Keywords: Building energy, internal loads, operational strategies, thermal comfort

1 Introduction

In order to minimize the loss and damage pertaining to adverse effects of climate change it has become imperative to deal with the causes for the same, greenhouse gas emission being one of them. COP 21 or CMP 11 foregrounds the need for zero net anthropogenic greenhouse gas emissions to be attained by the second half of the 21st century. According to Emission Database for Global Atmospheric Research, there has been an increase of 55.6% in world total CO_2 emission in just a period of 13 years (1990 to 2013). In the same time span India has witnessed a continuous increase by 4.4% to about 2.1 billion tonnes, making it fourth largest CO_2 emitting country (Olivier, et al., 2014). Since India is a developing country, it will continue to emerge as one of the largest emitter of CO_2 in the coming future. Therefore it becomes important to monitor and inhibit the emission from other possible sources. Building sector is one such source which provides many small reduction opportunities which can make a significant difference as a whole. UNEP report emphasizes that the building sector has the most potential for delivering significant and cost effective GHG emission reductions (UNEP, 2009).

In recent years many studies have been conducted to find effective methods pertaining to energy efficiency in buildings. The concept of energy efficiency is related to the energy supply required to maintain desirable interior conditions that minimizes energy consumption (Omer, 2008). Much work has been done in the area of building envelope elements (Sadineni, et al., 2011). Sadineni et al. have discussed the effectiveness of important building envelope components such as walls, fenestrations, roofs, thermal mass and infiltration in reducing the heating and cooling energy demands of the building. Significance of using high-albedo materials in building's envelope for reducing cooling energy use in building is highlighted in research work of Taha et al. (Taha, et al., 1992). Some research works have also highlighted issues relating to embodied energy in buildings. For example, Reddy and Jagadish have shown that using energy efficient or alternative building materials can reduce the total embodied energy of load bearing masonry buildings by 50% (Reddy & Jagadish, 2003).

There has been substantial research on the impact of building's thermal characteristics on space cooling and heating demand (Santin, et al., 2009). However, study on various other factors and techniques to achieve lower energy consumption is an area yet to be explored to its full potential. In recent studies, options other than just building envelope are being explored for reducing the annual building energy demands during the operational phase.

Study conducted in Netherlands by Vringer et al. stated that personal motivation plays a major role in determining the energy consumption in different households. They found 4% more energy is used by families which are least motivated to save energy (Vringe & Blok, 2007). Another study suggests that the occupant's characteristics and behavior can affect energy use by up to 4.2% (Santin, et al., 2009). Short et al. reported that natural ventilation is an effective measure for reducing building energy demands (Shorts, et al., 2004). During summers, annual cooling load can be reduced by a maximum of 7.7% while the house is maintained at 25°C (Florides, et al., 2002). Installation of garden on rooftop of 5 storey commercial building in Singapore resulted in annual energy consumption saving of up to 14.5% (Wong, et al., 2003). Akbari et al. stated that shade trees can yield seasonal cooling energy savings of 30% (Akbari, et al., 1997). Lighting also becomes an important factor in determining the energy consumption in a building. Simulation study performed on an office building showed that day lighting is capable of reducing artificial lighting consumption by 50 to 80% (Bodart & Herde, 2002). Field measurements on daylighting for fully air-conditioned building in Hong Kong showed that energy savings of up to 50% in electric lighting could be achieved for perimeter offices (Li & Lam, 2001). Work has also been done to evaluate the effect of using smart occupancy sensors on energy consumption. About 5% more energy can be saved by using the same as compared to non-adaptive fixed time delay sensors (Garg & Bansal, 2000).

Although building envelope plays a major role in deciding the energy consumption, the potential of various parameters in a building's interior spaces cannot be ignored in this regard. Moreover, while building envelope can be debated upon mainly in early design stages of any building, modification in internal parameter's can be implemented in an already existing building. As per Bureau of Energy Efficiency, the energy performance index (EPI) of office buildings in India varies from 200 to 400 kWh/ m^2/ year whereas similar buildings in North America and Europe have EPI of less than 150 kWh/ m^2/ year (Seth, 2011). Thus, in India where majority of existing buildings lack energy efficiency it becomes important to come up with solutions which can be applied at an individual level by the occupants with minimum cost interventions.

This paper identifies the potential for reduction in energy consumption without compromising on the comfort. The focus of the study was to evaluate non-structural changes in a building's interior spaces, i.e., various internal loads, namely, interior thermal mass, volume of interior spaces and type of lighting and operational strategies, namely, variable thermostat settings, dynamic window operations and the use of lighting controls which can be varied in order to attain maximum reduction in the annual operational energy consumptions. The scope of the study was limited to composite climate of India and only three types of annual energy consumptions – heating, cooling and lighting.

2 Details of the study

A simple institutional building located in IIT Roorkee campus was chosen for the detailed parametrical study of various internal loads and operational strategies. The climatic data of the analyzed area in which the building is located is summarized in Table 1.

Table 1. Climatic data of analyzed area

Meteorological station elevation	274 m above sea level
Latitude	29 deg. 51 min. North
Longitude	77 deg. 53 min. East
Climate type	Composite
Coldest month/average monthly temperature	January/13.6 °C
Hottest month/average monthly temperature	June/32.2 °C
Average annual temperature	23.7 °C

Table 2. Materials considered for the parameter interior thermal mass

Material	Density (kg/m³)	Specific Heat (J/kg K)	Conductivity (W/m K)
Wood (oak)	700	2390	0.19
Paper (bond)	720	1336	0.05
Foam (medium firm)	45	1470	0.03

The building is longitudinally oriented in north-south direction (Fig. 1) and has a built up area of 1280 m^2. It is composed of two floors and exhibits a simple rectangular geometry. It is a mixed use academic building which experiences occupancy 12h/day five days a week. A spatial walkthrough audit of building was conducted and three main types of spaces were identified – offices, classrooms and labs.

The exterior walls are plastered brick walls and construction is in situ, reinforced concrete. The east and west façades consists of single glazed glass windows throughout with aluminium frame with window to wall percentage 40%. The interior spaces of the building housed three important materials which were considered as interior thermal mass for the purpose of study. They are listed in table 2 along with their thermal properties.

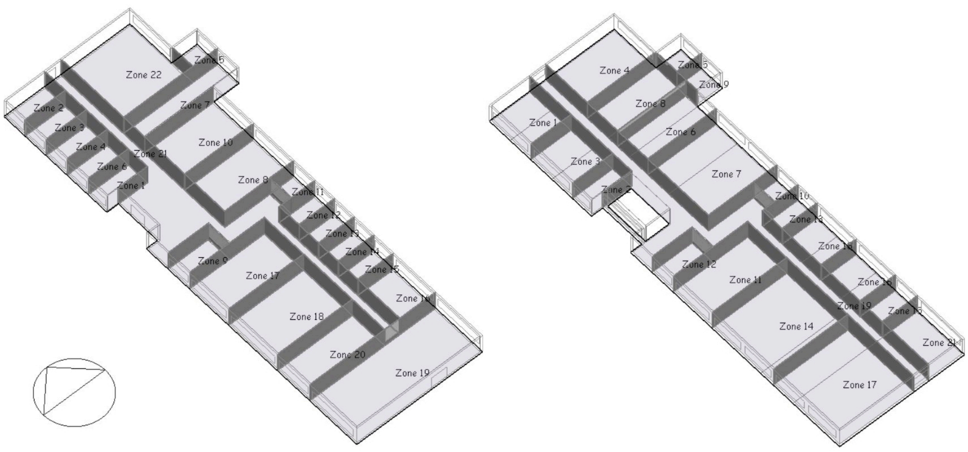

Figure 1. Building layout showing different zones in ground and first floor

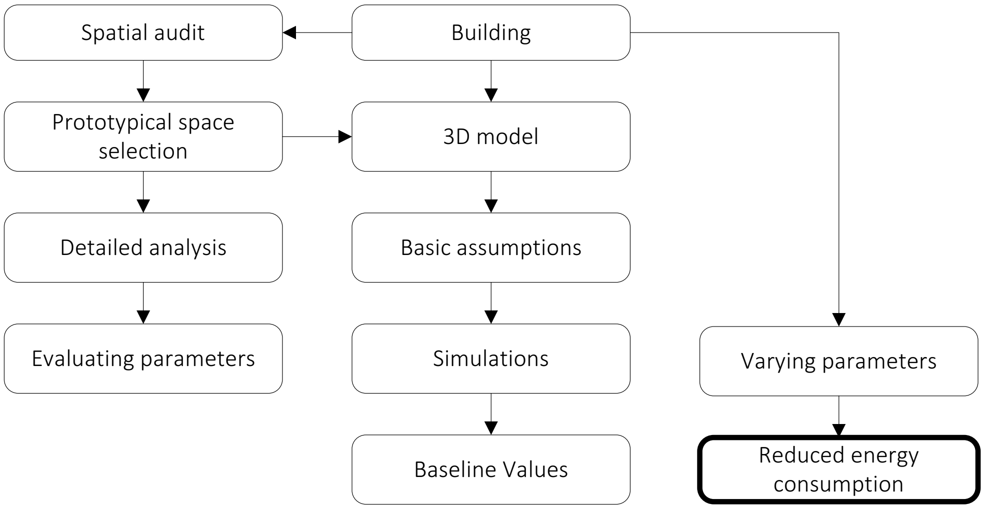

Figure 2. Hierarchy of the study

The three types of spaces selected differ from each other in terms of size, furniture, electrical equipments and occupancy. A prototypical study was conducted for each type of space. However, this study shows the example of office space only.

Best possible scenarios corresponding to each parameter based on the findings from prototypical study of each type of space were applied to the whole building so as to attain maximum reduction in the annual operational energy consumption. Figure 1 encapsulates the methodology of the study. Before varying the parameters, baseline values for annual cooling, heating and lighting energy consumption was calculated for all three prototypical spaces and the whole building in order to make the relevant comparisons. Here, the baseline values refer to the energy consumption taking place in the initial or baseline condition i.e. when the prototypes or the building is modelled and simulated as per existing condition without varying any internal thermal loads or operational strategies. The existing conditions for each zone such as internal thermal mass, occupancy, sensible gains from computers and other equipments and lighting energy are summarized in table 8. A comparative evaluation was also done in later part of the study that examined the effect of parameters and zone variations on cooling energy consumption (refer figure 5 and 6).

3 Prototype study

Table 3. Baseline conditions for each parameter for office prototype

Parameter	Baseline conditions
Interior thermal mass	Water = 0.08 m^3, Wood = 0.28 m^3, Paper = 0.48 m^3, Foam = 0.3 m^3, Aluminium = 0.15 m^3, Glass = 0.1 m^3 and Plastic = 0.12 m^3
Volume	133.28 m^3
Thermostat setting	Heating setpoint temperature = 22°C, Cooling setpoint temperature = 24°C
Window operation	Off
Lighting type	T5 (16mm dia.) Fluorescent, triphosphor, high-frequency control gear, surface mount
Lighting control	Off

The office space considered as a prototype is represented by zone 1 on first floor (Fig. 1). Simulation settings as per existing conditions taken from table 3 and 8 were assigned to the prototype for deriving baseline values. A typical schedule corresponding to 800hrs to 1800 hrs occupancy was defined. The monthly energy consumption values obtained are given in Table 3. The total annual cooling energy was 4526.6 kWh, annual heating energy was 537.8 kWh and annual lighting energy was 783.7 kWh.

Table 4. Prototype – office space: Monthly energy consumption

Month	Total Cooling (kWh)	Zone Heating (kWh)	Lighting (kWh)
January	11.89	215.19	66.77
February	94.04	77.82	61.15
March	220.82	11.80	65.21
April	538.93	0.00	61.15
May	700.72	0.00	69.57
June	705.04	0.00	62.41
July	742.23	0.00	69.57
August	559.77	0.00	68.02
September	457.59	0.00	63.96
October	355.10	4.26	69.57
November	113.32	62.64	65.21
December	27.15	166.16	61.15

The impact of different parameters stated previously is studied and analysed individually in the following sections. While one parameter is varied, others are kept constant as per baseline conditions (Table 3).

3.1 Internal thermal mass

While studying the impact of internal thermal mass on energy consumption, only interior furnishings are taken into account. Apart from materials listed in table 2, four more materials were identified for the prototype after conducting an audit of internal loads. These included water, aluminium, glass and plastic (Table 3). Due to the limitations of the software, all the interior components were represented by partitions. The partitions were then assigned the specific materials and corresponding thermal properties to represent different components. Figure 3 shows how different materials affect the heating and cooling energy demands in a space. It was found that at any given volume, foam resulted in higher energy consumption followed by paper whereas aluminium showed least impact compared to other materials.

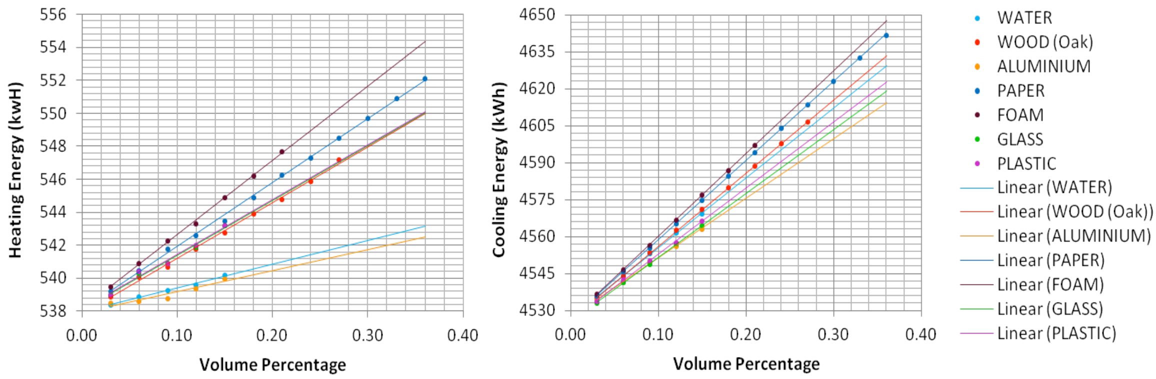

Figure 3. Interior thermal mass: Trendlines showing effect on heating and cooling energy consumption with change in volume percentage

Foam resulted in 0.9% more heating energy consumption and 0.3% more cooling energy consumption than aluminium. However, in the prototype maximum energy consumption was attributed to paper since it is present in more volume comparatively. Removing all components from the prototype resulted in 495.8 kWh annual heating energy and 3892.8 kWh annual cooling energy, 7.8% and 14% less than the baseline value respectively.

3.2 Volume

Volume of the prototype was 133.28 m^3 which takes into account all the internal spaces that requires heating or cooling to maintain the set thermostat range of 22°C - 24°C. These spaces included open lofts, open built-in shelves, open movable wooden shelves and extra room height which could be reduced without contradicting the standards given by National Building Code of India.

It was found that eliminating unnecessary volumes from the internal space resulted in significant decrease in annual heating and cooling energy consumptions. Four different scenarios were considered and energy consumption corresponding to each was calculated. The maximum possible reduction in volume was 34.76 m^3 which resulted in 26.3% and 12.2% decrease in heating and cooling energy consumption respectively. The cooling energy amounted to EPI of 101.3 kWh/ m^2/ year. Table 5 lists various scenarios and the corresponding energy consumptions.

Table 5. Volume: Various scenarios and corresponding energy consumptions

Scenario	Measure taken	Possible volume reduction (m^3)	Heating energy (kWh)	Cooling energy (kWh)
1	Open lofts and shelves covered	11.24	491.8	4344.7
2	Floor to ceiling height reduced to 3m by introducing a false ceiling	15.68	472.5	4269.4
3	Floor to ceiling height reduced to 2.8m by introducing a false ceiling	23.52	440.7	4144.4
4	Scenario 1 and 3 considered together	34.76	396.4	3972.8

3.3 Thermostat setting

The heating and cooling setpoint temperatures are related to the activity or usage of the zone. Heating set point temperature defines the ideal temperature in the space when heating is required which is usually during winter months whereas cooling setpoint temperature defines the ideal temperature in the space when cooling is required i.e. during summer months.

The study compared six scenarios (Table 6); scenario 1 being the baseline conditions (22°C - 24°C) whereas scenario 6 was based on Adaptive Comfort Criteria in which the indoor comfort temperatures were varied monthly. The Adaptive Comfort Criteria was based on the following equation (Brager & Dear, 2001) –

T_comf = 0.31 × T_(out-μ) + 17.8

Scenarios 2 to 5 were varied as given in table 6. The first value in brackets represents the heating setpoint temperature while the second value represents the cooling setpoint temperature. The negative sign indicates that the annual energy consumption has reduced while the positive sign indicates vice versa. Figure 4 is graphical representation of table 6 and it shows the annual trend in heating and cooling energy consumption.

Table 6. Thermostat setting: Energy consumptions corresponding to different scenarios for each month

Month	Scenario 1 (22°C - 24°C)		Scenario 2 (21°C - 25°C)		Scenario 3 (20°C - 26°C)		Scenario 4 (19°C - 27°C)		Scenario 5 (18°C - 28°C)		Scenario 6	
	Heating energy (kWh)	Cooling energy (kWh)	Heating energy (kWh)	Cooling energy (kWh)	Heating energy (kWh)	Cooling energy (kWh)	Heating energy (kWh)	Cooling energy (kWh)	Heating energy (kWh)	Cooling energy (kWh)	Heating energy (kWh)	Cooling energy (kWh)
Jan	215	12	153	1	100	0	58	0	32	0	187	78
Feb	78	94	46	62	24	37	12	19	5	7	98	144
Mar	12	221	4	175	1	135	0	99	0	67	33	246
Apr	0	539	0	482	0	426	0	374	0	328	6	453
May	0	701	0	626	0	558	0	496	0	439	2	557
Jun	0	705	0	638	0	575	0	517	0	461	2	518
Jul	0	742	0	667	0	596	0	529	0	467	2	524
Aug	0	560	0	492	0	428	0	368	0	315	3	401
Sep	0	458	0	396	0	341	0	288	0	239	7	343
Oct	4	355	2	302	0	251	0	203	0	156	26	332
Nov	63	113	38	79	21	49	9	27	3	8	81	172
Dec	166	27	116	10	76	2	44	0	24	0	143	92
Total	538	4526	358	3929	222	3398	123	2921	64	2486	589	3861
% Ch			-33	-13	-59	-25	-77	-35	-88	-45	10	-15

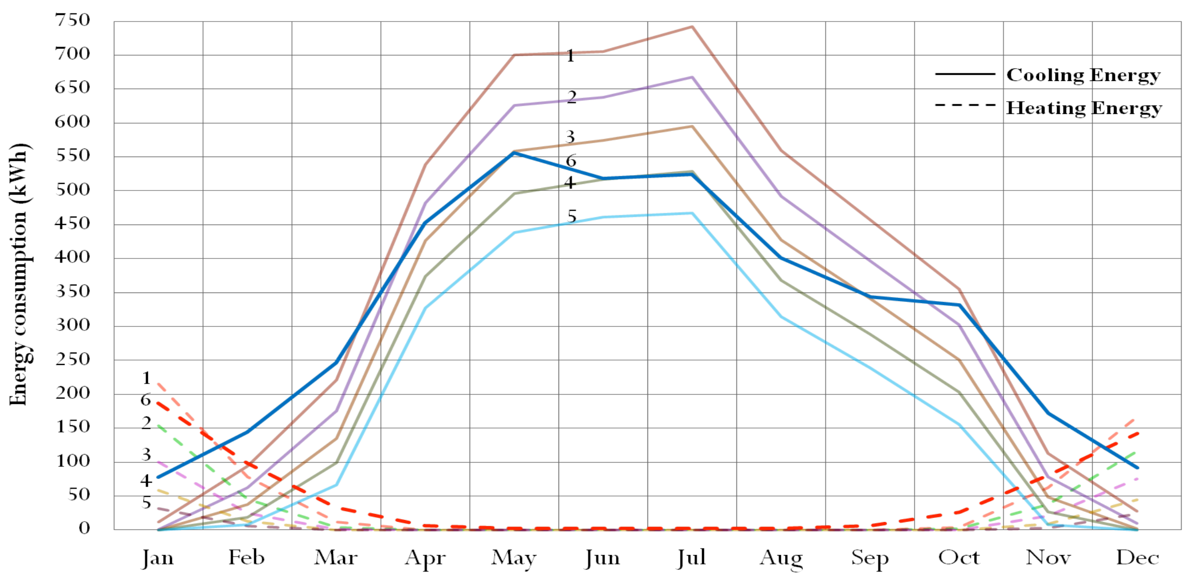

Figure 4. Thermostat setting: Trend in heating and cooling energy consumption for different scenarios

It was found that scenario 5 leads to maximum reduction in both heating and cooling energy consumption (45% and 88% respectively). This means that in order to save maximum energy the heating setpoint temperature should be kept as 18°C while cooling setpoint temperature should be kept as 28°C. However, as per Adaptive Comfort Criteria, the ideal average temperature during winter and summer months is 21.9°C and 25.8°C respectively. Adopting temperatures obtained from Adaptive Comfort Criteria led to an increase of 10% in the annual heating energy consumption and also the reduction in annual cooling energy was not very significant compared to other scenarios.

Therefore, for winter months (January, February, November and December) scenario 1 was taken as the best possible scenario whereas scenario 3 was considered best possible for the summer months. On keeping the heating setpoint temperature as 22°C during winter months and cooling setpoint temperature as 26°C during summer months the heating and cooling energy was found to be 522.8 kWh and 3555.9 kWh, indicating a percentage reduction of 2.8% and 21.4% respectively. In this case, cooling energy amounted to EPI of 90.7 kWh/ m^2/ year.

3.4 Window operation

Dynamic window operation is an important operational strategy which can play a key role in determining the thermal energy consumption of a building. A window operation schedule was defined as follows –

For winter months: until 09:00 = 0, until 17:00 = 1, until 24:00 = 0
For summer months: until 06:00 = 1, until 18:00 = 0, until 24:00 = 1

Here, 0 and 1 implies that windows are closed and open respectively. It was found that using natural ventilation proved to be beneficial for reducing annual cooling energy consumption by 3.4%. This is closer to the findings of Rijal et al. in which they estimated 4% reduction in energy demand on using window open algorithm (Rijal, et al., 2007). Table 7 shows the values of heating and cooling energy demand corresponding to each month.

Table 7. Window operation: Energy consumptions corresponding to different scenarios for each month

Month	Baseline		Window operation schedule on	
	Cooling Energy (kWh)	Heating Energy (kWh)	Cooling Energy (kWh)	Heating Energy (kWh)
January	11.89	215.19	7.4	214.7
February	94.04	77.82	71.5	75.3
March	220.82	11.80	195.8	26.6
April	538.93	0.00	497.2	1.0
May	700.72	0.00	668.2	0.0
June	705.04	0.00	695.8	0.0
July	742.23	0.00	745.2	0.0
August	559.77	0.00	578.9	0.0
September	457.59	0.00	460.7	0.0
October	355.10	4.26	326.7	11.0
November	113.32	62.64	110.0	60.4
December	27.15	166.16	16.3	163.1
Total	4526.60	537.87	4373.5	552.0

3.5 Lighting Type

Artificial lighting is estimated to account for 25%-40% of energy consumption in a commercial building (Krarti, et al., 2004). The type of lighting used in a space can lead to significant variations in lighting energy. In the study conducted on prototype various lighting types were modeled and change in baseline values for heating, cooling and lighting energy consumption was evaluated. The change in lighting energy was found to be most significant compared to heating and cooling energy consumptions.

The results showed that the replacing existing lighting with recessed LED lighting led to 53.7% reduction in lighting energy and 2.2% reduction in cooling energy consumption.

However, there was a slight increase of 3.8% in heating energy consumption which is insignificant compared to 53.7% reduction in lighting energy. The radiant fraction for recessed LED light was 0.37 compared to 0.72 for surface mount T5 (16mm) Fluorescent.

3.6 Lighting Control

Daylighting is an effective tool for reducing the lighting energy consumption in a building. According to Ihm et al., in an office space an annual energy savings of up to 60% can be achieved using dimming control strategy (Ihm, et al., 2008). The lighting control can either be linear or stepped. Linear day lighting makes use of smooth and continuous dimming from low end to high end so as to maintain the necessary light level. In continuous day lighting, light is adjusted based on amount of daylight that's always present in the space and at the same time ensures accomplishment of minimum light level without over-lighting the space.

Here, linear type is used for the purpose of analysis. The floor area is divided into two Lighting Areas – Lighting Area 1 and Lighting Area 2. Lighting area 1 is adjacent to the wall containing windows and consists of 1st (main) lighting sensor. Since all the lights in the zone are in lighting area 1, percentage zone covered by lighting area 1 is taken as 100% and percentage zone covered by lighting area 2 is taken as 0%.

On turning the lighting control on while keeping other parameters set to their baseline conditions (Table 3), the annual lighting energy consumption was found to be 119.7 kWh. The heating and cooling energy consumptions were found to be 569 kWh and 4364.8 kWh respectively.

4 Actual Building Application

The building was modelled as per baseline conditions given in table 3 for parameters – thermostat setting, window operation, lighting type and lighting control. The other two parameters, namely interior thermal mass and volume were varied for each zone as per the data given in table 8. Only one typical schedule corresponding to 800hrs to 1800 hrs occupancy is defined for the whole building to make the analysis consistent and repeatable. The occupancy density, internal thermal mass, sensible gains and lighting energy vary for each zone depending on the use/activity. The baseline values were found to be as follows –

Annual cooling energy was 284781.2 kWh (EPI = 131 kWh/ m^2/ year), annual heating energy was 26240.8 kWh and annual lighting energy was 35673.4 kWh.

Actual building application was based on the results obtained from prototype study. Various scenarios for achieving maximum reduction in heating, cooling and lighting energy consumption for each parameter were evaluated and best possible scenario was selected. Since aluminium and plastic results in lesser energy consumption at a given volume (figure 3), the interior thermal mass material was modified in each zone. Foam chairs were replaced by plastic and wooden tables and shelves were replaced by aluminium in each zone. Possible volume reduction for each zone was calculated leading to possible reduction of 662.7 m^3 and 666.3 m^3 on ground and first floor respectively. Heating setpoint temperature was kept as 22°C whereas cooling setpoint temperature was kept as 26°C for the whole building. Window operation was turned on with same schedule as defined in section 3.4. Lighting type was changed to recessed LED and lighting control was turned on.

Initially each parameter was modelled independently and the effect of each on whole building's annual energy demands was evaluated, followed by simultaneous application of all parameters.

Table 8. Ground Floor & First Floor: Zone wise details

Zone	Use/ Activity	Floor area (m^2)	Volume (m^3)	Internal Thermal Mass (m^3)	Occupancy (people/m^2)	Sensible Gains (W/m^2)		Lighting Energy (W/m^2 - 100 lux)
						Comp uters	Other	
GROUND FLOOR:								
2,3, 4,6	Office	24.0	81.6	Wood=0.14 Foam=0.08	0.04	2.4	5.7	4.0
8	Lab	78.7	267.4	Wood=1.24	0.4	7.9	2.0	2.9
22	Lab	138.8	471.8	Wood=0.7 Foam=0.5	0.17	7.1	1.9	2.9
10	Lab	78.7	267.4	Wood=0.7 Foam=0.3	0.19	9.7	1.6	3.7
13,14, 15	Office	20.0	68.0	Wood=0.14 Foam=0.08	0.05	2.7	6.5	5.8
16	Office	42.8	145.4	Wood=0.21 Foam=0.14	0.09	5.1	6.0	5.4
17	Class-room	62.5	212.4	Wood= 2.1 Foam=0.4	0.16	0	0	5.6
18	Lab	103.5	352.0	Wood=2.1	0.19	0	0	3.4
19	Store	168.0	571.2	-	0	0	0	4.1
20	Store	67.9	230.7	-	0	0	0	3.4
FRIST FLOOR:								
1,3	Office	39.2	133.3	Wood=0.28 Paper=0.48 Foam=0.3	0.18	11.5	8.2	4.0
4	Class-room	82.5	280.5	Wood=1.54 Foam=0.94	0.54	0	0	6.4
5,9	Office	15.0	51.0	Wood=0.18 Foam=0.12	0.13	7.3	8.6	3.9
8	Lab	60.0	203.8	Wood=0.7 Foam=0.7	0.5	27.5	0	4.9
6	Lab	60.0	203.8	Wood=1.24	0.4	0	0	2.9
7	Lab	119.9	407.7	Wood=0.6	0.07	0	0	1.3
11	Class-room	82.5	280.5	Wood=0.1 Foam=1.25	0.54	0	0	6.4
14	Store	130.9	445.1	Wood=1.35	0.23	0	0	4.0
17	Store	141.6	481.4	Wood=1.35	0.21	0	0	3.7
16,18	Office	40.0	136.0	Wood=0.18 Foam=0.14	0.1	5.5	6.5	4.0
15	Office	22.8	77.5	Wood=0.14 Foam=0.08	0.04	2.4	5.7	4.0
21	Office	48.0	163.2	Wood=0.21 Foam=0.14	0.08	4.6	5.4	4.0

5 Results and Discussion

From previous results it is clear that annual cooling energy consumption is approximately 8 times higher than annual heating energy consumption. Therefore, daily cooling energy demand was analysed for three different types of spaces for both floors separately. Two-way ANOVA was used to determine the variations in cooling energy consumption in different types of zones with variation of different parameters. For the regression analysis, three zones were selected from each floor based on three different types of spaces identified in section 2 (Figure 5 & 6). Their location, size, orientation and other details can be found in figure 1 and table 8. For each zone, five parameters were considered and varied as per the results of prototype study. This analysis was used in order to determine the respective influence of different zones and strategy variations on cooling energy consumption.

Independent application of various parameters on whole building pointed out the significance which one parameter had over another in terms of achieving maximum reduction in annual energy consumption. Table 9 summarizes the percentage reduction annual heating, cooling and lighting energy consumption with respect to each parameter.

Table 9. Percentage reduction in annual energy consumptions with respect to each parameter

Parameter	Heating energy	Cooling energy	Lighting energy
Interior thermal mass	0.4%	0.54%	-
Volume	13.3%	15.6%	-
Thermostat setting	1.9%	19.4%	-
Window operation	-	2.2%	-
Lighting type	2.8%	-	12.68%
Lighting control	-	3.8%	74.4%

Reduction due to thermal mass is nominal because of the low volume percentage of different materials. Adaptive Comfort Criteria restricted us to maintain the heating setpoint temperature at 22°C only. Therefore, percentage reduction in heating energy consumption due to thermostat setting is not very prominent, while the same parameter resulted in maximum reduction in cooling energy compared to others.

Varying all parameters as per specifications defined in section 4 (based on prototype results) simultaneously for the whole building resulted in the following –

Annual cooling energy consumption = 177706.7 kWh, showing reduction of 37.6%.
Annual heating energy consumption = 23603.1 kWh, showing reduction of 9.9%.
Annual lighting energy consumption = 9848 kWh, showing reduction of 72.4%.

Also, for the whole building, net conditioned floor area of 2173.1 m2, the cooling energy amounted to EPI of 81.8 kWh/ m^2/ year as opposed to the initial 131 kWh/ m^2/ year calculated under baseline conditions.

From two way ANOVA and regression analysis it was found that for ground floor there was a statistically significant interaction between the effect of parameter and zones on cooling energy consumption, $F(8, 2280) = 4.28$, $p < 0.05$. Variation in daily cooling energy consumption due to zones was found to be significant, $F(2, 760) = 260.8$, $p < 0.05$. The same is reflected in the graph shown in figure 5. For a same parameter, say interior thermal mass, cooling energy for zone 16 was 30% and 25% lower than that for zone 8 and zone 17 respectively. This can be attributed to the fact that zone 16 represents an office which is much smaller in size than the classroom (zone 17) and lab (zone 8). However, zone 8's cooling energy consumption is approximately 8% higher than zone 17 even though there size is almost same. This can be attributed to the sensible heat gain of 9.9 W/m^2 from computers and other equipments inside the lab. The similar behaviour is exhibited by all three zones for other four strategies also.

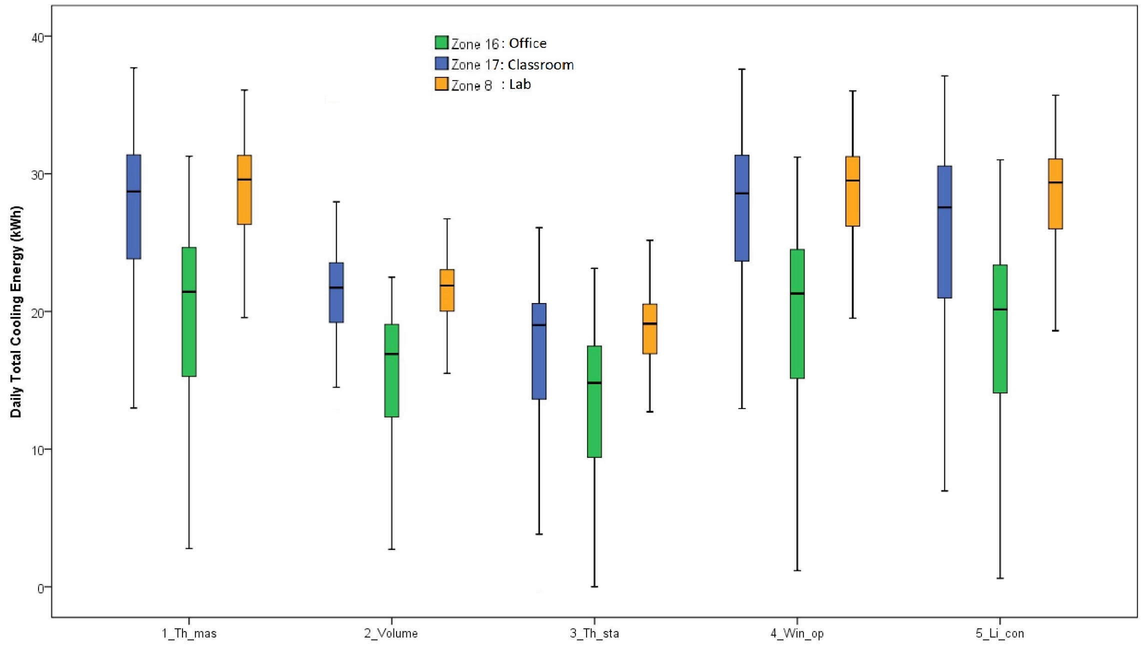

Figure 5. Influence of parameters and zones on cooling energy consumption – Ground Floor

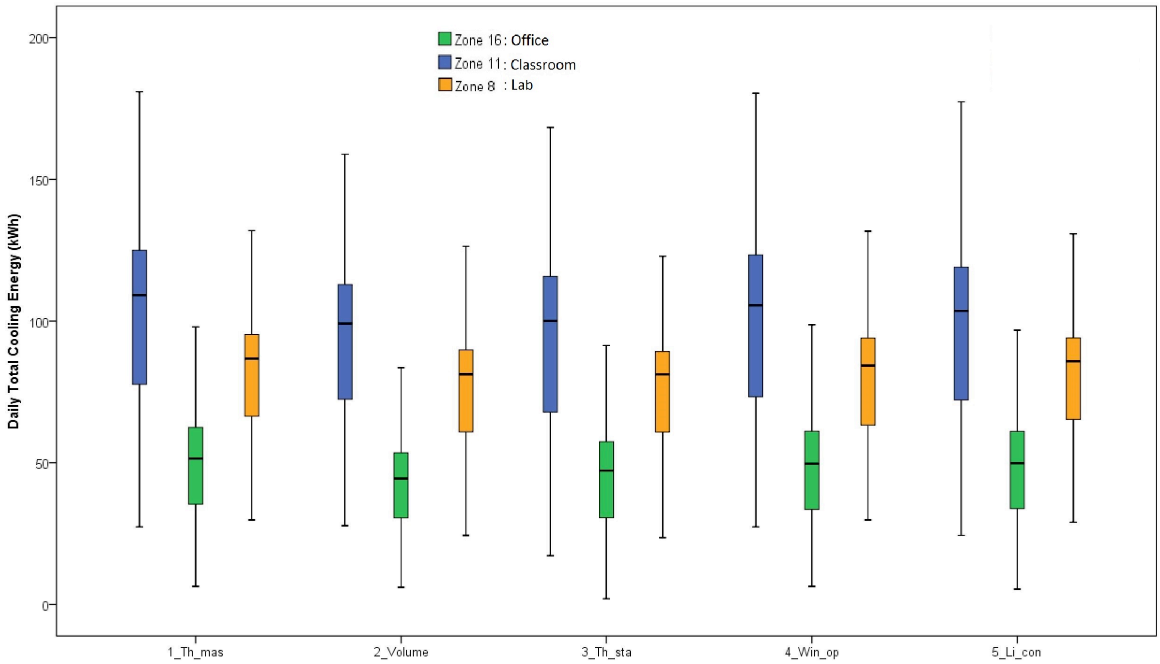

Figure 6. Influence of parameters and zones on cooling energy consumption – First Floor

Also, variation in daily cooling energy consumption due to different parameters in different zones was found to be significant, $F(4, 456) = 173.9$, $p < 0.05$ (Figure 5). For a same zone, say zone 16, highest reduction in cooling energy consumption was attributed to thermostat setting followed by volume parameter. It should be noted here that when we say attributed to thermostat setting or volume, it implies that we are talking about the parameters applied with modified settings as per the best scenario results obtained from prototype study.

Modifying interior thermal mass resulted in least reduction in cooling energy consumption compared to other parameters. Consumption due to thermostat setting and volume was 32% and 22% less than due to thermal mass respectively. The similar pattern is evident by all five strategies for zones 17 and 8.

For first floor, the interaction between the effect of parameters and zones on cooling energy consumption was found to be statistically insignificant, $F(8, 2280) = 0.66$, $p > 0.05$ while variation in cooling energy due to zones was found to be very significant, $F(2, 760) = 709.6$, $p < 0.05$. The same is reflected in the graph shown in figure 6. For all parameters, cooling energy consumption is around 52%-54% higher in zone 11 and 40%-41% higher in zone 8 compared to zone 16 whereas variation in energy consumption between zone 11 and 8 was approximately 16%-20%, zone 11 consuming higher energy. The above variations can be attributed to the size of the zone, zone 16 being smallest compared to other two.

It can also be seen from figure 6 that variation due to parameters is not very prominent in different zones, $F(4, 456) = 5.06$, $p < 0.05$ on the first floor as opposed to that on the ground floor. For a same zone, different parameters are showing almost same energy consumption trends with difference in mean value of each other as low as 0.4 kWh to a maximum of 9.8 kWh.

6 Conclusion

This paper reviewed various parameters pertaining to internal thermal loads and various operational strategies and the effect of their variation on a building's annual energy consumptions. It was found that while some parameters can lead to very significant reductions in energy consumptions, effect of others were not so prominent. By varying the parameters it was possible to achieve a reduction of approximately 38% and 10% in annual cooling and heating energy consumption respectively. Annual lighting energy consumption was reduced by 72.4%. It was also found through two-way ANOVA and regression analysis that the effect of various parameters on cooling energy consumption is context based i.e. it varied significantly depending upon the type and use of space for both exposed and unexposed roof conditions. First floor showed greater energy demand since its roof was exposed to exterior environmental conditions. Annual cooling energy consumption for first floor was 88% more than that of ground floor while annual heating energy was only 2.8% more. This can be attributed to the hot and dry summer months which are much longer compared to short winters and lack of thermal insulation in roof slab.

In the coming years the need for energy efficient buildings will continue to grow and it will become imperative to limit energy consumption by the buildings through every means possible. The strategies discussed in this paper provide considerable energy savings in a composite climate of India. Some of the operational strategies such as window operation, thermostat setting etc. do not require any additional capital investment and can be easily practiced by personally motivated individuals.

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Effect of location specific climatic diversities on comfort and energy consumption: A study on India's composite climate zone

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Abstract

This paper deals with climate severity variations experienced within the composite climate of India and its impact on comfort and energy consumption in residential buildings. We carried out a statistical clustering analysis of climate data for 20 different urban centres within this climate. A statistically significant difference in thermal severity was found between these locations. Adaptive thermal comfort criteria at these locations were evaluated based on seasonal average outdoor temperatures (Tout) and running mean outdoor temperatures (Trm) and the desirable indoor comfort band width was established. A typical residential base case model complying with national standards was simulated using Energy Plus software tool. Thermal performance variations in the base case as a result of location specific climate severities was analysed and its impact on the associated heating and cooling energy costs have been presented. Variances in the sensitivity of building envelope thermo-physical properties based on their impact on comfort and energy use between these locations was analysed. Life cycle costs associated with optimum retrofit strategies and differences in the cost-benefits among these locations have been presented. The findings highlight the advantages of envelope benchmarks which would include location specific performance and cost-benefit aspects over the existing climate zone wise benchmarks.

Keywords: Climate diversity, comfort, energy, cost.

1 Introduction

Thermal comfort is a basic necessity for any building as people spend a considerable time of their life in indoor environments. Comfortable environment is essential for general well-being and for improving the performance. Any building should be designed considering different aspects for making it thermally comfortable, rather than making it comfortable later using active systems. Several studies have been carried out in this field to make the building thermally comfortable at the design stages itself. Standards such as Energy Conservation Building Code (ECBC) are developed to provide general guidelines for designing for comfort and energy efficiency. These guidelines help to attain an acceptable range of parameters for indoor environmental quality. Studies were conducted by adopting several methods for the same. ECBC provides regulations for envelope performance through thermos-physical properties in terms of wall thermal transmittance (U-Value) and allowable window area (window to floor area ratio). This limits the maximum allowable inside surface temperature for walls and roofs.

Efficiency of buildings depend on the interactions between climate, building and occupant. Appropriate management of climate factors, building parameters and user behaviour results in a comfortable and efficient built environment. Understanding of the climate in which the building is located is a key factor for designing for comfort. Present standards provide generalised guidelines for different climate zones. However, there is a greater need for subcategorising the climate zones as the climate patterns are different across cities, even within the same climate zone. A study by M. Roriz, et al. shows the need for subcategorization based on climate diversities and method for subcategorization (Roriz, et al., 1999). In this study, they divided the Brazilian territory into 6500 cells and each cell were characterised by its geographic position and the monthly average of maximum temperatures, minimum temperatures, and relative humidity. This data was then used for categorising the city into different zones based on climatic factors. Studies shows that the climate diversity is common phenomenon throughout the globe. In a study to understand the thermal conditions of Nigeria, a similar phenomenon was observed (Eludoyin, et al., 2014). This study shows categorisation of climate zones based on temperature, relative humidity, effective temperature (ET), temperature–humidity index and relative strain index. Monthly temperature and relative humidity records for 59 years were used for this categorisation. The study also says that factors like urbanisation affect the climate diversity between cities. Another study by Aniruddha, et al. to delineate the comfort zone using GIS showed that the climate zone prescribed by the National Building Code of India (NBC) has further classifications. (Aniruddha, et al., 2015) The analysis of the weather data and the GIS data shows that there are variations in the climatic behaviour within one climate zone itself. In this study they further classify the climate zones based on the climatic behaviour so that the strategies for the fine zones will be almost similar. This helps the architect to take location specific decisions on design at the early design stage itself, improving the thermal comfort and efficiency of the buildings. Study by G.Fovell, et al. shows regionalisation of United States using hierarchical cluster analysis on temperature and precipitation (G.Fovell & C.Fovell, 1993). The climate data was analysed by grouping into 8, 14 and 25 clusters and the best clustering approach was adopted for the subcategorization of climate zones.

Growing energy use has resulted in issues such as over supply difficulties, depletion of energy resources and other environmental impacts. Energy consumption of residential and commercial buildings has increased between 20% and 40% in developed countries (Perez-Lombard, et al., 2008). Increasing demand for building services and comfort levels is a major reason for this. HVAC systems energy use itself is 50% of the building consumption and 20% of total consumption in the USA. The outdoor climate factors play a major role on the building thermal comfort performance which directly affect the energy consumption. The study by Trine Dyrstad Pettersen shows the variation of energy consumption due to climate, building and the users (Pettersen, 1994). Statistical analysis shows that climate factors such as temperature, humidity, wind, solar radiation, snow affect the energy consumption in buildings. A study by C.K. Cheung, et al. shows the increase in energy consumption in order to improve indoor thermal comfort (Cheung, et al., 2005). The study shows statistics of increase in usage of air-conditioners in high-rise apartments in China. This shows a need for developing passive strategies for improving thermal comfort. The study investigates the effect of six passive design strategies - insulation, thermal mass, glazing type, window size, colour of external wall and external shading devices. Another study by N. Bouchlaghem also shows the need for optimising the building envelope for thermal performance (Bouchlaghem, 2000). This study explains that there are two types of parameters affecting the thermal performance of the buildings. The first one include the climatic parameters such as solar radiation, air temperature, relative humidity and wind direction. The second one includes the design variables controlled by the architect/designer. Several other studies such as (Danielle , et al., 2012), (Che-Ming & Chi-Ming, 2002), (Rajasekar , et al., 2014), (Niklas, et al., 2007), (Monika & Pawel, 2011) also shows the importance of thermal comfort and energy efficiency. These studies have analysed different factors affecting indoor environmental quality, methods for determining the comfort and efficiency and also measures for improving them. Study by Holmes, et al. shows the need of using climate sensitive passive or low-energy design strategies in order to achieve thermal comfort (Holmes & Hacker, 2007). This will directly reduce the energy consumption in buildings to a large extend.

This article aims at studying the composite climate zone in India and the climate diversity within 20 selected cities in composite climate zone. The study investigates the effect of climate diversities on buildings' thermal comfort performance and the associated energy consumption. The cost implications of the strategies required for improving the thermal comfort in order to make the building compliant to ECBC were also analysed. Figure 1 shows the methodology adopted for this study.

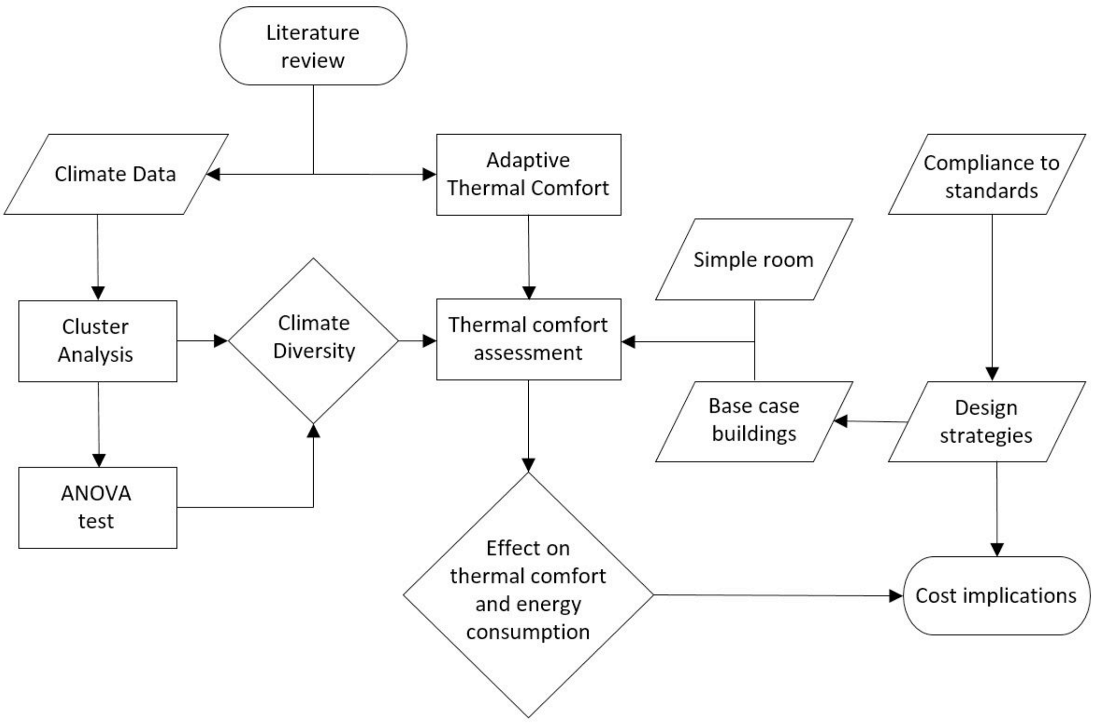
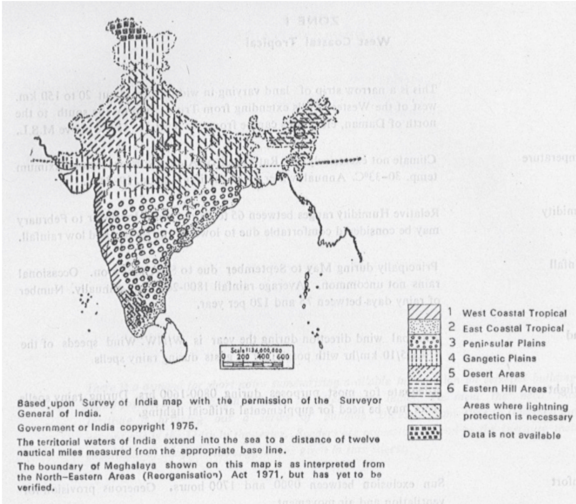


Figure 1. Methodology for the study

2 Background of the study

India had been broadly classified into six climatic zones for the purpose of building design (Narasimhan & Sharma, 1975) namely west coastal tropical, east coastal tropical, peninsular plains, gangetic plains, desert areas and eastern hill areas (Figure 2a). This was later replaced by the current system which classifies the country into five major zones namely hot-dry, warm-humid, temperate, cold and composite climate zones (Figure 2b). This is widely adopted by the national building code (NBC) as well as the energy conservation building code (ECBC) of India. Among the five zones, compose climatic zone represents more than 30% of India's geographic extent and includes 20 major urban centers including the capital city of New Delhi. The analysis and discussions in this article are focused on this climate zone.



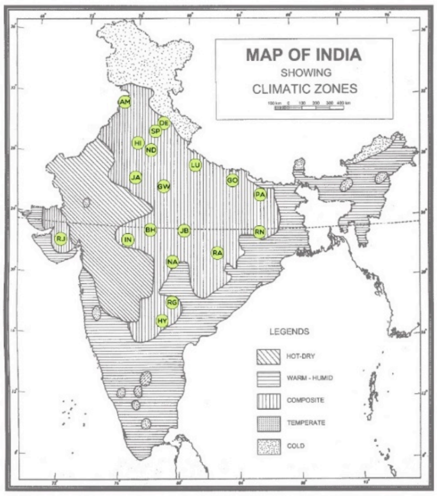


Figure 2. (a) Climate classification – old (b) Current climatic classification

3 Characteristics of the composite climate

The national building code defines composite climate as one which does not have the prevalence of any of the first four climates for six or more months in a year. Composite climate locations typically experience hot summers with daily outdoor temperature maximum ($T_{out\text{-}max}$) of about 40^o C- 44^{o}C and temperature minimum ($T_{out\text{-}min}$) of about 27^{o}C – 32^{o}C. They experience cold winters where $T_{out\text{-}min}$ falls up to 3^{o}C – 10^{o}C. They experience relatively dry summers with relative humidity (RH) ranging from 20%-30% and a period of humid post-summer where RH ranges between 60% – 90%. Intensity of direct solar radiation is very high during summer and that of diffuse radiation is high during post-summer months due to overcast sky conditions. The ECBC prescribe a set of thermal considerations for conditioned as well as naturally ventilated buildings located in this zone (Table 1).

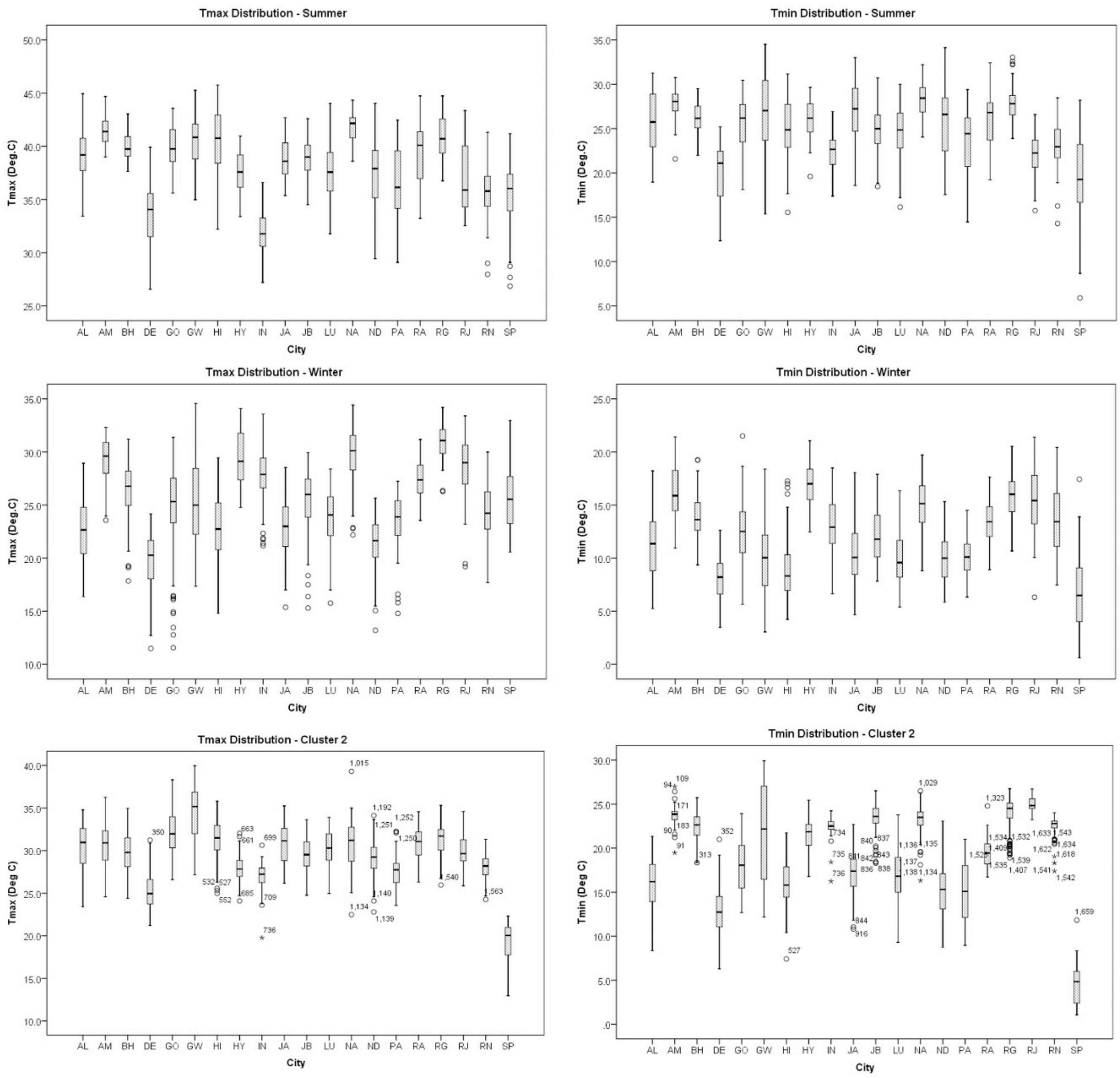
Table 1. ECBC recommended values

	24 hour use buildings	Daytime use buildings	WWR<= 40%	40%<WWR<= 60%
Component	**Maximum U-factor of overall assembly (W/m^{2}K)**	**Maximum U-factor of overall assembly (W/m^{2}K)**	**Maximum SHGC**	**Maximum SHGC**
Roof	U-0.261	U-0.409	-	-
Wall	U-0.440	U-0.440	-	-
Fenestration	U-3.30	U-3.30	0.25	0.2

The present study is intended to analyse and report the variations in thermal severities, resultant building performances in terms of thermal comfort and energy consumption. For this purpose, we consider twenty urban centres namely Allahabad (AL), Amritsar (AM), Bhopal (BH), Dehradun (DE), Gorakhpur (GO), Gwalior (GW), Hissar (HI), Hyderabad (HY), Indore (IN), Jabalpur (JB), Jaipur (JA), Lucknow (LU), Nagpur (NA), New Delhi (ND), Patna (PA), Raipur (RA), Rajkot (RJ), Ramagundam (RG), Ranchi (RN) and Saharanpur (SP).

3.1 Climate diversity analysis

Historic weather data of these twenty locations made available by Indian society of heating refrigeration and air conditioning engineers (ISHRAE) which are typically being used for building simulations were considered for the study. Considering the daily $T_{out\text{-}max}$, $T_{out\text{-}min}$, average RH (RG_{avg}) and average global solar radiation (GR_{avg}) a statistical cluster analysis was carried out for each of the twenty locations. This analysis typically groups the days of a year based on the statistical nearness of the four variables being considered. In this method, we found that the number of clusters varied between 4 and 5 for these locations. For the purpose of uniformity the maximum number of clusters were restricted to 4. The four clusters represent hot season (CL_1), cold season (CL_2), moderate season (CL_3) and monsoon season (CL_4). Figure 3 graphically compares the variation of $T_{out\text{-}max}$ and $T_{out\text{-}min}$ among the cities in the four clusters which show a wide difference in terms of the observed ranges.



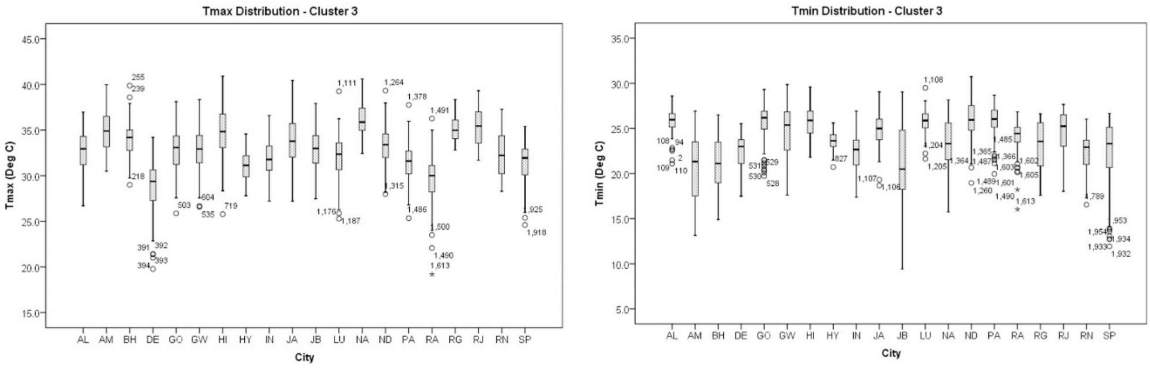


Figure 3. Statistical summary of $T_{out\text{-}max}$ and $T_{out\text{-}min}$

A more detailed summary of the analysis results are presented in table 2. It provides the summary of the variables in CL_1 and CL_2, the extent of their prevalence in the twenty cities and sequences them in decreasing order of severity during summer and winter. Mean values (μ) of the four variables in the two clusters and the number of days for which the cluster prevails have been shown in the table. For instance, μ-$T_{out\text{-}max}$ is found to be highest in Nagpur (NA) but it prevails for a duration of 58 days while that in Jaipur (JA) is found to be slightly lesser but prevails for a duration of 124 days. The table also provides the peak $T_{out\text{-}max}$ recorded in the corresponding location for a comparison purpose. Though the peak $T_{out\text{-}max}$ in some of the cities like Hissar (HI) and Allahabad (AL) exceed 45^{o}C they are positioned lower in the order, since the cluster analysis considers the relative variations in $T_{out\text{-}min}$, RH_{avg} and GR_{avg} on the corresponding days.

Table 2. Summary of hot and cold clusters

CL_1						CL_2					
City	**Peak $T_{out\text{-}max}$**	**μ-$T_{out\text{-}max}$**	**μ-RH_{avg}**	**μ-GR_{avg}**	**No of Days**	**City**	**Peak $T_{out\text{-}max}$**	**μ-$T_{out\text{-}max}$**	**μ-RH_{avg}**	**μ-GR_{avg}**	**No of Days**
NA	44.6	42.1	26.1	1081.9	58	SP	0.1	5.4	74.0	725.2	144
AM	45.0	41.7	33.5	1035.9	66	HI	3.2	8.6	69.5	667.3	110
GW	45.5	41.2	37.6	997.7	68	DE	3.3	9.3	65.4	655.8	150
RG	45.5	40.8	46.6	991.6	86	GW	2.8	9.4	62.7	652.0	126
HI	46.1	40.6	46.5	999.0	77	PA	5.6	9.5	77.8	441.4	62
RA	45.1	39.9	39.8	1020.6	95	ND	5.2	9.6	72.1	614.1	96
AL	46.0	39.1	45.2	992.9	93	JA	3.7	10.1	62.5	603.4	55
LU	44.3	39.0	47.1	1003.4	59	GO	5.4	10.3	87.3	496.9	35
RJ	43.9	38.6	58.9	1134.6	102	LU	4.8	10.6	70.3	711.7	124
JA	42.9	38.3	41.3	999.3	124	AL	4.5	10.7	73.7	629.8	83
ND	44.3	37.7	48.3	955.5	103	JB	7.4	11.2	72.3	615.7	53
BH	43.5	37.6	33.8	1068.4	100	RN	6.8	12.1	67.7	648.1	87
IN	41.8	37.4	29.8	1131.0	97	IN	6.3	12.3	49.5	812.6	129
HY	40.7	37.4	45.9	1040.1	102	RA	8.0	13.0	59.4	700.5	81
JB	42.7	37.4	44.4	990.2	109	BH	9.0	13.2	50.8	737.7	123
PA	43.0	37.3	51.1	983.3	90	RJ	6.1	13.7	53.2	778.2	82
GO	44.0	37.1	54.5	948.2	98	NA	8.4	14.2	53.3	781.2	121
RN	41.6	35.7	50.0	1031.2	88	AM	10.3	15.6	58.3	563.6	95
SP	41.5	35.5	55.6	1004.1	67	RG	9.9	16.3	66.1	758.2	128
DE	40.1	32.9	53.3	879.4	95	HY	11.7	16.4	51.9	818.4	91

Figure 4 presents the relation between $T_{out\text{-}max}$ and GR_{avg} in CL_1 and CL_2. The size of the bubble indicates the extent or duration of the hot and cold seasons (larger the bubble, longer the season). We find that there is a considerable diversity among these locations in terms of both severity and duration of the hot and cold seasons.

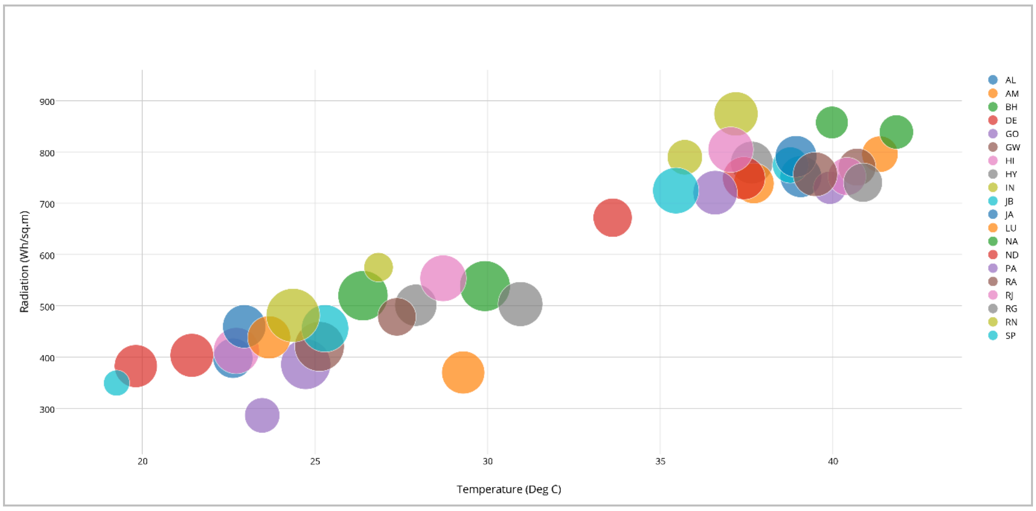


Figure 4. Relation between $T_{out\text{-}max}$ and GR_{avg} during hot and cold seasons

In order to ascertain the significance of diversity between the four clusters among the twenty locations, we carried out analysis of variance (ANOVA) tests with the clustered data. The results of the ANOVA tests are summarized in table 3. The results indicate that there is a statistically significant difference in the population means of clusters in the twenty locations. Similarly homogeneity of variance tests (Levene's test of absolute deviations) indicate that the population variances are significantly different in the twenty locations.

Table 3. Results of ANOVA test

		μ-$T_{out\text{-}max}$	**μ-$T_{out\text{-}min}$**	**μ-RH_{avg}**	**μ-GR_{avg}**
CL_1	Mean	$F(19,1569) = 55.55$ $p<0.01$	$F(19,1569) = 50.79$ $p<0.01$	$F(19,1569) = 71.77$ $p<0.01$	$F(19,1569) = 77.73$ $p<0.01$
	Variance	$F(19,1569) = 11.32$ $p<0.01$	$F(19,1569) = 13.88$ $p<0.01$	$F(19,1569) = 4.71$ $p<0.01$	$F(19,1569) = 13.67$ $p<0.01$
CL_3	Mean	$F(19,1649) = 103.1$ $p<0.01$	$F(19,1649) = 249.6$ $p<0.01$	$F(19,1649) = 236.1$ $p<0.01$	$F(19,1649) = 123.9$ $p<0.01$
	Variance	$F(19,1649) = 6.82$ $p<0.01$	$F(19,1649) = 48.95$ $p<0.01$	$F(19,1649) = 13.47$ $p<0.01$	$F(19,1649) = 9.39$ $p<0.01$
CL_4	Mean	$F(19,1933) = 64.05$ $p<0.01$	$F(19,1933) = 55.49$ $p<0.01$	$F(19,1933) = 206.7$ $p<0.01$	$F(19,1933) = 177.0$ $p<0.01$
	Variance	$F(19,1933) = 2.96$ $p<0.01$	$F(19,1933) = 29.05$ $p<0.01$	$F(19,1933) = 26.64$ $p<0.01$	$F(19,1933) = 6.36$ $p<0.01$
CL_2	Mean	$F(19,2068) = 119.1$ $p<0.01$	$F(19,2068) = 121.10$ $p<0.01$	$F(19,2068) = 117.14$ $p<0.03$	$F(19,2068) = 126.5$ $p<0.01$
	Variance	$F(19,2068) = 8.65$ $p<0.01$	$F(19,2068) = 8.09$ $p<0.01$	$F(19,2068) = 11.53$ $p<0.01$	$F(19,2068) = 7.25$ $p<0.01$

3.2 Evaluation of Adaptive thermal comfort

The optimum comfort temperatures (T_{comf}) for the twenty locations were calculated using the method proposed by Brager and de Dear (2001) represented in equation 1.

$$T_{comf} = 0.31 \times T_{out-\mu} + 17.8 \qquad \text{- eq. 1}$$

Figure 5 shows the comfort range evaluated for hot and cold clusters of the twenty cities. For the purpose of T_{comf} evaluation cluster mean T_{out} averages have been considered. We find that the T_{comf} varies from about 31°C to 24°C during the hot season and 28°C to 20°C during the cold season.

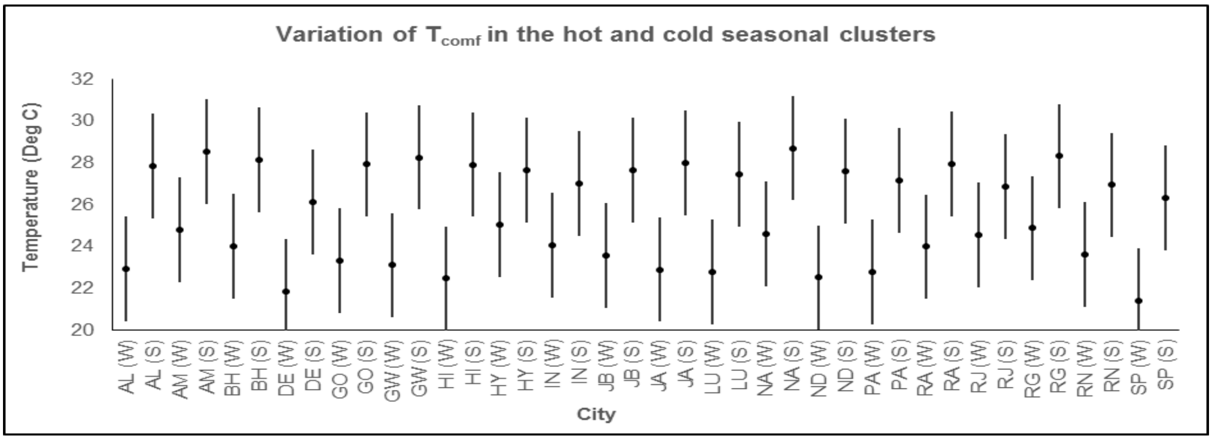


Figure 5. Variation of T_{comf} in hot and cold seasonal clusters

For the purpose of a detailed analysis climate and building performance in three cities – Nagpur, New Delhi and Dehradun – which represent the high, mid and low severity locations (based on the cluster analysis) have been discussed further. Cluster wise Adaptive Thermal Comfort range for the three cities have been calculated to analyse the comfort requirements in these cities. Table 4 shows the adaptive thermal comfort temperatures in Dehradun, Nagpur and New Delhi.

Table 4: Adaptive thermal comfort temperatures

CITY	Cluster	$T_{comf - min}$	$T_{comf – mean}$	$T_{comf - max}$
Dehradun	2	19.3	21.8	24.3
	3	21.0	23.5	26.0
	4	23.1	25.6	28.1
	1	23.6	26.1	28.6
Nagpur	2	22.1	24.6	27.1
	3	23.6	26.1	28.6
	4	24.5	27.0	29.5
	1	26.2	28.7	31.2
New Delhi	2	20.0	22.5	25.0
	3	22.0	24.5	27.0
	4	24.4	26.9	29.4
	1	25.1	27.6	30.1

4 Effect of climate diversities in a typical building

In order to evaluate the effect of the above variations on the building performance a simple test room of dimension 4m x 4m x 3.5m was modelled using energy plus software tool. The room was modelled such that its north and west walls were exposed and had a window to wall ratio of 11%. The room was simulated for two different modes – Air conditioned and naturally ventilated modes. Five different cases of operations – fully conditioned, day time conditioned and night ventilated, night conditioned and day ventilated and fully ventilated. For the ventilated building cases, the window operations were controlled using outdoor temperature controls. The building envelope was modelled as per the recommendation of the national building code and the simulations were carried out for the three locations. The room had an occupancy of two people and the internal loads include a computer and lighting loads from CFL lights which provide an illuminance level of 300 Lux. Table 5 presents the results of degree discomfort hours (DDH) based on T¬comf and the cooling/heating energy consumption associated with the test room.

Table 5. Degree Discomfort Hours and Energy consumption (KWh)

Condition		Dehradun	New Delhi	Nagpur
Fully conditioned	Heating energy	909.42	578.7	99.61
	Cooling energy	3108.83	5126.79	5865.44
	Total energy	4018.25	5705.49	5965.05
Daytime conditioned	**DDH**	8920	15114	13730
	Heating energy	2274.8	2038.64	1635.46
	Cooling energy	2173.32	3813.47	4292.88
	Total energy	4448.12	5852.11	5928.34
Night conditioned	**DDH**	18607	22858	23507
	Heating energy	2044.67	1733.75	1375.8
	Cooling energy	1878.68	3401.51	3837.97
	Total energy	3923.35	5135.26	5213.77
Fully ventilated	**DDH**	24136	30041	25572

We find a significant difference in the discomfort hours and annual cooling and heating energy consumption associated with these cities. For instance, under fully conditioned operation, New Delhi and Nagpur consume 42% and 48% more conditioning energy compared to Dehradun. The trend is similar in the case of a day-time conditioned operation. Though the intensity of variation in the case of a night conditioned operation (28% and 30% respectively), the trend in variation was found to be the same.

Based on this assessment, table 6 presents the required modification in building envelope thermal properties which is currently specified, so as to obtain similar energy consumption in these cities. While the objective is neither to recommend a relaxation nor stringency in existing values, it is to highlight the variations in energy saving potential of these cities with the prescribed properties. The impact of the variations on the cost is discussed further in section 6.

Table 6. Weightage factors for Building envelope thermal properties

City	24 Hour AC	Daytime AC	Night AC
RG	-32%	-32%	-33%
NA	-19%	-20%	-21%
AM	-19%	-19%	-21%
RA	-17%	-17%	-18%
GW	-14%	-14%	-15%
AL	-11%	-11%	-11%
HY	-10%	-11%	-12%
JA	-10%	-10%	-11%
RA	-9%	-10%	-11%
HI	-6%	-7%	-7%
GO	-5%	-5%	-4%
ND	-3%	-3%	-4%
JB	-3%	-3%	-4%
PA	0%	0%	0%
LU	2%	2%	2%
BH	5%	3%	3%
IN	11%	8%	8%
SP	19%	18%	18%
RN	20%	19%	19%
DE	31%	30%	30%

5 Effect of climate diversities on an apartment and an office buildings

The impact of location-specific climate severity variations on the comfort and energy consumption was further studied considering a typical residential unit and an office space. Figure 6 shows the floor plans of the residential unit and office space considered in the analysis. Both these units were modelled in energy plus tool. The residential unit had a floor area of 157 m^2 in which major occupied spaces include a living room (unconditioned), four bedrooms (conditioned), a kitchen and a dining space.

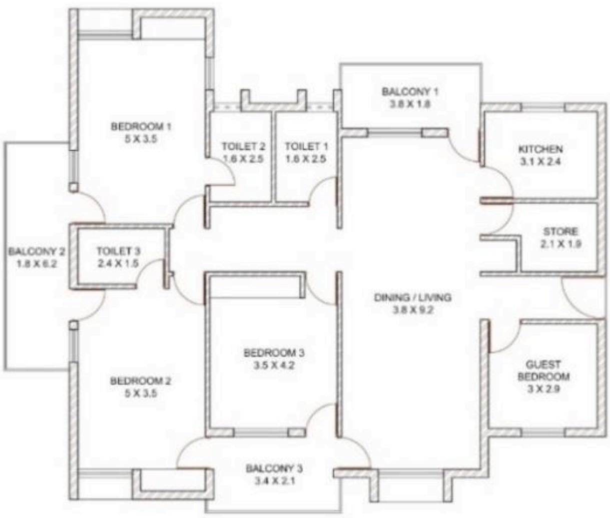


Figure 6 (a). Plan of residential unit

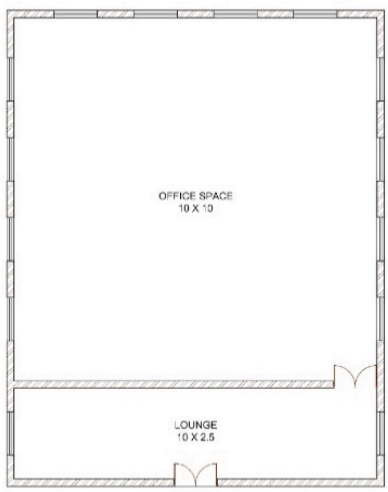


Figure 6 (b). Plan of office space

The office space considered has 100 m^2 floor area with north, east and west facades exposed while the south façade has a lounge acting as a thermal buffer. The exposed wall surfaces have a window wall ratio of 18% and 6mm single layer clear glass (U value = 5.77 W/m^2K, SHGC = 0.82, VLT = 0.88) is used for window glazing. 20cm thick brick wall with U value = 1.57 W/m^2K is used for construction. The office space can accommodate 15 people comfortably and has a room height of 3.5m.

Study shows that the apartment in New Delhi consumes less energy for heating and cooling as compared to Dehradun and Nagpur. Similar apartment at Dehradun consumes 3% more energy than New Delhi and that at Nagpur consumes 6% more energy than New Delhi, considering the three bedroom energy consumptions. For the building at Dehradun Bedroom 1 consumes 21% more energy and bedroom 2 consumes 17% more energy than bedroom 3. A similar trend can be seen for other cities also. Table 7 presents the summary of thermal comfort and energy consumption in the bedroom spaces of the residential unit considering three climatic locations.

Table 7. Degree Discomfort Hours and energy consumption (KWh) - Apartment

Condition		**Dehradun**			**New Delhi**			**Nagpur**		
		Bed room 1	Bed room 2	Bed room 3	Bed room 1	Bed room 2	Bed room 3	Bed room 1	Bed room 2	Bed room 3
Ventilated	DDH (Heat)	15884	19433	35017	29256	34189	51924	32419	38626	60530
	DDH (Cold)	26229	20954	11144	20097	15561	7720	8550	5765	1333
	DDH (Total)	42113	40386	46160	49353	49751	59644	40969	44390	61862
Night AC	DDH (Heat)	12659	14161	19564	25812	25860	26412	23730	26018	31509
	DDH (Cold)	10416	8165	4918	1566	1525	1502	2637	1887	920
	DDH (Total)	23075	22325	24482	27378	27386	27914	26367	27905	32429
	Heating energy	528.6	337.0	203.6	420.0	252.1	148.4	9.9	3.2	1.0
	Cooling energy	5088.5	5076.3	4430.1	5028.1	5028.0	4324.5	5540.9	5661.1	4926.0
	Total energy	5617.1	5413.2	4633.7	5448.0	5280.1	4472.9	5550.8	5664.3	4927.0

The annual energy consumption of the office space and its variations in the three cities is shown in table 8. The office space located at New Delhi consumed less energy as compared to Dehradun and Nagpur. Similar office space at Dehradun consumes 1% more energy than New Delhi and that at Nagpur has a 13% increase in energy consumption than New Delhi.

Table 8. Annual energy consumption (KWh) – Office space

	Dehradun	**New Delhi**	**Nagpur**
Heating	624.4	405.4	2.5
Cooling	24722.7	24679.2	28671.9
Total	25347.1	25084.6	28674.3

6 Assessment of economic impacts of the climate diversities

The economic implications associated with the climate diversities were assessed through life cycle cost analysis. We considered the energy consumption predicted using energy plus simulations and converted it to cost by considering the electricity rates in the three cities. Four different strategies were analysed and the cost implications are presented in table 8. Among these, strategy-1 (65mm external XPS insulation) and 3 (Glass 1 - Double glazing with U value = 1.8W/m^{2}K, SHGC = 0.2, VLT = 0.24) were considered so as to meet the prescribed ECBC envelope performance limits. Strategy 2 (100 mm exterior XPS insulation) and 4 (Glass 2 - Double glazing with U value = 1.5 W/m^{2}K, SHGC=0.2, VLT = 0.32) were considered so as to exceed the ECBC recommendations and considering the common industry practice.

Results shows that there is a considerable improvement in thermal performance and thus reduction in energy consumption costs by using these strategies. However, the initial investment for adding the strategies will be higher and hence the total cost (energy consumption cost + initial investment cost) will be higher. But in the longer run, there will be a higher savings as compared to the actual case energy consumption costs by using these strategies, even after considering the initial investment cost. The payback time required for these strategies were also calculated. Results are as shown in Table 9.

Table 9. Results of economic assessment

Strategies	Reduction in energy cost			Payback period (months)			Savings after 20 years		
	Dehradun	**New Delhi**	**Nagpur**	**Dehradun**	**New Delhi**	**Nagpur**	**Dehradun**	**New Delhi**	**Nagpur**
65mm exterior XPS insulation	24%	23%	25%	48	44	31	19%	18%	21%
100mm exterior XPS insulation	24%	24%	26%	73	67	47	16%	16%	20%
Glass 1	7%	10%	11%	20	12	10	6%	10%	11%
Glass 2	6%	10%	11%	22	13	10	6%	9%	10%

7 Discussions and conclusion

This paper presented the effect of climate diversities on indoor thermal comfort and the associated energy consumption. Composite climate zone of India extends over 30% of the area and thus shows a varied pattern at different cities. The clustering of climate data using the weather files obtained from ISHRAE showed the distribution of climate throughout the year. The clusters obtained roughly represents the four seasons and analysis showed that climate distribution has a considerable difference in the 20 cities studied within the composite climate zone. For instance, μ-$T_{out\text{-}max}$ is found to be highest in Nagpur (NA) but it prevails for a duration of 58 days while that in Jaipur (JA) is found to be slightly lesser but prevails for a duration of 124 days. Further the one way ANOVA test showed that the climatic variation between the cities is prevalent. The higher F values shown in table 3 represents this.

Detailed analysis of climate and building performance in three cities – Nagpur, New Delhi and Dehradun were carried out. These cities represent the high, mid and low severity locations (based on the cluster analysis). The adaptive thermal comfort ranges showed that these cities have different requirements. For instance the summer ATC range at Dehradun is 23.6 to 28.6^{o}C. The same at New Delhi is 25.1 to 30.1 ^{o}C and at Nagpur is 26.2 to 31.2^{o}C.

Effect of climate diversities on thermal comfort and energy consumption were presented based on the simulations using virtual models of a simple room with dimensions 4m x 4m x 3m. The indoor thermal comfort conditions were assessed and compared using Degree Discomfort Hours (DDH). Results showed that similar buildings in these cities had a varied thermal performance and energy consumption pattern. For instance, under fully conditioned operation, New Delhi and Nagpur consume 42% and 48% more conditioning energy compared to Dehradun. The trend is similar in the case of a day-time conditioned and night conditioned operation. Similar assessment was carried out for an actual apartment building of 157sqm area and a hypothetical 100sqm office space. Analysis shows that the apartment at New Delhi consumes less energy for heating and cooling as compared to that at Dehradun and Nagpur. Similar apartment at Dehradun consumes 3% more energy than New Delhi and that at Nagpur consumes 6% more energy than New Delhi. The rooms in the same building showed a varied thermal performance, which proved the importance of orientation. In the building at Dehradun, Bedroom 1 consumes 21% more energy and bedroom 2 consumes 17% more energy than bedroom 3. A similar trend can be seen for other cities also. Thus this article validated the difference in thermal comfort and energy consumption due to climate diversities. This study also helps to compare between cities and choose the site accordingly for better thermal performance and savings.

The cost implications of this difference in energy consumption were also analysed. The annual energy costs at these cities were calculated using the energy consumption and the unit energy cost at the three cities respectively. Building at Dehradun consumes higher energy than similar building at New Delhi, but considering the unit energy cost, building at Dehradun has lesser annual energy cost. New Delhi and Nagpur has 12% and 45% increase in annual energy costs than Dehradun respectively. Further, 4 strategies to improve the thermal comfort conditions and energy efficiency were assessed. The strategies were adopted such that using them makes the building compliant to ECBC standards. Addition of 65mm thick XPS insulation adds Rs.1,58,035/-, 100mm thick XPS insulation adds Rs.2,43,048/-, Glass 1 adds Rs.19,845/- and Glass 2 adds Rs.20,250/- to the base case (Office space). Hence, the initial total cost, considering annual energy cost and additional investment will be higher, but there is a promising reduction in energy consumption and in the longer run there is bigger saving in energy and cost. For instance, after 20 years, there is a saving of 16% in total cost for the building at Dehradun by adding a 100mm thick XPS insulation to the external walls. The same for similar buildings at New Delhi and Nagpur are 16% and 20% respectively. The payback period for the initial investment to add the strategies were also presented in the paper.

8 Scope for further work

Studies can be carried out by considering more cities and different building conditions. Analysing more cities will help in developing a larger database which can be used to design buildings in accordance to the specific climate diversities and thus attain better performing buildings. This can directly reduce a considerable amount of energy consumption used for conditioning the buildings. These studies can also help in selecting the right passive strategies for improving the buildings' thermal performance. Studies have to be extended to other climatic locations as well.

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The comfort of thermal variability: Short-term thermal transitions in the lobby space in Higher Education Institutions in the UK

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Abstract

This paper presents the results from the evaluation of thermal transitions in lobby areas of three higher education buildings located in Sheffield UK. The study was conducted during the four season of the year 2013-2014 involving 1,749 participants. Guided thermal comfort questionnaires, simultaneous climatic measurements and two spatial routes were used during the surveys. This study quantifies the thermal transitions that people experienced in Naturally Ventilated (NV) lobby buildings in their everyday life and the impact on their short-term thermal history. Findings from this study demonstrate the significance of people's thermal adaptation along the four seasons of the year influencing their short-term thermal perception. New patterns of thermal transitions modifying people's thermal perception were identified along with people's reactions to temperature changes. Results suggest that patterns in thermal perception can be identified in fieldwork, and that it could be possible to alter people's thermal perception in a positive direction through the judicious use of lobby spaces. In the long term, this could help to reverse the effect of Air Conditioning (AC) in people's thermal history and support the theory of the temporal thermal alliesthesia and thermal comfort in non-uniform environments. Further work is needed in this area focused on the energy saving potential.

Keywords: thermal history, transitional spaces, non-uniform environments, higher education buildings

1 Introduction

By 2020 energy demand is expected to increase 10% per 1°C increase in temperature in relation to AC configuration (Chua et al. 2013). The rapid rise on AC installation in climates regions where it is not required will dramatically increase energy consumption. In the UK it is expected that by 2050 all commercial buildings will be air conditioned (Walker, Shove & Brown 2014). Worldwide, strategies to reduce 1°C in air temperature in indoor environments are inconclusive due to the lack of information and understanding of people's thermal perception in real situations and their tolerance to temperature changes.

Recent thinking has revealed that dynamic environments not only offer better thermal comfort opportunities than fixed interior environments, but can also enhance people's thermal comfort perception (Parkinson, de Dear & Candido 2012). Thermal comfort research is expanding beyond the boundaries of fixed interior spaces and sedentary activities into more real, vibrant, variable and dynamic thermal situations that people experience in their everyday lives. Researchers have focused attention on the study of transient thermal environments (Liu et al. 2014; Parkinson, de Dear & Candido 2012), transitional spaces (Hui & Jie 2014; Pitts 2013; Vargas & Stevenson 2014) people's thermal history and thermal addictions (De Vechi, Candido & Lamberts 2016). Other psychological factors are memory, forgiveness and naturalness (Nikolopoulou, Marialena & Steemers 2003), thermal expectations (Jitkhajornwanich & Pitts 2002) and thermal alliesthesia (Parkinson & De Dear 2015). The interplay of all these novel variables may bring to light hidden factors of people's thermal comfort perception. Moreover, there may also be the opportunity to adjust people's thermal perception in a positive way by incorporating thermal variability in people's life thought PCA 'Personal Comfort Systems' (Zhang, Arens & Zhai 2015), temporal and spatial thermal alliesthesia (Parkinson, De Dear & Candido 2015) and repeated short-term thermal experiences (Vargas & Stevenson 2014).

2 Thermal transition in the lobby space

In real life, the thermal environments that people experience on a daily basis are frequently dynamic and transient (Liu et al. 2014). People experience thermal transitions in their daily lives when moving between different spaces as part of their daily routine. Even when remaining in the same place, people can experience transition as temperature can naturally vary over time. The lobby space offers an interesting setting to study thermal transitions because:

- It is an independent space with complex thermal connections to other interior areas
- It is designed to provide a transition space for people in dynamic state
- It offers people short-term experiences and changes in the physical conditions
- People experience repeated thermal transitions every day in the lobby area
- It could offer a key opportunity to help people to have a better thermal adaptation to the indoor environment in the long-term.

Although transient and non-uniform environments have been increasingly explored in the last decade, most of them have been measured in climatic chambers. The aim of this paper is to evaluate how people experience thermal transitions in lobby spaces in real life when moving from the exterior to interior environment. The research is focus on people's short-term thermal history in NV buildings in moderate climates. Lobby spaces in Higher Educational Institutions (HEI) are a particularly good case study for exploring thermal transitions. This is because students are transient users of university building and they move between buildings many times during the day in large numbers (Figure 1). HEI in the UK, also need to reduce CO2 emissions by 80% against the 1990 baseline by 2050 (HEFCE 2010) and are in urgent need of new ways of energy saving solutions.

This paper explores the following questions:

- How much thermal variation is there in the interior spaces comprising the transitional lobby area in a moderate climate, operating with NV and space heating in winter?
- To what extent does the thermal variation of transitional lobby spaces significantly impact on people's short-term thermal history when walking from exterior to interior environments?

Figure 1 Undergraduate students experiencing transition in the indoor and outdoor environment: 1) Arts Tower 2) Student Union 3) Sr. Henry Stephenson Building, Sheffield University, UK.

3 Methodology

Quantitative research using thermal comfort surveys were used for the fieldwork. A first stage involved the determination of a typical lobby unit of study, followed by an extensive thermal comfort survey 2013-2014 on random days during the four seasons of the year. The survey was designed to replicate the way that students use a composite lobby area in their daily routines. Four spaces were analysed in this study: 1) The exterior of the building, 2) the draught lobby, 3) the circulation space and 4) a seminar room. Two trajectories were evaluated (A and B) in order to measure the effect of the use of the lobby area on people's thermal perception in their final destination.

- Trajectory A: Exterior-draught lobby-circulation and seminar room
- Trajectory B: Exterior and seminar room

The lobby unit

The lobby unit in this study includes the main entrance of the building, the draught lobby (double door entry doors), and circulation areas not defined by vertical elements (walls or doors) connecting the draught lobby with interior spaces. A typical lobby layout was identified based on a preliminary survey of 50 new faculty buildings (2007-2012) in 25 Higher Educational Institutions throughout the UK. Based on the findings, a typical lobby unit for this study was proposed as follows:

- Double door draught lobby with parallel sliding doors (from 2.5 to 3.0 metres in width and from 2.5 to 3.5 metres height). Rectangular shape
- Distance between the two parallel doors (draught lobby) from 2.5 to 3.5m in length
- Average height around 3.2 metres (min=2.5m, max=5m)
- Typical average dimension of the immediate internal circulation areas: 5.6 metres width, 6.20 metres length and 5.7 metres height
- Lobby unit layout used mainly as a circulation space (no social areas included)
- NV building operation with heated spaces in winter

Findings from this survey determined the selection of the three case study lobby areas included in this research.

Sheffield, UK

Sheffield is located in South Yorkshire in England, 53.3836° N, 1.4669° W. It has moderate temperatures with a warm summer and rainfall in all months. The average low temperature varies from 2.0°C to 1.7 °C during December, January and February. The maximum average temperature varies around 21°C during July and August. It rains all year round with 8 to 13 rainfall days per month. The peak average wind speed occurs in the months from November to March with fluctuations between 10.9 to 12.3 m/sec. The lowest average wind speed occurs in spring and summer between 5.2 and 3.9 m/sec. The relative humidity fluctuates around 80% and sometimes peaks at 90% during spring (Met-Office-UK 2015).

Case study buildings

Three urban faculty buildings from the University of Sheffield were selected for this study sharing a very similar basic lobby unit design. They operate with NV during summer and with heated interior spaces during winter.

- Sir. Henry Stephenson building (HS)
- Jessop West building (JW)
- The Interdisciplinary Centre of the Social Sciences building: ICOSS Building (ICS)

Surveys Procedure

Participants arrived in smalls groups or individually, and they were assessed immediately one after another. After short instructions, they were asked to use trajectory A or B through the building randomly and to answer each section of the questionnaire at specific points (Figure 2). Subjects were guided thought the different spaces and also signs were located in the line of sight of the trajectories. Two types of 'right here, right now' thermal comfort questionnaires were used, Type A for route A and Type B for route B. Both questionnaires included the instructions, ethics form, thermal comfort perception sections and people's demographics. A seven point ASHRAE scale was used to measure people's thermal perception, three point McIntyre scale for thermal preferences, three point scale for temperature change perception and seven point scales for each of air flow and relative humidity perception. Participants spent 30 seconds in each space while answering the questionnaire and more minutes at the end of the survey filling their demographics information. The trajectories A and B in each building can be seen in Figure 3.

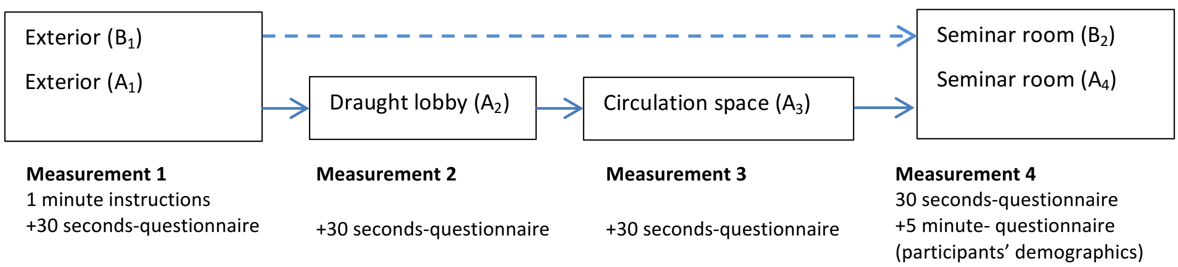
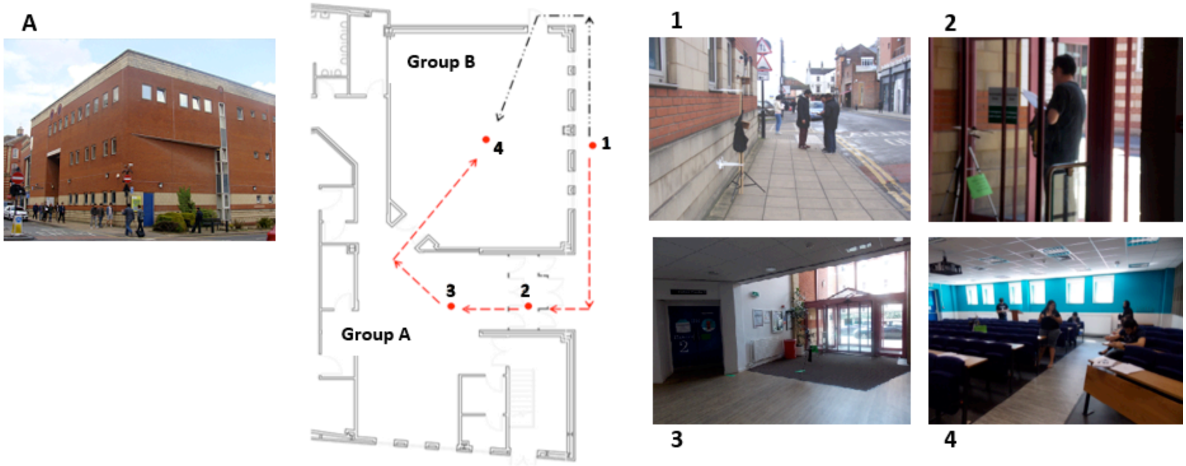
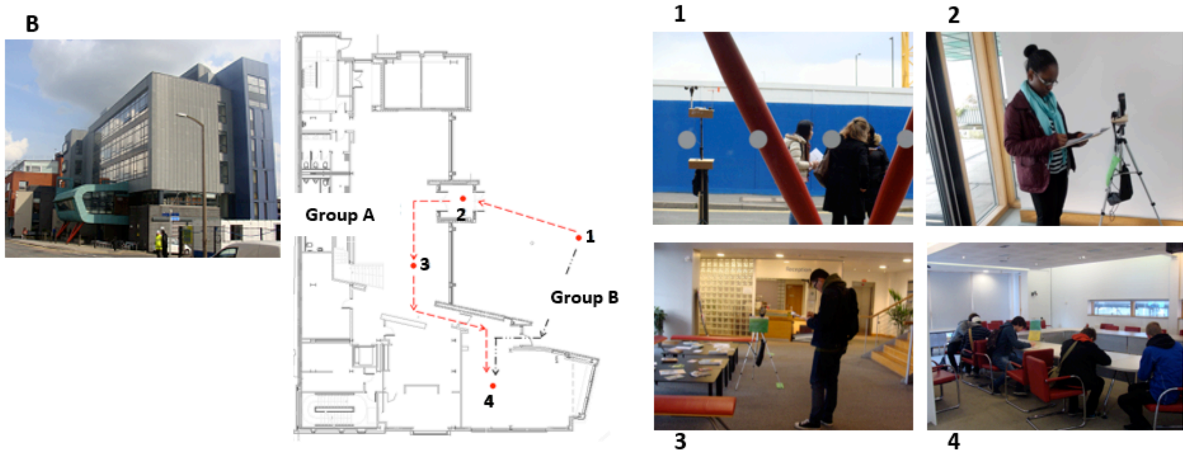


Figure 2 Survey procedure diagram

Case Study 1: Sr. Henry Stephenson Building (HS)



Case Study 2: ICOSS Building (ICS)



Case Study 3: Sr. Jessop West Building (JW)

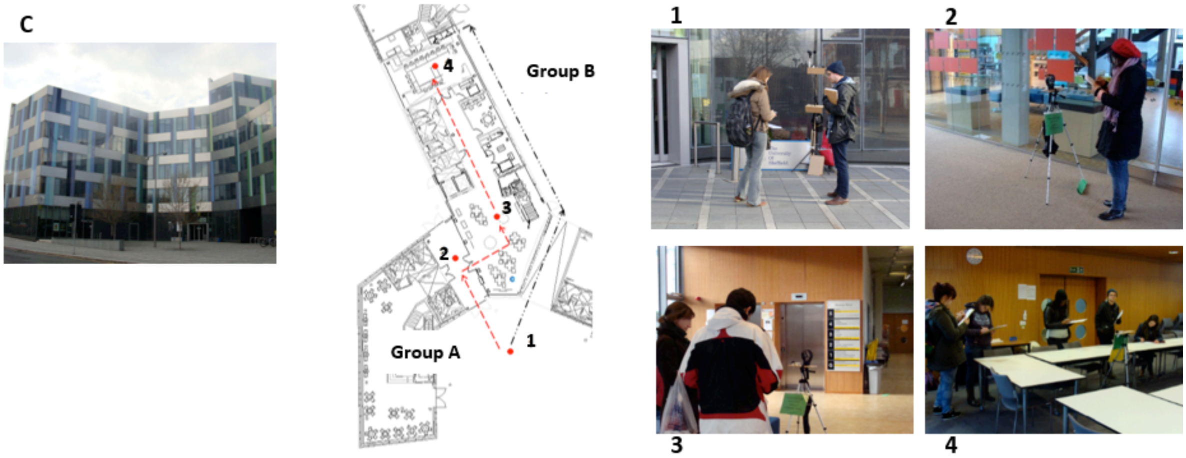


Figure 3 Case study Buildings and photographs of the spaces comprising the trajectory: 1) Exterior space, 2) Draught lobby, 3) Circulation space and 4) Seminar room. Red lines indicate route A and black lines route B.

Equipment

Four sets of data-logging equipment were used during the survey, one for each space. Air temperature (Ta), air speed (Av), relative humidity (rh) and globe temperature (Tg) were measured simultaneously while people were answering a very short questionnaire (Figure 4). The globe temperature was measured using a small data logging device (Thermochron i-button) inside a black painted 40mm table tennis ball (Ng & Cheng 2012; Nicol, Humphreys & Roaf 2012). Outside, the equipment was located at 1.70 metres and protected from direct solar radiation. Inside, the equipment was located at 1.10 m height in the centre of the spaces (Figure 5). Measurements were taken every 5 seconds in all the devices.

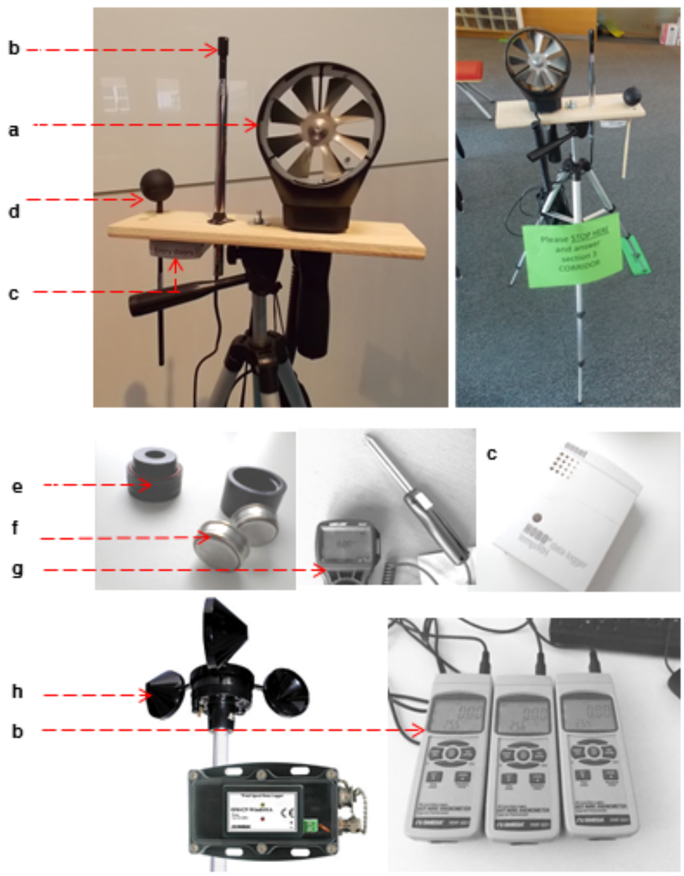


Figure 4 Equipment: a) vane anemometers (TSI Airflow LCA 501), b) OMEGA hot-wired anemometer, c) data-loggers (HOBO-U12-012), d) globe thermometer using a Thermochron i-button inside a black painted 40mm table tennis ball, e) water proof capsule for i-button, f) Thermochron i-button, g) portable manual hot wire anemometer (BSRIA TA-410), cup anemometer (OMEGA OM-CP-Wind 101A).

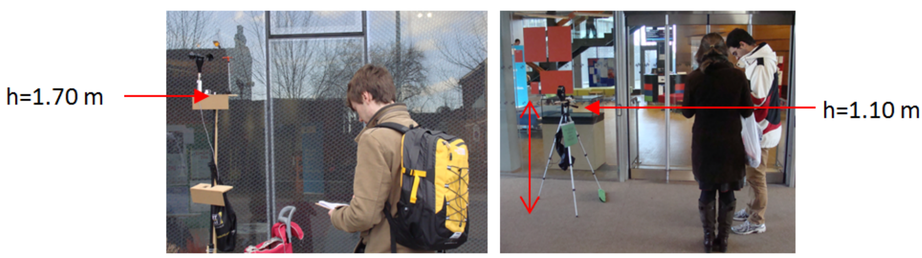


Figure 5 Height of the equipment at the exterior and interior spaces

Equipment considerations

Due to the limited budget and availability of equipment in this work, there were some limitations in the equipment selection that need to be taken into account:

1) Equipment Calibration: All of the equipment was tested together under the same climatic conditions. Since the university does not have a climatic chamber, a small office space was used to conduct measurements during 24 hours. All of the temperature instruments were programmed with exactly the same sampling time and measurements units (°C.) The instruments were located as far away as possible from the window. The space remained closed, with closed windows and dampers, avoiding solar radiation and direct sunlight (Figure 6) The vane anemometers (BSRIA) were calibrated by the manufacturer and supplied with an updated calibration certificate. This equipment served as a reference to compare with all of the new equipment used in this work, which was also previously calibrated by the manufacturer. Results showed the same measurement values in all the devices, however with very small differences in accuracy between the i-buttons and vane anemometers. The BSRIA equipment was more precise than the other equipment, therefore most of the data was taken from these devices and compared with the other instruments.

Figure 6 Equipment setup for calibration

2) Measurement of physical variables: Outdoor wind speed was measured with a cup anemometer, one limitation of this equipment is that it does not register speed winds below the starting threshold of 1.75 mph. A three-dimensional (horizontal and vertical) measurement of the wind speed is highly recommended since the wind direction varies very quickly, particularly at the exterior (Johansson et al. 2014). It is also recommended to use combinations of equipment, if necessary, in order to cover a good range of wind speed. However, it was not possible to combine instruments in this case. The equipment used to measure wind speed inside (hot-wire anemometer) has problems related to directionality. A unidirectional instrument is not best for this kind of field study; it is better to measure wind speed by using an omnidirectional hot-wire anemometer (Hwang et al. 2008; Nikolopoulou, Marialena & Lykoudis 2006), considering the equipment specifications described in the ISO 7726 standard. Based on preliminary evaluation and measurements, the unidirectional equipment was carefully positioned to measure the wind caused by the main entrance doors through the narrow draught lobby and corridor. In some cases, when it is known that the wind speed is unidirectional, it is possible to use a hot-wire anemometer after a test of direction in the space (EN.ISO.7726 2001). This was the available way to measure these variables under the previous considerations and limited budget.

Due to the limitations regarding accurate measurement of the globe temperature (i-buttons inside) and air speed (unidirectional), the results from this work are focused on air temperature. It is worth mentioning that participants' perception of the air speed and relative humidity were always within the comfortable band, indicating air temperature as the main variable affecting participants' thermal responses in this survey. Despite these limitations, results from this work provide valuable information and a general overview regarding thermal variations and participant's thermal perception in transitional spaces.

4 Results and Discussion

A total of 1,749 participants took part in the fieldwork, 155 in spring, 487 in summer, 447 in autumn and 660 in winter. Volunteers were from 84 different counties and the majority of the participants were undergraduate students from 18 to 24 years old (81%). 60% of the population were male and 40% female, 45% of the population were from United Kingdom and 55% were international students from 83 different countries. Participants' clothing and behaviour were not controlled; this was because the aim of the fieldwork was to mirror participants' behaviour in their everyday lives (Table 1). The exterior and interior air temperature in Sheffield during the survey are illustrated in Table 2.

Table 1 Participants' clothing in the four seasons of the year

	Spring	**Summer**	**Autumn**	**Winter**
Participants' clothing at exterior and interior	Mean=0.72 clo Min=0.30 clo Max= 1.42 clo SD=0.251	Mean=0.57 clo Min=0.30 clo Max= 1.49 clo SD=0.214	Mean=1.01 clo Min=1.0 clo Max= 2.0 clo SD=0.124	Mean=1.06 clo Min=1.0 clo Max= 2.0 clo SD=0.241

Table 2 Exterior climatic conditions during the surveys in 2013-2014

	Exterior	**Spring**	**Summer**	**Autumn**	**Winter**
Sheffield 2013-2014	Air Temperature	Mean= 19.1°C	Mean= 23.1°C	Mean= 14.1°C	Mean= 9.5°C
	Seminar rooms	**Spring**	**Summer**	**Autumn**	**Winter**
Sheffield 2013-2014	Air Temperature	Mean= 21.9°C	Mean= 23.5°C	Mean= 21.1°C	Mean= 20.0°C

Thermal variability in the lobby area

Results illustrated a wide range of thermal variability that occurred in only a few metres between the interior spaces comprising the lobby unit (Table 3). There were wider temperature variations at the exterior than in the interior spaces. The largest temperature differences between spaces were registered between the exterior and draught lobby. It was found that a correlation between the exterior temperature and interior temperature decreased for the interior spaces that were further from the exterior. In general, temperature ranges gradually narrowed from exterior to interior spaces. This pattern was also detected with relative humidity and air speed with closed windows.

Table 3 Average air temperature difference (ΔT) between spaces in the four seasons of the year. Exterior (EXT), Draught Lobby (DL), Circulation Space (CS) and Seminar Room (SR).

Henry Stephenson Building

Season	Air T °C	(EXT)	(DL)	(CS)	(SR)	(ΔT) EXT-DL	(ΔT) DL-CS	(ΔT) CS-SR	(ΔT) EXT-SR
Spring	**mean**	18.3	18.1	19.5	21.3	-0.2	+1.4	+1.8	**+3.0**
2013	min	14.0	16.0	19.0	21.0	+2.0	+3.0	+2.0	+7.0
	max	22.0	20.0	20.0	21.0	-2.0	0.0	-1.0	-1.0
	SD	4.0	2.0	2.0	0.3				
Summe	**mean**	25.2	23.0	23.0	23.1	-2.2	0.0	+0.1	**-2.1**
2013	min	21.0	21.9	21.9	21.0	+0.9	0.0	-0.9	0.0
	max	30.9	26.2	26.2	25.0	-4.7	0.0	-1.2	-5.9
	SD	3.7	1.4	1.4	1.2				
Autumn	**mean**	13.8	19.5	19.5	20.4	+5.7	0.0	+0.9	**+6.6**
2013	min	12.0	19.0	19.0	19.0	+7.0	0.0	0.0	+7.0
	max	19.0	20.0	21.0	21.0	+1.0	+1.0	0.0	+2.0
	SD	1.0	0.49	0.51	0.6				
Winter	**mean**	9.8	16.5	18.0	19.9	+6.7	+1.5	+1.9	**+10.1**
2014	min	8	13.0	17.0	16.0	+5.0	+4.0	-1.0	+8.0
	Max	17	21.0	21.0	25.0	+4.0	0.0	+4.0	+8.0
	SD	1.8	2.5	0.8	1.7				

ICOSS Building

Season	Air T °C	(EXT)	(DL)	(CS)	(SR)	(ΔT) EXT-DL	(ΔT) DL-CS	(ΔT) CS-SR	(ΔT) EXT-SR
Spring	**mean**	15.7	16.9	22.4	21.4	+1.2	+5.5	-1.0	**-5.7**
2013	min	15.5	16.0	22.0	20.0	+0.5	+6.0	-2.0	-4.5
	max	16.0	18.0	23.0	23.0	+2.0	+5.0	0.0	-7.0
	SD	0.25	1.0	0.5	1.5				
Summe	**mean**	21.5	21.6	25.0	23.2	+0.1	+3.4	-1.8	**-1.7**
2013	min	18.0	20.0	24.0	21.0	+2.0	+4.0	-3.0	-3.0
	max	29.0	25.0	27.0	25.0	-4.0	+2.0	-2.0	+4.0
	SD	3.2	1.6	0.7	1.0				
Autumn	**mean**	13.0	15.9	21.5	21.4	+2.9	+5.6	-0.1	**-8.4**
2013	min	8.0	12.0	19.0	19.0	+4.0	+7.0	0.0	-11.0
	max	20.0	20.0	23.0	23.0	0.0	+3.0	0.0	-3.0
	SD	4.0	2.0	1.4	0.9				
Winter	**mean**	9.3	12.3	19.6	18.6	+3.0	+7.3	-1.0	**-9.3**
2014	min	8.0	11.0	18.0	16.0	+3.0	+7.0	-2.0	-8.0
	max	11.0	15.0	21.0	21.0	+4.0	+6.0	0.0	-10.0
	SD	1.1	1.2	0.7	1.2				

Jessop West Building

Season	Air T °C	(EXT)	(DL)	(CS)	(SR)	(ΔT) EXT-DL	(ΔT) DL-CS	(ΔT) CS-SR	(ΔT) EXT-SR
Spring	**mean**	25.0	21.0	22.0	24.0	-4.0	+1.0	+2.0	**-1.0**
2013	min	25.0	21.0	22.0	24.0	-4.0	+1.0	+2.0	-1.0
	max	25.0	21.0	22.0	24.0	-4.0	+1.0	+2.0	-1.0
	SD	0.0	0.0	0.0	0.0				
Summe	**mean**	23.1	22.2	23.5	25.1	-0.9	+1.3	+1.6	**+2.0**
2013	min	19.0	20.0	22.0	24.0	+1.0	+2.0	+2.0	+5.0
	max	27.0	24.0	24.5	26.0	-3.0	+0.5	+1.5	-1.0
	SD	2.6	1.4	0.8	0.5				
Autumn	**mean**	14.8	16.9	19.6	20.3	+2.1	+2.7	+0.7	**+5.5**
2013	min	11.0	14.0	18.0	18.0	+3.0	+4.0	0.0	+7.0
	max	22.0	20.0	22.0	23.0	-2.0	+2.0	+1.0	+1.0
	SD	3.1	2.3	1.3	1.5				
Winter	**mean**	9.7	11.8	17.1	20.3	+2.1	+5.3	+3.2	**+10.6**
2014	min	6.0	10.6	16.0	17.0	+4.6	+5.4	+1.0	+11.0
	max	17.0	14.0	20.0	22.0	-3.0	+6.0	+2.0	+5.5
	SD	2.9	0.8	1.3	1.6				

Thermal transitions (Group A)

When analysing the air temperature correlations between consecutive spaces, the strongest correlation was found between the exterior and draught lobby space (r^2=0.74, p=0.0001<.05), followed by draught lobby and circulation (r^2=.54 p=0.0001<.05), and circulation and seminar rooms (r^2=.43 p=0.0001<.05) (Figure 7). In short, the exterior environment strongly influenced the way that the lobby unit was thermally connected in NV buildings. Moreover, it was found each season of the year created different thermal patterns in the given spatial sequence connecting the exterior environment with the interior.

People in Group A were grouped in 46 thermal bins in order to explore potential patterns. Each bin had different thermal sequences. A key finding was the identification of new thermal patterns shaped by the season of the year (Figure 8).

- 'Flat patterns' (temperature changes from min=0°C to max=2°C). Primarily occurring during spring and summer. This involved a relatively small exterior- interior air temperature range from 20°C to 23°C in the four spaces and only up to 2°C difference between spaces.
- 'Sudden patterns' (temperature changes from min=0°C to max=13°C). Corresponding primarily to autumn and winter, with larger exterior and interior air temperature range from 6.2°C to 26°C and with up to 13°C temperature difference between spaces.
- 'Irregular patterns' (temperature changes from min=0°C to max=10°C). These were identified primarily in summer, however, with few cases in autumn and winter. Air temperature differences were from 8.5°C to 27°C with up to 10°C difference from one space to another (exterior-draught lobby, draught lobby-circulation and circulation-seminar room).

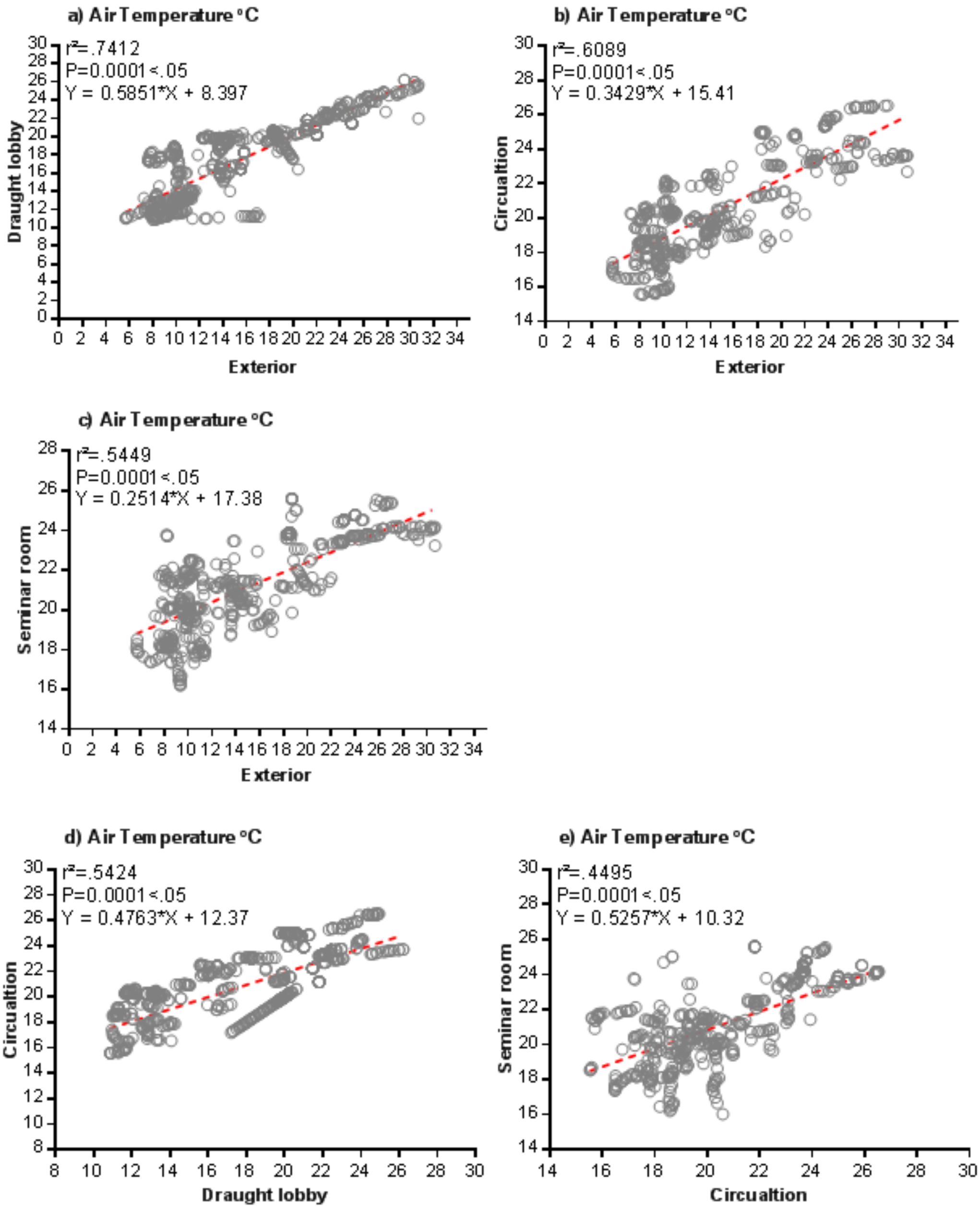
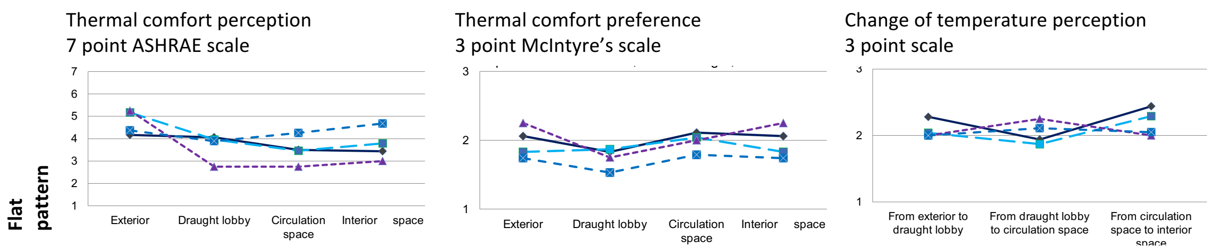


Figure 7 Air temperature correlations between spaces: a) exterior and draught lobby, b) exterior and circulation space, c) exterior and seminar room, d) draught lobby and circulation space and e) circulation space and seminar room.



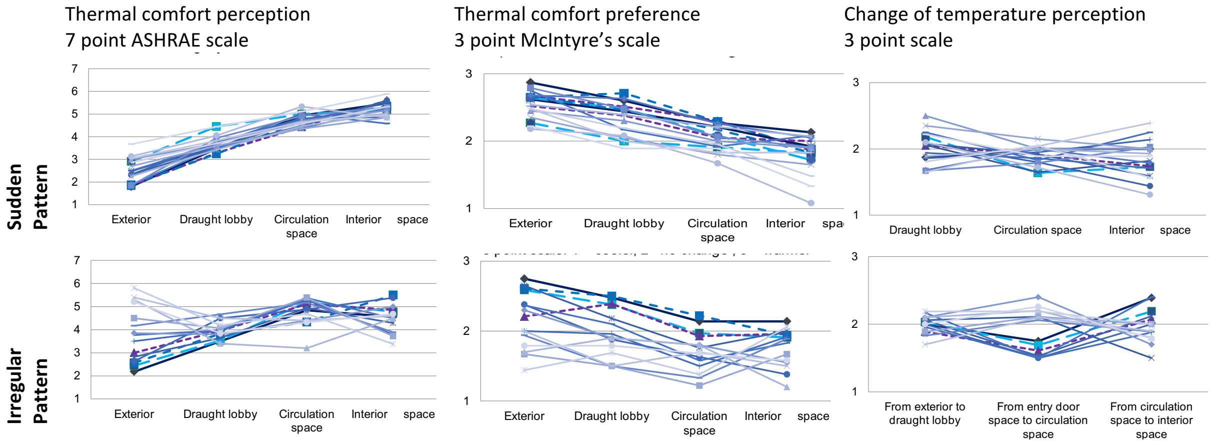


Figure 8 Thermal sequences and people's thermal comfort perception, thermal preferences and perception to temperature changes between the spaces comprising the lobby unit.

The understanding of these patterns as a background of people's thermal perception is a significant contribution to the discourse on thermal comfort. In this study, people's responses to air speed and relative humidity were always within the comfortable band in the four spaces, air temperature being the main factor altering people's thermal perception. Gradual thermal transition from the exterior to the interior (flat sequences) allowed people to have a better thermal adaptation inside of the buildings. Sudden temperature changes from cold to hot with no single thermal direction caused discomfort; however, sudden changes with the *same* thermal direction were more effective in providing thermal comfort to participants. Finally, the irregular pattern provoked a wide range of thermal responses, due to the effect of different temperature changes in different thermal directions. In some cases, spaces with the same climatic conditions were perceived different by the participants engaged with thus pattern.

- As expected, in flat patterns, using Friedman test, it was found that small temperature changes (less than 2°C) did not have a significant effect on participants' thermal perception ($p>.05$) when they moved from one space to another. An example of a flat pattern is illustrated in Figure 9.

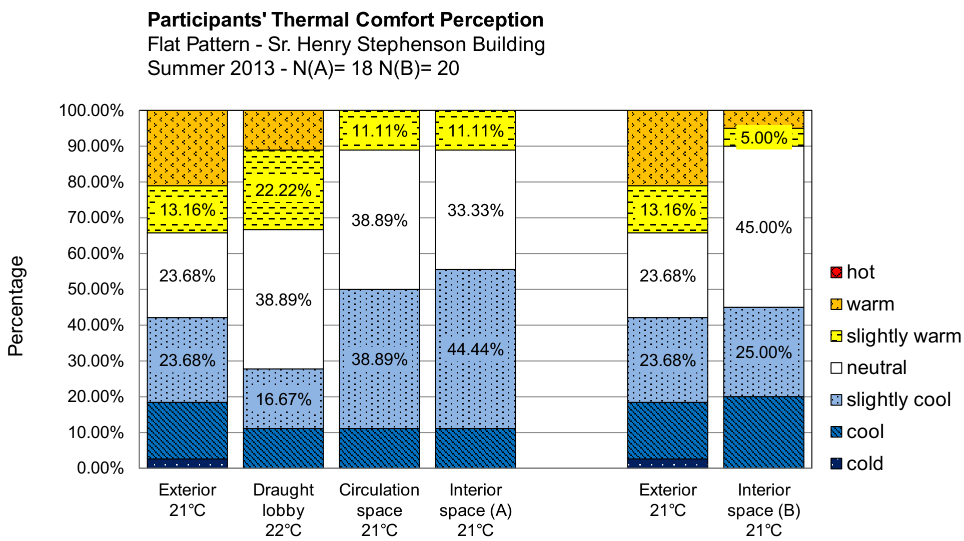


Figure 9 Participants' thermal perception in an example of a flat sequence

- In sudden patterns, from cold to hot, Friedman tests revealed significant differences in participants' thermal perception from one space to another in all the sudden sequences with ΔT larger than 2°C ($p<.05$). It was also found that in an air temperature range from 6°C to 13°C, an increase in temperature from 1°C up to 9°C was always significant, since in this temperature range people always preferred to be warmer. People's responses were more variable in temperature range from 14 to 23°C, and then again small temperature changes (±1°) were significant from 24°C onwards. An example of a sudden pattern been is illustrated in Figure 10.

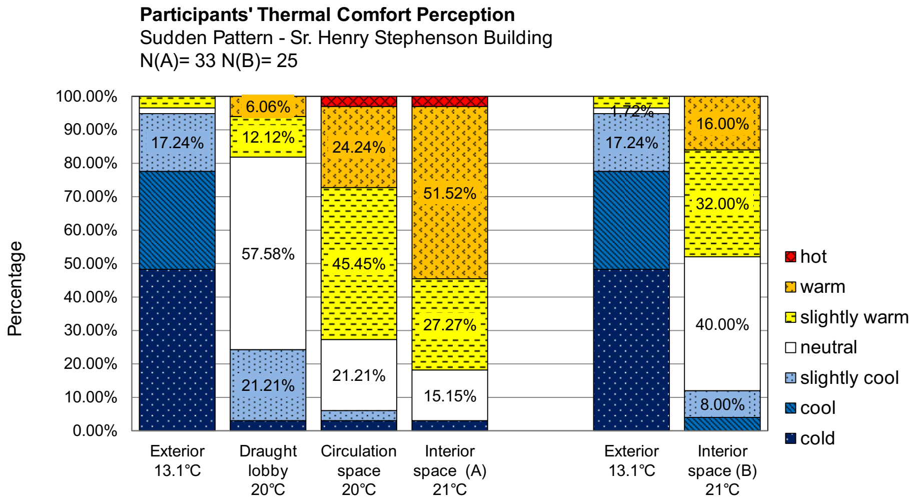


Figure 10 Example of participants' thermal perception from one space to another in a sudden sequence

- In irregular sequences, Friedman tests revealed significant differences ($p<.05$) in participants' thermal perception between the spaces in all the sequences. A Wilcoxon Signed Rank Test revealed no significant differences in participants' thermal perception between the exterior and draught lobby spaces when the temperature differences were less than ± 2°C. However, when the temperature ranges were from 25°C to 27°C (hot band) and from 8°C to 16°C (cold band), temperature changes of ± 1°C revealed significant differences in participants' thermal comfort perception. Likewise, there were no significant differences in participants' responses when the temperature differences between circulation space and interior space were less than ± 2°C. However, a temperature difference of ± 1°C in was significant when the sequence involved a temperature range from 23°C to 26°C. An example of an irregular pattern been is illustrated in Figure 11.

In brief, a short-term experience and the way that the spaces are thermally connected could significantly modify people's thermal perception and preferences in seconds. It seems that the order of the thermal connections can delay or bring forward a change in people's thermal perception. Thermal connections gradually increasing the air temperature in one direction (in this case from cold to hot) could help to influence people to experience a gradual increase in thermal perception towards the warm side, to the extent that they are more able to tolerate cooler conditions within the final interior space than is normally the case. In contrast, irregular connections, with changes of thermal direction, form variable thermal responses among people, causing delays or gains in their thermal responses. In some cases, the sum of these very short delays or gains seem to be large enough to ensure no overall significant differences in people's thermal perception between spaces with large temperature differences, or significant differences between spaces with the same temperature. Moreover, people can perceive the same thermal conditions in different ways.

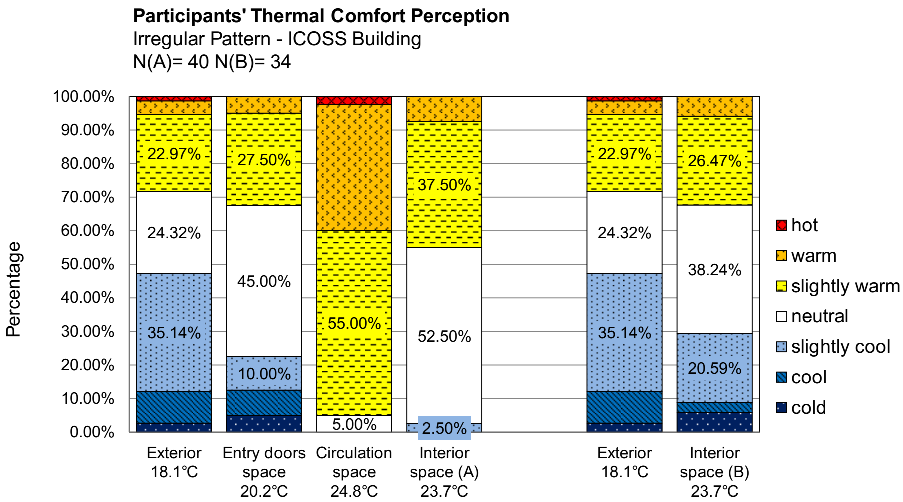


Figure 11 Participants' thermal comfort perception in an example of irregular pattern

Thermal transitions (Group A and B)

- A1 and B1 = exterior space, A2 and B2=Seminar room after transition

Flat sequences: There was no significant difference between group A_2 and B_2 ($p>.05$) (Figure 12). A narrower standard deviation in participants' responses was found in group A_2 in the four sequences, suggesting that group A experienced a gradual thermal adaptation, but not one strong enough to alter their thermal perception significantly. A pairwise comparisons showed no significant difference in thermal perception between group A_1-A_2 and B_1-B_2 ($p>.05$).

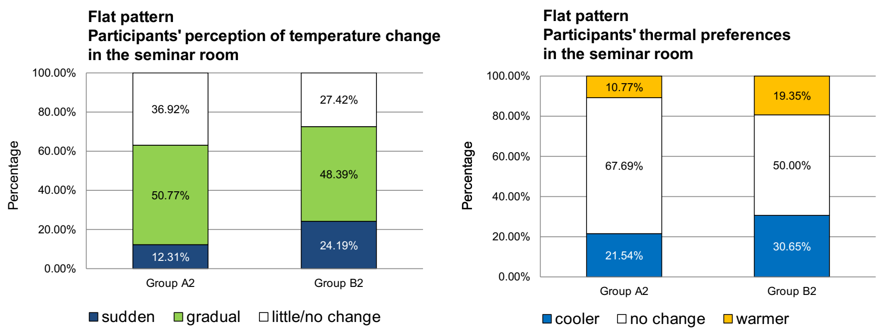


Figure 12 Flat sequences: participants' perception of temperature change and participants' thermal preferences.

In sudden patterns, the lobby unit had a significant effect in participants' perception in the seminar room ($p<.05$, $N(A)=441$, $N(B)=361$). Route A triggered more 'gradual', 'little' and 'no change' thermal preference responses in group A_2 than in group B_2 (Figure 13). In the irregular patterns, there were no significant differences between A2-B_2 ($p=.320>.05$, $N(A)=334$, $N(B)=207$). There were variable answers due to changing thermal direction; consequently, paired comparisons showed significant differences between A_1-A_2 ($p=.01<.05$

N=344) and B_1-B_2 (p=.006<.05 N=207). In the seminar room, group B_2 perceived more sudden temperature changes than with group A_2 (Figure 14).

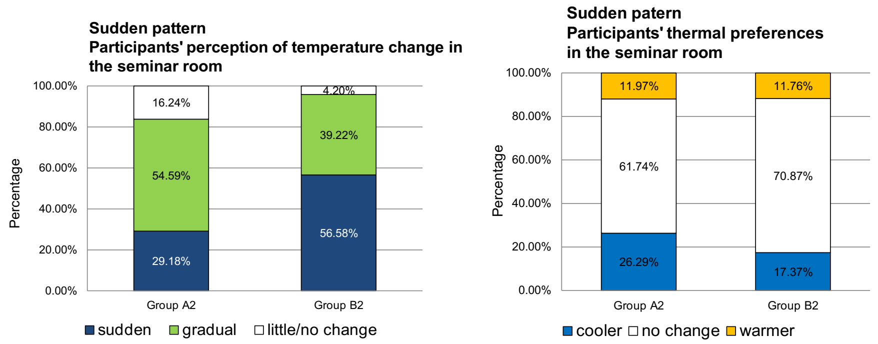


Figure 13 Sudden sequences: participants' perception of temperature change and participants' thermal preferences

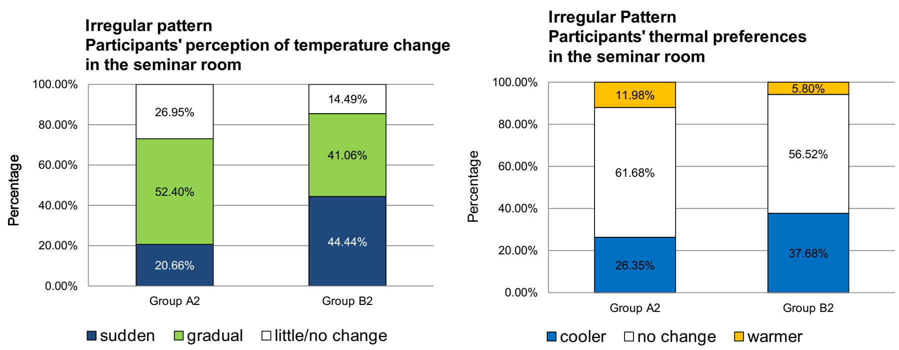


Figure 14 Irregular sequences: participants' perception of temperature change and thermal preference.

The comfort of thermal variability

In this study it was found that people were comfortable with the exterior environment during spring, summer and autumn (Figure 15). This could be due to the gradual thermal adaptation that people experience along the year. In the seminar room, people's thermal perception was opposite to the exterior environment in less than one minute, showing how quickly people change their thermal perception is also influenced by previous thermal experiences, in this case the exterior environment (Figure 15 and Figure 16).

In addition, findings exposed the wide range of temperatures at which people express comfort in each season of the year (Figure 17). People tagged their thermal perception to a given temperature in the exterior differently; this pattern was also found in the seminar room, however it was less dramatic (Figure 18). A quantification of the temperature difference (ΔT) between seasonal mean air temperatures (°C) in which different people express the same thermal perception is shown in Table 4. These findings provide a significant overview of the wide range of comfortable thermal perception that people experience during the year. After this analysis, the idea of attempting to provide thermal comfort to people through fixed thermal environment aiming for 80% of similar responses seems totally incorrect. The findings from this study support the thermal alliesthesia theory (Parkinson & de Dear 2015) that, thermal variability can provide a wider range of comfortable solutions encouraging people to develop more personal thermal adaptation strategies.

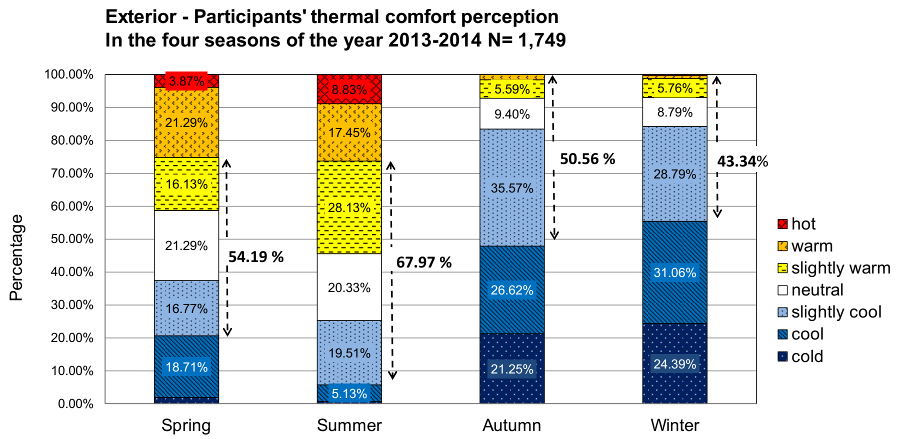


Figure 15 People's thermal perception at the exterior in the four season of the year

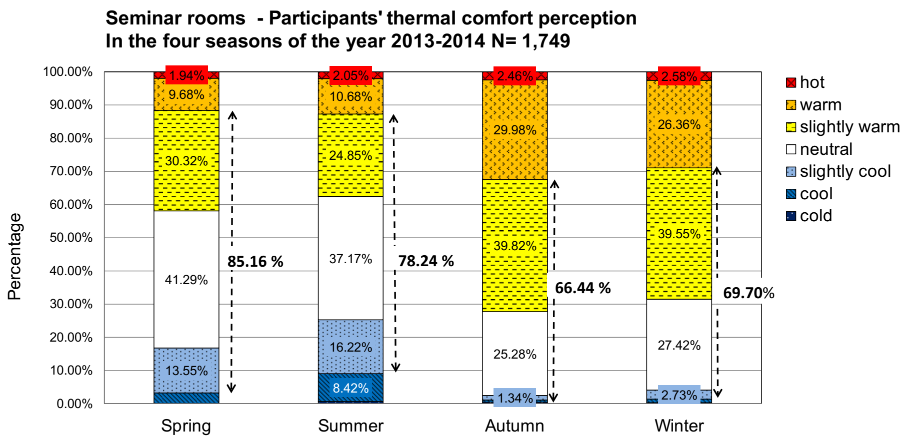


Figure 16 People's thermal perception in the seminar room

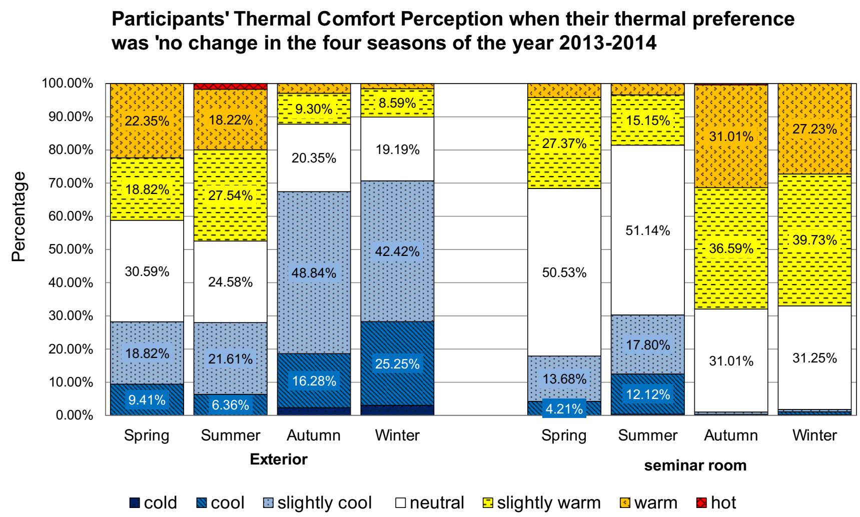


Figure 17 Participants' thermal comfort perception in the transitional spaces, when their thermal preferences were 'no change'

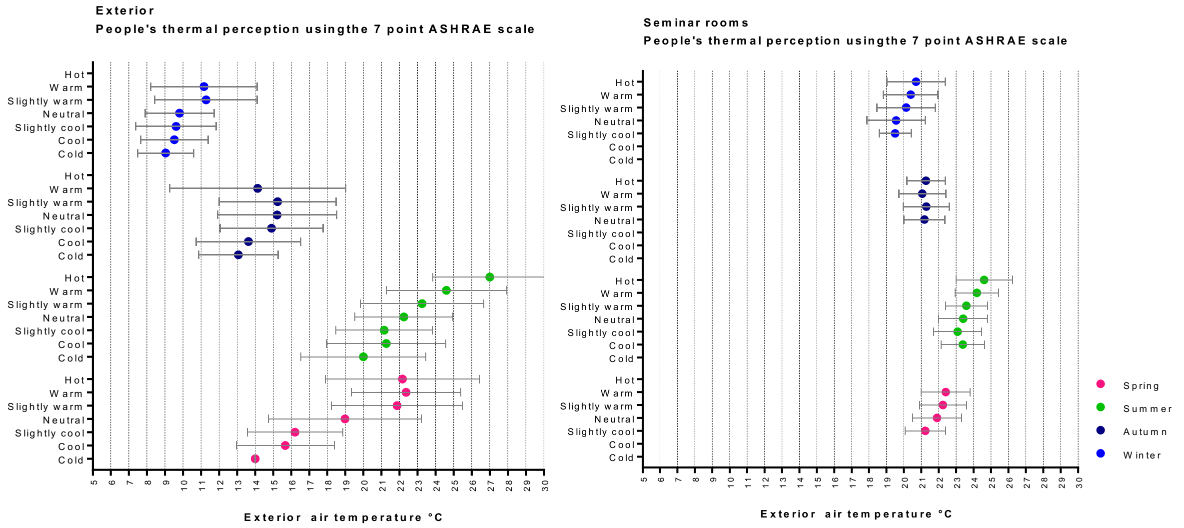


Figure 18 Participants' thermal comfort perception in the exterior space and seminar room in relation to temperature ranges per season.

Table 4 Participants' seasonal thermal comfort perception and mean air temperature difference (ΔT) in relation with the use of the 7 point ASHRAE scale. The table compares mean air temperatures, the symbol (*) indicates no answers registered in that category. The data includes results from the three buildings.

Exterior	**Spring (s)**	**Summer (sm)**	**Autumn (a)**	**Winter (w)**	**ΔT** (s-sm)	**ΔT** (sm-a)	**ΔT** (a-w)	**ΔT** (s-w)
Cold	14.00	20.00	13.07	9.04	+6.0	-6.9	-4.0	+5.0
Cool	15.67	21.27	13.63	9.52	+5.6	-7.6	-4.1	+6.1
Slightly cool	16.21	21.15	14.91	9.61	+4.9	-6.2	-5.3	+6.6
Neutral	18.98	22.24	15.21	9.81	+3.3	-7.0	-5.4	+9.2
Slightly warm	21.86	23.25	15.24	11.28	+1.4	-8.0	-4.0	+10.6
Warm	22.36	24.60	14.14	11.16	+2.2	-10.5	-3.0	+11.2
Hot	22.16	27.00	*	*	+4.8	*	*	*
Seminar rooms								
Cold	*	*	*	*	*	*	*	*
Cool	*	23.38	*	*	*	*	*	*
Slightly cool	21.2	23.09	*	19.50	+1.9	*	*	+1.7
Neutral	21.9	23.40	21.18	19.55	+1.5	-2.2	-1.6	+2.4
Slightly warm	22.4	23.59	21.29	20.13	+1.4	-2.3	-1.2	+2.1
Warm	22.4	24.19	21.06	20.39	+1.8	-3.1	-0.7	+2.0
Hot	*	24.61	21.27	20.70	*	-3.3	-0.6	*

Finally, in this study, people's long term thermal history also was an important factor affecting people's thermal perception. There was a significant difference in thermal perception between UK and international students, also between recently arrived students and students with more than one year of residence in Sheffield. UK and long term residents were more comfortable with cold temperatures and uncomfortable with hot summer temperatures, and females felt colder than males.

5 Conclusions

The results from this study offer a deeper level of understanding of the factors altering people's thermal perception in transitional spaces in a repeated real situation when in a dynamic state in moderate climates. This extensive field work could fit in well with the theory of temporal thermal alliesthesia (Parkinson, De Dear & Candido 2015), by demonstrating that thermal comfort can be found in non-uniform environments and that *corrective changes* on people's thermal comfort can be possible. Repeated short-term thermal experiences could have the potential to trigger a positive effect on people's thermal perception in the long term. However further work and new directions of research need to be used to measure this possible effect.

Results provide information that can help designers to think about the significance of transitional spaces as temperature regulators (e.g. dynamic lobby unit) when linking the exterior with the interior environment. At a deeper level, the dynamic lobby unit design should integrate wider options for different types of user (staff, visitors or residents) and activity (walking, waiting and socializing), perhaps with well-defined spatial boundaries for each type of activity. Designers need to be aware that people's thermal perception will be very variable in large lobby units hosting different activities and different types of users. Therefore, the spatial design needs to provide different adaptive opportunities to allow people to reach comfort.

Additional insights from this work includes the consideration of the three thermal patterns presented in this paper (flat, sudden and irregular) as a way to inform design strategies in transitional spaces. Also, it is worth considering the immediate exterior climatic conditions (a few metres away from the main entrance) as the starting point of people's thermal transition. A gradual thermal transition can be extended to a few metres before arriving in the lobby unit by taking advantage of landscape design to develop suitable tree placement (shade), pavement colours, greenery, geometric configurations, landscape interventions, water features and canopies. An urgent cross-correlation between significant findings established for outdoor thermal comfort strategies and those for transitional spaces needs to be conducted in order to create a more joined-up approach to building design in order to tackle sudden temperature changes. The recommendation from this paper is the use of gradual temperature changes with a single thermal direction for moderating thermal comfort perceptions; however, irregular patterns could also be used in a positive way when the objective is to reverse the effect of previous thermal conditions. Also, it is important to consider people's long term thermal history and the effect of people's thermal adaptation to the climatic conditions of the four seasons of the year.

The fact that thermal connections between spaces significantly affected people's thermal perception in sudden and irregular thermal patterns in this study is a signal to engineers and architects that more detailed modelling of spaces, which takes account of these thermal effects, is needed for effective design predictions. The results of this study imply a move away from steady state calculations for buildings towards more complex modelling which, in turn requires more research to establish the appropriate 'thermal alliesthesia' parameters and probabilities to work with for a given population moving through a particular configuration of thermal spaces. This in turn can help to contribute to the development of long term strategies to reduce AC usage and to adjust thermal connections in NV buildings in order to enhance people's thermal experience, while at the same time reducing energy use in buildings.

Some lessons learned from this work include: Firstly, the importance of taking into account the rapid change in people's thermal perception in very short periods of time. Careful attention should be taken when conducting fieldwork and thermal comfort surveys in steady state context, since people's responses could reflect the effect of previous thermal experience rather than the effect of the current space. Secondly, the importance of considering at least one year of people's thermal history, along with a detailed quantification of the indoor thermal variability, to understand the influence of the exterior environment in the four seasons of the year. In transitional spaces, the study of key thermal connections through transitional spaces could provide the knowledge for improving building thermal performance over the whole life cycle. This could also inform the periods of the year in which to implement energy saving strategies that use transitional spaces as a buffer zone between the exterior and interior environments. Finally, careful attention needs to be taking during the design, procedure and equipment selection stages of fieldwork studies involving people in dynamic state.

Further work quantifying transitional spaces and thermal variability in buildings needs more qualitative research. Additionally, the exploration of psychological variables could help to further contextualise the initial 'pattern' findings in this paper.

Acknowledgments
This research was founded by the National Council of Science and Technology of Mexico (CONACYT) with a complementary grant from the Council of Science and Technology of the State of Mexico (COMECYT). We would like to thank the Estates and Facilities Management from The University of Sheffield and all the undergraduate students that gave us a few minutes of their time to participate in the surveys.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Thermal adaptation to high indoor temperatures during winter in two UK social housing tower blocks

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Abstract
This work explores the hypothesis that exposure to high indoor temperatures during winter can change thermal expectations of the occupants, challenging the standard boundaries of thermal comfort and leading to excess in energy demand for heating. The analysis presented here is based on two case study social housing tower buildings where indoor temperatures during the heating season have been maintained at high levels for many years. Five-minute readings of air temperature and relative humidity were gathered from the lounges and bedrooms of twenty flats from February to October 2014. The measured air temperatures in the sampled period were overall much higher than the standard comfort criteria, with averages of 24.8±2.2°C for the lounges and 23.1±1.8°C for the bedrooms. Interviews were carried out with seventeen tenants in October, enquiring about their views on the indoor environment, the use of controls and their thermal sensation at the time of the survey. The results show that most people were satisfied with the temperatures in their flats, regardless of them being much higher than recommended levels most of the time. The occupants' adaptation to high temperatures could pose a great challenge to the implementation of energy use reduction strategies, if industry-based thermal criteria were to be met.

Keywords: Indoor temperature, winter, thermal history, social housing, adaptive comfort.

1 Introduction

Prediction of occupant acceptability of the indoor environment and estimation of the energy consumption associated with it relies on assumptions regarding occupant demand temperatures. Such assumptions are also used in building stock models and determine the estimated energy savings from building refurbishment, influencing governmental strategies and targets. A sensitivity analysis by Firth et al. (2010) of the primary input parameters in energy models resulted in a sensitivity coefficient of 1.55 for the heating demand temperature, which suggests that a 10% rise in the heating demand temperature leads to a 15.5% increase in the CO_2 emissions. This was significantly higher than the sensitivities of the other input parameters investigated, suggesting that heating demand temperature is the key determinant of energy use in housing.

The two widely used domestic energy calculation methodologies in the UK, BREDEM (Henderson and Hart, 2015) and SAP (BRE, 2014) use a two-zone model for space heating calculations with different demand temperatures. Zone 1 represents the living area with a typically used demand temperature of 21°C and zone 2 represents the rest of the house with demand temperature of 18°C (BRE, 2013). These values have been challenged by studies that measured lower indoor temperatures in English living rooms (Oreszczyn et al., 2006; Huebner et al., 2013; Teli et al., 2015). An extensive 2011 survey in 823 dwellings representative of the English housing stock resulted in mean room temperatures of 19.3°C for the living room, 18.8°C for the hallway and 18.9°C for the bedroom (BRE, 2013). Another study found significant variation in heating patterns with measured room temperatures ranging from 9.7°C to 25.7°C (Kane et al., 2015).

Further to the above, a historic upward trend in winter indoor temperatures has been highlighted, especially in bedrooms (Mavrogianni et al., 2013) and the 'rebound effect' from energy efficiency improvement measures has been estimated to a temperature take-back between 0.14-1.6°C due to improvements in thermal comfort (Sorrell et al., 2009). Although there is increasing measured data of indoor conditions in households, there is much less information on domestic thermal comfort compared with non-domestic buildings (Vadodaria et al., 2014) and processes that might affect comfort temperatures during winter, such as thermal adaptation, have not been sufficiently explored.

Recommended winter temperatures for living spaces

For the assessment of the indoor thermal environment of 'mechanically heated' spaces the international standards and guides recommend the use of the PMV model (ASHRAE, 2013; ISO, 2005; CEN, 2007; CIBSE, 2015). In addition, standard EN 15251 and CIBSE Guide A provide design values for winter temperatures based on PMV and assumed values for clothing insulation and metabolic rate. For living areas in domestic buildings the recommended design temperatures can be seen in Table 1. Interestingly, recently monitored temperatures in living rooms fall outside of EN 15251 Category I & II and CIBSE Guide A recommendations (BRE, 2013).

Table 1. Design indoor temperatures for residential buildings (living spaces)

	Design temperatures for winter	
	Design min (°C)	Range (°C)
EN 15251 (CEN, 2007) / 1.0 clo		
Category I[1]	21.0	21.0-25.0
Category II	20.0	20.0-25.0
Category III	18.0	18.0-25.0
CIBSE Guide A (CIBSE, 2015)		
Bedrooms (met=0.9, clo=2.5)	-	17.0-19.0
Living rooms (met=1.1, clo=1.0)	-	22.0-23.0

[1]EN 15251 categories represent different levels of expectation.

Recommended thermal criteria mainly focus on establishing minimum indoor temperatures for winter and maximum temperatures for summer, in order to avoid 'under-heating' in winter and 'overheating' in summer. The UK's 'Cold Weather Plan' recommends a minimum household temperature of 18°C for a sedentary person, wearing suitable clothing (Public Health England, 2014). However, it is stated that temperatures up to 21°C may be beneficial for health. The World Health Organisation recommends lower limits of 21°C for living rooms and 18^{o}C for bedrooms (World Health Organization (WHO), 2007; Marmot Review Team, 2011). These values are considered to be the “adequate level of warmth” in fuel poverty assessments (Department of Energy and Climate Change, 2015) and are used in energy calculations.

Upper winter indoor temperature limits are not typically provided in guidelines for the indoor environment. However, in the recent, updated version of CIBSE Guide A (CIBSE, 2015) a maximum temperature for winter is also provided for clo=1.0 and met=1.2 at 24.0^{o}C, which is recommended in order to avoid overheating. This term is rarely used to describe the indoor thermal environment in winter, when overheating can only occur due to uncontrolled use of heating. This is often considered to be a personal choice, not related to the climatic conditions or the building properties. However, the type of heating system and occupants’ interaction with building controls such as thermostats and windows can also contribute to high indoor temperatures. Winter ‘overheating’ has energy implications, which can be greater due to the possible adaptation of occupant’s thermal demand to high temperatures.

Thermal adaptation to indoor temperatures

The relationship between thermal comfort and indoor temperature has been the basis of adaptive comfort theory, with the assumption that people are able to match their neutral or comfort temperature to their indoor environment through adjustments and adaptive actions (Nicol et al., 2012). This was taken forward as a pathway towards energy use reduction, as it meant that people could adapt to lower or higher temperatures than previously assumed and therefore indoor temperature could follow an adaptive seasonal variation instead of narrow fixed comfort limits (McCartney and Nicol, 2002). On the other hand, people in air-conditioned buildings are accustomed to the narrow ranges of indoor conditions they experience, and therefore have higher expectations for ‘thermal stability’ (de Dear and Brager, 1998). Considering the above aspects of adaptation, what happens if people are exposed to high, artificially created indoor temperatures in winter?

Recent experiments in China with subjects from regions with different winter indoor temperatures highlighted the significant impacts of indoor thermal exposures on physiological adaptation and occupants’ levels of tolerance (Luo et al., 2015). A further investigation on indoor thermal history demonstrated that people who are adapted to comfortable indoor environments cannot be easily convinced to lower their expectations and accept under-conditioned environments (Luo et al., 2016). Thermal adaptation to energy-intensive indoor environments could have significant implications for future indoor temperature trends and corresponding energy use to achieve them.

The hypothesis is that changes in thermal expectation, behaviour and acclimatisation may not only apply to narrower indoor temperature ranges, but also to the indoor temperature levels people are exposed to. This paper explores whether warm indoor conditions during winter have a similar adaptation effect as stable air-conditioned environments in the summer. To investigate this question, this paper is focused on a case study social housing building where indoor temperatures during winter have been maintained at high levels for several years, due to a combination of communal electricity charges, building management, lack of understanding of heating controls and sedentary lifestyles. This paper explores the implications from the building occupants’ exposure to increased warmth during winter.

2 Case study buildings

A case study approach is used to analyse occupant response to high indoor temperatures during winter. The buildings used are two identical social housing tower blocks (Figure 1) located in the central Portsea Island area of Portsmouth, UK, owned and managed by the local authority Portsmouth City Council (PCC). The buildings were constructed in 1966 using precast prefabricated concrete panels and have 17 storeys with the same layout, including one and two bedroom apartments of $50m^2$ and $70m^2$ respectively. The flats are distributed along a central corridor and orientated towards East or West, at a slight angle (5^o from North). Exterior walls have an estimated U-value of 1 W/m^2K and the double-glazed windows which replaced the initial single-pane windows, have a U-value between 2.5-3 W/m^2K. Overall, the building fabric's thermal performance is poor and does not comply with the current, much stricter regulations for new constructions.

Figure 1. One of the two identical 17-storey tower blocks (left) and a storage heater in one of the flats (right).

Heating in the buildings is electrical, managed and mostly paid by Portsmouth City Council, with a small charge to the residents through the rent. Initially, the buildings were fitted with underfloor heating. However, due to system failure and maintenance issues, storage heaters were retrofitted in most flats. Therefore, there are flats in the buildings with storage heaters, others with a combination of both and flats with mainly underfloor heating. In most flats heating units are installed in the living room and hallway and approximately 40% have one also in the bedroom. Storage heaters are meant to be used under the 'Economy 7'-tariff, being charged during the night when lower electricity prices are offered by supply companies, and gradually releasing heat during the day. However, this is not the case for the tower blocks where additional charging, and consequently heat release, takes place during the day. This is due to complaints from residents whose homes have underfloor heating, which led to daytime provision of electricity for heating by the City Council resulting in high heating costs. As an example, for the year 2014 which had a winter 28% warmer than the average, the average electricity consumption for heating per flat was approximately 4,400 kwh/yr (or 74 Kwh /m^2 yr), which is 23% higher than the typical designed residential heating load (BSRIA, 2011).

3 Methodology

The indoor environment conditions, air temperature (T_a) and relative humidity (RH), were monitored in twenty-one flats within the two social housing buildings from February to October 2014. The contact details of forty-five residents were provided by Portsmouth City Council (PCC) as potential participants, shortlisted so as to achieve a good distribution of floor levels, orientations and flat types. From the 45 residents that were contacted by phone, 30 answered, 23 agreed to participate and 21 returned valid data.

Small data loggers (MadgeTech RHTemp101A) were placed in the living room and bedroom of each flat, configured to take readings at a frequency of 5-minute intervals. These data loggers follow the requirements of ISO 7726 (2001); the accuracy of the reading for the temperature is ±0.5^{o}C and the relative humidity calibrated accuracy is 3%. The data loggers were positioned so as to minimise direct exposure to solar radiation or the heating system and to avoid any disturbance to the occupants.

Interviews were carried out with seventeen of the tenants at the end of the monitoring period (October 2014). The interview questionnaire consisted of two parts, one asking about the occupants' general views on the indoor environment and their responses to it with the use of controls and the second part asking about their thermal comfort perception at the time of the survey.

Part 1- General evaluation

a) Assessment of the general conditions during winter and summer, in the bedroom and in the living room, on a 7-point scale from dry to humid, warm to cold, quiet to noisy, light to dark, stuffy to draughty.

b) Use of controls, i.e. operation of heaters and heater control settings, frequency of window opening, use of secondary heating sources or fans.

c) Temperatures considered as comfortable in winter and summer.

d) General satisfaction with the flat in terms of temperature, noise, daylight, air quality.

e) General questions: hours spent in the flat, room mostly used during the day, number of people in the household, age group and gender.

Part 2- Comfort conditions at the time of the survey

a) Thermal sensation vote on the ASHRAE 7-point scale (cold, cool, slightly cool, neutral, slightly warm, warm, hot)

b) Thermal preference vote on a 5-point scale (much warmer, a bit warmer, no change, a bit cooler, much cooler)

c) Overall comfort assessment on a 5-point scale from very comfortable to very uncomfortable.

d) Clothing level using a list of garments.

The interviews took place on the 1st and 2nd of October with outside average daily temperatures of 17.9^{o}C and 15.5^{o}C respectively and average daily relative humidity of about 90% (Gosport Weather, 2015). The heating was turned on by the City Council on the 25th of September after residents' request. The recording of indoor air temperature (T_a) and relative humidity (RH) continued during the interviews to enable comparison of occupants' thermal sensation responses with the indoor environmental conditions at the time of the survey.

4 Results and discussion

Based on the interview responses, residents had lived in their flats for a period between 1 and 16 years until the time of the interview and therefore all of them had experienced the indoor climate of their home for a considerable time. The average reported time spent at home is 18 hours ± 4, with most respondents spending their entire day inside the building. Therefore, participants' lifestyle is overall characterised by low activity levels and minimal exposure to outdoor climatic variations.

Indoor air temperature

The data loggers were placed in different types of flats, including both one-bedroom and two-bedroom flats, different floors, orientations and capacity of heating units. Using inferential tests, relationships between measured indoor temperatures and the above parameters were carried out in order to investigate their influence on the indoor thermal environment. No statistically significant relationship was found, suggesting that other parameters may have an influence on the indoor demand temperature.

The average measured air temperature in the investigated heating period (mid-February to early-April) during occupied hours was 24.8^{o}C (σ=2.2) for the lounges and 23.1^{o}C (σ=1.8) for the bedrooms. The occupied period used for the lounges is between 07:00 and 23:00 and for the bedrooms 23:00-07:00, based on occupants' responses to the interviews. This is an approximation as most residents do not have a fixed daily schedule, however they spend most of their day at home.

The air temperature distribution per room can be seen in the boxplots of figures 2 (lounges) and 3 (bedrooms). Temperature ranges were overall at much higher levels than the minimum acceptable winter temperatures of 21^{o}C for lounges and 18^{o}C for bedrooms (World Health Organization (WHO), 2007) and the CIBSE recommended for comfort of 22-23^{o}C for lounges and 17-19^{o}C for bedrooms (CIBSE, 2015). The occupants' general thermal evaluation of their lounge and bedroom is also illustrated in figures 2 and 3. Seven of the interviewees assessed their lounges' thermal environment as 'OK', whilst four assessed it as 'a bit cold', 'quite cold' or 'too cold' even though the average air temperature was above 25^{o}C (see Figure 2). Only four interviewees considered their lounge to be 'quite warm' in winter and two as 'too warm'. Two cases worth special consideration, flats 19 and 20. The resident of flat 19 characterised his lounge as too warm during winter even though the measured air temperature range is near the lower recommended limit. This person reported spending an average of 12 hours at home (including sleeping time), much less than most of the other interviewees. He was one of only two of the interviewees that work and spend considerable time outdoors and in different indoor environments. Therefore, his thermal experience and activity level is very different to the others'. On the other hand, the resident of flat 20 has one of the warmest lounges and yet evaluated it as being 'too cold' during winter. This participant is an elderly resident (88 years old, the oldest participant) and therefore health condition, reduced activity level and physiology may have strongly influenced her thermal sensation.

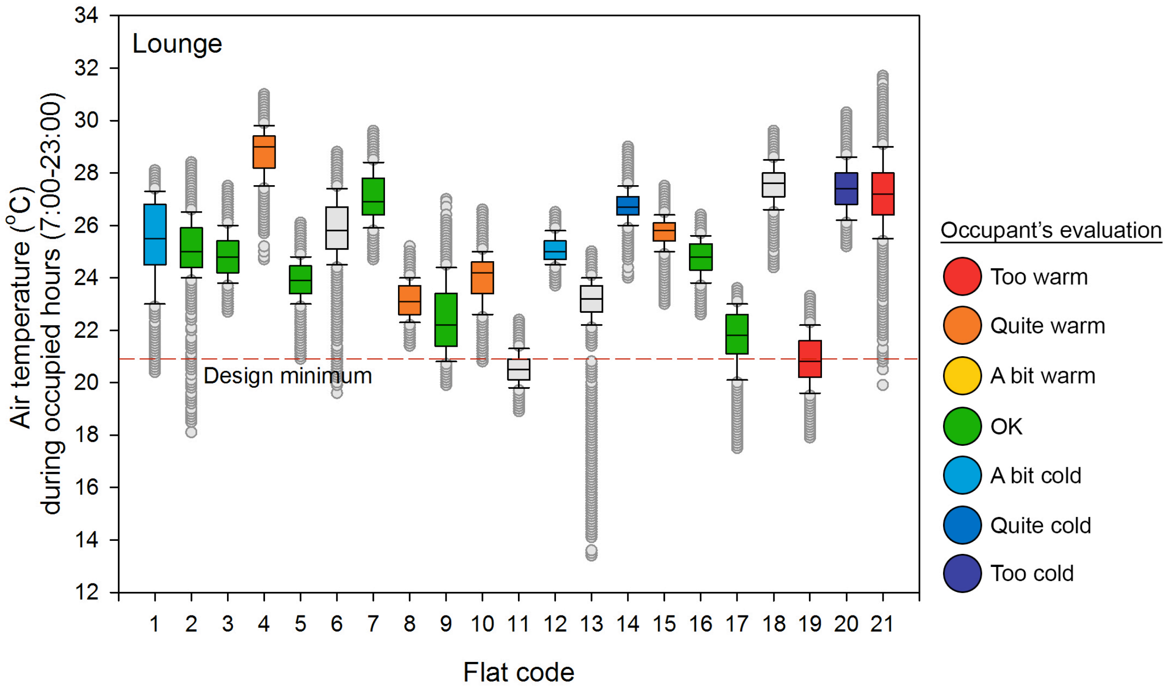

Figure 2. Air temperature box plots in the monitored lounges between 07:00 and 23:00 in the investigated heating period, with occupants' thermal evaluation (grey fill: no interview given). Box: the 50% of the measured air temperatures; whiskers: the 10th and 90th percentile; dots: outliers; black line: median.

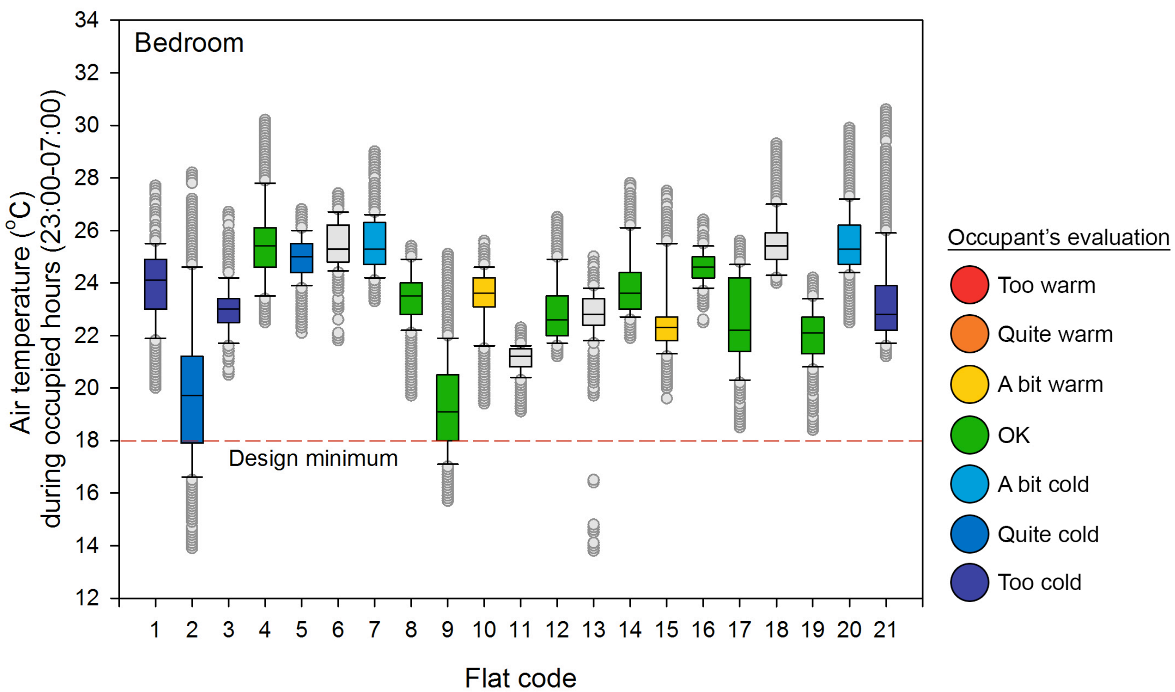

Figure 3. Air temperature box plots in the monitored bedrooms between 23:00 and 07:00 in the investigated heating period, with occupants' thermal evaluation (grey fill: no interview given). Box: the 50% of the measured air temperatures; whiskers: the 10th and 90th percentile; dots: outliers; black line: median.

Figure 4 shows the measured air temperatures in the 21 lounges during the two days with the highest diurnal variation (12th and 13th of March 2014). Meteorological data were provided by Gosport weather station (Gosport Weather, 2015), which is located 2 km west of the case study buildings. As can be seen in the temperature profiles of Figure 4 there was little variation of the indoor air temperature, even with diurnal change of up to 10^{o}C. The occupants clearly experience both high and relatively constant temperatures, in a similar way as people in air conditioned spaces are exposed to narrow temperature ranges. Based on the adaptive comfort principle, such exposures create expectations, which can be expected to happen regardless whether the narrow ranges refer to cooled or heated spaces (de Dear and Brager, 1998).

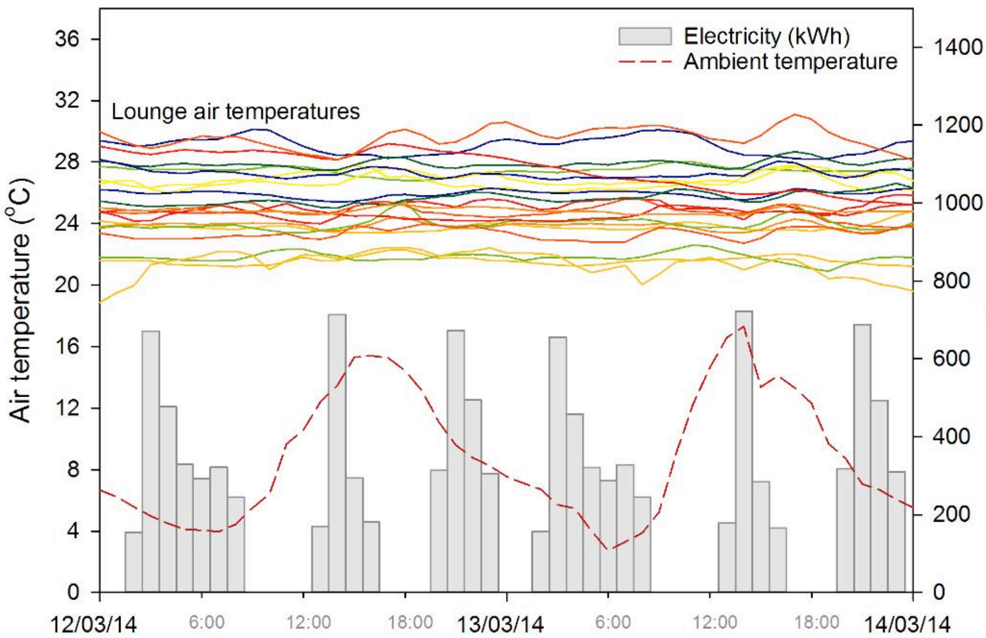

Figure 4. Measured hourly air temperature in the 21 lounges against the external ambient hourly temperature and the electricity consumption for heating in two days in March 2014. Weather data from Gosport weather station (Gosport Weather, 2015).

The average measured air temperature for the lounges in the summer period (June to mid-September) during occupied hours was 23.9^{o}C, which is 1^{o}C lower than the corresponding winter average temperature. The average measured summer air temperature for the bedrooms during the occupied night hours was 23.8^{o}C, only slightly higher than the average in winter. Therefore, occupants experience on average warmer conditions in winter than in summer. This probably explains why the majority of interviewees assessed their thermal environment in summer as 'OK' and only two found their lounge and bedroom as 'too warm'. Overall, the occupants did not express any concerns for uncomfortably high indoor summer temperatures, although air temperatures of up to 31^{o}C were registered during the monitoring period.

Use of heating controls

The interviewees were asked about how frequently they use the available heating controls (ON/OFF, 'input', 'output'). The 'input' setting regulates the amount of heat to be stored during the night, whilst the 'output' setting regulates the amount of heat the storage heater gives off. In the case of manual models, such as those in the case study buildings, the settings should be adjusted with the weather and daily requirements. As can be seen in figure 5, most respondents never use the available controls.

Figure 5. Frequency of use of storage heating switch controls.

With the residents' permission, the settings on all storage heaters at the time of the interview were recorded and then reviewed across 5 categories from low to high. As can be seen in Figure 3, the majority of heaters were set to 'high' and 'medium high' on both 'input' and 'output', even though it was only the beginning of the heating season (1st October). The majority of the respondents, 63% and 75%, reported that they never used the 'ON/OFF' switch of the heaters in the lounge and bedroom respectively and reported that they kept it constantly on. This differs significantly to the situation encountered in a nearby social housing tower block previously studied, where occupants pay their bills separately and preferred to switch the storage heaters off due to the increased costs incurred (Teli et al., 2015). This comparison highlights two issues: a) the lack of engagement with controls due to a lack of financial motivation to do so and b) the risk from changing the billing conditions in the case study buildings without first improving the building's thermal performance. This could lead to under-heated homes and fuel poverty, similar to the nearby tower block. Given the occupants' adaptation to high indoor temperatures, the implementation of such changes would be even more challenging.

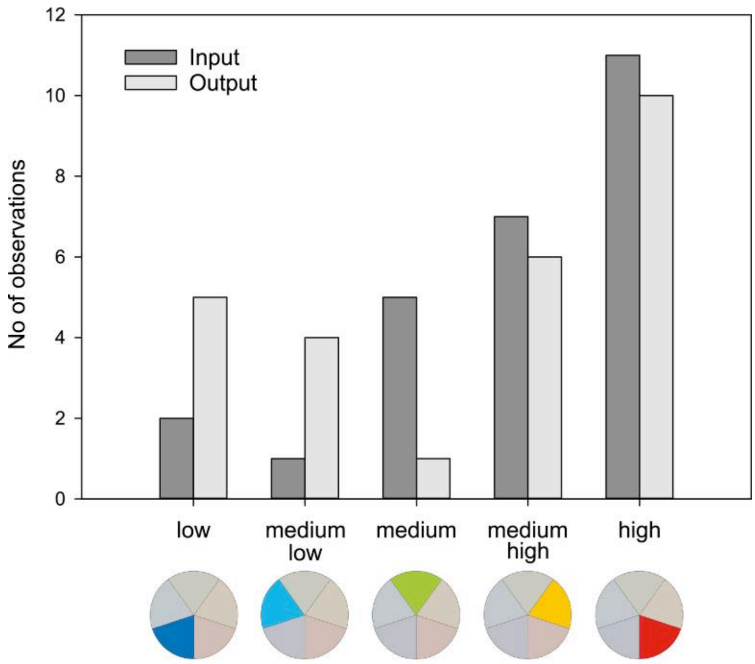

Figure 6. Observed settings during the interview visit.

Comfort conditions

Based on the adaptive comfort principle that people make adjustments in order to feel comfortable at the temperatures they typically encounter (Humphreys et al., 2016), the subjects in this study are expected to have adjusted their clothing to the high indoor temperatures they experience. The calculated clothing insulation values of the residents during the interviews support this, as the average value was 0.52 clo ±0.17, much less than the typically assumed 1 clo for winter (Table 1). The average air temperature during the 17 surveys was 24.0^{o}C ±1^{o}C.

The majority of interviewees are over 55 years old but their age is not expected to have influenced their comfort conditions as research has found that at a given activity and clothing level older people preferred the same thermal environments as younger people (Collins and Hoinville, 1980; Langkilde, 1979). Elderly people are vulnerable due to their lifestyle which involves low activity and high risk related to poor thermoregulatory responses (Parsons, 2014). However, their preferred temperatures have been found to be similar to those of young adults (Parsons, 2014).

The residents' neutral (comfort) temperature was calculated from their thermal sensation vote (TSV) and the indoor operative temperature at the time of the survey (T_{op}), using the equation $T_{comf}=T_{op}-TSV/b$ (Humphreys et al., 2007). As the radiant or globe temperatures were not measured in this study, the air temperature is used instead of the operative temperature. This should not affect the findings, given the overcast conditions during the interviews, the mild outdoor temperatures and the concrete construction of the buildings. Constant 'b' expresses the sensitivity of people to thermal changes and has been estimated through analysis of extensive survey data at 0.5K (Humphreys et al., 2013).

Figure 7 shows the calculated comfort temperature per interviewee, against the mean air temperature in the interviewee's lounge during occupied hours in the heating period. Thirteen of seventeen respondents reported a neutral thermal sensation during the interview, leading to a strong correlation of their comfort temperatures with the mean temperature they experience in their lounge (black dots in Figure 7). Eleven of them had a 'no change' preference, whilst two preferred 'slightly cooler', which is still within the comfort range. Four cases (red dots in Figure 7) reported a warm thermal sensation during the interview, resulting in lower comfort temperatures. However, from these 4 respondents, one had a 'no change' preference and the other three preferred only 'slightly cooler'. Therefore, their warm thermal sensation vote does not necessarily indicate discomfort. The average comfort temperature of the 17 respondents with consistent thermal sensation and preference votes at the time of the survey was 23.8^{o}C ±1.3^{o}C, whilst including the four interviewees with low comfort temperatures brings a mean comfort temperature of 22.8^{o}C ±2.5^{o}C.

For comparison, the predicted mean vote (PMV) was also calculated for each respondent using the measured air temperature and relative humidity, the clothing insulation as estimated from the questionnaire's checklist and the following assumptions: 1) a metabolic rate of 1.1 MET 2) a low air velocity of 0.5 m/s and 3) $T_a=T_{op}$. The PMVs ranged between -1.3 and 0.4, with an average of -0.4. Overall, the PMV lied mainly to the cold side of the scale due to the low clothing level of the subjects.

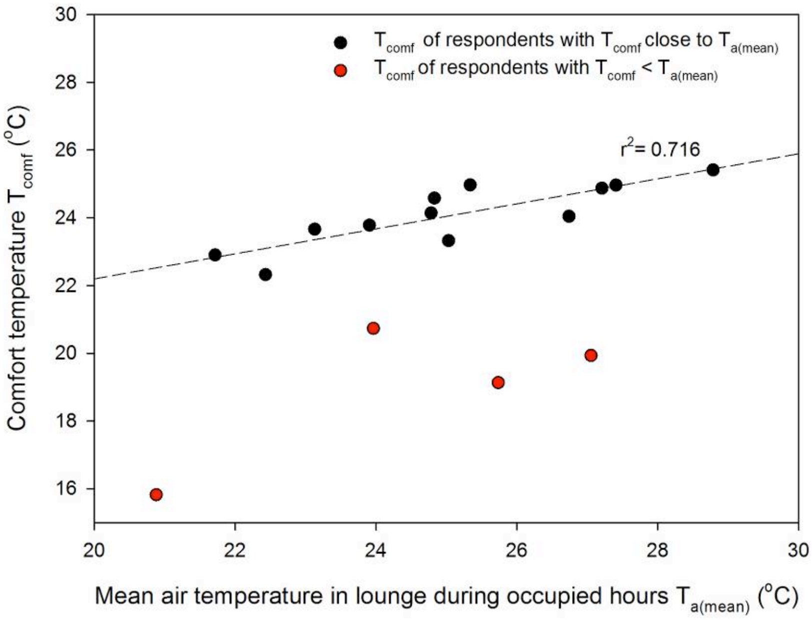

Figure 7. Calculated comfort temperatures for each interviewee, against the mean air temperatures in the lounge during occupied hours in the investigated heating period.

5 Conclusions

This paper presents results from a case study on the influence of thermal exposure to a particular indoor environment on occupants' comfort conditions. The analysis presented demonstrates that increased indoor temperatures combined with a sedentary lifestyle and minimal exposure to outdoors, or other variable thermal environments, may lead to a high level of thermal adaptation to these high temperatures. This poses a challenge to the standard boundaries of thermal comfort, leading to excess in energy demand for heating. The results suggest that thermal comfort research should look into incorporating indoor thermal history in predictions of occupant neutral temperatures.

The thermal sensation votes and the interview responses showed that most people were satisfied with the temperature in their flats both in winter and summer, regardless of being at much higher temperature than recommended levels most of the time. The results suggest that the residents have gone through behavioural and psychological adaptation, and possibly physiological acclimatisation due to warm exposure.

From this study, it can be inferred that occupants' adaptation to high temperatures would challenge the implementation of energy use reduction strategies, if industry-based temperature design criteria were to be met, as these would conflict with the occupants' 'adapted' comfort temperatures. On the other hand, the participants did not highlight issues of summer discomfort, even though measured temperatures were high, which suggests that their heat acclimatisation may have contributed to higher tolerance during summer. These findings highlight the significance of controlling the indoor environment, as high indoor temperatures do not only have direct effects, such as the instant increase in energy use for heating. On the long run, exposure to high indoor temperatures can lead to high comfort temperatures, which would have a long-lasting and challenging effect.

There are limitations in this study that should be noted, such as the small sample size (21 flats and 17 interviewees), the lack of more detailed information on characteristics of the participants that may have affected their thermoregulation (health, weight and height), the lack of a control group and of more detailed thermal comfort surveys. However, the extensive environmental monitoring and the face-to-face interviews have helped to highlight significant patterns, as discussed in the paper and highlighted above. Overall, the findings point to the need for further research to investigate the hypothesis introduced here.

Acknowledgments

This work is part of the Energy and Climate Change Division and the Sustainable Energy Research Group (www.energy.soton.ac.uk) on cities and is partly supported by the EPSRC Grant EP/J017698/1 "Transforming the Engineering of Cities to Deliver Societal and Planetary Wellbeing" and EP/K012347/1 International Centre for Infrastructure Futures (ICIF). D. Teli is a VINNMER Fellow supported by VINNOVA (Swedish Innovation Agency), Marie Curie Actions and the Profile 'Energy in Urban Development' within the Area of Advance 'Energy' at Chalmers University of Technology. Lastly, the authors would like to thank the residents who participated in this study and Portsmouth City Council for their help and support.

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Thermal comfort during temperature cycles induced by direct load control events

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Abstract

Direct load control (DLC) is a utility-sponsored demand response program which allows a utility to cycle specific appliances on and off during peak demand periods. Direct load control of air conditioners induces temperature cycles that might potentially compromise occupants' thermal comfort. In two separate experiments, 56 subjects' thermal comfort was closely examined during 6 DLC conditions and 2 control conditions simulated in a climate chamber, representing typical DLC-induced thermal environments in university lecture theatres. Results show that half of the DLC conditions were clearly accepted by subjects. Multilevel linear modelling of thermal sensation demonstrates that operative temperature, vapour pressure and the rate of temperature change are the three most important predictors during DLC events. Multilevel logistic regression indicates that in DLC conditions with lower adapting temperatures, thermal acceptability is significantly predicted by air speed and its interaction with operative temperature whereas in DLC conditions with higher adapting temperatures, by air speed, operative temperature and the rate of temperature change.

Keywords: direct load control (DLC); demand response; thermal comfort; temperature cycles; thermal transients

1 Introduction

1.1 Direct load control strategy and its impact on indoor thermal environment

Demand response provides an opportunity for consumers to play a significant role in the operation of the electric grid by reducing or shifting their electricity demand during peak periods in response to time-based tariffs or other financial incentives (Office of Electricity Delivery & Energy Reliability, accessed 2015-09-20). *Direct load control (DLC)* is a utility-sponsored demand response program which allows a utility to cycle specific appliances on and off during peak demand periods. In exchange, participating customers are entitled to financial incentives or discounted electricity bills. The most commonly targeted appliances in DLC programs are air conditioners, electric water heaters and pool pumps. Air conditioners are the focus of the present study. Direct load control of air conditioners typically consists of duty cycle restriction and temperature setback (Weller, accessed 2015-09-20); the former is the research interest of this paper. Under duty cycle restriction program, the air conditioner compressor is switched on and off at predetermined intervals with the fan on even if the set-point temperature is not met.

For the duty cycle restriction DLC approach, cycling the air conditioner compressors on and off for a given proportion of time will generate repeated rises and falls in air (operative) temperature. Depending on the DLC algorithms and building-specific characteristics, it is possible that indoor temperature fluctuation amplitude exceeds the range of thermal comfort zones in steady states and potentially causes thermal discomfort for building occupants. The previous work of the authors (Zhang and de Dear, 2015) have simulated thermal comfort impacts of 48 DLC algorithms in university lecture theatres with much higher occupant density and ventilation rate than the residence small business buildings, representing a "worst case" scenario for DLC-induced thermal environments. Although most of the simulation cases exceeded the permissible thermal comfort range defined by Fanger's Predicted Mean Vote (PMV) / Predicted Percentage Dissatisfied (PPD) method (Fanger, 1972), since the applicability of the PMV/PPD method in transient thermal environments is questionable (refer to the discussion in 1.2), the *actual* comfort impacts of DLC events must be examined in either laboratory experiments or field studies with human subjects.

1.2 Thermal comfort during temperature cycles, ramps and drifts

ISO 7730 (2005) defines temperature cycle as "variable temperature with a given amplitude and frequency". In ASHRAE 55 (2013), cyclic variations refer to "those situations where the operative temperature repeatedly rises and falls, and the period of these variations is not greater than 15 minutes". The maximum allowable peak-to-peak cyclic variation in operative temperature is 1.1°C. Temperature ramps and drifts are defined as "monotonic, non-cyclic changes in operative temperature" (ISO 7730, 2005; ASHRAE 55, 2013). Cyclic variations with a period greater than 15 minutes are also treated as ramps or drifts. The maximum change allowed for ramps and drifts in operative temperature during a period of time is shown in Table 1.

Table 1 Limit on temperature ramps and drifts by ASHRAE 55 (2013)

Time Period, h	0.25	0.5	1	2	4
Maximum Operative Temperature Change Allowed, °C	1.1	1.7	2.2	2.8	3.3

Hensen (1990) reviews 5 climate chamber experiments on cyclical temperature variations (Sprague and McNall, 1970; Wyon et. al., 1971; Wyon et. al., 1973; Nevins et. al., 1975; Rohles et. al., 1980). After this review, there has been no recent study on temperature cycles. Table 2 summarises their key experiment design parameters and main results. Regarding the range of comfort zone due to temperature variations, Table 2 reports inconsistent results from the experiments: Sprague and McNall (1970) reported narrowed comfort zones with increased rates of temperature change; Wyon et. al. (1971, 1973), nonetheless, found the opposite to be true—subjects tolerating greater amplitudes when the temperature changes more quickly; Nevins et al. (1975) and Rohles et al. (1980), however, concluded that fluctuation-induced comfort zones would not differ much from those obtained in steady state conditions. Possible explanations for these contradictions pointed out by Hensen (1990) related to distinct experimental designs, different voting scales, acceptability criteria adopted, test conditions and so on. Despite the confusion he concluded that, with cyclical fluctuating ambient temperatures, the bandwidth of acceptable temperatures decreases with increasing fluctuation frequency, and achieves its maximum under steady-state conditions.

Table 2 Summary of thermal comfort studies on temperature cycles

References	Sample size	Age group	Thermal conditions	Amplitude/frequency /rate of temperature change	Duration	Voting scales	Implications on the range of comfort zone due to temperature variations
Sprague and McNall (1970)	192	College age	M= 1.2 met; I_{cl} =0.6 clo; T_r=25.6 °C; RH=45%; v < 0.15 m/s.	Peak-to-peak amplitudes 0.6°C–3.3°C; 1.7 °C/h–10.9 °C/h; 1.0–2.0 cycles/h	3 h	Discrete/continuous 7 category thermal sensation scale	Decreased comfort zones with increased rate of change
Wyon et al. (1971)	8	19–25	T_r=28 °C, I_{cl} =0, RH=50%; T_r=25°C, I_{cl} =0.6 clo, RH=50%.	The amplitude is under subjects' control; 9°C/h, 30 °C/h	2 h mental work followed by 2 h rest	Spontaneous dial voting when the temperature was too hot or too cold	Increased comfort zones with increased rate of change
Wyon et al. (1973)	16	21–28	T_r=24.5 °C, M= 1.2 met; I_{cl} =0.6 clo; v < 0.1 m/s	Peak-to-peak amplitudes 2°C, 4°C,6°C,8°C; 15 °C/h, 30°C/h, 45°C/h, 60 °C/h; 1.9–7.5 cycles/h	7 h 48 mins on successive days	A different version of dial voting method	The width of comfort vote distribution increases with higher amplitudes, but discomfort votes increase as well
Nevins et al. (1975)	18	19–55	T_r=25 °C; M = 1.2 met; I_{cl} = 0.6 clo; RH = 50%; v = 0.25 m/s	Peak-to-peak amplitudes of 10 °C; 18.7 °C/h on average; 0.9 cycles/h	2 h	ASHRAE 7-point thermal sensation scale and 5 category comfort scale	Same comfort zone as in steady state conditions
Rohles et al. (1980)	804	18–23	M = 1.2 met; basal temperature 17.8 °C–29.4 °C; I_{cl} = 0.6 clo; RH = 50%;	Amplitudes 1.1°C–5.6 °C; 1.1–4.4 °C/h; 0.3–1.5 cycles/h	Variant	9 category thermal sensation scale and 7 category semantic differential comfort scale	Same comfort zone as in steady state conditions

(M—Metabolic rate; I_{cl}—clo value; T_r—reference/control temperature; RH—relative humidity; v—air speed)

Table 3 summarises 6 climate chamber experiments on temperature ramps and one experiment on temperature drifts. In respect to subjects' thermal sensitivity[1], the experiments consistently show it to be neither affected by clothing (Berglund and Gonzales, 1978a) nor age (Schellen et. al., 2010). Regarding thermal sensitivity vs. rate of temperature change, no consistent relationship can be observed in these studies. Comparison between Thermal Sensation Vote (TSV) and PMV reveals that generally these two parameters are in reasonably good agreement for young subjects (Griffiths and McIntyre, 1974; Knudsen et. al., 1989; Kolarik et. al., 2009; Schellen et. al., 2010). Knudsen et. al. (1989) concluded that the PMV model might be possible to predict thermal sensation for a rate of temperature change up to ±5.0 °C/h. As for thermal comfort zone width compared with steady states, contradictory results have also been reported: Berglund and Gonzalez (1978a and 1978b) and Schellen et. al. (2010) reported increased comfort zone width (thermal acceptability) than in steady states; Griffith and McIntyre (1974) reported the same comfort zone width; Rohles et. al. (1980) and Knudsen et. al. (1989) reported decreased comfort zone while Kolarik et. al. (2009) reported inconsistent results for different ramps. As mentioned before, discrepant thermal acceptability criteria are likely an important cause of the inconsistent findings; another factor might include human thermoregulation control mechanisms that will be discussed in the following.

[1] Thermal sensitivity is defined as ΔTSV/ΔT by Berglund and Gonzalez (1978) where ΔTSV means change of thermal sensation vote on the ASHRAE 7-point scale and ΔT means change of operative temperature.

Table 3 Summary of thermal comfort studies on temperature ramps and drifts

References	Sample size	Age group	Thermal conditions	Amplitude/ range/ frequency/ rate of temperature change	Duration	Voting scales	Thermal Sensitivity	Validity of PMV/PPD methods in predicting thermal comfort zone
Griffiths and McIntyre (1974)	32	16–19	T_r=23 °C; I_{cl} = 0.7–0.9 clo; v < 0.1 m/s; vapour pressure within 10 mb ±2·2 mb	±1.5 °C, ±3 °C, and ±4.5 °C from 23 °C; ±0.5 °C/h, ±1.0 °C/h, ±1.5 °C/h	6 h	Bedford Warmth Scale and 7 category subjective voting scale	No difference	Thermal comfort zone agrees well with predicted by PMV/PPD
Berglund and Gonzalez (1978a)	36	18–28	T_r=25 °C; M = 1.2 met; I_{cl} = 0.5, 0.7, 0.9 clo; v = 0.1 m/s; T_d=12 °C	±2 °C, ±4 °C, and ±6 °C from 25 °C; ±0.5 °C/h, ±1.0 °C/h, ±1.5 °C/h	4 h	ASHRAE thermal sensation scale and binary acceptability scale	Higher during ±1.0 °C/h ramp than during ±1.5 °C/h ramp, but inconsistent with ±0.5 °C/h ramp	Thermal acceptability is wider than predicted by PMV/PPD for all ramps
Berglund and Gonzalez (1978b)	24	19–33	T_r=25 °C; I_{cl} = 0.32–0.72 clo; v = 0.1 m/s; T_d=10 °C, 20 °C	23 °C–27.8 °C; 0.6 °C/h	8.5 h	ASHRAE thermal sensation scale and binary acceptability scale	—	Thermal acceptability is wider than predicted by PMV/PPD
Rohles et. al. (1980)	84	18–22	I_{cl} = 0.8 clo	One-hour drift: 22.3 °C–27.8 °C, Half-hour drift: 22.3 °C–26.1 °C; Up to 4.44 °C/h for one-hour drift, 5 °C/h for half-hour drift	0.5–1 h	9 Category thermal sensation scale and 9 category thermal comfort ballot	—	Thermal comfort zone is slightly narrower than predicted by PMV/PPD
Knudsen et. al. (1989)	40	21–25	T_r=19.5 °C, 21.5 °C, 23.5 °C; M = 1.2 met; I_{cl} = 0.8 clo; RH = 50%; vapour pressure 1.28 kPa	±3 °C, ±7.5 °C from 21.5 °C; ±1 °C/h, ±5 °C/h	1.5–3 h	ASHRAE thermal sensation scale and 4 category acceptability scale	No difference	Thermal comfort zone is narrower for both ±1 °C/h and ±5 °C/h ramps in the cooler side than predicted by PMV/PPD model
Kolarik et. al. (2009)	52	19–28	T_r=24.4, 21.4 °C; M = 1.2 met; I_{cl} = 0.5, 0.7 clo; RH = 50%;	Experiment 1: 22 °C–26.8 °C; Experiment 2: 17.8 °C–25 °C; ±0.6 °C/h, ±1.2 °C/h, +2.4 °C/h, +4.8 °C/h	1–8 h	ASHRAE thermal sensation scale, 4 category acceptability scale	No difference for +1.2 °C/h, +2.4 °C/h, and +4.8 °C/h ramps, but sensitivity is significantly higher for +0.6 °C/h in experiment 1	Decreased comfort zone for 4.8 °C/h ramp; increased comfort zone for 0.6 °C/h in the warm side; same (similar) comfort zone for the other ramps
Schellen et. al. (2010)	16 (all men)	Young: 22–25; Old: 67–73	T_r=21.5 °C; M = 1.2 met; I_{cl} = 1.0; v = 0.19±0.03 m/s; RH = 40%	17°C–25°C; First 4 h: +2 °C/h; Last 4 h: –2 °C/h	8 h	ASHRAE thermal sensation scale and 4 category comfort scale	Generally the same for young and old subjects	TSV agrees well with PMV for young subjects, but is 0.5 unit lower for old subjects; slightly increased comfort zone

(M—Metabolic rate; I_{cl}—clo value; T_r—reference/control temperature; RH—relative humidity; v—air speed; T_d—dew point temperature)

In spite of previous studies on temperature cycles, ramps and drifts, there has been no study to date directly looking at the thermal comfort impacts of temperature cycles induced by direct load control strategies of peak electricity demand management. The present study tries to address this issue through laboratory experiments with university student subjects, simulating lecture theatre settings as a worst-case DLC-induced thermal environment; specifically it elaborates on the following two research questions: What are subjects' thermal comfort responses to variant DLC air conditioning events? What are the main environmental and demographic factors that affect subjects' thermal comfort and how do these factors interact with each other?

2 Methods

2.1 Participants

Two separate experiments on simulated DLC air-conditioning events with different adapting temperatures were performed. Participants for the two experiments were recruited from the university students, regardless of age, degree and discipline. Key anthropometric characteristics of the subject were listed in Table 4. All participants wore a standardised clothing ensemble consisting of a short-sleeve T-shirt, athletic shorts, sandals and their own underwear, representing typical clothing ensemble in Australian universities during summer time. T-shirts and shorts were 100% polyester to avoid any transient absorption and desorption heat effects. The uniform's intrinsic clothing insulation was estimated to be 0.5 clo including the insulation of the chairs (0.1 clo) used inside the climate chamber.

Table 4 Anthropometric characteristics of participants (Mean ± Standard Deviation)

Sex	Number	Age (year)	Height (cm)	Weight (kg)	DuBois Area (m^2)
Experiment 1					
Male	14	24.4 ± 4.8	178.1 ± 5.9	79.8 ± 18.9	1.97 ± 0.21
Female	14	27.0 ± 8.1	162.8 ± 7.4	53.9 ± 5.3	1.57 ± 0.11
Total	28	25.7 ± 6.7	170.5 ± 10.2	66.8 ± 19.0	1.77 ± 0.26
Experiment 2					
Male	14	24.1 ± 6.4	174.9 ± 4.1	73.4 ± 9.3	1.88 ± 0.12
Female	14	24.6 ± 6.5	162.9 ± 7.1	56.5 ± 7.0	1.60 ± 0.12
Total	28	24.4 ± 6.3	168.9 ± 8.4	65.0 ± 11.8	1.74 ± 0.19

2.2 Experiment conditions

The authors' previous simulation study on thermal comfort impacts of DLC air-conditioning strategies in university lecture theatres (Zhang and de Dear, 2015) have identified off cycle fraction, cycling period, cooling set-point temperature before DLC events and building envelope thermal performance as the most influential factors affecting thermal environments during DLC events. As a *fractional factorial design* (Gunst, 2009), 8 DLC algorithms were selected from 48 simulation cases conducted in Zhang and de Dear (2015) by the *orthogonal array* method (Fowlkes and Creveling, 2012). The orthogonal arrays stipulate the way of conducting the minimal number of experiments that could give the full information of all the factors that affect the performance parameter. For each experiment, participants will experience 1 control condition (no DLC event) and 3 experiment conditions (DLC events). All four conditions in Experiment 1 have a cooling set-point temperature (adapting temperature) of 22 °C whereas 24 °C for conditions in Experiment 2. The simulated operative temperature (t_{op}) and relative humidity (RH) for each condition were illustrated in Fig. 1 and Fig. 2.

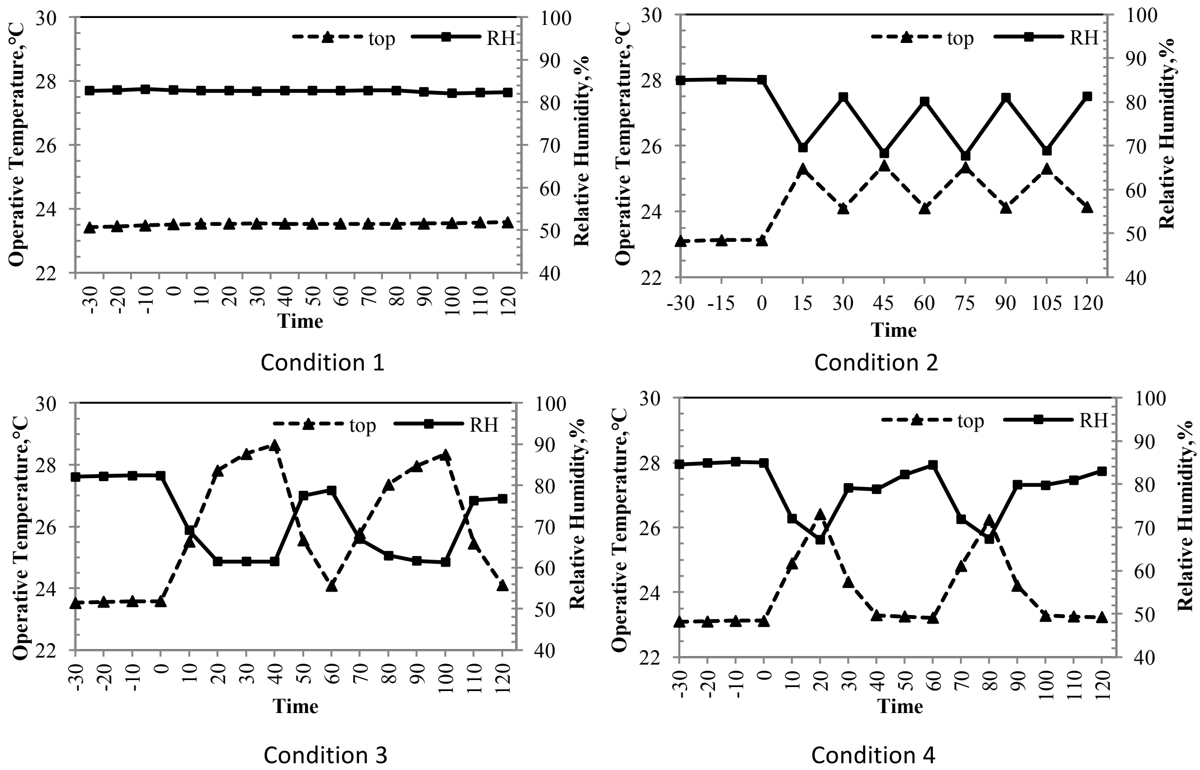


Fig.1. Simulated operative temperature and relative humidity in four conditions of Experiment 1

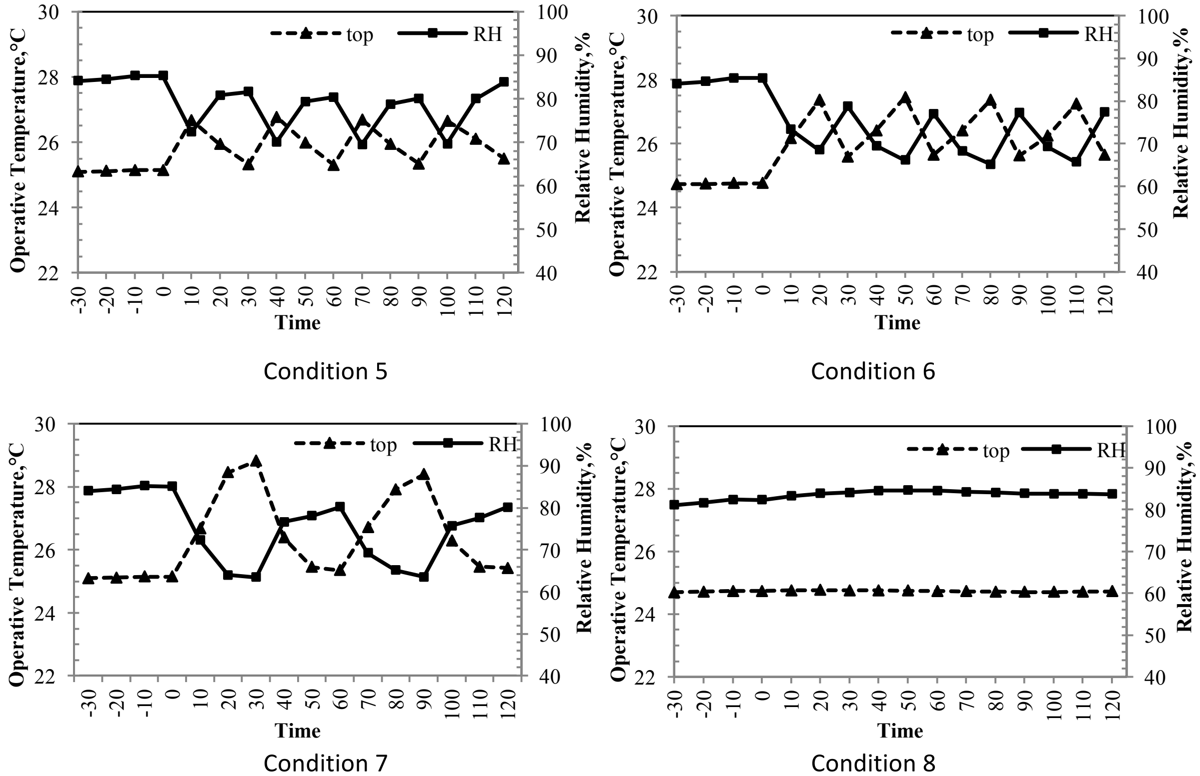


Fig. 2. Simulated operative temperature and relative humidity in four conditions of Experiment 2

2.3 Experimental set-up

The experiments were conducted in the summer of 2014 so that subjects were assumed to be naturally heat acclimatized. A climate chamber (8.85 m × 6.85 m, 2.60 m in height with an accessible raised floor of 250 mm) with temperature and humidity control was used to re-create the various DLC events in the research design and accommodate human subjects. The constant air volume air-conditioning system provided heating and cooling as well as constant fresh air supply at 10 L/s/person during the experiments. The outdoor simulation corridor alongside the climate chamber rendered the typical Sydney DLC event day outdoor condition reported in Zhang and de Dear (2015)—30.8 °C. During the experiments, the air temperature, globe temperature, relative humidity and air speed were measured every five minutes throughout every session. The globe temperature was measured at 0.6 m height in the occupied zone using thermistors (± 0.2 °C accuracy) inserted in 38 mm Ping-Pong balls painted malt black and served as the control temperature to implement the temperature cycles as depicted in Fig. 1 ad Fig. 2; the air temperature was measured at 1.1 m height in the occupied zone by INNOVA 1221-Thermal Comfort Data Logger; the wall-mounted humidity sensors at 1.7 m height monitored atmospheric moisture in the chamber. Seven fast-response Dantec thermal anemometers (Omnidirectional Transducer 54T21 for Indoor Air Flows) were mounted at 1.1m height adjacent to each subject where they measured air speed at a sampling rate of 1Hz.

2.4 Procedure

In each experiment, 28 subjects were divided into 4 sub-groups. The sequences of experimental conditions to which the four sub-groups were exposed, were balanced in a 4×4 Latin-square design. All participants were required to attend a 1-h induction session one week before the experiments started. The purposes of the induction were to provide training on the thermal comfort questionnaires and also the cognitive performance tests. Results on cognitive performance tests are not the focus of this paper and will be discussed elsewhere. Participants experienced four conditions throughout four successive weeks. The experimental session lasted for 2.5 hours. During the first half hour, participants acclimatized to the cooling set-point temperature (also the adapting temperature, 22 °C for Experiment 1 and 24 °C for Experiment 2). The subsequent 2 hours were formal experiment period in which thermal comfort questionnaires were administered to subjects via a bespoke iPad application every 5 minutes until the session ended. Thermal comfort questionnaires included a 7-point ASHRAE thermal sensation scale (with continuous slider scale to enable real TSV numbers), and a binary thermal acceptability scale. At the end of every session, subjects were presented with a binary overall acceptability question asking about each experimental session's thermal acceptability as a whole.

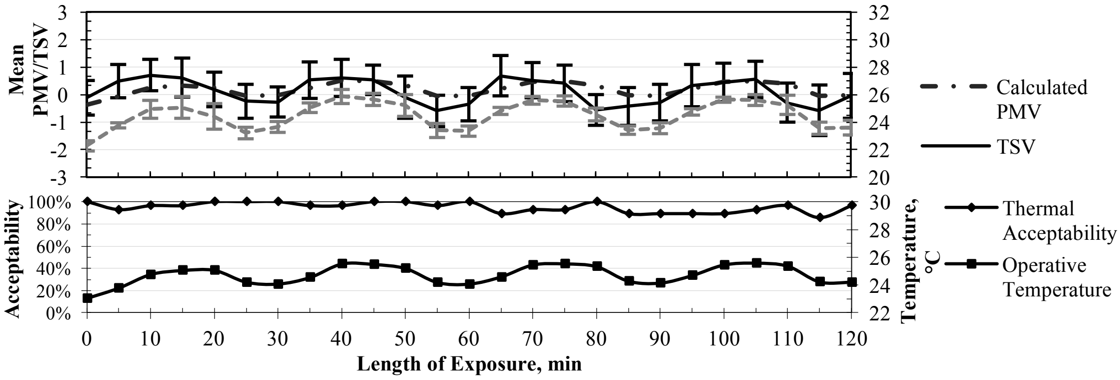
3 Statistical analysis

Multilevel linear modelling (MLM) is designed to deal with the violation of the assumption of independent errors expected when individuals within groups share experiences that may affect their responses or there are repeated measures for the same individuals. This experimental study is a three-level repeated cross-sectional design (LEMMA, accessed 2015-09-20): thermal environments were clustered within experiment conditions, which are in turn clustered within participants. Each participant attended four experiment conditions (including a control condition) in which they were exposed to various thermal environments (determined by the specific DLC event). The Level 1 variables are thermal environmental parameters such as operative temperature, vapour pressure, air speed, rate of temperature change, and time variables such as subjects' length of exposure. The Level 2 variable is the experiment condition. The Level 3 variables are demographic variables, i.e. subjects' age and sex. Multilevel linear modelling of participants' thermal sensation was implemented through SPSS Mixed Models, Version 22. Multilevel logistic modelling of participants' thermal acceptability and overall acceptability was implemented by *glmer* function in R, Version 3.2.0. To manage multicollinearity between predictors and help with interpreting the models, Level 1 variables that do not have a meaningful zero point were centred by their respective grand means (Tabachnick and Fidell, 2012).

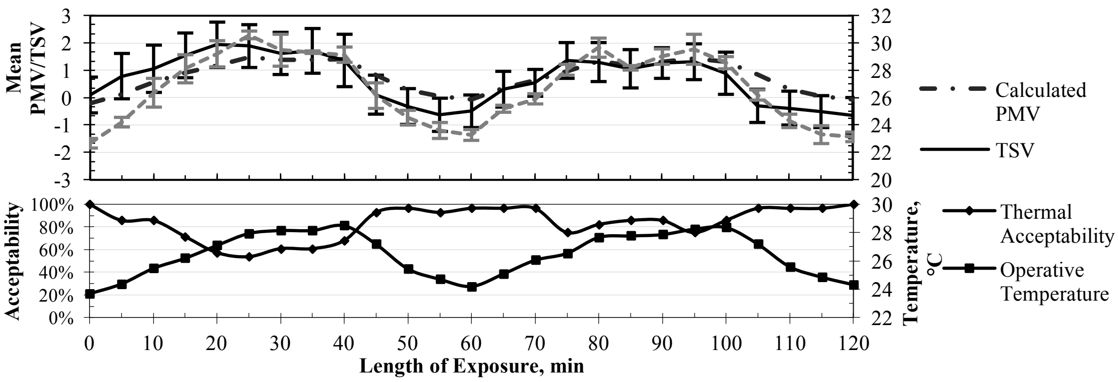
4 Results

4.1 Thermal perception during DLC events

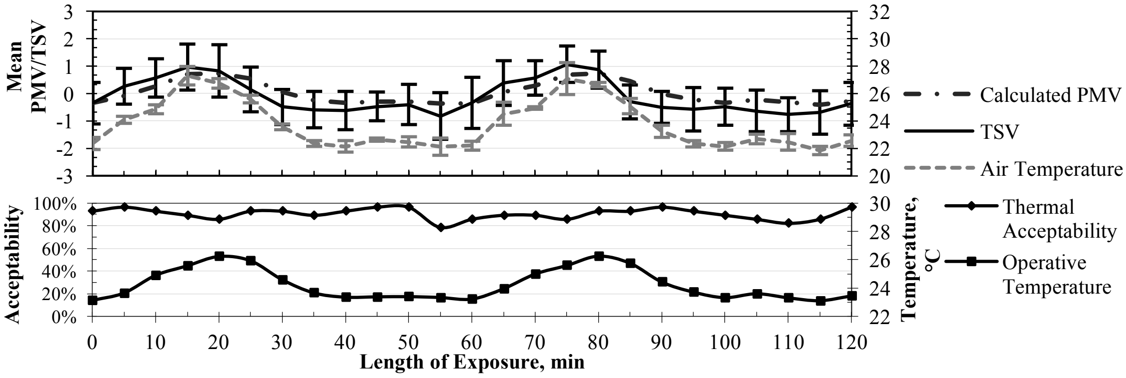
Fig. 3 depicts the time series data for air temperature and operative temperature monitored in the climate chamber for 6 DLC conditions in two experiments, along with subjects' TSV and thermal acceptability ratings every 5 minutes. For comparison, the calculated PMV results using on-site measured parameters were also plotted on the same graph. The temperature fluctuation amplitudes in Condition 3, 4 and 7 ranged between 5 °C to 7 °C (air temperature) and were higher than those in Condition 2, 5 and 6 which were generally around 3–4 °C. Comparing TSV with the calculated PMV, it is evident that the previously mentioned overshoot effect (overestimate of warm and cool sensations) commonly occurred in both sudden warming and sudden cooling stages during all DLC events, with that in large temperature cycles (Condition 3, 4 and 7) being especially pronounced. Also, this overshoot was usually stronger during the first cycle, but was attenuated during subsequent cycles. Thermal acceptability votes in Conditions 2, 4 and 5 were almost above 80% throughout the whole DLC event while in Condition 3, 6 and 7, thermal acceptability strayed from 80% limit for different durations. Detailed experimental effects during DLC events will be discussed in the following sections.



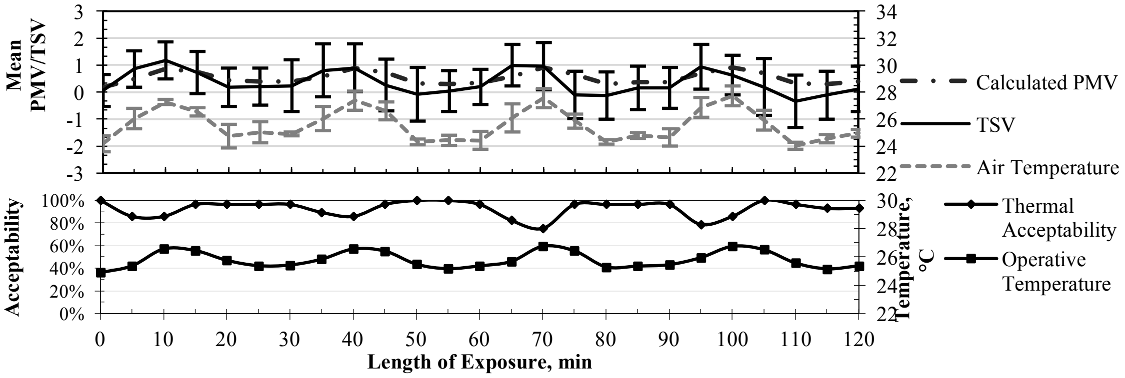
Condition 2



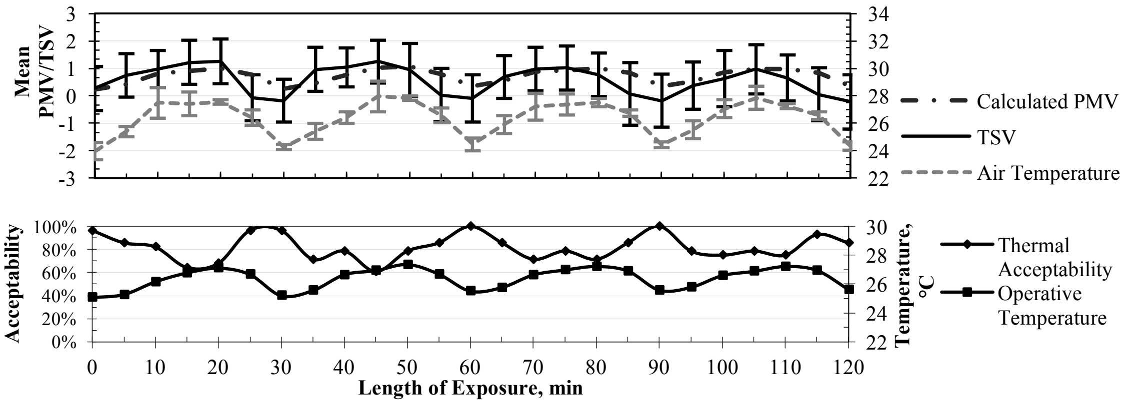
Condition 3



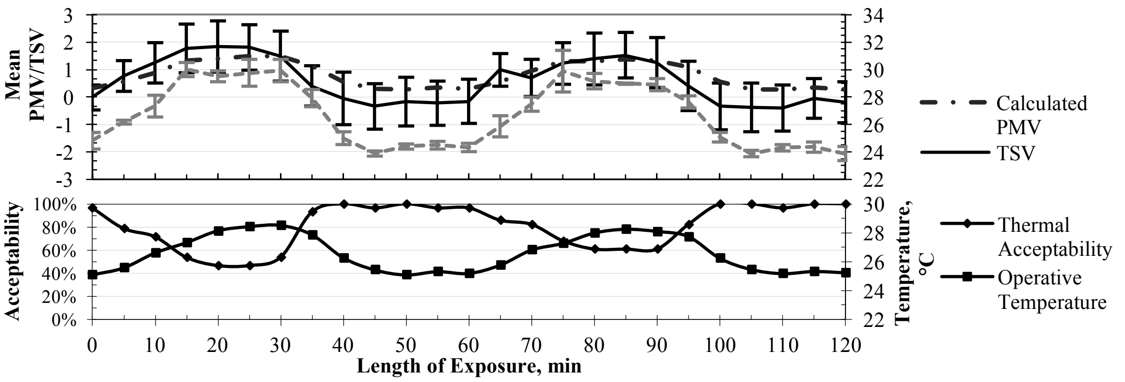
Condition 4



Condition 5



Condition 6



Condition 7

Fig. 3 Air temperature, operative temperature, calculated PMV, subjects' TSV and thermal acceptability in 6 DLC conditions (error bars indicate Standard Deviation)

4.2 Predictors of TSV during DLC events

Steady-state experiments by Rohles (1973) and Rohles and Nevins (1971) on 1600 college-age students revealed correlations between TSV and temperature, humidity, sex, and length of exposure. Air speed was also a significant predictor for subjects' thermal sensation (Fanger, 1972). However, under transient exposures, the rate of skin temperature change has been clearly demonstrated to be related to thermal sensation in thermal transients (Ring and de Dear, 1991; Attia and Engel, 1981; Rohles, 1981). Schellen et. al (2010) reported age difference regarding thermal sensation. The above-mentioned parameters along with experiment condition (Level 2 variable) have been tested in the MLM with possible two-way interactions. The rate of operative temperature change in the ambient environment was adopted instead of the rate of subjects' skin temperature change since the latter was not monitored during the experiments.

Level 1 main and within-level interaction effects

There are five main significant predictors that have been detected by both experiments—operative temperature, vapour pressure, rate of temperature change, length of exposure and air speed. The operative temperature, vapour pressure and rate of temperature change were significantly positively related to TSV, while occupants' length of exposure in the thermal environment and the air speed were significantly negatively related to TSV. Note that the effect of the rate of temperature change on TSV confirms the previously mentioned overshoot effect (Hensel, 1981; Ring and de Dear, 1991). It is expressed as either a positive/negative value representing a warm/cold overshoot respectively.

Apart from the main effects, there were significant interaction effects observed between some main predictors, although these effects were not consistent in both experiments. Significant interaction effect means that main predictors not only affect subjects' thermal sensation independently, but also have a joint impact. Specifically, the relationship between TSV and one main predictor would be modified by different levels of values of other main predictors. For Experiment 1, taking Condition 3 as an example, the relationship between TSV and air speed (the regression coefficient) was significantly modified by the value of the operative temperature. If the operative temperature was higher than the mean value in Experiment 1, the air speed had larger negative impacts on TSV than when the operative temperature was lower than the mean value. Similarly, the relationship between TSV and rate of temperature change was also significantly modified by two other parameters—air speed and subjects' length of exposure. The overshoot of subjects' TSV due to a warm temperature change would be ameliorated by a higher air speed that was above the mean value and longer length of exposure in this environment. On the contrary, if the air speed was lower than the mean value and subjects were just exposed to this warm temperature change, the overshoot effect of TSV would be more pronounced.

Experiment 2 produced more interaction effects between the main predictors than Experiment 1. Taking Condition 6 as an example, the relationship between TSV and operative temperature—known as thermal sensitivity—was significantly modified by subjects' length of exposure in this environment. The longer the exposure, the less thermal sensitivity they had. The relationship between TSV and vapour pressure—humidity sensitivity—was also significantly modified by subjects' length of exposure as well as the operative temperature value. However, subjects' length of exposure had a positive impact on subjects' sensitivity to humidity, meaning that the longer they stayed in a humid environment, the larger the impact of humidity on TSV. The operative temperature also had a positive modification on subjects' sensitivity to humidity, which was strengthened at higher operative temperature. There were also two parameters that significantly modified the relationship between TSV and rate of temperature change: the vapour pressure and length of exposure. The overshoot of subjects' TSV due to a warm temperature change was augmented by higher vapour pressure but attenuated by longer length of exposures.

Condition effects and cross-level interactions

Experiment condition, the Level 2 variable, was tested by MLM along with interactions with Level 1 main predictors for the two experiments and results are shown in Table 5. It is worth mentioning that the relationship between TSV and centred operative temperature (thermal sensitivity) significantly varied across conditions in both experiments ($p < 0.05$ for Experiment 1 and $p < 0.001$ for Experiment 2). In Experiment 1, Condition 3 had significantly higher thermal sensitivity (0.170 TSV/°C) than that (0.058 TSV/°C) in Condition 1, 2 and 4 ($p < 0.05$). In Experiment 2, the thermal sensitivity in Condition 7 (0.336 TSV/°C) was significantly higher ($p < 0.05$) than that (0.115 TSV/°C) in Condition 5, 6 and 8.

Table 5 The effect of experiment condition and cross-level interactions on TSV for two experiments

Level 2 predictors and cross-level interactions	Experiment 1	Experiment 2
Experiment condition	$p < 0.05$	NS
Experiment condition × centred operative temperature	$p < 0.05$	$p < 0.001$
Experiment condition × centred vapour pressure	NS	NS
Experiment condition × centred air speed	NS	$p < 0.05$
Experiment condition × length of exposure	$p < 0.01$	NS
Experiment condition × rate of temperature change	NS	NS

(NS—not significant)

Sex and age effects and cross-level interactions

The effects of subjects' sex and age, as well as their interactions with Level 1 main predictors, were also tested by MLM for two experiments and results are presented in Table 6. Neither sex nor age had a significant effect on thermal sensation during DLC events; nor did these two factors have significant interactions with Level 1 predictors. The only exceptions were an interaction between sex and rate of temperature change in Experiment 2, and an interaction between age and rate of temperature change in Experiment 1.

Table 6 The effect of subjects' sex, age and cross-level interactions on TSV for two experiments

Level 3 predictors and cross-level interactions	Experiment 1	Experiment 2
Sex (Female=0, Male =1)	NS	NS
Sex × centred operative temperature	NS	NS
Sex × centred vapour pressure	NS	NS
Sex × centred air speed	NS	NS
Sex × length of exposure	NS	NS
Sex × rate of temperature change	NS	$p < 0.05$
Centred age	NS	NS
Centred age × centred operative temperature	NS	NS
Centred age × centred vapour pressure	NS	NS
Centred age × centred air speed	NS	NS
Centred age × length of exposure	NS	NS
Centred age × rate of temperature change	$p < 0.05$	NS

(NS—not significant)

In order to establish which main predictors or interaction effects (the independent variables) had greater effects on TSV (the dependent variable) in a multilevel multiple regression analysis, standardized regression coefficients which have removed the units of measurement of predictor and outcome variables were calculated for all Level 1 main predictors and interaction effects by applying Equation (1) from Hox (2002).

$$Standardized\ coefficent = \frac{unstandardized\ coefficient \times Standard\ Deviation\ of\ explanatory\ variable}{Standard\ Deviation\ of\ outcome\ variable} \quad \text{Equation (1)}$$

Standardized coefficients reveal that for both experiments, operative temperature, vapour pressure and rate of temperature change were generally the most important predictors for thermal sensation during DLC events. In Hensen's extensive transient thermal comfort literature review (Hensen, 1990), he pointed out that four studies on the effect of varying humidity on thermal sensation and thermal comfort (Gonzalez and Gagge, 1973; Nevins et. al., 1975; Gonzalez and Berglund, 1979; Stolwijk, 1979) all indicated that the relative humidity range between 20% to 60% did not have an appreciable effect on the thermal comfort of sedentary or slightly active, normally clothed persons, providing the operative temperature was within or near the comfort zone; relative humidity became more important when conditions were warmer and thermoregulation depended more on evaporative heat loss. Obviously during warm and humid temperature cycles induced by DLC events, relative humidity had a bigger impact on thermal sensation, which could be even more pronounced than the temperature effect.

4.3 Predictors of thermal acceptability during DLC events

Previous literature has not directly looked at how thermal acceptability could be predicted from thermal environmental and demographic parameters. In this study, a multilevel logistic regression has been adopted to identify significant predictors for thermal acceptability during DLC events for both experiments. Table 7 shows predictors for thermal acceptability in both experiments and odds ratios calculated for significant predictors. In Experiment 1, operative temperature was not a significant predictor for subjects' thermal acceptability vote, whereas the air speed and the interaction between operative temperature and air speed were both highly significant. The odds ratio of air speed implied that holding the operative temperature fixed, thermal acceptability would increase greatly if air speed was higher than the mean value. Similarly, in Experiment 2, there were three significant Level 1 predictors, namely operative temperature, rate of temperature change and air speed. Length of exposure was not significant; however its interaction effect with rate of temperature change was significant. The odds ratio for centred operative temperature indicated that, holding rate of temperature change, centred air speed and length of exposure at fixed values, the odds of voting acceptable would increase if the operative temperature was higher than its mean value 25.9 °C. Similarly, holding the other three parameters fixed, the odds of voting acceptable would go down when the rate of temperature change increases towards the warm direction and go up when the air speed increases from its mean value 0.05 m/s.

Table 7 Estimate of predictors for probability of voting acceptable in both experiments

Experiment	Fixed effects	Estimate	Std. Error	z value	Significance	Odds Ratio
Experiment 1	(Intercept)	3.330	0.614	5.425	5.79E-08 ***	27.942
	Centred operative temperature	-0.088	0.191	-0.462	0.644	
	Centred air speed	21.334	8.722	2.446	0.014*	1.84E+09
	Centred operative temperature × Centred air speed	9.955	2.566	3.880	0.0002***	21050.719
Experiment 2	(Intercept)	6.149	0.805	7.636	2.25E-14***	468.151
	Centred operative temperature	-0.847	0.273	-3.100	0.002**	0.429
	Rate of temperature change	-0.128	0.025	-5.022	5.12E-07*	0.880
	Centred air speed	15.786	4.735	3.334	0.001***	7.17E+06
	Length of exposure	-0.303	0.168	-1.804	0.071	
	Rate of temperature change × length of exposure	0.048	0.020	2.397	0.017*	1.049

(***: *p*<0.001; **: *p*<0.01; *: *p*<0.05)

4.4 Overall acceptability of tested DLC events and limits on temperature cycles, ramps and drifts

For each subject in each experiment, the proportion of unacceptable votes throughout a DLC event was calculated to represent the proportion of time in a specific condition that this subject felt the thermal environment to be unacceptable (*p*). This parameter was correlated with subjects' overall acceptability votes in multilevel logistic regression model and was highly significant in predicting overall acceptability in both experiments. Plots of predicted probability of overall acceptability for both experiments were shown in Fig. 4. In order to guarantee a 90% overall acceptability of DLC events, the proportion of time that the thermal environment is deemed unacceptable should not exceed 35%, according to Fig. 4. Applying this criterion to the judgement of overall acceptability for 6 DLC conditions based on the thermal acceptability plots in Fig. 3, Condition 2, 4 and 5 were clearly acceptable while Condition 3 was borderline.

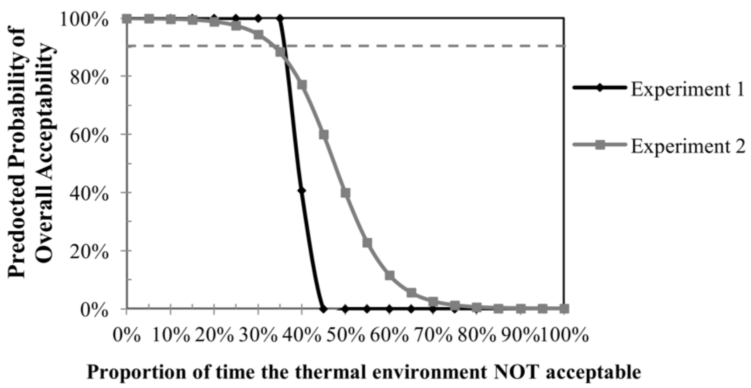


Fig. 4. Predicted probability of subjects' overall acceptability of DLC events against proportion of time the thermal environment is deemed unacceptable

5 Conclusions

This experimental study has explored university students' thermal sensation and thermal acceptability during various DLC events. The following conclusions can be drawn:

- Comparison with TSV and PMV indicates overshoot effects in both sudden warming and sudden cooling stages during DLC events. Out of 6 DLC conditions tested, 3 of them were clearly accepted by subjects.
- During DLC events, operative temperature, vapour pressure, rate of temperature change, length of exposure, air speed, along with several interaction effects significantly predicted subjects' thermal sensation, among which operative temperature, vapour pressure and rate of temperature change were the most important predictors for both experiments. Thermal sensitivity in two large temperature cycles (Condition 3 and 7) was significantly higher than that in small temperature cycles or the control condition. Subjects' sex and age generally did not significantly affect TSV.
- In Experiment 1, air speed and its interaction with operative temperature significantly predicted subjects' thermal acceptability; in Experiment 2, air speed, operative temperature, the rate of temperature change as well as its interaction with subjects' length of exposure all significantly predicted subjects' thermal acceptability.

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WINDSOR CONFERENCE 2016

MAKING COMFORT RELEVANT

WORKSHOP 2.1

Domestic Comfort in Different Climates

Invited Chairs: David Shipworth and Hom Rijal

WS2.1: Domestic Comfort in Different Climates.
Chairs: David Shipworth and Hom Rijal

While the majority of comfort studies have been done in non-domestic buildings, there is considerable data on internal (ambient) temperatures in domestic environments from different climate regions around the world. This data shows surprising spatiotemporal variability within dwellings, and variability between dwellings at any given time. There is substantially less comfort data, but where comfort data is also available, occupants frequently report being comfortable at temperatures well outside those expected by the established models. The lack of comfort data makes interpretation of ambient temperature data problematic. Interpretations range from suggesting that occupants are adopting a wide range of adaptive behaviours ranging from whole-house temperature control to local (personal) adaptive measures to create comfort; through to occupants being substantially uncomfortable for considerable periods in their homes. This workshop will start with presentation of temperature and comfort data from countries including the UK and Japan, and will then flow into a discussion of the interpretation of the data in terms of its variability, and its implications for our understanding of occupant comfort in homes in different climate regions.

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

The problem of overheating in European dwellings

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Abstract
The awareness of climate change and the increasingly urgent need to reduce carbon emissions in buildings and cities is growing in parallel with concerns with the comfort of occupants due to the rising temperatures. Recent comfort theories have acknowledged the interaction between people and their surrounding environment. BS15251 and TM52 have suggested a methodology that addresses comfort and overheating in naturally ventilated buildings. However, criteria need to be easily applied, overheating should be easily quantifiable. This paper looks at the criteria from CIBSE TM 52 and discusses their applicability to a typical archetype located in a set of cities in Europe. This follows work assessing the energy performance and thermal comfort of dwellings for morphed climates for the year 2020, 2050 and 2080. However, there are a set of variables that can significantly modify the results of an overheating assessment. In particular, the occupancy profile can significantly influence criterion 1 of TM 52 because it is couched in terms of occupied hours. Likewise, criterion 2 due to its weighted calculations on a daily basis is deemed to be difficult to apply. There is a danger that simplifications are made and criterion 1 prevails as the sole criterion to apply. A clear set of profiles may minimize this deficiency. An attempt to suggest a weekly profile for criterion 2 is also discussed.

Keywords: Overheating, climate change, comfort, resilience

1 Background

1.1 Temperature rise

There is growing evidence that the global climate is changing and that this is a result of human activities. Increased levels of greenhouse gas emissions and other forms of environmental degradation such as the increase of waste in landfills and destruction of rainforests help cause global warming, acid rain, depletion of the ozone layer and increased frequency of extreme weather events. Natural resources, such as energy and water, could be at risk if no action is taken to reduce demand, adopt renewable as against finite resources, reuse and recycling of materials and recovering part of the damage already made (IPCC, 2014).

Concerted actions have been promoted to tackle the problem of global warming and as much as possible minimise man-made contributions to an aggravated scenario. In particular, there is a real need to reduce urban carbon emissions to prevent temperatures rising to unprecedented levels. The recent Climate Change summit COP21 held in Paris in December 2015 emphasised the urgent need to limit temperatures rises well below 2K - and if possible attempt to limit it to 1.5K. This is an important climate deal that commits all countries to cut emissions after the Kyoto protocol comes to an end in 2020. Another factor in the deal is the requirement for nations to assess their progress towards meeting their climate commitments and submit proposals for revision of their own defined targets (non binding) every 5 years

(COP21, 2015). This may avoid the need to strike perennial deals and is expected to minimise delays in its implementation. The need for frequent revisions will hopefully make governments and people move from simple awareness's to more tangible actions.

1.2 Green agenda

Buildings account for 40 % of total energy consumption in the European Union (EPBD, 2010). Therefore, it is imperative to reduce the use of fossil fuel energy that is contributing to green house gas emissions whilst promoting the use of renewables. Recent energy supply uncertainty (threats of blackouts) and price rises have been a drive to nearly zero carbon buildings (ZCH, 2009). Reducing heating losses, increasing energy efficiency and adopting renewable energy have been at the forefront of most EU regulations (EPBD, 2010; EED, 2012). However, an increasing use of new technologies and an interest in comfort cooling associated with global warming has counterbalanced the expected reduction of carbon emissions and in some cases has even aggravated its growth.

The Energy Performance of Buildings Directive (recast) has imposed that all new buildings should be nearly Zero Energy-Buildings from 2020 (EPBD, 2010). The directive is to be transposed to the state members which can define the parameters and the method they will use to achieve the European target of 20% reductions in energy and inherent carbon emissions, 20% increase in energy efficiency and 20% increase in the renewable sector, all by the year 2020. In the UK buildings are responsible for almost 50 per cent of the countries' carbon emissions. So ambitious plans for new dwellings to be zero carbon by 2016 have been proposed by the UK government and are aligned with the European Policy.

However, European regulations still mainly address the heating season. Emphasis on reducing heat losses by building fabric and infiltration is promoting compact buildings, lightweight, very airtight and sometimes relying on mechanical ventilation albeit with heat recovery. While these solutions are effective at minimising heating loads while providing comfortable temperatures in the cold spell, they can have an aggravating impact in the hotter periods. Consideration for passive solutions for heating and cooling need to be taken in parallel, even in mild climates. This means that buildings and cities need to become resilient to more frequent extreme weather events and to heat-waves in particular.

Design solutions for new and refurbished of buildings need to be low energy whilst envisaging the present requirements and needs without compromising the needs in the future and as much as possible contributing to sustainable buildings and cities. This grows in parallel with concerns about the comfort of the occupants and the opportunities available to restore or maintain acceptable environments. These are primary defences against the effects of climate change (Nicol *et al*., 2012; Roaf *et al*., 2015). Furthermore, low energy design becomes even more relevant in scenarios of instability in the energy supply. It is also important to take into account the needs of an ageing population and the problem of fuel poverty even in industrialised countries.

Regulations, Standards and Guidelines are good references to access and quantify the impact of changes in buildings. In Europe, EN 15251 (BSI, 2007) and its current redraft look at thermal comfort in naturally ventilated buildings using the Adaptive Comfort approach. More recently CIBSE Technical Memorandum TM52 (2013) has provided criteria by which to judge overheating risk in buildings. While more real data is still needed to validate these models, recent developments in dynamic building simulation software give an opportunity to test future scenarios.

2 Overheating in dwellings

Studies indicate that overheating is already a problem in a prototype tested across different climates in Europe (Brotas and Nicol, 2015). This is also indicated by others (Psomas *et al*., 2016; AECOM, 2012; Mavrogianni *et al*., 2014). There are also records which suggest that European dwellings which have been refurbished to improve the thermal performance in winter are now facing overheating problems in summer. This is also identified in new buildings designed to achieve the PassivHaus standard (Psomas *et al*., 2016).

See Figure 1 for a representation of the energy consumption for heating and cooling for a mid-floor flat in different countries in Europe and for climate predictions of 2020, 2050 and 2080 (Brotas and Nicol, 2015). Whilst this model has high internal gains (assumed as representative of an increasing use of appliances in dwellings), this clearly highlights the predominance of cooling loads even in mild climates. This can be further exacerbated with climate change aggravated emissions scenarios and Urban Heat Island phenomena (Santamouris, 2014; Lafuente and Brotas, 2014; Kolokotroni *et al*., 2010). Moreover, it can influence in the way passive technologies such as natural ventilation are viable options to mitigate the impact of climate change in buildings (Kolokotroni *et al*., 2006; Santamouris and Kolokotsa, 2013; Santamouris, 2014). The rapid urbanisation of cities, the pressure associated with land cost and scarcity of space, has resulted in a more compact urban landscape with high and dense constructions and materials and less open/green spaces. All these factors can aggravate or even prevent the possibility of adopting design solutions and strategies that can be effective in avoiding or reducing the need for mechanical systems for cooling and increasing the proportion of the year during which neither heating nor cooling is required.

While dwellings have been less prone to adopting such active systems to deal with temperature rises, there is a growth in sales of air-conditioning units or energy inefficient cooling devices across Europe. Unprecedented recent heat waves particularly affecting vulnerable populations, raise awareness of the impact of overheating on people's health (WHO, 2009). Heat-waves characterized by long duration and high intensity have the highest impact on mortality (Santamouris, 2015; WHO, 2009).

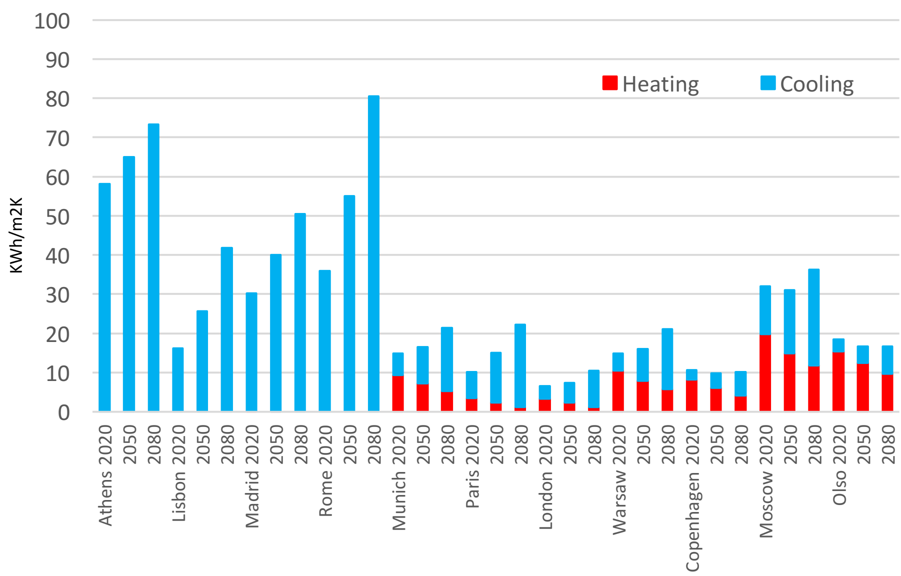

Figure 1. Heating and cooling energy consumption for a dwelling in cities in Europe at 2020, 2050 and 2080

2.1 Method to assess the likelihood of overheating

The methodology suggested in European Norm and British Standard BS 15251 (2007) to address the environmental parameters in naturally ventilated buildings is described in Nicol and Humphreys (2010). This was largely based in field studies undertaken in European cities, mostly in office buildings under the European project SCATs (McCartney and Nicol, 2002). This is acknowledged in the goals of the standard, but casts doubt on the suggestion that "The standard is [thus] applicable to the following building types: single family houses, apartment buildings, offices, educational buildings", etc. (BS 15251, 2007).

While its applicability in domestic buildings can be questioned there is little evidence of contradictory indications. Oseland's paper from 1995 comparing comfort perceptions in homes, offices and climate chambers highlighted that people are less sensitive to temperature variations in their home (Oseland, 1994). It also identifies that offering occupants control over the temperature, by allowing an interaction with the building (i.e. opening windows) or personal attitudes and behaviours (i.e. dress code) is the optimum strategy for energy efficiency and comfort in buildings. Nicol (2016) presents evidence that the limits for comfort in free-running residential buildings are typical of the general building stock but suggests the use of mechanical temperature conditioning to control temperatures is used in a different way to that assumed for non-residential buildings.

A key aspect is the establishment of indoor environmental parameters for building system design and energy performance calculations according to a set of categories of buildings that are defined based on the expectations of the occupants in relation to the space requirements. This differentiates free-running from mechanically ventilated buildings in their associated acceptable temperature ranges. In its essence this embodies the 'adaptive method' already acknowledged in International standards across the globe (BS 15251, 2007; ASHRAE, 2010), suggesting that the temperature that occupants will find uncomfortable relates to the outdoor conditions in a predictable way. The range of acceptable temperatures can be narrower in free-running buildings which have more sensitive occupants and other buildings are likewise defined by the nature of the building.

The TM52 (CIBSE, 2013) follows this research in particular addressing overheating and providing guidance to designers to identify overheating in naturally ventilated buildings. A commonly used approach to identify overheating has been to look at the proportion of occupied hours with temperatures above a certain threshold. In the UK, following guidance from the superseded CIBSE guide A (2006), overheating was likely to occur if operative temperatures exceeded above 28^{o}C for more more than 1% of occupied hours. However, this limit was set irrespective of the outside conditions. Conditions for naturally ventilated buildings were set to be more flexible than under conditioned spaces but the occupant behaviour and the local climatic conditions were not fully considered. More recently it suggests the use of the criteria proposed in TM52 (CIBSE, 2015; CIBSE, 2013: Nicol *et al.*, 2009).

The likelihood that a building will overheat can be predicted using monitoring or simulation. The simulation tool used should be able to calculate Operative Temperature, T_{op} and Running Mean Outdoor Temperature, T_{rm} to account for the adaptive model. It should be able to account for a realistic occupancy pattern of the building and the adaptive behaviour of the building occupants. However, there is clearly a lot of uncertainty especially in predictions with future climate scenarios. Other studies have highlighted problems associated with the reliability and variability of results for different climates, the morphing of future climates, the assessment of embodied energy and life cycle in the selection for solutions and materials, internal gains, occupancy profiles, operation modes and even the experience of the researcher in representing a model accurately (de Wilde *et al*., 2008: Hacker *et al*., 2008; Din and Brotas, 2016; Taylor *et al*., 2014). These uncertainties are beyond the scope of this paper which presents a case study in various scenarios to discuss trends. It focuses on the pitfalls of trying to predict overheating in buildings and discusses solutions and criteria for more thorough analysis in future studies.

2.2 TM52 overheating criteria

Criteria by which the danger of overheating can be assessed or identified in free range buildings have been proposed base on previous studies in particular research undertaken for the project SCATs. A relationship between the indoor comfort temperature calculated from the data and the running mean of the outdoor temperature was derived from a broad survey of buildings in free-running mode (Nicol and Humphreys 2010):

$$T_c = 0.33T_{rm} + 18.8\ (^oC) \tag{1}$$

Where T_c is the predicted comfort temperature when the running mean of the outdoor temperature is T_{rm}.

According to TM52 the designer should aim at remaining within the category II limits: Normal expectation (for new buildings and renovations) with a suggested range of ± 3K (BS 15251, 2007) of the comfort temperature T_c. This limit has been updated in the EN16798 (2016) rewrite as +3K for the upper limit of the indoor operative temperature and -4K for the lower limit. Then from equation (1) it follows that the upper limit of the range is T_{max} where

$$T_{max} = 0.33\ T_{rm} + 21.8\ (^oC) \tag{2}$$

Simply exceeding T_{max} momentarily cannot be a reasonable justification to classify a building as overheating. Likewise, for criteria to be easily applied, overheating should be easily quantifiable.

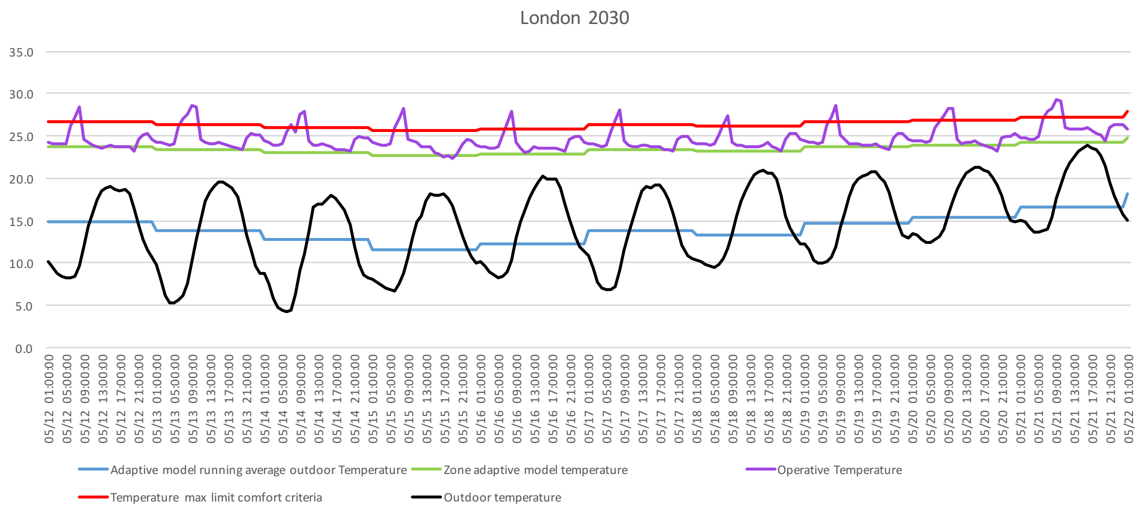

Figure 2. Temperatures to assess overheating criteria

Figure 2 presents the operative temperature of a living room (with kitchen) and the comfort temperature and threshold upper limit comfort criteria. The operative temperature is clearly above the adaptive model temperature. But are the few instances where indoor temperatures are above the threshold enough to characterize this as an overheating space?

It can be noticed as well that the amplitude of outdoor temperature is fairly regular. Yet, the adaptive running average outdoor temperature reaches its lowest of 12°C at 15/05 at 14:00 and increases by two or three degrees in a short period. As the temperature upper limit comfort criteria is dependent on this plus 3K, it may be the hysteresis temperature to pass or fail a limit of comfort.

The three criteria defined in TM52 (CIBSE, 2013) provide a proposed method by which the danger of overheating can be predicted. The method was developed by the CIBSE overheating task force and the description of the method given below is from CIBSE TM52 (CIBSE, 2013)

The first criterion sets a limit for the number of occupied hours that the operative temperature can exceed T_{max} during a typical non-heating season, assumed for the TM52 as between 1 May to 30 September. The second criterion deals with the severity of overheating within any one day, which is given in terms of temperature rise and duration and sets a daily limit for acceptability. The third criterion sets an absolute maximum acceptable temperature for a room (CIBSE, 2013)

The criteria are all defined in terms of ΔT the difference between the actual operative temperature in the room at any time (T_{op}) and T_{max} the limiting maximum acceptable temperature calculated as shown in Equation 2.

$$\Delta T = T_{op} - T_{max} \tag{3}$$

ΔT is rounded to the nearest integer. ΔT will be negative unless the room is overheated. The three criteria for assessing whether a building is overheating are listed below.

***Criterion 1: Hours of exceedence* (*H*e)**

The number of hours (*H*e) during which Δ*T* is equal to or greater than one degree (K) during the period May to September inclusive shall not be more than 3 per cent of occupied hours.

If data are not available for the whole period (or if occupancy is only for a part of the period) then 3 per cent of available hours should be used.

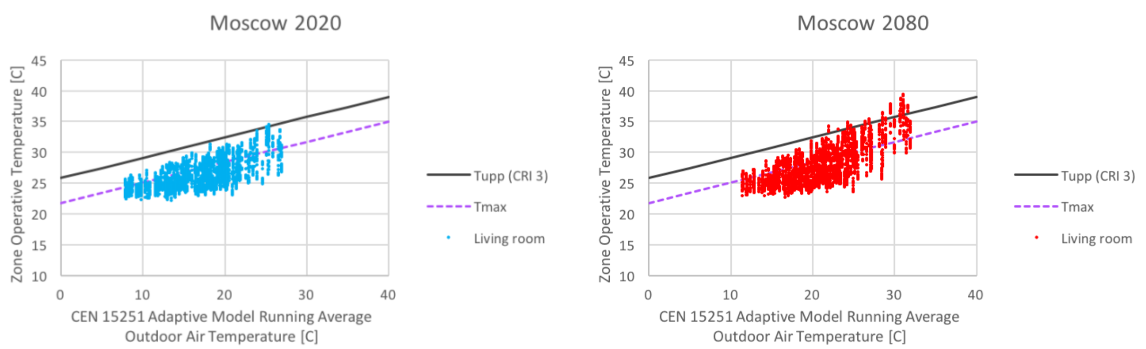

Figure 3 Likelihood of overheating with exceeding thresholds of Operative temperature versus Running Average Outdoor air temperature for Moscow in 2020 and 2080

Figure 3 shows the maximum and upper thresholds for the operative temperature with reference to the running average outdoor air temperature. This provides a visual indication of the range of temperatures achieved in a space as well as the likelihood of these exceeding the reference thresholds.

Quantifying the number of hours that the operative temperature indoors exceeds a maximum (T_{max}) and a upper limit (T_{upp}) for a certain period, can provide an indication of whether the space is likely to be overheating. The 'hours of exceedence' criterion adopts a concept similar to the percentage of hours above a certain threshold previously suggested in CIBSE Guide A. The 3% maximum limit of occupied hours is suggested in BS EN 15251 (2007).

***Criterion 2: Daily weighted exceedence* (W_e)**

To allow for the severity of overheating the weighted exceedence (W_e) shall be less than or equal to 6 in any one day where:

$$We = \sum(h_e \times w_f) = (h_{e0} \times 0) + (h_{e1} \times 1) + (h_{e2} \times 2) + (h_{e3} \times 3) \quad (4)$$

where the weighting factor $w_f = 0$ if $\Delta T \leq 0$, otherwise, $w_f = \Delta T$, and h_{ey} is the number of hours when $w_f = y$.

An indication that the temperatures of a space are above a certain value may not be enough to assess the severity of overheating. If this exceedance is not significantly higher than the limit it may not be perceived as discomfort, as adaptive mechanisms may take place. However, if this exceedance is significant or for a period longer than a few hours it becomes problematic.

***Criterion 3: Upper limit temperature* (T_{upp})**

To set an absolute maximum value for the indoor operative temperature (T_{upp}) the value of ΔT shall not exceed 4 K.

$$(T_{upp} \leq T_{max} + 4) \quad (5)$$

The threshold or upper limit temperature is fairly self-explanatory and sets a limit beyond which normal adaptive actions will be insufficient to restore personal comfort and the vast majority of occupants will complain of being 'too hot'. This criterion covers the extremes of hot weather conditions and future climate scenarios (CIBSE, 2013).

2.3 Uncertainty factors influencing the criteria

The TM52 memorandum suggests an applicability across Europe. The data on which the adaptive standard developed were mainly conducted in offices throughout Europe. While it may be argued that the diversity of latitudes and climates across Europe may require a similar variety of periods of assessment, the five hottest months will give a reasonable indication of the likelihood of overheating in local buildings.

A second aspect that seems relevant in the criteria is the method used to account for occupied hours. It is reasonable to expect that overheating in buildings is a problem when it occurs in occupied periods. Conversely, temperatures on the other end of the spectrum (cold weather) can affect occupants and cause significant degradation to the building i.e. interstitial condensation, mould growth, eventually compromising its integrity or cause aggravated health problems to the occupants.

It is therefore interesting to discuss the impact the occupancy pattern has on the assessment of the overheating criteria. Buildings that are occupied during daytime hours are more likely to fail the criteria as the assessment considers the hotter period of the day. Likewise, assuming a permanent occupation of 24hrs all year will spread and may dilute the impact of a high percentage of overheating hours that occur during day. It is not unheard of that consultants may extend the occupancy profile for an hour or so to avoid a building being classified as overheating. Another situation that frequently occurs in domestic buildings is that they are unoccupied during day hours at least in week days. Adopting a predominantly night profile plus weekends can potentially reduce significantly the risk of failing criteria. Thinking about possible future trends towards working from home and of the ageing of populations, it is reasonable to assume a permanent occupation on domestic buildings with more than a single occupancy. This was the adopted option on this study.

According to the above British Standard 15251 and Technical Memorandum, the criteria to assess overheating are applicable when the running mean outdoor air temperature is between 10 and 30^{o}C during the period of assessment. The 30^{o}C limit is related to the conditions which applied in the data on which the standard is based. In mild climates, it is unlikely that the running mean outdoor temperature will exceed the upper threshold. Conversely, the lower range defines the need to heat not cool. However, with global warming, temperatures may well begin to reach this limit in many European cities. Questions that may arise when assessing overheating include:

How to quantify the hours when the T_{rm} is above 30^{o}C? Is this assumed as a threshold where active systems for cooling will need to be put in place? Then how it this moderated? Or shall it be assumed as an immediate overheating hour? This can easily be adopted for Criteria 1 and 3. But how to quantify the range of exceedance for Criterion 2? As the limit of 6 degree-hours? or shall it be accounted in terms of ΔT? Results from the case study presented will give an insight into this discussion.

3 Model

The present case study is located in the city of London. A base case model of a mid-storey flat (67m^2) is adopted based on statistics of housing stock broken down by type and in line with a rapid urbanisation of cities.

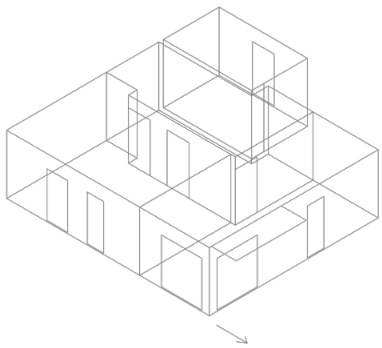

Figure 4 Wireframe model thermal zones

The main façade is oriented east and the secondary faces north (see Figure 4). The thermal characteristics of the envelope comply with the Minimum Fabric Energy Efficient Standard (FEES) for 2016 from UK Part L1A regulations: external walls (U-value 0.18 W/m^{2}K), party walls (0 W/m^{2}K), semi-exposed wall (0.17 W/m^{2}K) and windows (U-value 1.4 W/m^{2}K and G-value 0.63). The layout and further details from the building envelope, ventilation and systems specifications are defined after Zero Carbon Homes (ZCH, 2009; ZCH, 2012). The occupancy profile is defined for 3 people in a domestic environment, assuming one person is permanently at home. This agrees with future trends towards home-working and an ageing population that may stay indoors most of the time. However, the assessment of overheating will account in scenario “occupancy day” a period of occupancy between 8am and 6pm for 7 days in the week between 1st May and 30th September. This selected period is to account for the hotter period of the day. Scenario “all” will assess overheating on a 24hr occupancy for 7 days a week. Please note this assessment is independent of the actual occupancy of the space. This is acknowledged as a conservative value for the periods the space is unoccupied, and will therefore attract lower internal gains.

The assessment of 24hours dissipates the impact of peak periods over longer hours. Conversely, it should be kept in mind that high density materials commonly found in cities can delay the impact of UHI in buildings for a couple of hours. So early evening hours may experience higher temperatures.

The initial base case assumes an infiltration specified as 0.3 ac/h as design level. A single side night cooling ventilation (driven by wind and stack effect) influence individual rooms is activated when indoor temperature is above 24°C and the delta differential to the outdoor is less than 2°C. An internal blind shading device with 0.1 visible and solar transmittance is activated when the indoor temperature rises above 24°C and solar radiation incident on the window is above 120 W/m^2. The thermal characteristics of the base model and adopted strategies are already fairly sustainable and energy efficient to a very good standard.

The second combination of strategies is a result of previous studies, to be published elsewhere, and in line with the findings by other authors. Shading, ventilation and thermal mass are identified as first line strategies to mitigate temperature rises in dwellings (Gupta and Gregg, 2012; Mavrogianni *et al,* 2014; AECOM, 2012). The second model assumes a cross ventilation defined as a multizone airflow network driven by wind direction, speed, orientation of the opening and temperature difference between indoors and outdoors. As before the night cooling ventilation is activated when the indoor temperature is above 24°C and the delta differential to the outdoor is less than 2°C. While this replicates an automatic system it can also represent to some point an occupant opening the windows when he feels hot and leaving them open until the space cools down to a perceived comfort.

This model also integrates an external shading device with similar transmittance characteristics and operating profile as the previous internal device. The selection of solutions was based on realistic proposals that would not significantly interfere with land scarcity and high real state value in cities or could eventually be adopted in a refurbishment. No restrictions from listed areas were considered in the adoption of external devices. However, the window opening is reduced to 30% to account for security measures or opening just a fraction of the window.

A third model assumes internal gains being significantly reduced. Data for operation and power for lighting (low energy) and equipment (energy efficient) was retrieved from the Guide A from CIBSE (2015). Internal gains are assumed for this model to be relatively low in line with the idea that appliances must become more efficient in the near future, if we are to achieve the CO_2 reduction targets for mitigating climate change (EED, 2012).

All the dynamic simulations were made with EnergyPlus software, version 8.4.0. The criteria for the assessment of overheating were compiled in a spreadsheet. Weather data was retrieved from the climate generator predictor from The University of Southampton (CCWorldWeatherGen, 2013).

4 Results and Discussion

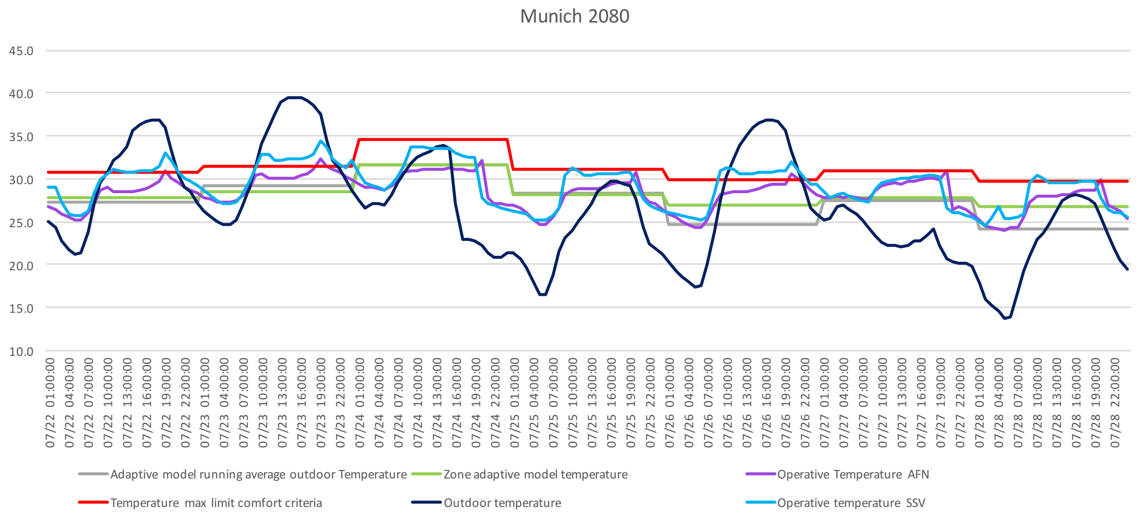

Figure 5. Extreme week for Munich for the year 2080. Operative temperature for model with cross ventilation (AFN) and single side ventilation (SSV).

Figure 5 shows the operative temperature for model 1 assuming single side ventilation and an internal blind (SSV) and for model 2 optimised with cross ventilation and an external shutter. In terms of the TM52 criteria both models pass the criteria (see Table 1 for details).

Table 1. TM 52 Criteria for both models under analysis

	C1 %	C2 days	C3 occurrences
SSV	**2**	**0**	**5**
AFN	**0**	**0**	**0**

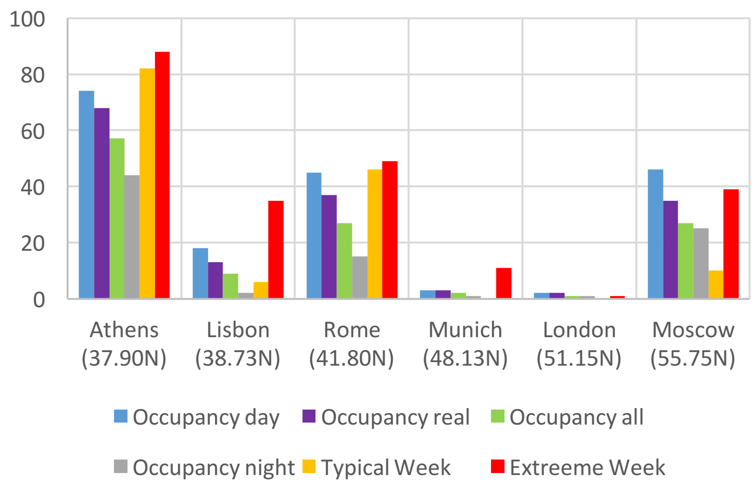

Figure 6. Criterion 1 (3% above threshold) for different locations and reference periods with the 2080 climate

Figure 6 presents results for criterion 1 for varying occupancy profiles, from 9am til 6pm, the real occupancy of that particular room (8 till 11pm), a permanent 24 hour schedule and a night occupancy form 0 till 8am and 7pm till midnight. A Typical Summer Week (nearest average temperature for summer) and an Extreme Summer Week (nearest maximum temperature for summer) have been retrieved from the EnergyPLus weather files. They vary for the different climates presented (see Table 2 and Table 3 for an indication of the dates). Results presented for these week periods are based on a 24 hours' permanent occupancy (all). Longer hours of occupancy result in a reduction of the percentage of overheating. Moscow presents a reduced reduction between the permanent and the night occupancy. This may be a result of a lower daily amplitude or the impact of UHI.

Some weather files present very unusual peak temperature periods. These may compromise compliance with criteria 2 and 3. While the adoption of the adaptive running outdoor average temperature may attenuate this phenomena, there is an ongoing discussion about whether criterion 2 instead of a 6 degree-hours per day should not be extended to a week period. This would avoid failing criteria on certain climates by a very small margin. This could eventually be twisted by selecting the start week day of the simulation and planning for these peaks to fall on an unoccupied period (i.e. weekend for services). A week assessment would prevent these omissions and attenuate its impact for the criteria.

The typical and extreme weeks do not seem to present a consistent variation amongst the climates here presented, though there are some similarities of the week criterion assessment between Athens and Rome and between Lisbon, Munich and Moscow. The results from adopting a particular week in the summer period for the criterion 2 do not seem to be very consistent. Preliminary data not presented here further recognises this difficulty.

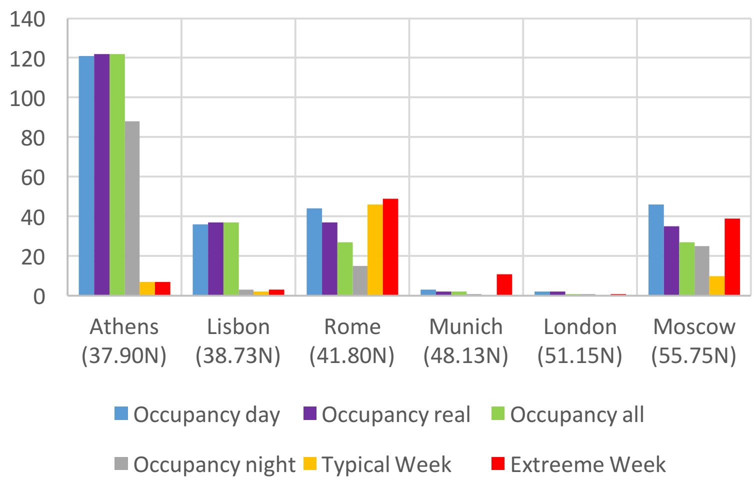

Figure 7. TM52 Criterion 2, number of days the daily temperature-weighted exceedance W_e is greater than 6 degree-hour

Figure 7 presents the Daily weighted exceedence W_e for different occupancies at various locations in Europe with a climate file morphing 2080. Figure 8 presents a similar method but accounting for a week period of exceedance above 21 degree-hours. This approach is meant to simplify the collation of data and will account for possible periods that fall outside a typical or extreme reference week. A comparison between the two periods suggests that the daily period will be more sensitive to small variations. While a method should be relatively easy to apply (hence 24 hours during 7 days) its accuracy is also important as it may compromise sensitivity analysis between different variables. This is important as the TM52 criteria can be a good mechanism to evaluate the impact of different design solutions to minimise overheating.

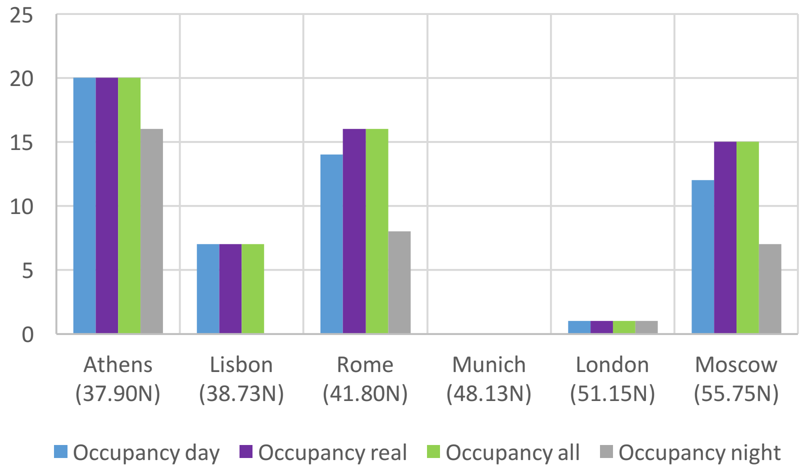

Figure 8. Overheating criterion over a week period when it exceeds 21 degree-hours, for different locations across Europe for the climate 2080.

Figure 9 presents results for criterion 3 for different occupancy profiles. As before caution should be taken to define the occupancy profile as it may strongly influence the validity of results obtained. Unlike the first two criteria the third criterion tends to exaggerate the effect of extended hours of occupancy. This defines a maximum temperature limit threshold, beyond which adaptive opportunities may not be sufficient to restore comfort.

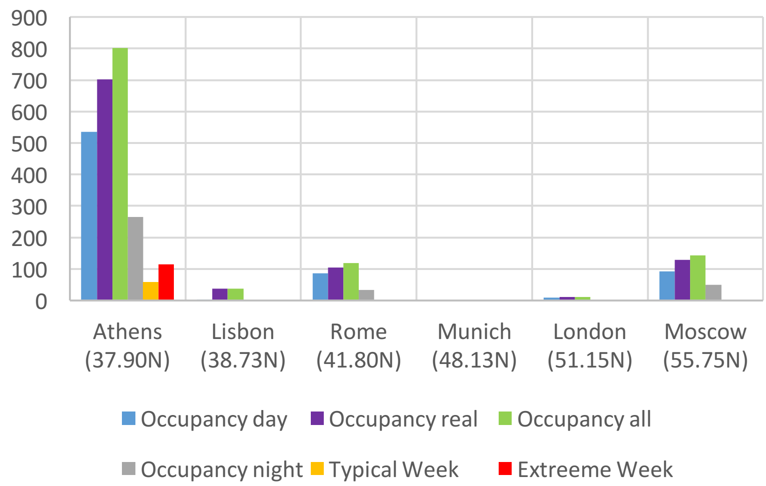

Figure 9. Criterion 3 for different occupancy solutions at different city locations across Europe for the climate of 2080.

Tables 2 and 3 show the combination of the three TM52 criteria to a prototype simulated at various cities on Europe. While this particular model has been selected as representative of an overheating scenario in most of the climates, it also raises questions whether the three criteria would need to be checked. Likewise, can a building failing two criteria out of three for a small number of instances (Lisbon and London) be at risk of overheating? The representation of possible alternative approaches in terms of length of the period under assessment is the start of an ongoing project. It still needs a significant compilation of different simulation models or monitoring data to derive sensible conclusions.

Table 2. TM52 criteria for different periods for analysis in Athens, Lisbon and Rome. Highlighted in green are the TM52 criteria that passes for the day occupancy and in orange the misses.

	Athens (37.90N)	C1	C2		C3
		%	days (6 degree-hr)	weeks (21 degree-hr)	occurrences
2020	Occupancy 9-18	52	89	14	119
	day	44	90	16	138
	Occupancy all	34	90	16	138
	night	20	45	9	19
	Typical week (29 Jun - 5 Jul) all	51	6		8
	Extreme week (3 - 9 Aug) all	61	6		39
2050	Occupancy 9-18	63	105	18	311
	day	55	105	19	378
	Occupancy all	44	105	19	391
	night	31	70	13	80
	Typical week (29 Jun - 5 Jul) all	67	7		29
	Extreme week (3 - 9 Aug) all	73	7		86
2080	Occupancy 9-18	74	121	20	536
	day	68	122	20	703
	Occupancy all	57	122	20	802
	night	44	88	16	266
	Typical week (29 Jun - 5 Jul) all	82	7		59
	Extreme week (3 - 9 Aug) all	88	7		114

	Lisbon (38.73N)	C1	C2		C3
		%	days (6 degree-hr)	weeks (21 degree-hr)	occurrences
2020	Occupancy 9-18	1	1	1	8
	day	1	2	1	10
	Occupancy all	1	2	1	10
	night	0	1	0	2
	Typical week (5 - 11 Aug) all	0	0		0
	Extreme week (15 - 21 Jul) all	0	0		0
2050	Occupancy 9-18	1	2	1	8
	day	1	2	1	10
	Occupancy all	1	2	1	10
	night	0	1	0	2
	Typical week (5 - 11 Aug) all	1	0		0
	Extreme week (15 - 21 Jul) all	1	0		0
2080	Occupancy 9-18	18	36	7	4
	day	13	37	7	37
	Occupancy all	9	37	7	37
	night	2	3	0	1
	Typical week (5 - 11 Aug) all	6	2		0
	Extreme week (15 - 21 Jul) all	35	3		0

	Rome (41.80N)	C1	C2		C3
		%	days (6 degree-hr)	weeks (21 degree-hr)	occurrences
2020	Occupancy 9-18	13	21	4	11
	day	10	23	4	11
	Occupancy all	7	23	4	11
	night	4	6	2	0
	Typical week (24-30 Aug) all	0	0		0
	Extreme week (27 Jul - 2 Aug) all	2	0		0
2050	Occupancy 9-18	23	38	7	41
	day	18	41	7	45
	Occupancy all	13	41	7	45
	night	7	12	2	4
	Typical week (24-30 Aug) all	12	2		0
	Extreme week (27 Jul - 2 Aug) all	27	4		0
2080	Occupancy 9-18	45	75	14	86
	day	37	78	16	104
	Occupancy all	27	78	16	119
	night	15	27	8	33
	Typical week (24-30 Aug) all	46	6		0
	Extreme week (27 Jul - 2 Aug) all	49	7		0

Table 3. TM52 criteria for different periods for analysis in Munich, London and Moscow. Highlighted in green are the TM52 criteria that passes for the day occupancy and in orange the misses.

	Munich (48.13N)	C1	C2		C3
		%	days (6 degree-hr)	weeks (21 degree-hr)	occurrences
2020	Occupancy 9-18	2	2	0	0
	day	2	2	0	0
	Occupancy all	1	2	0	0
	night	0	0	0	0
	Typical week (15 - 21 Jul) all	0	0		0
	Extreme week (22 - 28 Jul) all	1	0		0
2050	Occupancy 9-18	2	2	0	0
	day	2	2	0	0
	Occupancy all	1	2	0	0
	night	0	0	0	0
	Typical week (15 - 21 Jul) all	0	0		0
	Extreme week (22 - 28 Jul) all	2	0		0
2080	Occupancy 9-18	3	4	0	0
	day	2	5	0	0
	Occupancy all	2	5	0	0
	night	1	0	0	0
	Typical week (15 - 21 Jul) all	0	0		0
	Extreme week (22 - 28 Jul) all	11	0		0

	London (51.15N)	C1	C2		C3
		%	days (6 degree-hr)	weeks (21 degree-hr)	occurrences
2020	Occupancy 9-18	2	3		
	day	2	3	1	3
	Occupancy all	1	3	1	3
	night	1	3		
	Typical week (29 Jun - 5 Jul) all	0	0		0
	Extreme week (17 - 23 Aug) All	0	0		0
2050	Occupancy 9-18	2	3	1	9
	day	2	3	1	9
	Occupancy all	1	3	1	9
	night	1	2	1	0
	Typical week (29 Jun - 5 Jul) all	0	0		0
	Extreme week (17 - 23 Aug) All	0	0		0
2080	Occupancy 9-18	2	3	1	10
	day	2	3	1	12
	Occupancy all	1	3	1	12
	night	1	2	1	2
	Typical week (29 Jun - 5 Jul) all	0	0		0
	Extreme week (17 - 23 Aug) All	1	0		0

	Moscow (55.75N)	C1	C2		C3
		%	days (6 degree-hr)	weeks (21 degree-hr)	occurrences
2020	Occupancy 9-18	26	45	8	3
	day	21	47	10	3
	Occupancy all	15	47	10	3
	night	7	8	2	0
	Typical week (6 - 12 Jul) all	11	2		0
	Extreme week (29 Jun - 5 Jul) all	26	3		0
2050	Occupancy 9-18	29	48	10	17
	day	25	52	13	22
	Occupancy all	18	52	13	22
	night	10	14	4	5
	Typical week (6 - 12 Jul) all	8	1		0
	Extreme week (29 Jun - 5 Jul) all	34	4		0
2080	Occupancy 9-18	46	62	12	93
	day	35	70	15	130
	Occupancy all	27	70	15	143
	night	25	38	7	50
	Typical week (6 - 12 Jul) all	10	1		0
	Extreme week (29 Jun - 5 Jul) all	39	5		1

5 Conclusions

Climate change is creating more and more potentially devastating and unpredictable events at a global scale. A green agenda is a required global trend towards sustainability, addressing resilience to combat climate change (COP21, 2015). In particular overheating is already a problem in some locations and building types across Europe. It is therefore relevant to clearly identify a common methodology to assess its magnitude. The application of TM52 criteria, based on the adaptive comfort method and the relationship of the operative temperature to the running outdoor mean temperature seems to be a step forward on previous suggestions of a fix threshold.

This paper raised some problems associated with the application in practice with using simulations tools as the assumptions to be made.

An important aspect is associated with the increase in global temperatures and the limit of applicability of the criteria to 30^{o}C. Similar approaches have been developed in the USA by de Dear and Brager (2002) and in hot climates like Pakistan by Nicol *et al.* (1999) and suggest a broader range of applicable temperatures. Except for extreme heat wave events, most of the climates in Europe do not reach such high temperatures, so the limiting thresholds may be safe. Nevertheless, climatic file predictions up to the year 2080 are already affected. As they are being used more and more when assessing long term impacts of solutions, it is timely to address these questions. Adaptive opportunities and climatic adaptation may mean that Europeans may well behave as other populations from hotter climates already do. This will then mean the formula suggested at BS 15251 and TM52 may be extended without significant rises in discomfort.

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Evaluation of indoor environment in super-insulated naturally ventilated housing in the south of the United Kingdom.

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Abstract
Improved energy performance standards are resulting in better insulated and more airtight building. In such buildings ventilation can be provided by natural ventilation and decentralised mechanical systems or with whole-house mechanical ventilation with or without heat recovery. Whole-house mechanical ventilation systems are associated with operational energy use, embodied energy and maintenance. Conversely, natural ventilation systems that provide insufficient fresh air are thought to potentially compromise indoor air quality and may be associated with overheating in summer.
This paper reports on a study funded by the NHBC Foundation of the indoor environment of eight super-insulated naturally ventilated homes in the south of the UK. One year of monitoring temperature, relative humidity, CO_2, CO, NO_2, CH_2O and TVOC was undertaken. In addition a building survey was undertaken and the occupants were interviewed in relation to their perceived comfort levels. The buildings are currently being modelled to simulate changes in occupancy, airtightness and ventilation and construction.
Initial monitoring results suggest good air quality and comfortable internal environments can be achieved with natural ventilation. No correlation was found between CO_2 and TVOC levels. Building occupants were shown to effectively control their environment and in certain cases were instrumental in maintaining comfortable internal temperature.

Keywords: Indoor air quality, thermal comfort, decentralised ventilation

1 Introduction

The quality of the indoor environment of buildings is critical for the wellbeing of its occupants and research suggests it can impact on health and productivity as well as mood and other psychological characteristics (Alker, 2014; Fisk and Rosenfel, 1997; Fisk et al, 2012; Park JS. and Yoon CH., 2011; WHO, 2010; Clancy, 2011). The indoor environment can be characterised by a number of different variables including:

- indoor thermal comfort, which is affected by temperature, relative humidity, air movement, as well as the personal aspects such as activity, clothing and physical characteristics;
- indoor air quality, which is affected by sources of pollution and dilution of pollution;
- quantity and quality of daylight and light, which is affected by the design and configuration of openings in the building and internal finishes and spatial design as well as specification and design of auxiliary lighting;
- acoustic environment, which is affected by building fabric and spatial design;
- the relationship to vegetation, including internally and externally;

- usability of space, including such considerations as accessibility, practical use, and privacy; and
- quality of environment in terms of aesthetics, identity and other psychological aspects associated with buildings and occupants.

The interaction between these characteristics is complex and occupants may not necessarily be aware of what is impacting on their feeling of wellbeing or lack of it. Links have been made between these building characteristics and the occupants' wellbeing and a number of good practice design and development guides focusing on the above list of building characteristics are beginning to be implemented (Delos Living LLC, 2015; Alker, 2014). However, this field still lacks evidence for clear causal relationships between approaches to building design and health of occupants (Ucci, 2016). This research aims to contribute to this field of research by investigating two interrelated indoor environment characteristics namely: indoor air quality and thermal comfort in highly insulated buildings with decentralised ventilation.

The focus on highly insulted buildings with decentralised ventilation systems addresses the current UK building industry debate on how to ventilate buildings efficiently and effectively that have been built with an energy efficient building fabric. To address climate change through reduced carbon emissions, buildings are being built to be better insulated and more airtight. Providing good indoor air quality and thermal comfort is particularly important in this scenario as while better insulated and airtight buildings have advantages, such as warmer buildings in heating-based winter climates, they also have potential disadvantages, such as increased risk of high level of indoor air pollutants as the result of reduced ventilation and airchange rates. Reduced ventilation in more insulated buildings can also contribute to buildings overheating in summer, even in mild maritime climates such as that of the United Kingdom, and overheating in the UK is already being experienced in buildings of different construction types including energy efficient and inefficient construction types (AECOM, 2011; Mavrogianni et al, 2015; NHBC, 2012; Zero Carbon Hub, 2015).

In addition, the Intergovernmental Panel on Climate Change's Fifth Assessment Report on Climate Change (Pachauri and Meyer, 2014) predicts that ambient temperatures will rise and in the south of the United Kingdom and this is expected to result in a 4 °C increase of the mean summer temperatures and a 2 to 3°C increase of the mean winter temperature by the 2080s under a medium emissions scenario (Jenkins et al., 2009). Such temperature increases are not evenly distributed and in particular heat waves within urban environments have been associated with negative health impacts and increased summer deaths. (Watts et al, 2015). Buildings should be able to provide healthy and comfortable environments despite these extreme weather conditions.

The drive for energy efficient and low carbon building designs in the UK has seen an increased interest and application of centralised systems of mechanical ventilation with and without heat recovery, as well as an increased adoption of the Passivhaus Standard. While post occupancy assessments of Passivhaus developments show a good correlation between post occupancy energy performance and pre-construction simulation and good indoor air quality, some highly insulated buildings with mechanical ventilation and heat recovery (MVHR), including certified Passivhaus dwellings, have been shown to overheat in southern, central and northern Europe (Mcleod et al, 2013). Furthermore, the installation of MVHR represents an additional financial and embodied carbon cost and requires maintenance and replacing at regular intervals (Beko et al, 2008). Most UK dwellings are currently naturally ventilated (Taylor et al., 2014) and when considering an energy performance retrofit, decentralised systems are easier and cheaper to install. Whether centralised mechanical ventilation is always the best solution for the UK climate has also been questioned in terms of effective energy efficiency (Schiano-Phan et al, 2008; Sassi, 2013).

In conclusion, the hypothesis investigated is that decentralised and natural ventilation systems may well provide adequate indoor air quality and thermal comfort while also performing well in terms of energy use. This paper reports on the initial results from the monitoring of eight highly insulated dwellings with decentralised and natural ventilation, in relation to the indoor pollutant levels measured and the building performance in the summer heat wave experienced at the end of June 2015. The research is funded by the NHBC Foundation.

2 Research method

Eight highly-insulated homes ventilated through decentralised and natural systems in the south of the UK were monitored for one year. The dwellings were selected to provide a selection of different construction types, including heavy and light weight construction, and ventilation types, including systems based on the use of passive vents and through the wall mechanical extracts. Buildings detailed plans and specification were used to calculate the key parameters for comparing the buildings and assessing the performance. The dwellings that had not previously been tested for airtightness were tested. The building data was used to simulate the performance of the buildings in IES to simulate changes in occupancy, airtightness and ventilation and allow for more a level of comparison between the building's ventilation systems.

For a period of one year, measurements were taken for temperature and relative humidity at 30 minute intervals. Temperature loggers were placed in 4 rooms of the dwellings on different levels and with different orientations and including a living room and a bedroom. Relative humidity loggers were placed in the living room and one or two other rooms. The loggers used included the Hobo U10 and U12 (Temperature measurement range: -20°C to +70°C, Relative humidity range: 25%(U10)/5%(U12) to 95%) and Tinytag Ultra temperature only and temperature and RH combined (Temperature measurement range: -25 °C to +85°C, Relative humidity range: 0 to 95%). CO_2, CO, NO_2, CH_2O and TVOC measurements were taken over two hour periods on three visits to the dwellings during different seasons. A Wolfsense IQ-604 probe was used with CO_2, CO, temperature and RH sensors installed plus an additional SEN-0-NO_2 Nitrogen Dioxide sensor and SEN-B-VOC-PPB Low range PID sensor b(0-20,000 ppb) for VOC's to take measurements every minute. A Formaldehyde meter (Wolfsense FM-801) was used to measure average levels over a period of an hour. Trend measurements of the indoor air pollutants were taken in one of the case study buildings over several months in winter.

In addition building occupants were interviewed in relation to their perceived comfort levels and their use of the building including their adaptations to achieve comfort at three times throughout the year to gain feedback in respect of different seasons and weather conditions.

3 Indoor air quality: pollutants, their impacts and sources in buildings

Good indoor air quality should have no known contaminants at harmful levels (Clancy, 2011). Potential contaminants of indoor air in buildings include human bioeffluents including carbon dioxide (CO_2), external air, volatile organic compounds (VOCs) including formaldehyde (CH_2O), tobacco smoke, radon, ozone, carbon monoxide (CO),oxides of nitrogen including nitrogen dioxide (NO_2), bacteria, fungal spores, mites and fibres (ISO, 2008). The impact of indoor pollutants depends on the susceptibility of the occupants, their level of exposure and the potential harmful effects of the substance, which can include sensory irritation, causing fatigue, headache and shortness of breath, chronic pulmonary disease, and cancer. (Chianga and Laib, 2002; Clancy, 2011; Daisey et al, 2003; Kephalopoulos et al, 2006; Wargocki et al, 2000; WHO, 2010)

This research focussed on CO_2, CO, NO_2, CH_2O and TVOC, the 'classical' pollutants as defined in the Scientific Committee on Health and Environmental Risks (SCHER, 2007) report "Opinion on risk assessment on indoor air quality" in addition to temperature and relative humidity. CO, CH_2O and NO_2 are classified as high priority chemicals in the European Commission publication "*Critical appraisal of the setting and implementation of indoor exposure limits in the EU"* (Kotzias, 2005).

CO poisoning is a leading cause of death from indoor chemical (WHO, 2010; Kotzias, 2005). CO is produced as a result of incomplete combustion of fuels in faulty, poorly maintained or ventilated cooking and boiler appliances, or open fires burning biomass fuel. Tobacco smoke also is a source of CO (Kotzias, 2005). CH_2O is a known animal and human carcinogen and even low concentrations, lower than those associated with cancer, can cause sensory irritation (WHO, 2010). Building and furniture board materials are a source of CH_2O as is tobacco smoke. NO_2 results from the burning of fossil fuel and levels elevated in relation to the German indoor guidance level of 60 $\mu g/m^3$ are found in 25% and 45% of dwellings in Germany and Italy respectively (Kotzias, 2005). Furthermore, research linked a 20% increased risk of lower respiratory illness in children with elevated NO_2 levels from 15µg/m3 to 43 µg/m3 (WHO, 2010). For these three chemicals clear guidance on exposure is provided and listed in Table 1.

TVOC is a measure of combined volatile organic compounds. These include such chemicals as benzene, derived from solvents and combustion fuel; toluene and tetrachloroethylene, derived from solvents; and other carbon based chemicals. Sources of VOCs in buildings include materials and furniture, leather and textiles, paints, varnishes, sealants, thinners, adhesives, household products (cleaning products, pesticides, moth repellents, air fresheners) and personal care products (cosmetics, perfumes) (European Commission, 2002). VOCs are differentiated according to their boiling points and classified as VVOC, very volatile organic compounds; VOC, volatile organic compounds SVOC, semivolatile organic compounds. Background levels are around 0.05-.4ppm (Wolfsense, 2014). According to research by Kephalopoulos (2006) more than 900 VOC have been identified in buildings, 250 have been measured at concentrations higher than 1ppm, and typically in one building VOC levels are usually lower than 1-3 mg/m^3. The health impacts are primarily of a sensory nature. Recommended exposure levels are difficult to formulate due to the mixture of chemicals and measuring techniques and WHO does not state any recommended exposure limits. Research attempting to define exposure levels has derived exposure levels from sensory responses or from statistical surveys of existing levels (Seifert, 1999) and a selection of suggested exposure levels classifications are listed in Table 1.

Table 1 - Chemical exposure limits in indoor environments for selected chemicals

CHEMICAL	WHO (2010) *exposure limits*	Building Regulations F1 (2010) *exposure limits*	Baubiologie (Baubiologie Maes, 2008)	*Level of concern*	EPA_ National Ambient Air Quality Standards (EPA, 2016) *exposure limits*	The Well building standard (Delos Living LLC, 2015) *exposure limits*	Other sources of standards
CO_2			<600ppm 600-1000ppm 1000-1500ppm > 1500ppm	None Slight Severe Extreme		800 ppm	School average levels for full day not to exceed 1500ppm (Building Bulletin, 2006)
CO	90ppm - 15 mins 25ppm - 1 hour 10ppm - 8 hours 6ppm - 24 hours	90ppm - 15 mins 50ppm - 30 mins 25ppm - 1 hour 10ppm - 8 hours			35ppm - 1 hour 9ppm - 8 hours and not to be exceeded more than once per year	9 ppm	
NO_2	200 $\mu g/m^3$ (100ppb) exposure limit 1 hr 40 $\mu g/m^3$(20ppb) exposure limit annual average	150ppb - 1 hour 20ppb long term exposure			100ppb - 1hr (98th percentile of 1hr daily max. concentrations, averaged over 3 years) 53ppb - 1 yr (an. mean)		
CH_2O	100 $\mu g/m^3$ (80ppb) over a 30-min period and long term exposure		<16 $\mu g/m^3$ (13ppb) 16-40 $\mu g/m^3$(13-33ppb) 40-80 $\mu g/m^3$(33-65ppb) >80 $\mu g/m^3$(65ppb)	None Slight Severe Extreme		27 ppb	China, Japan, Portugal and UAE cite 80ppb maximum for their IAQ standards. France has 40ppb and Hong Kong's "excellent class" IAQ requirement is at 25ppb. (Wolfsense, 2015)
TVOC		300 $\mu g/m^3$	< 100 $\mu g/m^3$ 100-300 $\mu g/m^3$ 300-1000 $\mu g/m^3$ > 1000 $\mu g/m^3$	None Slight Severe Extreme		500 $\mu g/m^3$	China/Portugal - 600$\mu g/m^3$ / Dubai 300$\mu g/m^3$ LEED (before occupancy) 500$\mu g/m^3$ (Wolfsense, 2014) <200 $\mu g/ m^3$ Comfort range 200–3000 $\mu g/ m^3$ Multifactorial exposure 3000–25,000 $\mu g/ m^3$ Discomfort >25,000 $\mu g/ m^3$ Toxic (Mølhave, 1991) The value of 300 $\mu g/m^3$ was suggested by Seifert (1999) based on statistical surveys of German homes. 1000$\mu g/m^3$ was set as exposure limits in German standard (AGÖF, 2013)

CO_2 is considered to affect the indoor air quality even though it is primarily understood as an indicator of ventilation rates and is not considered a health hazard in its own right (ISO, 2008). As an indicator of ventilation rates CO_2 has been used as a basis for designing ventilation solutions but levels of CO_2 are not necessarily directly linked to levels of other pollutants (Dougan and Damiano, 2004; Nga et al, 2011). As opposed to sources of other pollutants, which are not necessarily linked to occupancy levels in buildings, CO_2 levels are considered to be more accurately linked to levels of bioeffluents and therefore odours that might be unacceptable to occupants (Dougan and Damiano, 2004; Petty, nd). Elevated CO_2 levels have also been shown to moderately to significantly detrimentally affect certain (six to seven out of nine) decision-making office-based activities at 1000ppm and 2500ppm respectively (Satish et al, 2012). Extremely high levels above 10,000 ppm not normally found in buildings can cause drowsiness and at much higher levels can cause unconsciousness (Cancy, 2011).

The sources of pollutions found in the case study buildings included the occupants, building materials and consumer products, but in all case study buildings the occupants were conscious of using consumer products that had low VOCs and only using those they felt really necessary, for instance none of the occupants used air fresheners. Most building materials were typically low emissions options such as timber rather than carpet flooring.

4 Ventilation and infiltration

Air is introduced in buildings from outside through infiltration and ventilation and this dilutes pollutants in buildings, subject to the air outside being pollutant-free. Infiltration is defined in the Building Regulations (2010:13) Approved Document F1, Means of Ventilation as “the uncontrolled air exchange between the inside and outside of a building through a wide range of air leakage paths in the building structure”. This is in contrast with ventilation that is controlled and provided through natural or mechanical means (Building Regulations, 2010). The regulations differentiate between buildings with higher and lower infiltration rates and require different solutions for each. Buildings that are tested to have a higher infiltration rate than $5m^3/hm^2$ at 50 Pa are assumed to have air change rate per hour of 0.15 at ambient pressure, which will contribute to the fresh air provision in the building and consequently the area of controlled ventilation can be reduced compared to buildings with less air infiltration.

The case study buildings all have decentralised and naturally ventilated systems. The Building Regulations ADF1 (2010) list four main types of ventilation: trickle and other vents in conjunction with intermittent mechanical extract (five of the case studies can be classed as operating with such a system); passive stack ventilation system (three case studies use this system); continuous mechanical extract (centralised or decentralised); and continuous MVHR. All case study buildings have operable windows that provide purge ventilation as required.

The effectiveness of the natural ventilation that uses natural systems such as temperature differences and wind pressure to drive the ventilation through a passive stack system or windows is subject to the external weather conditions, obstructions, wind and the internal building configuration and the design of window and other openings. Mechanical ventilation is independent of variables external to the building and only marginally affected by internal layouts (Clancy, 2011).

The provision of fresh air in relation to the volume of the building together with the control of sources of indoor air pollutants are the main influences on indoor air quality.

5 Overheating in dwellings

The effectiveness of the natural ventilation will also have an impact on the risk of overheating, as do other building fabric elements such as thermal insulation, thermal mass, shading and the potential for temperature stratification. (Mavrogianni, 2014; Porritt, 2011; Porritt, 2012). In naturally ventilated buildings the occupants have the benefit of being able to manipulate their building to make it more comfortable and this control facility is also known to make occupants more tolerant of their environment. (Baker and Standeven, 1996; Brager and de Dear, 1998).

The temperature considered to constitute overheating in naturally ventilated buildings is higher than in mechanically ventilated buildings, and this is now not only documented in research related to adaptive thermal comfort (Nicol and Humphreys, 2002; 2009) but integrated to some degree in the British Standard (2007) BS EN 15251:2007 and ASHRAE (2010) Standard 55.

The indoor comfort temperature set by CIBSE Guide A (2006) for the summer are 25°C for living rooms and 23°C for bedrooms and overheating is deemed to have occurred if one percent of the occupied hours over one year exceed 28°C and 26°C for living and bedrooms respectively. CIBSE Guide A (2006) also notes that temperatures over 24°C can impair sleeping and this suggests that it is important to differentiate when the peak temperatures occur.

According to BS EN 15251:2007 the acceptable internal temperatures would rise with the external temperatures in line with the adaptive thermal comfort model. The formula to calculate the indoor maximum compared with external temperature is:

indoor maximum = 0,33 external temperature + 18,8 + 2 (or +3 or +4 depending on the predicted percentage of persons dissatisfied (PPD) with the elevated temperature).

This would mean that an external temperature of 28°C would result in internal temperature of 30°C-32°C to feel acceptable for 85-94% of people.

The monitored temperatures will be related to both CIBSE Guide A (2006) and BS EN 15251:2007 standards.

6 Results: Indoor Air Quality

Winter measurements of indoor air quality were overall adequate to good (Table 2). The CO levels were well within all recommended levels. CH_2O levels were sound in relation to the WHO (2010) standard of 80ppb but if the Baubiologie Standard (Baubiologie Maes, 2008) were considered one reading in particular would be considered ‘severe concern’ at 63ppb and also in excess of The Well Building Standard (Delos Living LLD, 2015) of 27ppb. It is worth noting that case studies 1, 4, 5, 7 and 8 all had wood burning stoves and the occupants of case study 6 were tobacco smokers. These aspects would impact on the CH_2O and NO_2 levels. The elevated reading was taken in case study 4 which had no other particularly elevated readings and did contain a significant amount of decorative objects and fabrics, which could have contributed to the elevated readings. The monitoring is continuing for another winter which will allow for further readings to be taken. TVOC levels were all within the The Well Building Standard of 500 µg/m³. The highest levels were measured in case study 6 where the occupants smoke indoors (446 µg/m³), and these exceed the Building Regulations (2010) standard of 300 µg/m³, which is also the top limit of Baubiologie Standard's “slight concern”. Case study 5 measurements for TVOCs is slightly about 300 µg/m³ and this could be the results of craft products used in the home.

The CO_2 levels measure in half the case studies were within The Well Building Standard (Delos Living LLD, 2015) limit of 800ppm and half above that but within the Building Bulletin (2006) target of 1500. The Baubiologie Standard (Baubiologie Maes, 2008) would class all but one as of 'slight concern' and one of 'severe concern'. However, as discussed above the levels of CO_2 are more representative of the sensory quality of the air and the occupants in the case study house all reported the quality of air to be good on a seven point likert scale, suggesting the air change rate was sufficient to provide air quality perceived to be good.

The chemical concentrations that appear of concern are those of NO_2 which were all measured to be above the recommended by WHO (2010) and case study 3 and 8 have higher levels than the EPA (2016) recommendation of 53ppb. The fact that the 72 ppb were measured in case study 3 located in central London and the fact that case study 3 had very high air change rates of 10 ach, much higher than all the other case studies, would suggest that the external air might be the cause for the elevated levels.

Table 2 – Winter measurements of indoor air quality, temperature and relative humidity over a period of 90 minutes average.

Case study	CO_2 ppm	CO ppm	NO_2 ppb	CH_2O ppb	TVOC µg/m³	Temperature °C	Relative Humidity %RH
1	814.5	1.3	44	10-15	277.0	18.7	48.9
2	1151.7	1.2	44	10-15	274.0	21.5	47.9
3	702.7	0.1	72	10	10.3	25.0	23.3
4	732.5	1.83	40	62	81.5	19.6	48.9
5	697.34	1.02	46	17	332.7	19.7	48.2
6	1045.7	5.0	43	10-20	446.1	21.5	42.9
7	734.0	0.5	43	32	59.8	20.3	47.6
8	1071.6	0.07	56	20-29	208.7	21.2	40.3

The results support the view that CO_2 levels are not necessarily related to the indoor air pollutant levels. As shown on Figure 1, the levels of CO_2 rise with occupancy while the TVOC levels slightly decrease. And as discussed above the occupant feedback correlates more accurately with the levels of CO_2 than the levels of any other chemical.

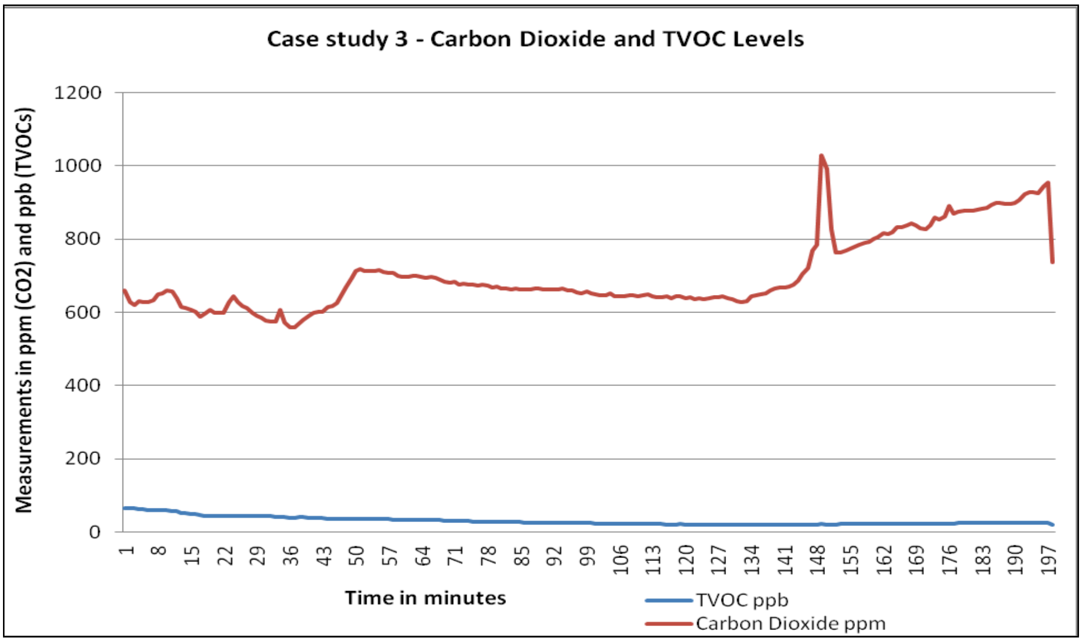

Figure 1 – Example of relation of CO_2 to TVOC levels

The results overall suggest that decentralised ventilation systems can provide adequate to good indoor air quality during the winter period when ventilation is kept to a minimum and infiltration can be at times the main source of fresh air. In view of the somewhat elevated NO_2 levels a second set of winter readings will be taken to confirm and allow a second examination of the existing readings.

7 Results summer overheating

In respect of the summer indoor environment quality and overheating during peak summer temperatures, the living spaces, which were all situated on the ground floor, performed well in relation to CIBSE Guide A (2006) limit of 25°C for living rooms (Table 3) over a two week period, which included the heat wave experienced at the end of June 2015. During the two week heat wave case study 4, which experienced the highest peak temperatures outside London, experienced temperatures over 25°C in the living room for only a small percentage of hours (4.7%) (Table 4). In the bedrooms over the two week period the temperature exceeded 24°C between 22.00-8.00 for 7.5 hours of which 4 hours were below 25°C.

The relationship between interior temperatures and building level and orientation can be best illustrated in case study 6 where the ground floor rooms are cooler than the first floor rooms and the south facing rooms warmer than the north facing rooms. This difference can be seem to different degrees in all case studies and whether or not they are heavy or light construction does not seem to impact on this relationship between building levels and orientation. Some apparent anomalies such as case study 7 north facing bedroom being hotter than the south facing bedroom can be explained by the existence of a large rooflight in the north facing room.

Table 3 – Temperatures in °C monitored during summer heat wave June-July 2015 (minimum and maximum temperatures are shown in parentheses).

CASE STUDIES M=masonry T=timber frame MV=vents and decentralised extracts PV=Passive vent system	living room south ground floor	living room west	kitchen north	living room north ground floor	bedroom east ground floor	living room south north facing	room 1st fl. south facing	bedroom 1st fl. north facing	bedroom 2nd fl. south facing	bedroom 2nd fl. north facing	external temperature
1 - Oxfordshire - M - MV	22.02 (20.5) (23.4)						23.28 (20.9) (27.4)	23.37 (22.0) (25.9)	25.12 (21.6) (29.2)		18.68 (32.2) (11)
2 - Oxfordshire - M - MV	21.72 (19.9) (23.7)								24.20 (19.8) (32.2)		18.68 (32.2) (11)
3 - London - T - MV	25.82 (21.3) (33.7)					24.45 (19.5) (33.7)	25.94 (21.3) (34.1)		26.24 (19.8) (39.8)		20.93 (38.5) (11.3)
4 - Gloucestershire - T - MV	21.09 (15.0) (30.0)			20.80 (14.5) (29.4)			21.33 (15.5) (29.7)			20.85 (14.3) (30.2)	17.94 (31.1) (10.2)
5 - Gloucestershire - T - MV note a	23.03 (20.0) (27.5)			23.11 (20.2) (27.7)			25.16 (21.9) (30.0)			25.04 (22.0) (29.7)	17.94 (31.1) (10.2)
6 - Somerset - T - PV note b	20.81 (18.4) (19.2)		20.25 (19.1) (20.1)				21.10 (18.6) (21.7)	22.54 (21.3) (22.4)			17.65 (27.1) (12.2)
7 - Somerset - M - PV note b	23.37 (21.9) (24.9)				23.94 (23.3) (24.5)		22.46 (21.5) (23.4)	23.39 (22.3) (28.7)			17.65 (27.1) (12.2)
8 - Somerset - M - PV note b	19.44 (19.1) (20.1)	18.73 (18.4) (19.1)					21.92 (21.3) (22.4)	20.43 (18.6) (21.7)			17.65 (27.1) (12.2)

Note a - occupants on holiday over two week monitoring period of heat wave

Note b - monitoring period 24th-27th June did not include peak heat wave

Table 4 - Distribution of temperatures in °C measured in living room in case study 4 as percentage of overall hours over heat wave period.

15°C	16°C	17°C	18°C	19°C	20°C	21°C	22°C	23°C	24°C	25°C	26°C	27°C	28°C	29°C	30°C
1.2%	1.5%	3.6%	8.5%	20.4%	22.2%	15.3%	10.9%	7.6%	2.1%	2.0%	1.4%	1.2%	1.1%	0.9%	0.2%

There was no direct correlation evident between overheating in lightweight and heavy weight construction. While all the case studies were different in design and context and it would have been difficult to assess through monitoring the impact of thermal mass, the results suggest that through appropriate design a comfortable environment can be achieved in the current UK climate with light weight construction. The modelling of the case studies will be able to test thermal mass as a variable for each case study to establish the difference in performance and the impact of future climatic contexts.

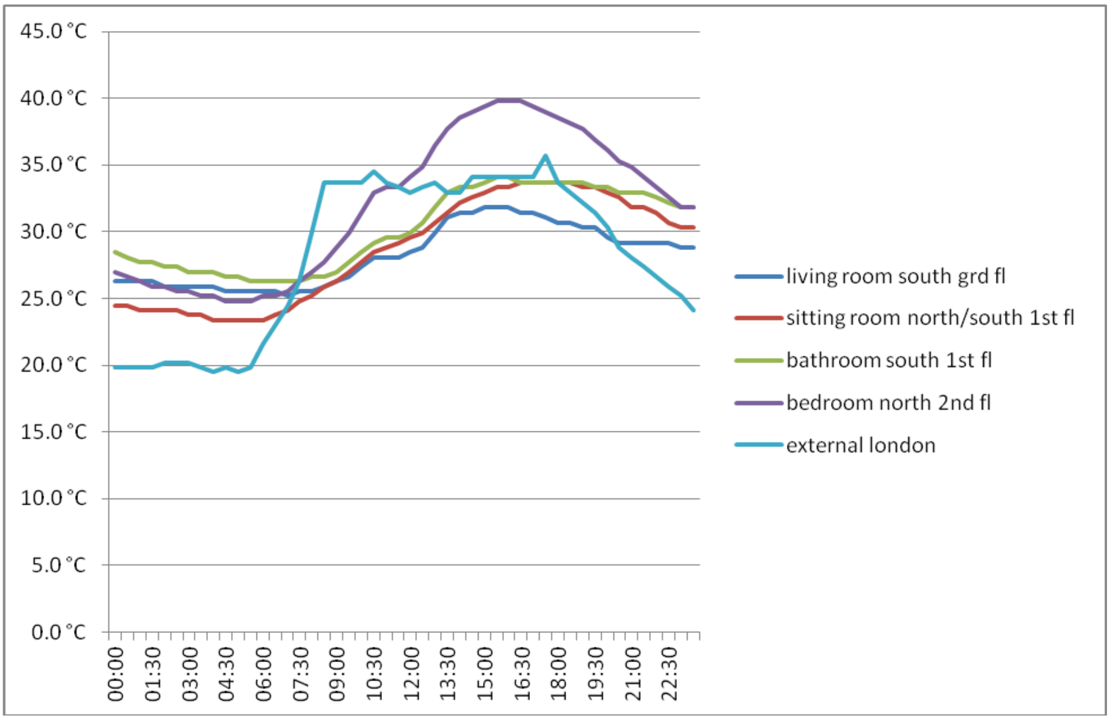

Figure 2 – A 24 hour period in case study 3 in London shows how the external temperature is significantly lower than the internal suggesting a missed opportunity for cooling.

Some effective cooling strategies were described by the occupants. One design included a generous central stairs with rooflights at the top to exhaust the air and ample windows to allow fresh cooler air into the building. By adopting this simple strategy the occupants reported immediate cooling benefits. The most problematic case study was the one located in London, which experienced higher ambient temperatures. Despite the more challenging context, as shown on Figure 2 the external temperature at the beginning of the day was significantly lower than the internal suggesting the full cooling potential of cool night air was not being realised. The design of ventilation has a good potential to contribute to thermal comfort the current UK climate, however the design of windows and other openings needs to be more carefully considered, as well as the air flow path. Case study 1 also has a central stairs and rooflights at the top of the stairs as case study 4, but the occupants reported it to be ineffective as a means of driving airflow for cooling. The relationships between windows, internal layouts, and the height of the building are critical to the effectiveness of ventilation.

8 Conclusion and further development

The case studies monitored had a variety of infiltration rates and ventilation systems, the contexts varied as well as the building designs and construction. A direct comparison between case studies is not appropriate but some general lessons can be learnt. Overall the study suggests that decentralised ventilation systems in highly insulated buildings can provide adequate to good indoor air quality. The study also suggests that overheating can be addressed in both heavy mass and lightweight well insulated construction in the current UK climate. A number of additional conclusions can be drawn.

1 - The study found no relation between CO_2 and TVOC levels or other chemicals and therefore confirms the literature that emphasises the role of CO_2 as an indicator of perceived quality of air as opposed to actual pollutants. In the case studies investigated the CO_2 levels were above the ideal, however the perception of the occupants was still of good air quality.

2 - The contributors to indoor air pollutants have to be carefully investigated. The study highlighted some instances where high pollutants levels were measured without a clear source. Some clear sources such as tobacco smoking and stoves can be easily identified, but other more subtle sources such as craft materials and cleaning products have to be taken into account. The occupants' survey included a list of potential sources of pollutants for the occupants to identify any they used and a visual inspection identified materials and products that could be a source of pollutants. However, to fully understand where the pollutants come from a more extensive investigation needs to be undertaken.

3 - In the London case study where overheating did occur, the ability to adjust the internal environment by opening windows and doors and shading the space from the sun, resulted in the occupants experiencing the well-understood 'forgiveness factor' and despite the elevated temperatures not feeling uncomfortable. Similar tolerance was noted with most of the occupants interviewed.

4 – The building occupants' knowledge of how to 'use' the building was invaluable in terms of making it comfortable. It was very evident that the occupants were able to maximise what the building could do in terms of creating a comfortable environment. Such knowledge is key in maximising building efficiency as well as comfort.

Finally, as mentioned in the introduction, the relationship between all building characteristics that contribute to a healthy indoor environment is very complex and even just the relationship of the indoor air quality, thermal comfort and ventilation system studied in this research can only provide a suggestion of the causal links. More data is required from more and different building types. In particular, it has been shown that poorly insulated buildings suffer from overheating (Mavrogianni et al, 2015) but there is little data on the indoor air quality of such buildings. A more comprehensive survey of the indoor air environments of dwellings including all the variables is required.

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Assessing of thermal comfort in multi-stories old and new residential buildings in China

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Abstract

In China, the most common heating system in old residential buildings is district heating systems without private control. However, in 2010, the standard JGJ26-2010 has a mandatory requirement on the heating system namely that it should be installed with household-based heat meters and Thermostatic Radiator Valves (TRVs) for each radiator. Many previous studies have demonstrated that the PMV model performed well for Chinese buildings, however, studies lack of to identify how the upgraded standards will affect thermal comfort in both types of old and new buildings. Hence a thermal comfort survey was carried out in both new and old dwellings according to updated standards.

The survey was carried out in two sets of dwellings in cold zone of North China in winter, that is, 7 new and 7 old apartments, starting from 15th February and ending at 15th March of 2014, the winter season when heating is on. During the survey, occupants' thermal sensation, clothing insulation etc. were collected by subjective questionnaires, and important environmental parameters were measured concurrently by proper sensors, according to the ISO 7730, ISO 7726 and ISO 10551. The results show that the correlations between Predicted Mean Vote (PMV) and people's Actual Mean Vote (AMV) in new and old apartments. In addition, percentage of acceptable of occupants is higher in new apartments when compared with that in the old apartments. Another finding from this study is that females respond worse thermal acceptability to indoor thermal environment, when compared with males in both new and old apartments.

Keywords: Thermal comfort, PMV, Residential building, China

1 Introduction

Thermal comfort has a significant impact on occupants' productivity and health, and it plays an important role when evaluating the performance of buildings. In the past 40 years, the Predicted Mean Vote (PMV) model developed by Fanger has been considered as the most important landmark, and it has been adopted by many building design standards, such as ASHRAE 55 and ISO 7730, to evaluate thermal comfort conditions in buildings. People spend majority of the time occupancy in their domestic dwellings (ASHRAE55, 2010; ISO7730, 2005). Therefore it is essential to evaluate the thermal sensation of occupants in residential buildings and understanding how people have feeling to their thermal environment and useful to ensure the thermal comfort responses to efficient energy use in future work. Numerous studies in both thermal environment and thermal responses have been investigated in residential buildings (Han, et al., 2009; Wang, 2006; Cao, et al., 2014; Luo, et al., 2014; Anon., 2009; Oseland, 1994). Moreover, previous researchers report about thermal comfort on winter conditions related to energy consumption in residential buildings. Hong et al. focused on thermal comfort of occupants on domestic conditions in England in winter, results showed that better insulation and energy efficient heating system lead to better thermal comfort and related to energy demand (Hong, et al., 2009). Field study of Cao et al in Chinese residential buildings showed that the mean indoor temperature in dwellings installed with individual boiler heating system compared to that in district heating system exceeded 1.6°C (Cao, et al., 2014). Becker and Paciuk used the Fanger's model as standard and conducted field study in 189 dwellings in winter, the results from survey showed the actual mean votes(AMV) were significantly higher than predicted mean votes(PMV), in addition gender, age of occupants have no obviously effect on thermal responses (Becker & Paciuk, 2009). Field study of the thermal comfort conditions in residential buildings were conducted in two zone of China, Yang et al found that 68% of occupants feel slightly cool in winter and neutral temperature were much higher than indoor air temperature (Yang, et al., 2013).

Generally, China can be separated into five climatic zones namely severe cold, cold, hot summer and cold winter, hot summer and warm winter and moderate as shown in Figure 1 (GB50178-93, 1993). In 1996, the Chinese government firstly announced an energy conservation design standard JGJ26-95 for new heating residential buildings. This standard focuses on energy efficient measures in order to reduce the energy consumption of residential buildings in Severe Cold and Cold Zones of China. Since 1996 the development of new residential buildings with district heating systems has started to be guided by the new developed standard. However, in 2010, the newer standard revised and has a mandatory requirement on the heating system namely that it should be installed with household-based heat meters and Thermostatic Radiator Valves (TRVs) for each radiator, room temperature can be adjust within a range (JGJ26-2010, 2010). In China, the most common heating system in old residential buildings is district heating systems, which are operated by constant water flow rate and variable water temperature. Whilst there are no heating control systems and occupants can only open their windows or doors to adjust indoor thermal conditions (Xu, et al., 2009).

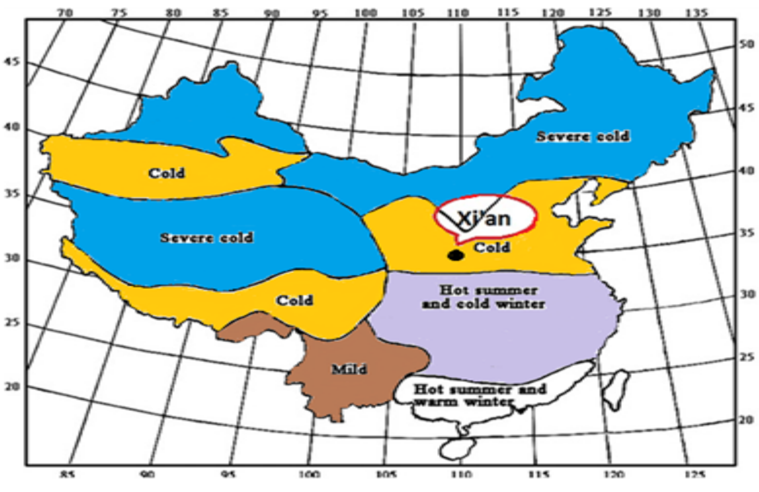


Figure 1. Five climatic zones of China based on GB50178-93

Many previous studies have demonstrated that the PMV model performed well for Chinese buildings (Yang, et al., 2013; Han, et al., 2007; Peng, 2010; Wang, 2006), however, studies lack of to identify how the upgraded standards have effect on thermal comfort in both types of old and new residential buildings. To exam this issue for Chinese residential buildings on winter conditions, a thermal comfort survey was carried out in both new and old buildings according to updated standards, in the winter of 2014 and thermal comfort experiment is produced from 7 old apartments and 7 new apartments in same district. This study is to determine the validity of applying the PMV model in two types of residential buildings: old building comprised uncontrolled heating with payment based on floor area; New residential building install personal control on the heating system(TRVs), together with 'pay for what you use' tariffs. Furthermore, the purpose of study is to identify the difference of occupants' thermal sensation in two type buildings. In addition, the comparative analysis was presented on result from householders in new and old building in this paper.

2 Methodology

2.1 Building description

The investigations were conducted between 15th February and 15th March 2014. This field study had been carried out in Xi'an of Shaanxi province in north China. Xi'an city is typical city in cold zone in China and has a cold and dry climate in winter in cold zone. Figure 2(a) shows a typical district heating system with TRVs in new building and Figure 2(b) shows a typical district heating system without personal control. The two types of buildings are both multi-story and each apartment contains one living room and two bedrooms. The new residential building was newly built within five years and the old building was built late 1990s.

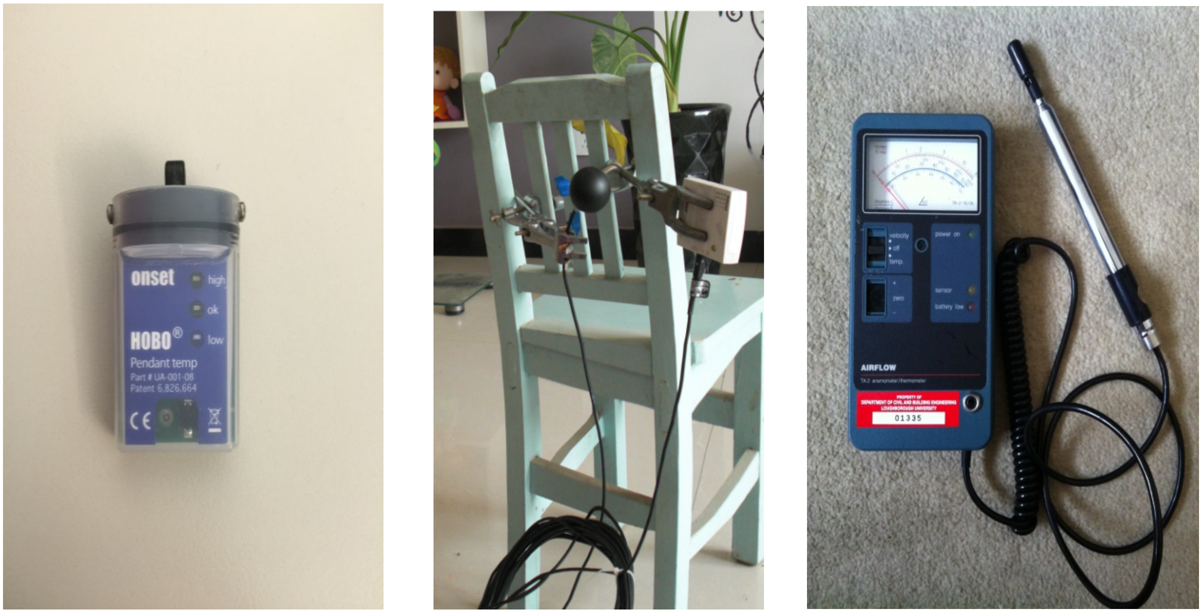
(a) (b)

Figure 2(a). Sample of typical district heating with TRVs in new building; (b) Sample of typical district heating without TRVs in new building

2.2 On site measurements and instruments

The experiment is divided into both subjective questionnaires survey and objective measurements. The subjective surveys were based on the thermal sensation reported by occupants. In addition, the gender should be considered into the evaluation of thermal comfort in both types of building. Equilibrium between males and females has also been considered during the selection of occupants. In this study, there are two occupants that will participate in each apartment that one male and one female. Moreover the ages of occupants range from 18 to 65. The clothes insulation and thermal sensation were carried out from the interviewed survey and the simultaneous measurement of environmental parameters of air temperature, mean radiant temperature (MRT), air velocity and relative humidity.

A HOBO data logger (Fig.3a) was used to measure the indoor air temperature in living room in each apartment. The air temperature measurements ranged from -20 to 70°C and accuracy of temperature is ± 0.35°C from 0° to 50°C. For measuring the relative humidity, the range is from 5% to 95% RH and the accuracy of RH is ±2.5% from 10% to 90% RH (typical), to a maximum of ±3.5%. Furthermore, mean radiant temperature was estimated from globe temperature and also assessed using a 38mm diameter black Ping-Pong ball globe thermometer (Fig.3b) and it had been calibrated in chamber. Indoor air velocities were measured by hot-wire anemometer (Fig.3c) at 0.1m, 0.6m and 1.1m height during interview survey. The range of the hot-wire anemometer for air velocity is from 0 to 15m/s with an accuracy of ±0.05. All the equipment accuracies correspond to ISO 7726 (ISO 7726, 2001).



(a) (b) (c)

Figure 3. Experimental devices

2.3 Questionnaire survey

The questionnaire was developed based on the standard of ISO 10551 (ISO 10551, 2001) and used in each apartments. In order to ensure valid and accurate results, all questionnaires had been translated into Chinese based on thermal comfort standard (Liu & Qin, 2006). A consent form was issued and the actual mean votes (AMV) form was explained to them. There are three main questionnaires: first is application form to take part in the thermal experiments that involved the name, age, physical conditions. Second is the main thermal sensation of participants and how they feel about the thermal environments. It includes the 7-point ASHRAE sensation scale, ranging from -3(cold) to +3(hot) and 0(neutral). Additionally, the three thermal performance scales were provided by warmer, no change, cooler. And the personal acceptability of indoor thermal environment is two scales of yes or no, following with question: “would you accept this indoor thermal environment?”. The third one is used to identify the clothing insulation values for females and males and it divided into two parts, one is participants identifying the clothing insulation values and given a total figure for it, another one is observed by observer from distance. The spot measurement of thermal comfort survey was conducted on individual occupants who were seated watching TV in living room in each apartment. All occupants were kept seated for 45mins and they were asked to fill AMV form after 30mins and 45mins. The survey involved 28 subjects in total, 14 females and 14 males. Averagely, there were two times questionnaires survey during interviews, one was conducted at begin day of whole experiment periods, and another one was conducted at the final day of whole experiment periods. Therefore, total valid questionnaires are 112, there were 56 questionnaires from new apartments, and 56 questionnaires from old apartments.

3 Results and discuss

3.1 Indoor climates in new and old apartments

Statistical summaries of the variations of indoor air temperature for 7 new apartments and 7 old apartments during investigation period are given in table 1. The mean outdoor air temperature is 8.9°C, the maximum and minimum temperatures are 27.7°C and -1.9°C respectively during the investigation. According to the results of questionnaires, in old apartments, the majority of occupants respond that the windows were opened because it was hot inside apartments and they prefer to have cooler indoor environments. It also can be seen from table 1, results show that the mean indoor temperature in all old apartments is 22.5°C and the indoor air temperature in new one is 20.7°C which is respectively 1.8°C lower than the value measured in old apartments. The mean radiant temperature (MRT) ranged from 22.5°C to 23.3°C in old apartments, whilst in new apartments, the mean value of MRT with a ranged of 19.8°C–21.9°C. The mean Relative humidity obtained in the old apartments was 48.3%, which is slightly higher than 43.5% in the new apartments. The indoor air velocity in old apartments ranged from 0.03m/s–0.05m/s respectively in new apartments has value range from 0.01m/s–0.06m/s. Meanwhile, shows that the majority of air velocity in both new and old apartments was low, with a mean value of 0.056 m/s, which was not more than 0.15 m/s, which meets the winter thermal comfort standard (Wang, et al., 2011). The metabolic rate were observed and ensured same activities of estimated values of 1.1 met in each apartment during interview.

Table 1. Summary of the indoor climate measurement data

Residential Building Types	Home No.	Indoor Air Temperature		
		Mean	Max.	Min.
Old apartments	1	22.2	23.6	16.7
	2	22.6	24.7	18.1
	3	22.4	23.5	18.2
	4	22.5	25.2	16.1
	5	22.9	24.8	17.3
	6	22.2	25.7	15.7
	7	22.7	25.1	17.2
New apartments	1	21.0	23.4	17.4
	2	20.9	22.4	17.5
	3	20.8	22.2	15.8
	4	21.1	22.2	17.3
	5	21.6	22.6	16.1
	6	19.7	23.2	15.8
	7	19.6	23.4	15.9

3.2 Clothing insulation

The statistical summaries of clothing insulation values were taken from what occupants themselves as estimated from clothing insulation lists. The values are given in Table 3.2. Based on the chair insulation effect on occupants, in this study the insulation of the chair is assumed to be 0.35clo as all participants were sitting on a fabric sofa during the survey (de Dear & Brager, 1997). Clothing insulation value ranged from 0.78clo to 1.197clo with a mean value of 0.9clo in new apartments. In old apartments, the clothing insulation values varied from 0.608clo to 1.28clo with a mean value of 0.79clo. Clothing is a behavioural adjustment that directly affects heat balance(RP-884) and responds one of key thermal adaptive responses (de Dear & Brager, 1997). Figure 4 show that the relations between clothing insulation level and indoor temperature. From liner correlation the coefficient of determination R^2 can be observed as 0.12 for old apartments and 0.08 for new apartments.

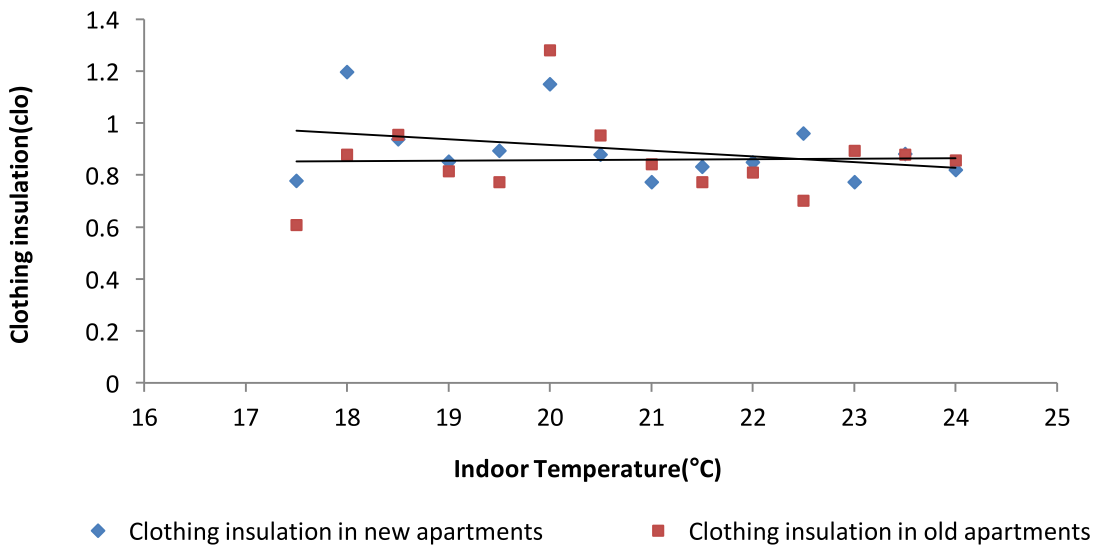


Figure 4. Comparison of clothing insulation between old apartments and new apartments

3.3 Thermal comfort responses

3.3.1 Comparison of thermal sensation vote in new and old apartments

Figure 5 shows that the occupants' overall the thermal sensation voted for the surveyed new and old apartments. For the new apartments, majority of subjects voted the range from slightly cool (-1) to slight warm (+1). It can be seen that 29% of occupants feel neutral (0). However, the greater number of occupants in old apartments voted the range from slightly warm (+1) to warm (+2) and also have 16 percentage of occupants voted hot (+3) that much more than none of subjects vote hot (+3) in new apartments. From figure 5 indicated that in old and new apartments, majority of occupants voted within the central three categories against that the ASHRAE Standard 55-2004 specified that an acceptable thermal environment should have 80% of occupants vote for the central categories (-1,0,+1).

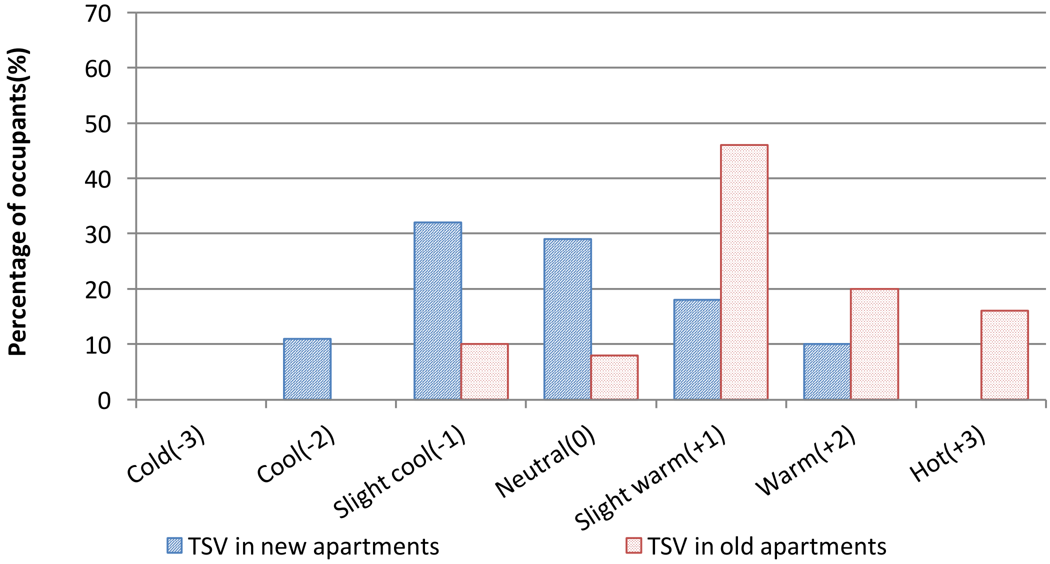


Figure 5. Comparison of thermal sensation vote of occupants in new and old apartments

Regression of binned actual mean votes of occupants as a function of air temperature is presented as two linear regression equations (de Dear & Brager, 1997) as following:

$$AMV=0.1550T_a-3.2461 \qquad (1)$$

$$AMV=0.1681T_a-3.1986 \qquad (2)$$

Where Ta is air temperature, AMV is actual mean votes. The equation (1) and (2) were used to carry out the neutrality. The neutral temperature for AMV in old apartments and new apartments were determined 20.9°C and 19.0°C, respectively (when the mean thermal sensation vote = 0).

3.3.2 Investigating validity of PMV model

The correlation between the calculated PMV and the reported AMV are presented in Figure 6. The correlation coefficients in new and old apartments are 0.70 and 0.73 respectively. It indicate that the PMV model performed well on predicting occupants' thermal comfort in both new and old apartments and provide an indication of the contribution of Fanger model. According to de Dear and Brager pointed that thermal adaptation can be achieved from three categories: behavioural adjustment, physiological acclimatization and psychological habituation (Brager & de Dear, 1998). Evidence reviewed in this paper indicated that thermal sensations of occupants have strong correlation to psychological and behavioural adjustment. Discrepancies observed could mean that there are psychobiological adaptations factors involved in thermal comfort of occupants in new apartments may have higher acceptable, result from controllability of heating system. Furthermore, In this study, occupants in new apartments are able to achieve their psychological expected or satisfied indoor environment via adjust TRVs set point, thus they respond more acceptable of indoor environment than those in old ones. Oppositely, occupants in old apartments have no opportunity to control environmental set point by control systems. Therefore, they respond discomfort with their indoor environments, in particular, they only can open window when room were overheated. It also can be consider that difference of the heating bill payment between new and old apartments. This is can be due to the occupants in new apartments can potential reduce indoor set point by using TRVs to save energy use related to less heating bill payment. Thus they provide better thermal responses. Evidence concluded in this study show that new building standard lead to better thermal comfort of occupants compared with old one.

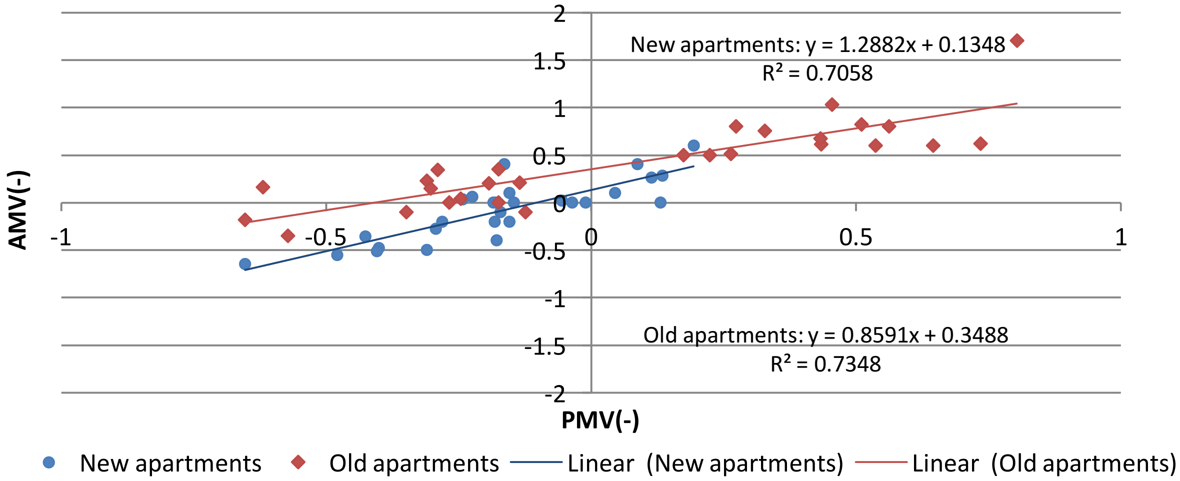


Figure 6. Regression lines of AMV versus PMV in new and old apartments

3.3.3 Thermal preference

Figure 6 shows the thermal preference scale from occupants' survey, 57% occupants in old apartments want to change their indoor environment to be cooler, while 28% occupants do not want to change their environments. However, in new apartments, occupants provide higher acceptable of indoor environment, 42% occupants do not want to change their environments. One possible explanation being put forward was that there are control systems in new apartments, and occupants can control TRVs to change heating set point in order to get their actual satisfied environments. However, occupants in old apartments only can open window when they not satisfied with their indoor climates. It is interesting to note that the similar findings were investigated from field study by Cao et al in Chinese residential buildings during winter period. It was found that the occupants in apartments with individual boiler heating respond higher acceptable evaluation than district heating without private control. This can be due to indoor environments were controlled by the users according to their actual demand in individual boiler heating apartments (Cao, et al., 2014).

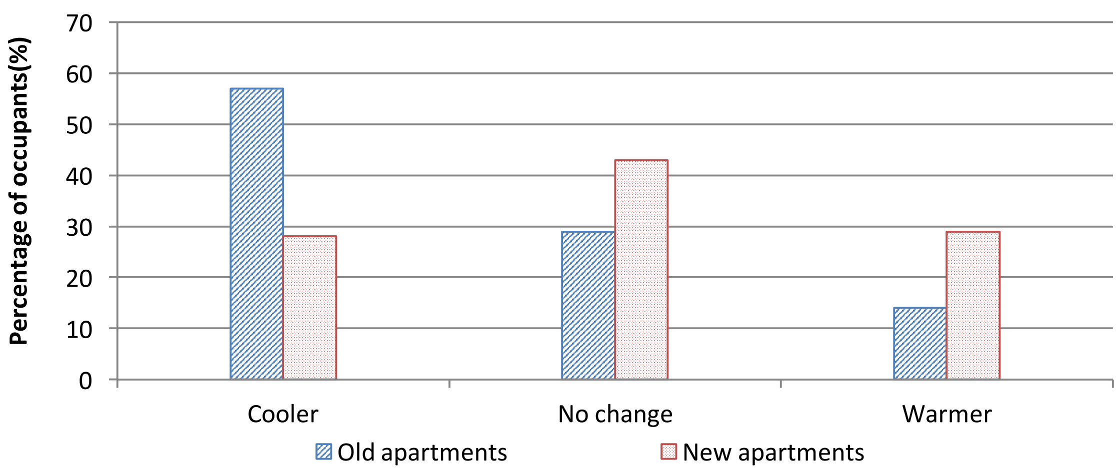


Figure 6. Distribution of thermal preference in new and old apartments

3.3.4 Indoor environment acceptability

Indoor environment acceptability votes reflect occupants' acceptability to the total environment (Wang, et al., 2011). Overall there are over 57% of satisfactions for thermal environment in the new apartments higher than that of 29% in old apartments (Fig.7). One possible explanation being put forward was that the indoor air temperature in old apartments higher than that in new ones, and occupants in old apartments prefer to have cooler indoor environment as well. Furthermore, it needs to take into account that the adaptive factors in new apartments should be considered into this field study.

In addition, gender influence thermal performance of AMV and reflect that the personal factors are important to be considered. Gender differences on thermal comfort were investigated based on objective and subjective surveys in Chinese building during winter period, Lan et al. of laboratory experiments showed not only the male skin temperature is constantly higher than that of female but also the female is more sensitive to air temperature. Furthermore, females prefer warmer conditions than males (Lan, et al., 2008). According to interview survey, overall female occupants were more dissatisfied with indoor thermal environment than male occupants in either new or old apartments. In the phases of occupants were not satisfied with indoor environment, difference between females and males were more prominent than that in phase of satisfactions votes (Fig.7). From the results, overall, the 71% female and male occupants are satisfied to the thermal environment in old apartments. Generally, a comparative analysis of data collected from males and females in old apartments show a slightly disparity of thermal sensation between them. However, generally females have much higher complaint than males in both types of building. Comparing the female comfortable sensation, the higher numbers of females in old apartments feel uncomfortable than males in new ones.

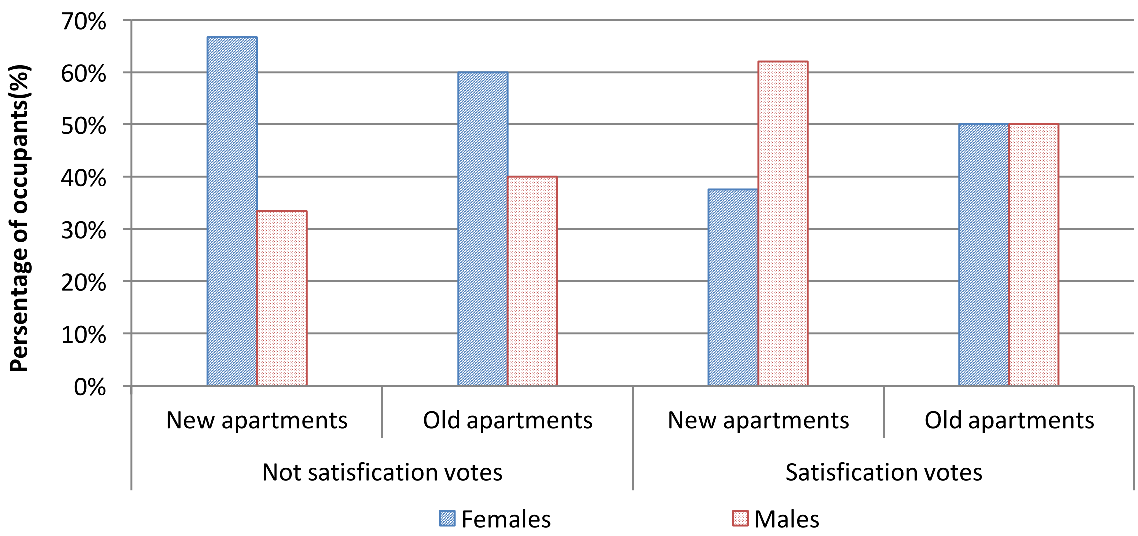


Figure 7. Distribution of thermal acceptability for females and males in old and new apartments

4 Conclusions

This experiment is based on subjective responses of 28 occupants that provided thermal sensation data from survey in the old and new apartments according to updated standards during winter season in North China. The conclusions are as follow:

- According to the results, the indoor temperature differences between old and new apartments were obvious. The mean indoor temperature in all old apartments is 22.5°C and the indoor air temperature in new one is 20.7°C which is respectively 1.8°C lower than the value measured in old apartments.
- The study investigated that the correlations between clothing insulation level and indoor temperature. From liner correlation the coefficient of determination R^2 can be observed as 0.12 for old apartments and 0.08 for new apartments.
- The greater number of occupants in old apartments voted the range from slightly warm (+1) hot (+3). Furthermore, thermal preference scales from occupants' survey show that 57% occupants in old apartments want to change their indoor environment to be cooler.
- A main issue to consider when reducing building energy consumption is not to sacrifice indoor thermal comfort. With the finding of energy consumption, adjustment of indoor set point temperature by using TRVs in new apartments, they provide better thermal responses than those in old ones. Evidence concluded in this study show that new building standard lead to better thermal comfort of occupants compared with old one.
- Overall there are over 57% of satisfactions for thermal environment in the new apartments higher than that of 29% in old apartments. The sensation differences in old and new apartments might be caused by occupants' psychological expectation. Furthermore, overall females have much higher complaint than males in both types of apartments.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Prediction methods of thermal comfort for naturally ventilated houses in hot humid climate

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Abstract
A suitable method of thermal comfort classification is important to represent the comfort achieved in buildings and so to evaluate design alternatives. This paper assesses methods to quantify the performance of naturally conditioned residences in hot humid weather of Brazil. A model of social housing building and variations in its constructive systems were simulated using DesignBuilder software and the performances calculated through different thermal comfort classification methods. The goal was to compare the rates and select the method more sensible to design variations and the influence of air movement, an important strategy for maximizing heat loss and thus improving the thermal comfort of buildings in hot humid climate.
The methods employed were the adaptive methods of Auliciems (1981, cited in Szokolay, 2004), Nicol and Humphreys (2002), and de Dear and Brager (2002), combined with the air movement effect in thermal comfort presented in Szokolay and Docherty (1999), Nicol (2004) and ASHRAE (2010) respectively, besides Fanger model (Fanger, 1972) and degree-hours. The index proposed by de Dear and Brager (2002) was more sensitive to variables changes, covering a greater range of thermal zones, besides greater linearity with method of degree-hour, used in the regulation of energy efficiency level in the country.

Keywords: thermal comfort, thermal performance, building simulation, natural ventilation

1 Introduction

Environmental comfort can be understood as a set of environmental conditions that allow humans to feel thermal, visual, acoustic and anthropometric welfare, in addition to ensuring the quality of air and the olfactory comfort (Lamberts et al, 2014).

The growing environmental concern has stimulated the development of techniques and methods to improve the thermal performance of buildings so that they provide comfort to its occupants with the lowest possible energy consumption of artificial air conditioning systems and by optimizing the passive conditioning. Taking advantage to the climate for thermal comfort purpose minimize the needs of energy to cooling or heating the buildings helping the energy savings issue.

Thermal performance analysis forms vary according to the purpose and available resources. Evaluation by analysing thermal comfort variables is frequent in the literature. These variables have its relationship with comfort settled through equations that establishes its impacts on experienced sensation, the thermal comfort indices. In the case of hot and humid climates, the influence of air movement stands out because it is one of the main bioclimatic and energy efficiency strategies since it can provide internal heat removal of the building and increases heat loss of the individuals due to convection.

This paper assesses available methods to quantify thermal performance of naturally ventilated residences; the main goal is to select a method suitable for the analysed conditions climate, sensible to design variations and the influence of air movement in the performance of residential building in hot humid climate.

Among the existing possibilities four thermal comfort indices besides the degree-hours method were taken to compose this study. The degree-hours method was chosen due to its use in the Brazilian Quality Technician Regulation for Energy Efficiency Level of Residential Buildings (Brazil, 2012).

2 Thermal Comfort Indices

The thermal comfort indices had been settled with different aims like defining comfort, exposure limits, comfort zone in different environments and performance evaluation. They were stablished during studies in temperature controlled environments or real situation resulting in the heat balance models and the adaptive comfort models respectively.

An example of the heat balance model is the widespread PMV/PPD index proposed by Fanger (1972), in which a large number of adults were asked about their thermal sensation when exposed to different environmental conditions inside a climatic chamber. It has become the foundation of international thermal comfort standards such as ISO 7730 (2005) and ASHRAE 55 (1992) and has widely been used (Nguyen et al, 2012).

Francis and Edwards (1995) cites the reliability of the PMV index for British perception of comfort, however, alerts about the failings of the speed assessment of PMV through ISO 7730 at higher temperatures and when the mean radiant temperature differs from the air temperature. In this case, the authors remind the importance to correct calculate the operative temperature through the ISO 7730. De Dear and Brager (2002) attest PMV index is appropriate for environments with artificial air conditioning, though occupants of naturally ventilated buildings adapt to a wider range of conditions, which normally reflect the patterns of the external temperature.

Some studies have proposed an expectancy factor, to be multiplied with PMV, in order to improve its applicability for occupants of non-air-conditioned building in tropical region. For Kwong et al (2014) even though these adaptive PMV models have been proposed, each tropical region has individual lifestyle and cultural routine demanding depth study to improve the applicability of these models directed to each region.

Adaptive models recognize that thermal sensations are the result not only of physiological but also psychological factors parameters, such as the expectation that each user has on indoor thermal conditions of the building and the possibility of the influence (opening and closing windows control equipment, HVAC and shading mechanisms for example) (de Dear and Brager, 1998).

Szokolay (2004) cites Humphreys (1978) that after analysis of a large number of comfort studies correlated thermal neutrality with the usual climate and suggested a comfort equation for free-running buildings, and also Auliciems (1981) that reviewed the data and complemented it, proposing a new equation and a psycho-physiological model of thermal perception which represents the basis of adaptive models. Its comfort temperature is given by Equation 1 presented in Table 1.

The study considers the comfort zone in a range of ± 2.5°C above the comfort temperature and also considers the air movement as a factor that can cause an increase in upper limit comfort temperature zone by physiological cooling. According Szokolay and Docherty (1999) the equation for the increase in upper limit comfort temperature for this index (Equation 2 in Table 1) should be used for air speeds up to 1.5m/s.

Nicol and Humphreys (2002) reaffirmed that the adaptive approach allows estimating the indoor temperature in which building occupiers are most likely to be comfortable, especially in free-running buildings and that the comfort temperature depend on the outside temperature. The relation between the comfort temperature and external temperature is established by Equation 3 (Table 1). It is recommended a variation of ±2°C in comfort temperature when you cannot use alternative adaptation as the use of air movement and change of clothes. Nicol (2004) adds that air speeds above 0.1 m/s and constant up to 1 m/s allow comfort temperature rises in accordance with Equation 4 (Table 1).

De Dear and Brager (2002) proposed an adaptive comfort index relating the average outdoor air temperature with the internal operative temperature instead of the dry bulb temperature. It is recommended for naturally ventilated places where occupants must be in sedentary activity (1-1.3 met) with light clothing between 0.5 and 0.7clo and able to free adaptation of clothing and thermal conditions between the inside and the outside. The American standard ASHRAE 55 (2010) and the European Standard EN 15251 (2007) adopted the principle. The index is represented by Equation 5 (Table 1) and the range to 90% of satisfied people is ± 2.5°C in comfort temperature, to 80% of satisfied people it is ± 3.5°C.

ASHRAE Standard 55 (2010) considers the air speed as a factor that can cause an increase in upper limit comfort temperature by physiological cooling. According to the standard, the air speed necessary to compensate for a temperature increase above the warm-temperature border are shown in Figure 1. Besides considering the air speed, it also considers the difference between the radiant temperature and air temperature. In order to achieve the equation from the graph in Figure 1, which is not informed, it was used the program DataFit version 9.0.59 (Oakdale Engineering, 2009) (Equation 6 in Table 1).

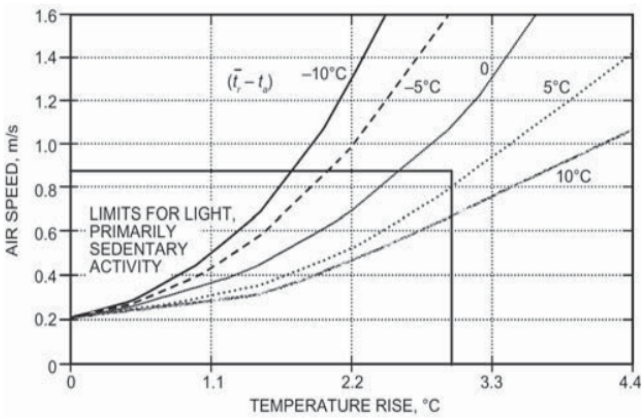

Figure 1. Air velocity to increase the comfort temperature limit. Source: ASHRAE, 2010

Table 1. Comfort indices equations and equations that consider the effect of air movement

Thermal comfort indices	Equations that consider the effect of air movement
$T_c = 0{,}31T_e + 17{,}6$ Equation 1 (Auliciems, 1981; apud Szokolay, 2004) Variation ±2.5°C	$dT = 6(v-0{,}2) - (v-0{,}2)^2$ Equation 2 (Szokolay and Docherty, 1999a)
$T_c = 0{,}54\ T_e + 13{,}5$ Equation 3 (Nicol and Humphreys, 2002) Variation ±2,0°C	$dT = 7 - (50/(4+10v^{0,5})$ Equation 4 (Nicol, 2004)
$T_c = 0{,}31T_e + 17{,}8$ Equation 5 (de Dear and Brager, (2002) Variation ±2,5°C	$dT=a+b*x_1+c*x_2+d*x_1^2+e*x_2^2+f*x_1*x_2+g*x_1^3+h*x_2^3+i*x_1*x_2^2+j*x_1^2*x_2$, Equation 6 where: x_1 is the difference between radiant and air temperature, °C x_2 is the air velocity in m/s and constants are:
Where: T_e is the average monthly temperature, °C T_c is the comfort temperature, °C dT is the temperature rise by use of air velocity, °C V is the air velocity, m/s	See constants below (Oakdale Engineering, 2009)

a=-8,95E-03	e=4,86	i=-1,61E-02
b=9,03E-03	f=0,14	j=2,48E-03
c=1,67	g=-1,33E-04	
d=-2,18E-04	h=-3,58	

(Oakdale Engineering, 2009)

3 Method

The thermal performance of the elements of a building is associated directly with its external climatic variables, so the weather data used in computer simulation is of greater importance. The weather data used represents the climate of the city of Natal in Brazil, a seaside town in northeast region with latitude 05°45’54” south and longitude 35°12’05”. The city has hot and humid climate, characterized by low thermal amplitude (daily and seasonal), high humidity and intense solar radiation.

The climate of the city is represented by a TRY weather data (Test Reference Year) obtained by Goulart et al. (1998) from a database range between the years 1951 and 1970. It consists of information of 14 climate variables over 8760 hours which is equivalent to the interval of one year. Due to climate changes resulting from the city's growth it would be recommended to use a newer weather data, however it did not exist until the research time.

Cirne (2006) presented a monitoring of speed and direction of winds in the city, held at the airport between 2002 and 2005, in which the author identified predominant incidence from southeast with air velocity more frequent between 5 and 8m/s. Venâncio (2007) citing Araujo (2001) presents the following graphs in Figure 2 and 3 with temperature and humidity data of typical days for the city. Figure 2 shows the small thermal amplitude on site, with daily thermal amplitude of 6°C and seasonal thermal amplitude of 2°C. Figure 3 shows variation about 20% in daily relative humidity and seasonal variation slightly below 10%.

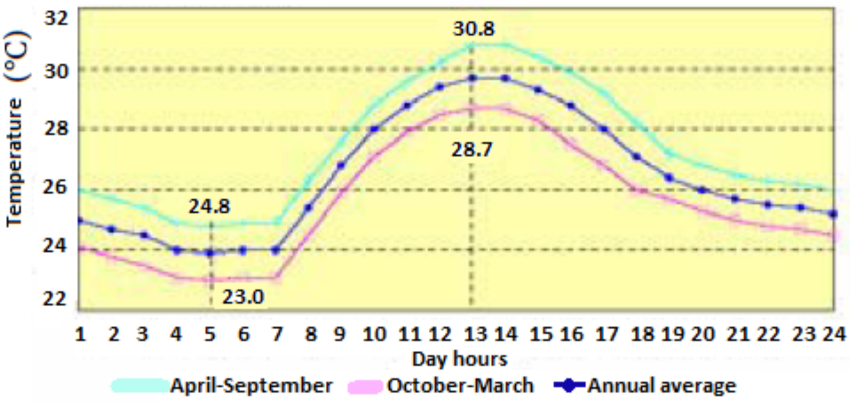

Figure 2. Graph of typical day temperature. Source: Venâncio (2007) citing Araujo (2001)

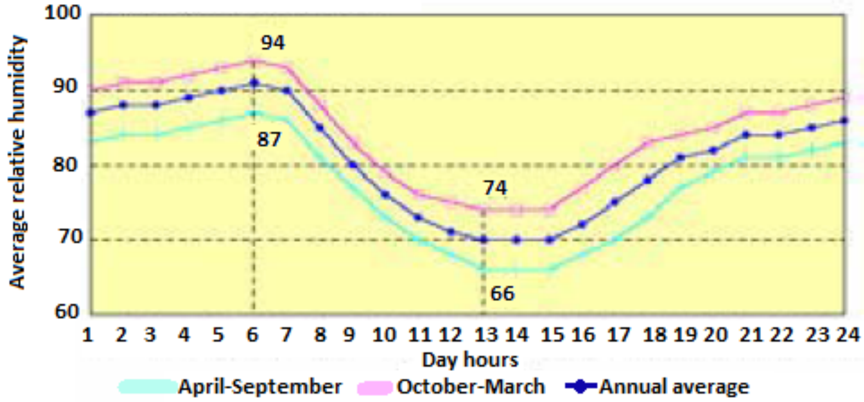

Figure 3. Graph of typical day humidity. Source: Venâncio (2007) citing Araujo (2001)

The method to compare the thermal comfort indexes and select the one more sensible to design variations and the influence of air movement in hot humid weather had three stages (Figure 4). First, it was made simulation of a housing base case and variations in the constructive systems in hot and humid climate using DesignBuilder software. Then, the comfort indexes combined with the effect of the air movement in comfort sensation, plus Fanger model and degree-hours were used to evaluate all cases. Last, it was used a graphic, for visualization of the simulation results, representing the occurrence of thermal zones according to each index (discomfort to cold, comfort, comfort with the use of ventilation and heat discomfort) over the hours of the day, every day the year (Negreiros and Pedrini, 2011). After this, it was possible to compare the results of the cases and the indices.

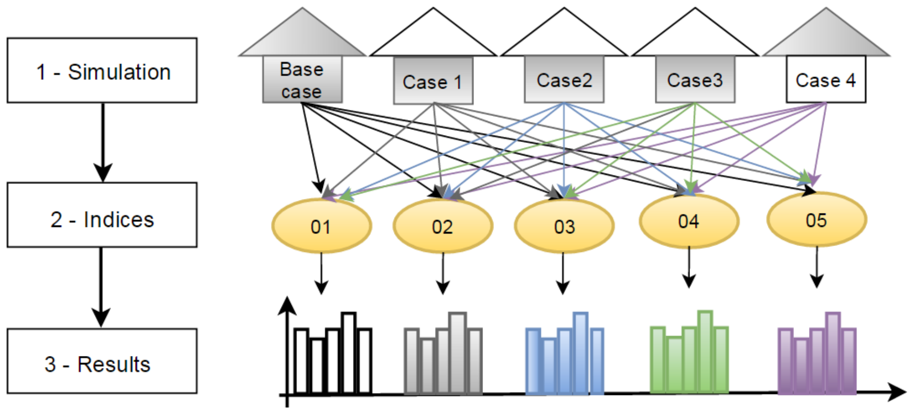

Figure 4. Method steps

3.1 Simulation

The residence prototype used in the simulations has a total area of 33.24m², divided into two bedrooms, a bathroom, a living room and integrated kitchen with ceiling height of 2.45m (Figure 5). Once the program configures the openings with glass, these were patterned glass solar factor equal to 1, so that the entire incident radiation is transmitted by simulating an open window. The routines considered 100% of opening area 24 hours to be able to assess the ventilation potential.

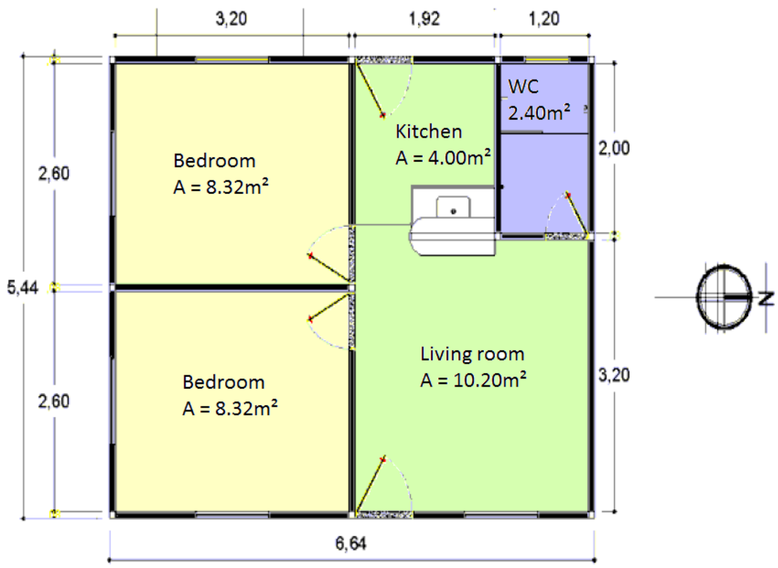

Figure 5. Base Case used in simulations

Routine occupation considered an average family of 4 people, 1 couple and two children. The rooms are occupied by a maximum of two people (0.24pessoas/m^2), while room and kitchen can be used by the whole family (0.28pessoas/m^2). The adopted metabolism was 110W/person and light work metabolic factor of 0.9.

The routine occupation in the bedrooms is 100% occupancy between 22:00 to 06:00 and occupation of 50% between 18:00 and 22:00, assuming two people occupying the bedrooms. In the living room was admitted an occupancy of 100% between 06:00 and 07:00h, time of possible use of the whole family and 50% occupancy between 07:00 and 22:00h, assuming that two people are still around all day.

Lighting routines were based on occupation times of the rooms, using 18h to 22h. It was adopted the use of compact fluorescent lamps with 15W in the bedrooms, 30W in the living room/kitchen and 15W in the bathroom. The equipment set were a television 20", 90W of average power and a gain of 6,33W/m^2; it was not considered the use of any equipment to the other rooms.

The base case model was modeled with aerated autoclaved concrete panels modulated as construction system, a homogeneous mixture of mortar with foam, creating a fluid material that is poured over standard molds. This constructive system was chosen for being used in social habitation research during the time of the study. The base case also used the walls with light color, clay tile roof and lining presence. Variations used clay tile without lining, light color roof with and without lining, and also dark walls. The variations and its characteristic are presented in Table 2.

Table 2. Base case and variations used in simulations

Type	Construction System	Transmittance U (W/m².K)	Absorptance α	FCS %
ROOF				
RB – base case	Clay roof with lining Tile Thickness: 1,0 cm Thickness of liner: 1,0 cm	2,24	0,8	5,4
R1			0,2	1,8
R2	Clay roof without lining Tile Thickness: 1,0 cm	4,55	0,8	10,9
R3			0,2	3,64
WALLS				
WB – base case	Aerated autoclaved concrete panels walls Thickness: 0,08cm	3,03	0,8	9,6
W1			0,2	2,4

Evaluation

The first step to carry out the evaluations is the calculation of comfort temperature according to each method. All indexes analyzed based on the external monthly average temperature to calculate the neutral temperature and this was calculated for each day as an average temperature of 30 days prior to it, considering that this would be a representative temperature for the user acclimatization to the environment at the time.

Then, the boundaries of the thermal zones were defined. The zone of discomfort to cold and comfort were calculated according to the variations to comfort temperature established by each indices. Next, it was establish the limit of the comfort zone with the use of ventilation and heat discomfort zone. This was calculated using the equations that consider the air velocity to increase comfort temperature limit in accordance with each index.

It was used the value 0.8 m/s for air velocity in all the equations because this was the upper limit to air speed defined by ASHRAE (2010) for light, primarily sedentary activities, obtaining an increase of 4.2°C in the comfort temperature shown in the first equation, 3.4°C in the second equation and a varied value in the third equation since it depends on the difference between the radiant temperatures and air, plus the air velocity.

The thermal comfort indices of Auliciems (1981) and Nicol and Humphreys (2002) occur comparing the internal air temperature of the simulated cases with the pre-established thermal zones limits. For de Dear and Brager index (2002), the operative temperature of each year hour is calculated and compared with the pre-established limits. The operative temperature is calculated using the equation defined by ISO 7730 (2005) (Equation 7).

$$t_o = A t_a + (1 - A) t_r \qquad \text{Equation 7}$$

Where:

t_o: operative temperature, in °C

t_a: air temperature, in °C

t_r: mean radiant temperature, in °C

A : factor that depends on the speed, according to Table 3

Table 3. A factor values as a function of airspeed. Source: ISO 7730 (2005)

Air velocity (m/s)	A
v < 0,2	0,5
0,2 < v < 0,6	0,6
0,6 < v < 1,0	0,7

4 Results

The weather file, together with the base case and four variations (light color roof, clay roof no liner, light color roof no liner and dark walls), were evaluated using the five methods (Fanger model, Auliciems index, Nicol and Humphreys index, de Dear and Brager index and degree-hours). The comparison between the models is shown in Figure 6, which brings the annual hours evaluated and classified in each thermal zone (discomfort to cold, comfort, comfort with ventilation and heat discomfort). After it is presented the results about performance evaluation of the design variables used.

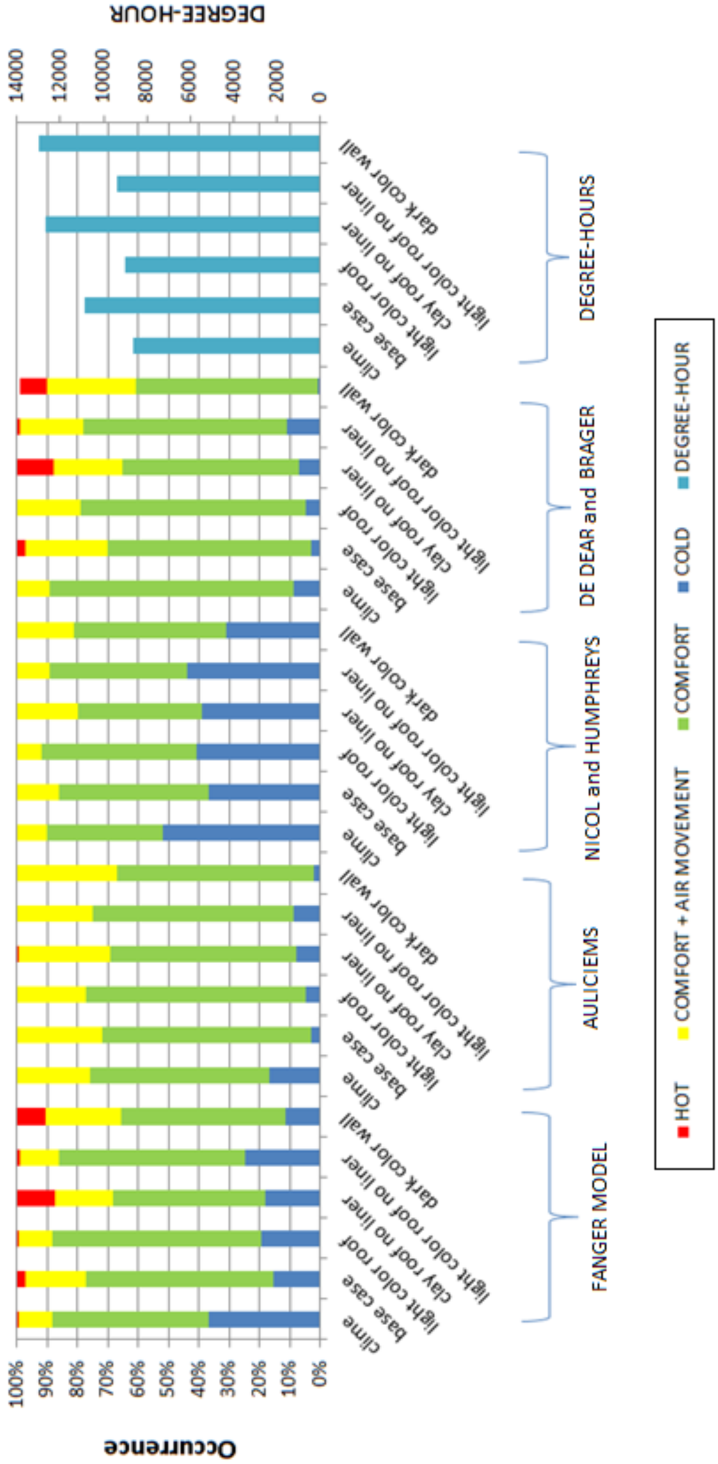

Figure 6. Thermal comfort models comparison

According to the results, Fanger model and Nicol and Humphreys model have higher results of cold discomfort range. The Nicol and Humphreys model considered the weather in discomfort for cold in 52% of the years hours, including early evenings hours. According to degree-hours method, set with a base temperature for cooling of 26°C, the weather is the case with less hours in discomfort. It demonstrates that Fanger model and Nicol and Humphreys model are less tolerant to the lower temperatures occurred.

Auliciems model and Nicol and Humphreys model have smaller results variations for the different cases, focusing results in smaller performance ranges. These models presented few hours of the year in heat discomfort.

Higher similarity occurs in Fanger model, de Dear and Brager model and degree-hours. Fanger model and de Dear and Brager model have the largest variations of hours within the comfort ranges for the different cases analyzed.

All indices considers on average 20% of the hours of the year in each case in comfort due to the use of ventilation, showing how this bioclimatic strategy has great influence in the improvement of housing comfort level. The more comfort hours due to ventilation helps reducing the use of mechanical ventilation and air conditioning systems, directly minimizing energy consumption.

Regarding the performance of the different simulated cases, although the ranking differs according to the method of evaluation, the light color roof with liner case showed the greatest number of comfort hours, followed by the base case and light color roof without liner. The case with most heat discomfort hours is the clay roof without lining, followed by the case with dark walls. With the intense solar radiation, a climate characteristic, the use of materials with low absorptance decreases heat absorption, presenting smaller number of hours in heat discomfort.

The use of two construction systems in the envelope with values for solar heat factor larger than the one allowed by the standard (clay roof without lining and high absorptance wall) showed higher impairments in the prototype's performance, with the highest records of heat discomfort hours, confirming be values that compromise the performance.

Although the base case walls material have higher transmittance than stipulated in the standard (3,03W/m².K), its use combined with a low absorptance showed good performance, with low solar heat factor.

5 Conclusions

The study exploring methods of building thermal performance assessment for hot and humid weather in naturally ventilated houses in Brazil used simulation of a house model and case bases to compare the results of different thermal comfort indexes. It was used the adaptive methods of Auliciems (1981, cited in Szokolay, 2004), Nicol and Humphreys (2002), and de Dear and Brager (2002), combined with the air movement effect in thermal comfort presented in Docherty and Szokolay (1999), Nicol (2004) and ASHRAE (2010), respectively besides Fanger model and degree-hours. The residence was simulated in DesignBuilder Program, an interface for Enegyplus software, and the data analysis reflects the differences in comfort levels indicated by the different indices.

The study concluded that the comfort index from de Dear and Brager (2002) is more indicated to evaluate the thermal performance in the study case once it is more sensitive to changes in project variables in the region. The index shows greater changes in the occurrence of hours in the different thermal zones of performance when the model had its parameters altered, allowing more clear differences among the cases.

The index also presented a greater linearity with the method of degree-hour which is used in the locally regulation of the level of energy efficiency, besides the benefit of being and adaptive index (takes into account the principle of the individual's environment accommodation), and to consider the influence of the mean radiant temperature using the operating temperature for comfort calculation and use the difference between radiant temperature and the air temperature in the equation to increase the heat temperature due to the use of air movement.

Natural ventilation proved to be efficient to improve thermal performance in many hours of the year, being the simplest strategy to promote thermal comfort when the internal temperature becomes high. Natural ventilation to obtain comfort is suitable for climates where the outside air temperature is in acceptable conditions of comfort, because through this strategy the internal temperature equals the external temperature, cooling the place. Therefore design alternatives for enabling permeability, use of hollow elements and continuous spaces are welcome.

Regarding the variables used in the simulations, the case with light color roof with liner provided the best results, adding more hours of comfort during the year. The case with clay roof and no liner turned out to be the least suitable, because it has more hours of discomfort heat in the year. The absorptance use also showed to be a factor that direct influences the performances; low absorptance materials presented better performance, with less number of hours in heat discomfort.

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Effect of Set-point Variation on Thermal Comfort and Energy Use in a Plus-energy Dwelling

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Abstract

When designing buildings and space conditioning systems, the occupant thermal comfort, health, and productivity are the main criteria to satisfy. However, this should be achieved with the most energy-efficient space conditioning systems (heating, cooling, and ventilation). Control strategy, set-points, and control dead-bands have a direct effect on the thermal environment in and the energy use of a building. The thermal environment in and the energy use of a building are associated with the thermal mass of the building and the control strategy, including set-points and control dead-bands. With thermally active building systems (TABS), temperatures are allowed to drift within the comfort zone, while in spaces with air-conditioning, temperatures in a narrower interval typically are aimed at. This behavior of radiant systems provides certain advantages regarding energy use, since the temperatures are allowed to drift, and it also allows the occupants to benefit from adaptive opportunities. This study presents the results of thermal environment measurements and energy use in a single-family dwelling during a one year period. A radiant floor heating and cooling system was used to condition the indoor space and the operative temperature set-points were varied during the heating and cooling seasons. The results show that a lower temperature set-point will result in a decreased energy use but it might require the occupants to adapt to slightly lower temperatures in the heating season, and vice versa in the cooling season. The terminal unit and the thermal mass of the building have significant effects on the applicability of lowered indoor temperature set-points.

Keywords: adaptive opportunity, temperature drift, thermal indoor environment, floor heating and cooling, energy use

1 Introduction

Buildings are complex structures where different components and systems interact with each other. The main task of buildings and the installed mechanical systems (heating, cooling, and ventilation) is to provide a comfortable and healthy indoor environment to the building occupants.

While creating the necessary indoor conditions for human occupancy, other crucial aspects should also be considered: energy efficiency and environmental friendliness. These two principles apply to envelope design, material selection, and also to the choice and design of space conditioning systems.

Recently there have been research efforts regarding the development of low-energy houses, passive houses (The International Passive House Association, 2015) and active houses (The Active House Alliance, 2015). In several cases, overheating has been reported from low-energy and passive houses (Janson, 2010), (Rohdin et al., 2014), (Holopainen et al., 2015), (Maivel et al., 2015), (Larsen and Jensen, 2011), and the main reasons for overheating have been identified as large glazing areas, poor or lack of solar shading, lack of ventilation (Larsen, 2011), lack of thermal mass, and lack of adequate modeling tools in the design phase (Phillips and Levin, 2015). Other problems such as varying room temperatures (Rohdin et al., 2014), (Holopainen et al., 2015), too low air temperatures in winter, stuffiness and poor air quality, and too low floor surface temperatures in winter (Rohdin et al., 2014) have also been reported in low-energy and passive houses. These results indicate that there is a need for improvement and a need for more data regarding the performance of houses that are designed for low energy use targets.

In order to evaluate the thermal indoor environment and energy performance of different heating and cooling systems, a detached, single-family house, which was designed for plus-energy targets (a house that produces more energy from renewable energy resources than it imports from external resources in a given year, according to the definition given by the European Commission (2009)), was operated for one year under different heating and cooling strategies. During the measurement period, thermal indoor environment and energy performance of the house were thoroughly monitored and recorded.

The main findings are presented considering the achieved thermal indoor environment according to national and international standards and resulting energy use with the different heating and cooling strategies. Improvement suggestions regarding the design and operation of the building and its heating and cooling systems are provided.

2 Details of the house

2.1 Construction

The test house was a single family, detached, one-story house with a floor area of 66.2 m^2 and a conditioned volume of 213 m^3. The house was constructed from pre-fabricated wooden elements that were made from layers of laminated veneer lumber boards, which in combination with I beams in between formed the structural elements. The house was insulated with a combination of 200 mm mineral wool and 80 mm compressed stone wool fibers. The house was supported on 200-300 mm concrete blocks and the space between the ground and the house's floor structure was covered which created a crawl-space below the house.

Figure 1. Exterior views of the house, seen from North-West (left) and South-West (right)

Inside the house, there was a single space which combined kitchen, living room and bedroom areas. The technical room was completely insulated from the main indoor space, and had a separate entrance. The glazing façades were partly shaded by the roof overhangs. No solar shading was installed in the house except for the skylight window. All windows had a solar transmission of 0.3. The largest glazing façade was oriented to the North with a 19° turn towards the West. Figure 1 shows the exterior views of the house.

The surface areas and thermal properties of the envelope are given in Table 1.

Table 1. Thermal properties of the envelope

	North	South	East	West	Floor	Ceiling
Walls, Area, [m^2]	-	-	37.2	19.3	66.2	53
Walls, U-value, [W/m^{2}K]	-	-	0.09	0.09	0.09	0.09
Windows, Area, [m^2]	36.7	21.8	-	-	-	0.74
Windows, U-value, [W/m^{2}K]	1.04	1.04	-	-	-	1.04

2.2 Heating, cooling, and ventilation system

The house was mainly heated and cooled by the hydronic radiant system in the floor using the low temperature heating and high temperature cooling principle. The system was a dry radiant system, consisting of a piping grid installed in the wooden layer. The details of the floor system were: chipboard elements with aluminum heat conducting profiles (thickness 0.3 mm and length 0.17 m), PE-X pipe, 17x2.0 mm. Pipe spacing was 0.2 m. A wooden floor covering was used with a thickness of 14 mm and a thermal conductivity of 0.13 W/mK. The available floor area for the embedded pipe system installation was 45 m^2. The design flow rates in the heating and cooling modes were 619 kg/h and 336 kg/h, respectively. The flow rates were calculated according to EN 15377-2 (European Committee for Standardization, 2008).

The floor heating and cooling system was coupled to a reversible air-to-brine heat pump. The minimum and maximum cooling capacities and the nominal power input in the cooling mode were 4.01, 7.1, and 2.95 kW, respectively. The minimum and maximum heating capacities and the nominal power input in the heating mode were 4.09, 7.75, and 2.83 kW, respectively.

A flat-plate heat exchanger was installed between the hydronic radiant system of the house and the air-to-brine heat pump. The pipes between the heat exchanger and the heat pump were filled with an anti-freeze mixture (40% ethylene glycol) to avoid frost damage during winter.

A mixing station which linked the radiant system with the heat source and sink, and a controller of the radiant system controlled the flow to each loop, and the supply temperature to the radiant system. The operation of the radiant system was based on the operative temperature set-point that was adjusted on a room thermostat (a matt gray half-sphere) in 0.5°C intervals and on the relative humidity inside the house to avoid condensation during summer.

The house was ventilated mechanically by an air handling unit (AHU). The mechanical ventilation was only used to provide fresh air into the house since the main sensible heating and cooling terminal of the house was the radiant system. The design ventilation rate was 0.5 ach. The intake air was taken from the crawl-space.

Passive and active heat recovery options were available in the AHU. The passive heat recovery was obtained by means of a cross-flow heat exchanger and this passive heat recovery system had an efficiency of 85% (sensible heat). By-pass was possible. The active heat recovery was achieved by means of a reversible air-to-water heat pump that was coupled to the domestic hot water tank. The AHU could supply fresh air at a flow rate of up to 320 m^3/h at 100 Pa. The two air supply diffusers can be seen on the technical room wall in Figure 2.

Further details of the components and the system can be found in (Kazanci et al., 2014), (Skrupskelis and Kazanci, 2012), and (Kazanci and Olesen, 2014).

3 Methods

During the measurements the house was located in Bjerringbro, Denmark. The thermal indoor environment and energy performance of the house were monitored from 26/9/2013 to 1/10/2014.

3.1 Experimental settings

The house was unoccupied during the measurement period and heated dummies were used to simulate the occupancy and equipment schedules (internal heat gains). The details of the dummies are given in (Skrupskelis and Kazanci, 2012).

The occupancy and equipment schedules were adjusted with timers. Two dummies were used to simulate occupants (the dummies had the same surface temperatures as a person would have) at 1.2 met (ON from 17 hours to 08 hours on weekdays and from 17 hours to 12 hours on weekends), one dummy (equipment #1, 120 W, 1.8 W/m^2) was always ON to simulate the house appliances that are always in operation, the fourth dummy (equipment #2, 180 W, 2.7 W/m^2) was used to simulate the house appliances that are in use only when the occupants are present and the fifth dummy was used to represent additional lights (180 W, 2.7 W/m^2, ON from 06 hours to 08 hours and from 17 hours to 23 hours until 27th of May 2014, and after this date, ON from 20 hours to 23 hours, every day). The house had ceiling mounted lights ON from 21 hours to 23 hours, every day (140 W, 2.1 W/m^2). Additionally, there was a data logger and a computer (80 W, 1.2 W/m^2), and a fridge (30 W, 0.4 W/m^2) which were always ON.

3.2 Measurements and measuring equipment

The air and globe temperatures were measured at 0.1 m, 0.6 m, 1.1 m, 1.7 m, 2.2 m, 2.7 m, 3.2 m and 3.7 m heights, at a central location in the occupied zone following EN 13779 (European Committee for Standardization, 2007).

The globe temperatures were measured with a gray globe sensor, 40 mm in diameter. This sensor has the same relative influence of air- and mean radiant temperature as on a person (Simone et al., 2007) and, thus, at 0.6 m and 1.1 m heights will represent the operative temperature of a sedentary or a standing person, respectively. The air temperature sensor was shielded by a metal cylinder to avoid heat exchange by radiation. Both the globe and air temperature sensors have ±0.3°C accuracy in the measurement range of 10-40°C (Simone et al., 2013). The output from the sensors was logged by a portable data logger.

Figure 2 shows a panoramic view of the interior of the house, the measurement location and the sensors used for the measurements.

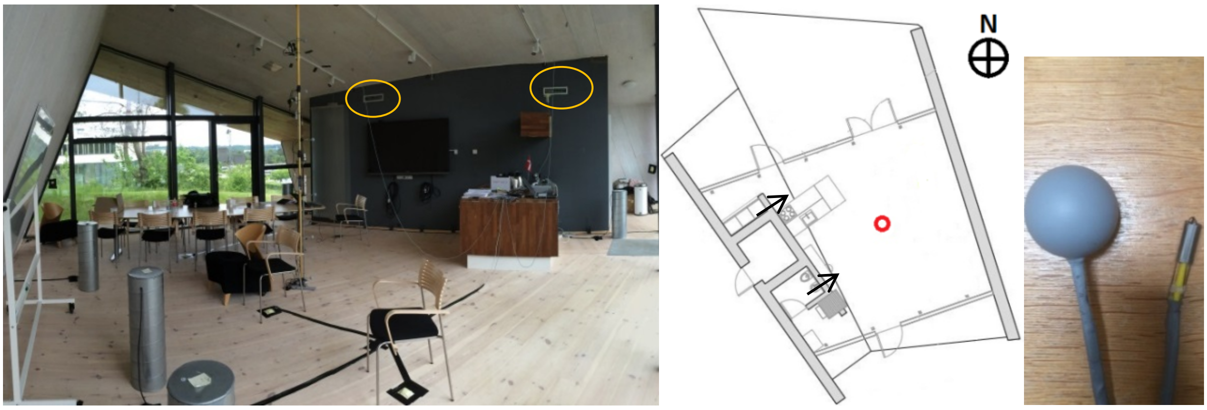

Figure 2. Panoramic view of the interior (left), the measurement location (middle) and the globe and air temperature sensors (right)

The energy consumptions of the air-to-brine heat pump, mixing station, and the controller of the radiant system were measured with wattmeters. The energy consumption of the AHU was measured through a branch circuit power meter (BCPM). The wattmeters that were used to measure the consumption of the mixing station and the controller of the radiant system had an accuracy of ±2% ±2 W. The wattmeter that was used to measure the consumption of the air-to-brine heat pump had an accuracy of 3%. The BCPM's accuracy was 3% of the reading.

A full specification of the parameters measured and the measuring equipment can be found in (Kazanci and Olesen, 2014).

4 Experimental operation of the heating, cooling, and ventilation system

For the first part of the experiments in the heating season, floor heating was operated without any ventilation, with different operative temperature set-points. In the second part, floor heating was supplemented by warm air heating from the ventilation system, and during the last part of the heating season, floor heating was operated with passive heat recovery from the exhaust air. The design ventilation rate was 0.5 ach.

Table 2 shows the most important boundary conditions for these strategies in the heating season (FH: floor heating, HR: heat recovery, HRPH: heat recovery and pre-heating).

Table 2. Periods and experimental settings of the different cases, heating season

Period	***Average external air temperature [°C]***	***Floor heating set-point [°C]***	***Ventilation***	***Case abbreviation***
26^{th} of Sep to 21^{st} of Nov	8.2	22	Off	FH22
21^{st} of Nov to 18^{th} of Dec	4.0	20	Off	FH20
18^{th} of Dec to 16^{th} of Jan	4.6	21	Off	FH21
16^{th} of Jan to 10^{th} of Feb	0.0	21	On, heat recovery and pre-heating**	FH21-HRPH
10^{th} of Feb to 10^{th} of Mar	5.0	20	On, heat recovery and pre-heating**	FH20-HRPH
10^{th} of Mar to 3^{rd} of Apr	5.5	21	On, heat recovery	FH21-HR
3^{rd} of Apr to 1^{st} of May*	9.0	20	On, heat recovery	FH20-HR

*: The dummies simulating the occupants and a dummy (equipment #2) were OFF during this experimental period.

**: Heat recovery refers to the passive heat recovery and pre-heating refers to the active heat recovery in AHU. The supply air temperature was between 30 to 34°C, except for the periods with low outside air temperatures when it dropped to 27°C.

The operation of the HVAC system followed a similar approach during the cooling season. The house was cooled by floor cooling and was ventilated with the mechanical ventilation system with passive heat recovery from the exhaust airflow (by-pass was possible). Different operative temperature set-points and different ventilation rates were tested. Internal solar shading covering 20 m^2 (manually operated) was installed on the North façade on 30/07/2014 and it was used in the fully down position until the end of the experiments.

Table 3 shows the most important boundary conditions for the strategies used in the cooling season (FH: floor heating, CS: cooling season, FC: floor cooling, HV: higher ventilation rate, S: solar shading).

Table 3. Periods and experimental settings of the different cases, cooling season

Period	*Average external air temperature [°C]*	*Floor cooling set-point [°C]*	*Ventilation type and ventilation rate*	*Solar shading*	*Case abbreviation*
1st of May to 27th of May*	14.7	20**	Heat recovery, 0.5 ach	No	FH20-CS
27th of May to 19th of June	18.7	25	Heat recovery, 0.5 ach	No	FC25
19th of June to 13th of July	18.7	25	Heat recovery, 0.8 ach	No	FC25-HV
13th of July to 30th of July	22.7	24	Heat recovery, 0.8 ach	No	FC24-HV
30th of July to 21st of Aug	18.1	24	Heat recovery, 0.8 ach	Yes	FC24-HV-S
21st of Aug to 1st of Oct	16.0	24	Heat recovery, 0.5 ach	Yes	FC24-S

*: The dummies simulating the occupants and a dummy (equipment #2) were OFF during this experimental period. **: Floor system was in heating mode, transition period. ***: The house was not cooled from 20/06/2014 to 23/06/2014 to allow repairs to be made to the HVAC system.

5 Results and discussion

5.1 Heating season

The performance of different heating strategies was evaluated based on the indoor environment category achieved according to EN 15251 (European Committee for Standardization, 2007). The following categories are given according to EN 15251 (European Committee for Standardization, 2007) for sedentary activity (1.2 met) and clothing of 1.0 clo. Table 4 shows the indoor environment categories achieved for different heating strategies and during the entire heating season.

Table 4. The category of indoor environment based on operative temperature at 0.6 m height, heating season

Indoor environment category/case	***FH22***	***FH20***	***FH21***	***FH21-HRPH***	***FH20-HRPH***	***FH21-HR***	***FH20-HR***	***Total, average***
Category 1 (21.0-25.0°C)	92%	2%	37%	22%	11%	67%	35%	45%
Category 2 (20.0-25.0°C)	97%	44%	92%	72%	61%	98%	77%	80%
Category 3 (18.0-25.0°C)	100%	95%	100%	93%	99%	100%	100%	98%
Category 4*	0%	5%	0%	7%	1%	0%	0%	2%

*: Category 4 represents the values outside Categories 1, 2, and 3.

Figure 3 shows the operative temperature at 0.6 m height and the external air temperature during the heating season.

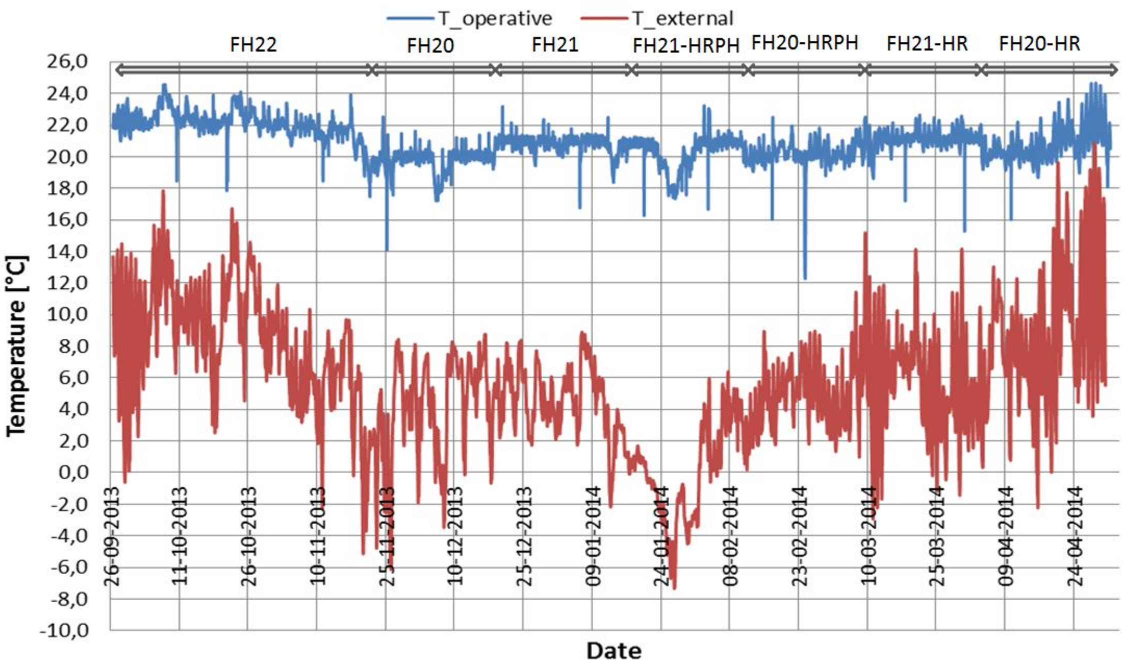

Figure 3. Operative temperature and external air temperature during the heating season

The results show that even though different heating strategies were tested, the overall performance regarding the indoor environment was satisfactory, i.e. 80% of the time in Category 2 according to EN 15251 (European Committee for Standardization, 2007). It may also be seen that there were periods when the indoor environment was outside Category 3: for 2% of the time it was in Category 4.

It was possible to keep the indoor operative temperature close to the set-point, although the systems struggled to achieve this when the outside temperatures were below -5°C. In addition to the increased heating demand, one possible explanation for this is that both the air-to-brine heat pump and the AHU were affected by the lower outside air temperatures.

The operative temperature set-point of 20°C proved to be too low. This is because even though the ventilation system would be heating the indoor space, the floor heating system did not start the water circulation in the loops until the operative temperature had dropped below 20°C. This resulted in several periods with room temperatures below 20°C.

5.2 Cooling season

The performance of different cooling strategies was evaluated based on the indoor environment categories given in EN 15251 (European Committee for Standardization, 2007) for sedentary activity (1.2 met) and clothing of 0.5 clo. In addition, the hours above 26°C, 27°C and 28°C were calculated following DS 469 (Danish Standards, 2013) and following the most recent building code in Denmark, Bygningsreglement 2015 – BR15 (The Danish Ministry of Economic and Business Affairs, 2015).

According to DS 469 (Danish Standards, 2013), 26°C should not be exceeded for longer than 100 hours during the occupied period and 27°C should not be exceeded for longer than 25 hours. Even though these specifications are given for offices, meeting rooms, and shops, it is considered to be applicable also for residential buildings. It should be noted that according to DS 469 (Danish Standards, 2013), mechanical cooling would normally not be installed in residential buildings in Denmark.

Denmark is one of the first countries to include the adaptive thermal comfort approach in its building code. In the most recent building code in Denmark, Bygningsreglement 2015 – BR15 (The Danish Ministry of Economic and Business Affairs, 2015), the temperatures given in DS 469 (Danish Standards, 2013) have been increased by 1°C, which now states that in residential buildings, 27°C should not be exceeded for longer than 100 hours during the occupied period and 28°C should not be exceeded for longer than 25 hours. The reasoning behind this is that it is possible to open windows and create air flow in residential buildings (The Danish Ministry of Economic and Business Affairs, 2015).

The indoor environment categories achieved, and the hours above 26°C, 27°C and 28°C as a function of the cooling strategy are given in Table 5, and the operative temperature and external air temperature during the cooling season are given in Figure 4.

Table 5. The category of indoor environment based on operative temperature at 0.6 m height, cooling season

Indoor environment category/case	*FH20-CS*	*FC25*	*FC25-HV*	*FC24-HV*	*FC24-HV-S*	*FC24-S*	*Total, average*
Category 1 (23.5-25.5°C)	52%	56%	36%	54%	39%	22%	41%
Category 2 (23.0-26.0°C)	73%	72%	49%	72%	58%	36%	57%
Category 3 (22.0-27.0°C)	87%	87%	75%	91%	84%	72%	81%
Category 4	13%	13%	25%	9%	16%	28%	19%
Hours above 26°C	48	129	79	87	7	0	350*
Hours above 27°C	19	71	38	34	0	0	162*
Hours above 28°C	6	35	19	13	0	0	73*

*: Although the overheating hours cannot be directly added for the different cooling strategies, their total is given to indicate the duration of overheating during the cooling season.

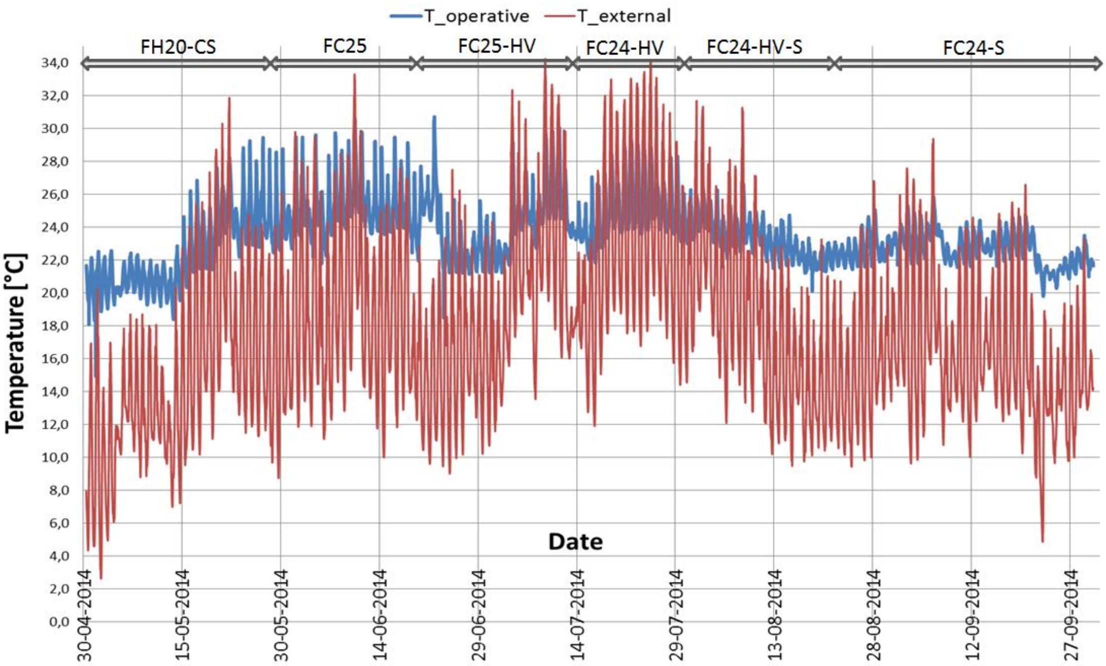

Figure 4. Operative temperature and external air temperature during the cooling season

The house performed worse in the cooling season than in the heating season; for 57% of the time the operative temperature was in Category 2 and for 19% of the time it was outside the recommended categories in EN 15251 (European Committee for Standardization, 2007). This occurred mainly in the transition periods (i.e. May and September) and due to overheating, which was a problem during the cooling season, except in August and September. The hours above 26°C and 27°C exceeded the values recommended in DS 469 (Danish Standards, 2013) and the hours above 27°C and 28°C exceeded the values recommended in BR15 (The Danish Ministry of Economic and Business Affairs, 2015).

Decreasing the operative temperature set-point and increasing the ventilation rate helped to address the increased cooling load, but with a higher energy consumption. This is mainly due to the longer operation of the floor cooling and to increased cooling of the supply air.

The results show that even though the floor system was in heating mode during most of May (transition period), floor cooling could have been activated in the second half of May, which would have reduced the overheating hours and improved the indoor environment.

Cooling demand of the house was high and the most significant problems were the large glazing façades including the lack of solar shading and the lack of thermal mass to buffer sudden thermal loads. In the current location of the house, direct solar radiation from the South façade was not a problem, because of the orientation and longer overhang on the South façade. Most of the overheating hours were in the late afternoon (i.e. from 18:00 hours until sunset), when there was direct solar gain through the North façade.

5.3 Energy performance

The HVAC system's energy use included the air-to-brine heat pump, mixing station, controller of the radiant system, and the AHU. The energy use of individual components can be found in (Kazanci and Olesen, 2016) and in (Kazanci and Olesen, 2014).

Heating degree days (HDD) and cooling degree days (CDD) were calculated for each case using a base temperature of 17°C and 23°C, respectively. Table 6 shows the average energy use per day and heating or cooling degree days per day, following the methodology described by (Quayle and Diaz, 1980), for each heating and cooling strategy.

Table 6. Energy use of the HVAC system

Case	*HDD*	*CDD*	*Total [kWh]*	*Total, average [kWh/day]*	*HDD/day or CDD/day*
FH22	496	-	539.7	9.5	8.7
FH20	350	-	453.4	16.8	13.0
FH21	361	-	480.6	16.6	12.5
FH21-HRPH	425	-	713.7	28.5	17.0
FH20-HRPH	337	-	531.4	18.9	12.0
FH21-HR	275	-	370.7	15.4	11.4
FH20-HR	220	-	358.0	12.8	7.9
FH20-CS	97	-	250.7	9.3	3.6
FC25	-	15	138.7	6.0	0.7
FC25-HV	-	20	189.8	9.0	1.0
FC24-HV	-	36	184.3	10.8	2.1
FC24-HV-S	-	12	189.3	8.6	0.5
FC24-S	-	6	212.4	5.3	0.1

The results show that the energy consumption increased markedly when the warm air heating (FH21-HRPH and FH20-HRPH) was in operation, and these strategies struggled to provide the intended thermal indoor environment despite the increased energy consumption. The energy consumption during the cases FH20 and FH21 were close to each other, but a more satisfactory thermal indoor environment was achieved with FH21. The last two cases in the heating season, FH21-HR and FH20-HR, have lower energy consumption and achieved a more satisfactory thermal indoor environment compared to the cases with the same set-points without ventilation (FH21 and FH20). The FH22 strategy had the lowest energy consumption (although it had the highest operative temperature set-point) and the best thermal indoor environment, although this was partly due to the relatively high external air temperatures during this period.

During the cooling season, the increased ventilation rate and lowered operative temperature set-point increased the energy consumption. This was expected, due to higher power input to the fans in the AHU and longer operation time of the pump in the floor cooling system. The increased energy consumption contributes to a more comfortable thermal indoor environment, but other strategies should be employed to reduce the cooling demand by means of energy efficient measures (e.g. lower ventilation rates when the house is unoccupied, natural ventilation when the outside conditions are suitable, decreased glazing area, solar shading, a better orientation of the house and so forth). The effects of different building and HVAC system improvements on the energy consumption and thermal indoor environment were parametrically studied and reported by (Andersen et al., 2014).

Throughout the 12-month operation of the house, the heating and cooling systems were active with respective set-points also during the transition periods (i.e. May and September) but it is not practical to provide constant heating or cooling during the transition periods, therefore the heating and cooling system operation and the switchover between these modes require careful consideration. Operation of the systems needs to be improved to avoid unnecessary heating and cooling in the transition periods.

Previous studies (Kazanci et al., 2014), (Skrupskelis and Kazanci, 2012), and (Andersen et al., 2014) showed that the large glazing façades (including the lack of solar shading) of the house resulted in a high heating and cooling demand and this drastically decreased the energy performance of the house. This was confirmed by the experiments; the currently installed heating and cooling systems of the house struggled to achieve a comfortable thermal indoor environment during the cold periods in winter and overheating was a significant problem during the cooling season.

The results show that the house would have benefited from a higher thermal mass to buffer the sudden thermal loads, especially during the periods in cooling season when there was direct solar gain and during the transition periods. This confirms a previous simulation study (Andersen et al., 2014) which showed that the house would benefit from increased thermal mass, in terms of energy performance and thermal indoor environment.

During the measurements, natural ventilation was not implemented. If occupants were living in the house, it is likely that they would have taken certain actions to make themselves comfortable during the overheating periods or during the periods with low indoor temperatures. Some of these examples could have been adjusting the clothing, opening windows, etc. The effects of natural ventilation on indoor thermal environment and energy use were simulated using commercially available simulation software, IDA ICE, in previous studies (Andersen and Schøtt, 2014), (Andersen et al., 2014). The results of these studies showed that the implementation of natural ventilation with a set-point of 24°C, slightly improved the thermal comfort indoors (3% longer in Category 1 according to EN 15251 (European Committee for Standardization, 2007)) and considerably decreased the cooling energy use (51% compared to the no natural ventilation case).

6 Conclusion

A detached, one-story, single family house designed for plus-energy performance was operated for one year. During this period different heating and cooling strategies were compared and the energy performance of the house and its thermal indoor environment were monitored. The main conclusions are as follows.

During the heating season, it was possible to provide the intended operative temperature inside the occupied zone except during periods when the external air temperatures were below -5°C.

The performance of the house in terms of maintaining a comfortable thermal indoor environment was worse in the cooling season than in the heating season. Overheating was a significant problem, and the main reasons for this were the large glazing façades, the orientation of the house, the lack of solar shading, and the lack of sufficient thermal mass to buffer the sudden thermal loads.

The house had a high heating and cooling demand that could easily have been reduced at the design phase. Although, it might be possible to address the excessive heating and cooling loads by adjusting set-points, water and air flow rates, these would result in increased energy use, as in the present study. It is crucial to minimize the demand before attempting to satisfy it in the most energy efficient way.

The operation of the heating and cooling system during the transition periods was problematic and this affected the thermal indoor environment and energy performance negatively. Further studies are required to optimize the thermal indoor environment and operation of the heating and cooling system during the transition periods.

The lower indoor temperatures in winter and higher temperatures in summer require the occupants to adapt and to use certain adaptive measures to make themselves comfortable. This also applies to the transition periods, where there might not be a dominant heating or cooling load on a daily or even hourly basis. In such situations, the adaptive actions of the occupants would play a crucial role in the thermal comfort and also in the operation of the heating and cooling systems, and, hence, on the annual energy performance of the building.

Acknowledgement

This study was financially supported by the Danish Energy Association's Research and Development Program (ELFORSK), project no. 344-060, "Sustainable plus-energy houses".

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WINDSOR CONFERENCE 2016

MAKING COMFORT RELEVANT

WORKSHOP 2.2

Comfort Teaching, Tools and Techniques

Invited Chairs: Runa Hellwig and Stefano Schiavon

WS2.2: Comfort Teaching, Approaches and Tools.
Chairs: Runa Hellwig and Stephano Schiavon

Teaching comfort or how to design a satisfactory indoor environment has become an essential part of the curriculum in many undergraduate and graduate programs in architecture and building science and technology. Using the example of thermal satisfaction the workshop aims to open a discussion on the challenging task to teach this topic. The human perception of the thermal environment is more complex and nuanced than requirements defined in standards, guidelines or sustainability rating systems imply. The multidisciplinarity of the topic comprises heat transfer aspects, physiological and psychological aspects and the translation into a certain design for the built environment. The easiest way to teach this topic is just to report on the requirements and follow these requirements like a cooking recipe, providing numbers which seem to be exact and can easily be interpreted as definite limits. But satisfaction with the thermal environment is different: it is complex; there is impact from the climatic background, from the cultural experience, it is highly individual and varies with time. The solutions humans have been using to make themselves comfortable in the built environment are as diverse and colourful as the architectural solutions of our vernacular built environment is. The workshop will provide examples how this diversity could be taught by making use of comfort tools, such as the CBE Thermal Comfort Tool, and by providing the students the opportunity of experiencing diversity by their own. These examples should serve to open an intensive discussion on what are the challenges and how to master these challenges.

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Modelling stratification and thermal comfort in an office with displacement ventilation using computational fluid dynamics

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Abstract

Computational fluid dynamics (CFD) provides a powerful tool with which to make predictions of thermal comfort within buildings in order to support design development. In this paper, a CFD modelling study is described which was carried out to support the design of a large open plan office with ventilation provided by an underfloor air distribution (UFAD) system. The ventilation design has two novels aspects: first, the UFAD system is operated at low velocity to achieve a displacement ventilation type air flow; and secondly, the extract path for the return air path is via atria to centralised extract points on the top floor of the building, rather than through ceiling voids. This strategy reduces ductwork and allows the ceiling slabs to be exposed to provide thermal mass. It also allows the possibility for passive extract ventilation at roof level. We show how a CFD model of a simplified concept model for the office was used to address key aspects of the design with a focus on the prediction of factors affecting thermal comfort. We compare the results of the CFD models with a theoretical model for UFAD ventilation. Further, we describe sensitivity studies which were used to assess the extent to which modelling simplifications can be made with a view to upscaling the CFD model to a model of the full office.

Keywords: CFD, underfloor air distribution, displacement ventilation, stratified ventilation systems, thermal comfort

1 Introduction

In this paper we report a study in which Computational Fluid Dynamics (CFD) modelling was used to develop an understanding of design factors affecting thermal comfort in a large open plan office with a novel ventilation strategy. The ventilation strategy consists of an underfloor air distribution system (commonly referred to as UFAD) with extract pathways for return air via central atria to extract points on the top floor of the building.

UFAD ventilation systems were first introduced in the 1950s to cool computer rooms (Lin and Linden, 2005) and are now a relatively established practice in many parts of the world (Loudermilk (1999), Bauman and Webster (2001)). In recent decades UFAD has started to be used more widely in the UK building industry (Maroulas et al. (2016)). Figure 1 shows a typical UFAD ventilation configuration. The key features of the strategy are low-level supply of conditioned air and high-level extract. The convection produced by heat gains within the space used to produce thermally stratified conditions. The stratified conditions are exploited to improve the energy efficiency of the system vs. mixing ventilation systems (by increasing the temperature of the return air) and to achieve better air quality in the occupied part of the space (e.g. a ventilation effectiveness of 1.2 vs. high level mixing ventilation (ASHRAE 2013)).

A UFAD system creates three distinct zones within the thermal stratification: a lower mixed zone, a transitional middle zone around the height of convective heat sources from people and equipment, which is more strongly stratified, and an upper mixed zone (Figure 1). If the velocity of the supply at the floor is very low there is little mixing close to the floor diffusers and the stratified layer extends almost to the floor, in which case the configuration is described as Displacement Ventilation (DV). In both cases, the system is designed so that the warm upper layer is above the occupied zone and so does not affect the comfort of occupants (ASHRAE, 2013).

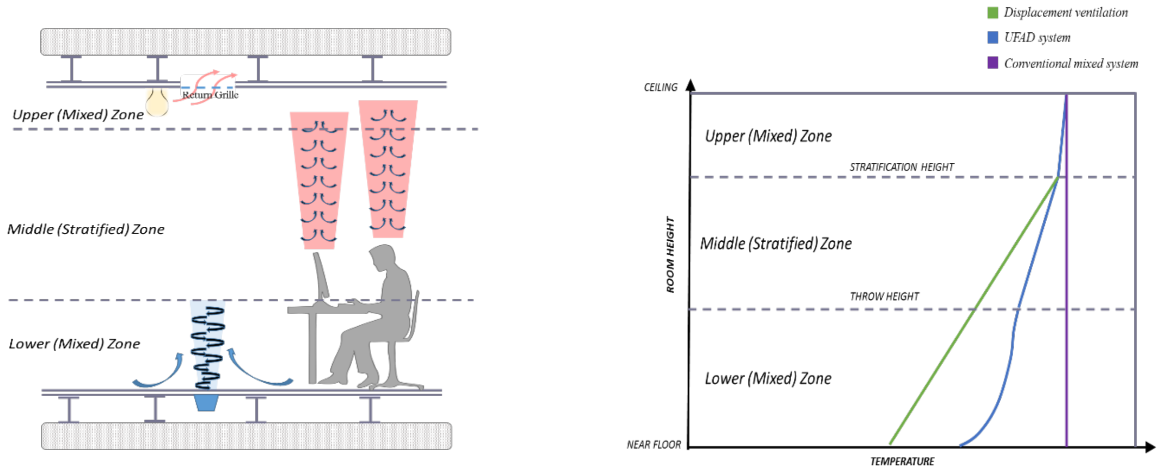

Figure 1: (a) Schematic of an UFAD ventilation system for a simple office layout. (b) Vertical temperature distribution for a conventional mixed system, a UFAD system and a displacement ventilation system. (ASHRAE, 2013)

Figure 2 shows a schematic of a conceptual model for UFAD systems (Lin and Linden 2005). The system consists of three components: localised heat sources on the floor of the space, which create thermal plumes; floor diffusers, which create an upward flow in the form of a 'fountain' (explained more below); and a ventilation extract at high level. A steady state is reached when the net volume flow into the upper layer, supplied by the volume flux of the plumes and the net volume flux of the fountains, is equal to the total ventilation rate supplied from the floor diffusers (and equal to the extract ventilation rate).

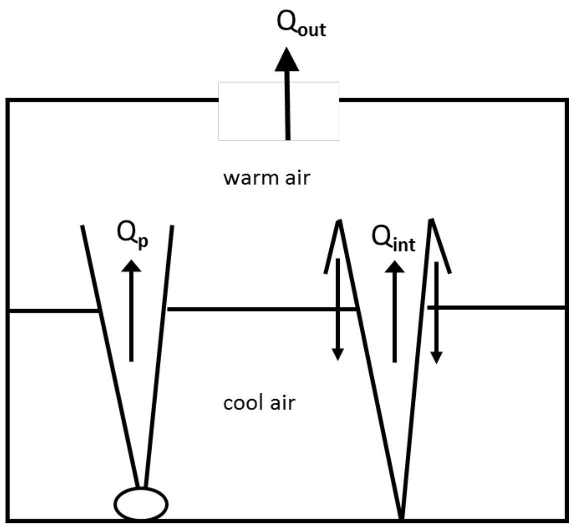

Figure 2: Schematic of a theoretical UFAD system with one heat source and one floor diffuser and ceiling extract ventilation (Lin and Linden 2005).

In the case of an open plan office, the main convective heat sources are occupants and IT equipment. These heat sources transfer heat to the cooler air around them, through warm surfaces and, in the case of IT equipment, direct heat rejection from cooling fans. The convection currents coalesce to form thermal plumes which rise naturally through the space until they reach their point of neutral buoyancy (where the temperature of the ambient air matches that of the plume).

Ventilation air is supplied to the space from a raised floor plenum through floor diffusers, which are typically circular plates with some configuration of openings. The flow from the diffusers takes the form of an upwardly or horizontally directed negatively buoyant turbulent jet, sometimes with the addition of swirl. This jet rises until its vertical momentum reduces to zero under the action of negative buoyancy, after which point the flow direction reverses and the air falls back towards the floor; for this reason the flow generated is described as a 'fountain'. The height at which the flow reverses is known as the diffuser's throw, and it depends on the specific geometry of the diffusers, the momentum of the flow through the diffuser and the temperature difference between the air in the space and the supply plenum.

For designers, a conventional approach to model thermal comfort in offices would be to use a zonal dynamic thermal model. These models typically assume that each space within the building is well-mixed and characterised by a single temperature. A UFAD-DV system, as has been described above, will lead to thermal stratification which zonal models are generally unable to predict. Another approach is to add a theoretical model for the stratification effects into the zonal model. On such model is reported below. Alternatively, CFD can provide a valuable tool to model in detail the spatially varying nature of the heat sources and ventilation air flows and also allows non-standard geometries to be considered.

For the UFAD-DV system described above key aspects of the physics of situation that the CFD model should be able to simulate are:

- The heat gains from occupants, lighting and equipment, including the relative split between convective and radiative heat outputs.
- The nature of the air flow and turbulent mixing from the floor diffusers.
- The nature of the extract (return) air flow from the space.
- Solar heat gain through the building façade, roof and fenestration.
- Radiative and convective heat exchange with the room soffit (whether drop ceiling or exposed ceiling slabs) and with the floor and underfloor plenum.

In this paper we will describe how a CFD model has been used to model these aspects of a UFAD-DV system with application to a specific design project. The structure of the paper is as follows: in the remainder of this section we describe the case study office building and the comfort criteria that were assessed; in Section 2, we describe the modelling methodology used; in Section 3 we describe the results of the models; in Section 4 the results are discussed and the conclusions are given.

1.1 Case study office

The office building for which the models were developed is a large deep plan office building in London, UK, for which Arup were the mechanical services engineers. The building has three stories each of 16,000m^2 useable floor area. The clear floor-to-ceiling height has been set to 4.5m for ground and first floor and 5.5m for the second floor to allow for the development of stratification and a distinct mixed upper layer. Figure 3 and Figure 4 show the layout of a portion of the building, representing approximately one quadrant of the floor area. The main part of the ground floor of the building is ventilated in self-contained zones, but the first floor and second floor are completely open plan and are ventilated using underfloor air distribution. The return air from the first floor passes under buoyancy through atria-voids in the second floor slab and then, together with the return air from the second floor, is extracted through vents situated above the core sections, using either mechanical extract ventilation or, if conditions allow, passive extract ventilation at roof level. Both floors have windows on the façade and the second floor has a number of skylights in the roof.

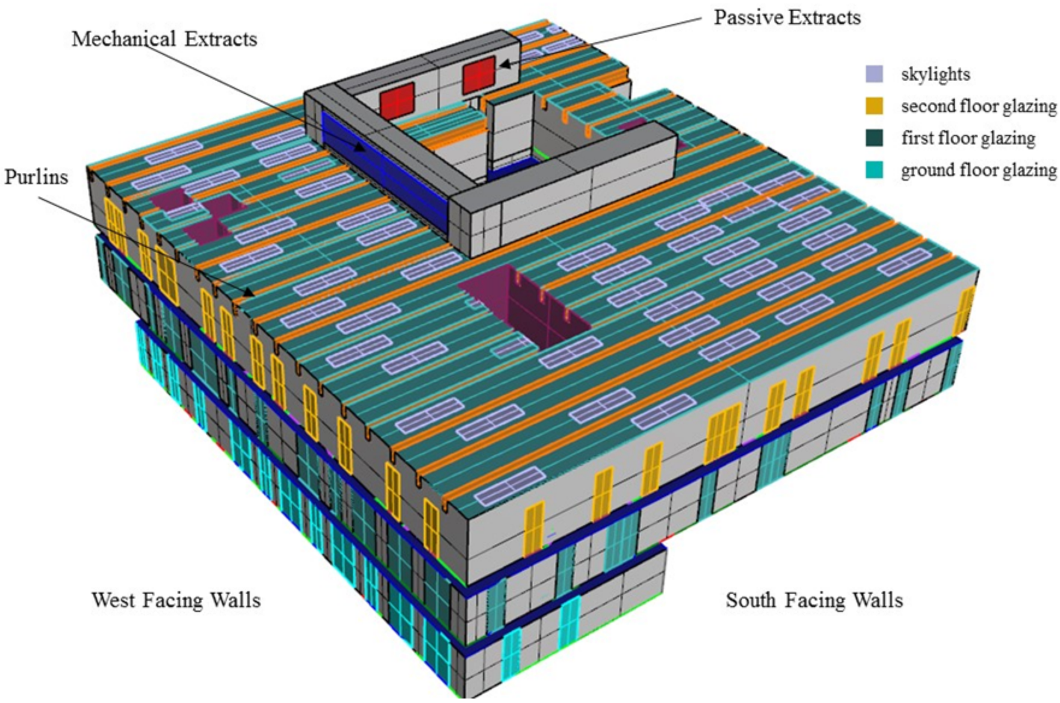

Figure 3: One quadrant of the open plan office design viewed from the south and west facades. The top left and right boundaries connect to other parts of the office. (see also Figure 4).

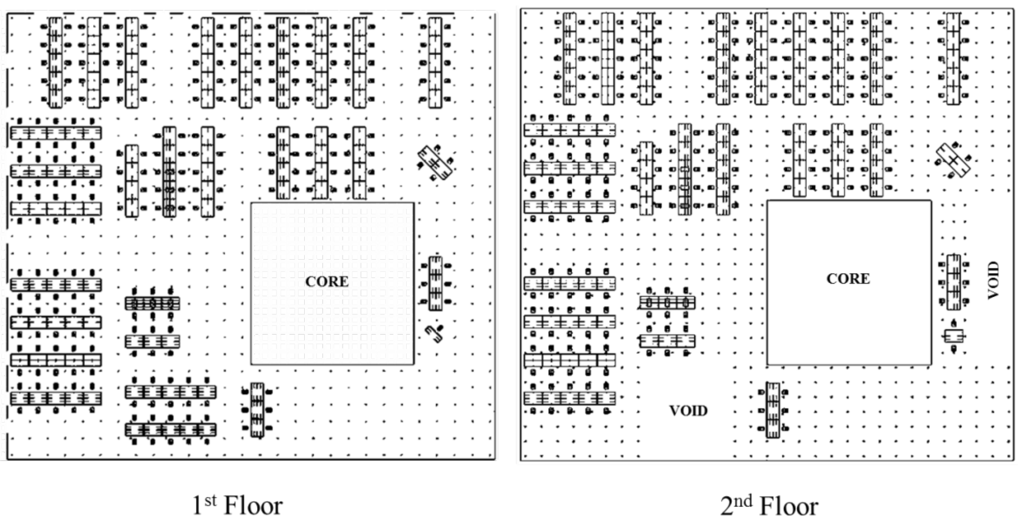

Figure 4: Floor plan of the quadrant of the open plan office design showing the cores and atrium-voids in the floor slab on the 2nd floor which provide the return air path from the 1st floor to the extract points at the core.

The flow rate per floor diffuser was kept to a low level (20 l/s per diffuser) in order to create a displacement type flow. The key reasons for seeking to establish a DV flow were:

- A lower supply air velocity in the DV system would reduce the risk of cold draughts and enable the users to sit at closer proximity to the circular floor diffusers.
- A DV would start displacing the air borne contaminants from a lower level compared to a UFAD system (i.e. stratification starts at a lower height), thus creating a better indoor air quality at lower levels which is suitable for sedentary activities.
- Pressure drop through the circular diffusers would be lower in a DV system compared to a UFAD system hence the annual fan energy consumption would also be lower. Based on the *fan laws*, a decrease in flow rate per diffuser would result into a decrease *in the square* for the pressure drop.
- Due to the reduced mixing effect at lower heights (i.e. air distribution profile from the diffuser is less of a jet), in the DV system the return air temperature is higher which means the cooling provided to the space is increased at fixed flow rate (ASHRAE, 2013).

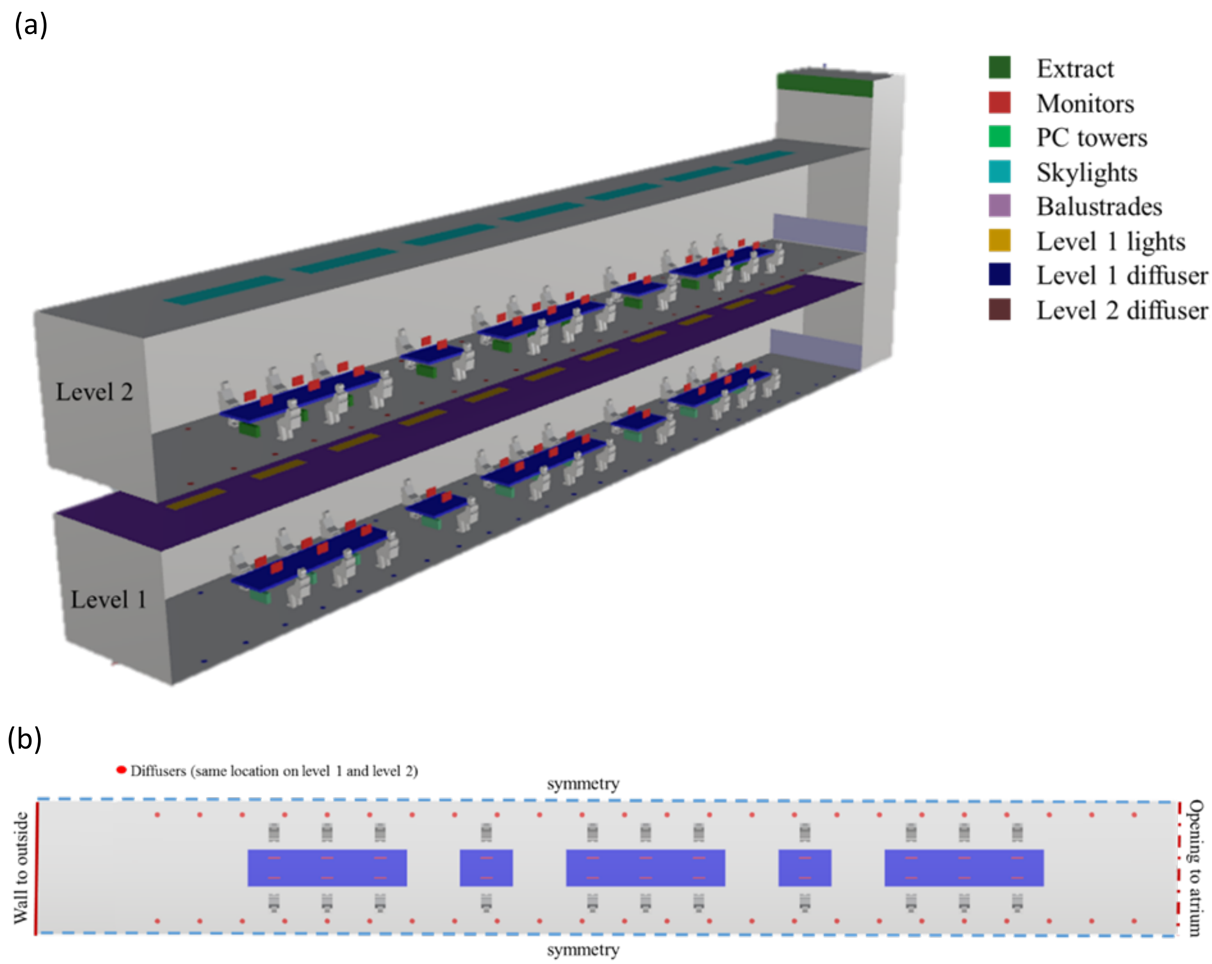

Figure 5: (a) 3D layout of the CFD model, representing a slice through the large open plan office; (b) Plan view of the modelled space, which is representative of Level 1 and Level 2.

In order to develop a methodology with which to construct at CFD model of the building, a simplified slice model was first developed which represented a section through an office with similar characteristics. This model was used to investigate the effect of the floor depth in order to establish the maximum acceptable spacing of the atria-voids. The slice model was also used to investigate different modelling approaches before attempting to model the more complex geometry of the office. It is the development of this slice model that is described in this paper. Modelling carried out using the methodology developed for a larger section of the office (Figure 3) has been reported elsewhere (Maroulas et al. (2016)).

The geometry of the slice model is shown in Figure 5 and Figure 4. The office has two floors connected by an atrium at one end of the floor plate. Air is supplied through a series of circular diffusers located behind the occupant's seats on Level 1 and Level 2. Air is extracted at high level at the top of the atrium via a mechanical extract. Two depths of floor plate were investigated: 40 m and 20m.

1.2 Comfort targets

Guidance for acceptable air and operative temperatures in offices in the UK, CIBSE TM52 (2013), indicates the maximum acceptable operative temperature in offices to be 26.0 °C. This criterion assumes 0.5 clo and is based upon European Standard BS EN 15251:2007 (2007). It is also important to consider the degree of asymmetry in the radiant field as if it is sufficiently large then it can cause discomfort. Parsons (2013) states that for people in light clothing and in sedentary activity, the radiant temperature asymmetry from a warm ceiling should be less than 5°C.

Current BCO thermal comfort criteria is given in the Guide to Specification (2009). This states that air temperatures should be controlled in the range 24 ±2 °C. In addition, less than 3°C head to ankle difference in air temperature (for a seated person) is recommended in EN ISO 7730 (2005).

2 Methodology

2.1 Theoretical Model

In order to provide a comparison with the CFD model we have used a theoretical model developed by Lin and Linden (2005) and Liu and Linden (2006). The conceptual model providing the basis for the theoretical model is shown in Figure 2. It represents a simplified air distribution system in which cool air is delivered from diffusers in the floor (fountains) and plumes originate from point sources. In this model it is assumed that the room will be stratified into two distinct layers: a lower layer in which the discharged cool air from the diffuser fully mixes with the room air and a warm upper layer above the interface in which air moves towards the extract. The theoretical model was developed using small-scale salt-bath models in the laboratory and combines models from earlier work on plumes in enclosures (Linden et al 1990) and negatively-buoyant fountains (Bloomfield and Kerr 2000).

2.2 CFD model

The CFD software used was ANSYS CFX v16.1 (2016). The model was a steady-state analysis at one climate condition. Radiation was modelled using a discrete transfer radiation model and turbulence was modelled using an SST-k-Ω turbulence model.

The analysis condition was a peak summer condition obtained from the CISBE Design Summer Year (DSY) for London Heathrow (CIBSE, 2009). The hour identified has high solar gains through the skylights and has a warm external air temperature. The hour which was selected was 2pm on the 22nd July. At this hour the external air temperature (dry bulb temperature) was 32 °C. The direct solar radiation was 465 W/m^2 and the diffuse solar radiation was 343 W/m^2. This type of peak summer scenario is one which would often be used to assess summertime overheating in buildings in the UK.

The computational mesh was generated using Sharc Harpoon v5.6e (2016), and was an unstructured hex dominant mesh, with increased resolution around the heat sources (people, monitors and desktop PCs, lights and skylights) and the diffusers. Prism layers were added to all thermal boundaries and heat sources. The size of the computational mesh was approximately 6 million cells. A series of sections and planes through the mesh are shown in Figure 6.

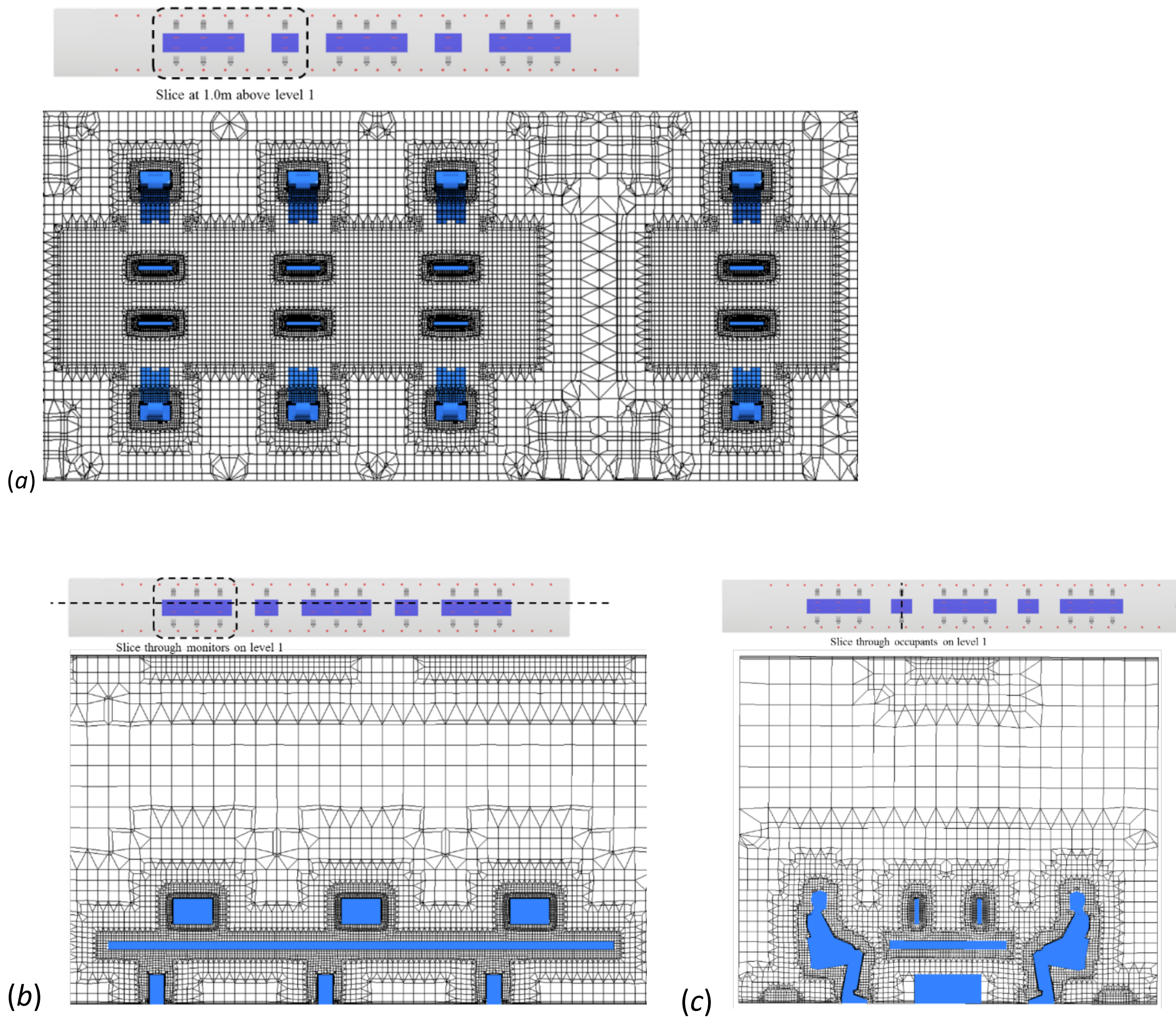

Figure 6: View of mesh at (*a*) 1.0m above Level 1; (*b*) section through the mesh cutting through the monitors on Level 1; and (*c*) section through the mesh cutting through the occupants on Level 1.

The boundary conditions were specified as follows:

- The external walls, Level 2 ceiling (roof) and Skylights were prescribed a sol-air temperature and a thermal resistance value based on the construction build ups. The sol-air temperature was determined from a dynamic thermal model, developed using the Arup in-house software Oasys BEANS v15.0 (2016).

- The raised floor plenum was not modelled explicitly in the CFD model; instead the Level 1 and Level 2 floors and Level 1 ceiling were modelled as surfaces with an adjacent temperature corresponding to an assumed air temperature in the plenum of 18.0°C. The supply temperature to the office was 19°C, assuming a 1°C heat pick up in the plenum. The inclusion of the floor plenum in the model is important in order to model the thermal interaction (particularly via radiant gain) to the plenums and ceiling slabs.
- The sides of the model were specified as symmetry boundaries.
- All other boundaries were assumed adiabatic (zero heat transmission), except for the heat sources.
- Heat transfer was assumed to be steady state and no effects of thermal mass were included.

  Radiative heat transfer was modelled using the ANSYS-CFX discrete transfer participating media model. Longwave and shortwave radiation were modelled as a combined wavelength band.

Table 1: Boundary conditions for the opaque surfaces of the façade at 2pm on 22nd July .

	Material information	Boundary Resistance in CFD model [W/m².K]	Adjacent/Sol-air Temp [°C]
Ceiling L1	U-value 2.25 W/m².K	3.18	18.0
Ceiling L2/Roof	U-value 0.15 W/m².K	0.15	36.1
Floor L1	U-value 1.8 W/m².K	3.66	18.0
Floor L2	U-value 1.8 W/m².K	3.66	18.0
South Wall L1	Cast concrete, insulation, U-value 0.2 W/m².K	0.21	59.8
South Wall L2	Cast concrete, insulation, U-value 0.2 W/m².K	0.21	59.8
Clear Skylights	U-value 2.2 W/m².K, g-value 0.25	2.86	31.6

Table 2: Transmitted radiation through the skylights at 2pm on 22nd July.

	Transmitted Diffuse Radiation [W/m².K]	Transmitted Direct Radiation [W/m².K]
Clear Skylights	30.4	66.0

The number of occupants and the IT equipment for each occupant was identical on both Level 1 and Level 2. Level 1 has electric lights in the ceiling, while Level 2 is lit naturally through the skylights.

2.2.1 Floor diffuser representation

Air was supplied at 20 l/s per diffuser. The flow rate used is potentially somewhere between a classical UFAD system (30-35 l/s per diffuser) and a displacement ventilation system (ASHRAE 2013). In total there were 48 floor diffusers in the model providing a total of 5.08 l/s/m^2 floor area.

An important aspect of the model is the representation of the floor diffusers. Obtaining a reasonable representation of the throw and mixing characteristics of the circular diffusers is expected to be important for the thermal stratification prediction. As the ultimate objective was to model several hundred floor diffusers in the larger quadrant model, a relatively simple representation of the floor diffusers was used, in which the diffuser was modelled as a circular opening with the physical size of the complete diffuser grille and turbulence characteristics adjusted through a calibration exercise. Other more complex and mesh intensive alternative representations are possible, but may not have been suitable for the larger more complex office.

To calibrate the throw of the diffusers a simple isothermal "box" model was created consisting of a single diffuser in the floor, an empty room and an extract in the ceiling. Figure 7 shows the geometry used for this simple diffuser box model. By changing the turbulence characteristics at the diffuser inlet (which can be specified in the CFD model by specifying the k and Ω of the inlets) the velocity profile at different distances away from the diffuser can be approximately matched to the manufacturer's data. In the manufacturer's documentation which was used for the diffusers only the vertical velocity profile was provided, however horizontal throw is also expected to be important.

Figure 8 compares the predicted throw profiles from the best performing CFD box model to the manufacturer's specification. It can be seen that the CFD model slightly under-predicts the velocity at low level which will likely result in less mixing close to the floor than in reality. The best agreement to the manufacturer's throw data was achieved when using a k- Ω turbulence condition at the inlet with a turbulent kinetic energy (k) of 1 m^2 s^{-2} and the turbulent eddy frequency (Ω) of 0.2s^{-1}. These settings were then used at the inlet diffuser boundaries in the larger slice model.

Figure 9 compares the calibrated diffuser representation with the default ANSYS-CFX 16.1 turbulence option "Medium (Intensity=5%)". The vertical decay of the diffuser flow is less rapid than in the calibrated case.

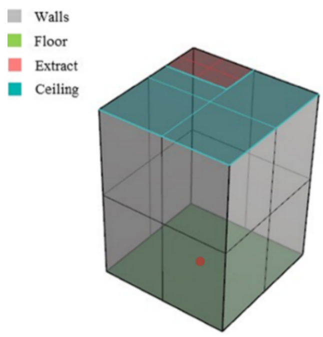

Figure 7: Geometry and corresponding CFD model used to asses throw profile of the diffusers.

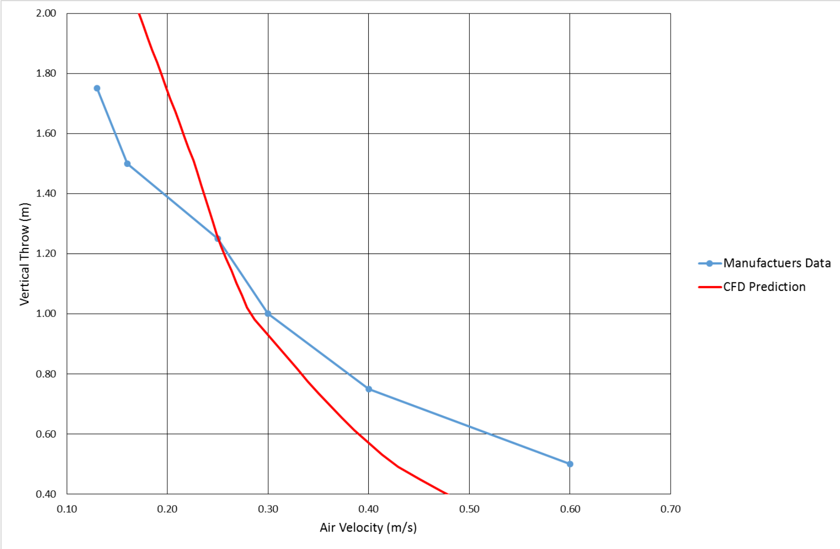

Figure 8: Comparison of CFD predicted throw profiles to suitable manufacturer's data for a diffuser.

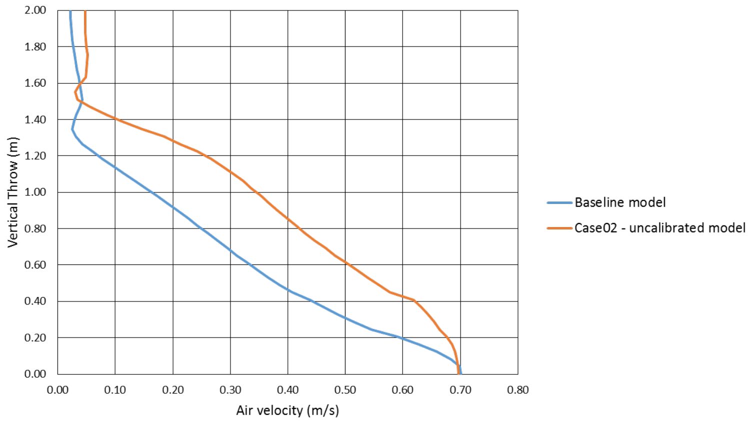

Figure 9: Vertical throw from calibrated and un-calibrated diffusers.

2.2.2 Heat Loads

The people, lighting and IT equipment loads applied in the model are summarised in Table 3 and Table 4. A constant load per person of 75 W sensible heat output was applied which is consistent with a person doing moderate office work (CIBSE, 2015). 62% of the sensible heat output was convective, 32% was radiant. For the lighting load on Level 1, the load per unit area was assumed to be 11W/m^2 which is at the upper end of the general allowance for UK offices (CIBSE, 2015). 70% of their sensible heat output was convective, 30% was radiant. The lights on Level 2 were assumed to be switched off, as the skylights are expected to provide sufficient daylight to the Level 2 office. The IT loads in the CFD model include a monitor and a desktop PC (stored below the desk) for each occupant. The desktop PCs are based upon "model A" in CIBSE Guide A (2015), which give off 90% of their heat convectively and 10% radiantly. The monitors are based upon the flat panel monitor "model A" in CIBSE Guide A (2015), which give off 60% of their heat convectively and 40% radiantly. In the models described below the heat sources were applied on the surface of geometrically realistic volumes, with the exception of one model, in which the heat gains were spread out uniformly over the floor and soffit.

Table 3: People and lighting loads.

	Area (m^2)	No. of people	People Loads			Light Load	
			Per Person (W)	Total (W)	Per m^2 floor (W/m^2)	Per m^2 floor	Total (W)
Level 1	189.0	22	75.0	1650	8.7	11.0	200
Level 2	189.0	22	75.0	1650	8.7	0	0

Table 4: Equipment loads.

	Level 1		Level 2	
	Quantity	Load (W)	Quantity	Load (W)
Monitor (90W per user)	22	1980	22	1980
Desktop PC (73W per user)	22	1606	22	1606
Total		3586		3586

3 Results

3.1 Baseline model

The baseline model (which we will refer to as Case 1) had the following specification:

- A 40m floor depth from the façade to the atrium.
- Discrete heat sources- all people, IT equipment, lights and monitors are represented individually as geometrically realistic volumes in the model.
- Diffusers were calibrated against suitable manufacturer's data, a described in Section 0.
- Solar radiation through the skylights is isotropic i.e. it is not directional. The total solar gain applied through the skylights is the sum of the direct and the diffuse solar radiation at 2pm on 22nd July.
- Radiation is single band i.e. no distinction is made between long and shortwave radiation.
- All walls have a boundary condition applied which takes into account the thermal resistance based on the material properties of the construction build up and the temperature of the adjacent space. If the adjacent space is outside, a sol-air temperature at the hour of interest is applied as the external boundary condition.

3.1.1 Air temperature predictions

In Figure 10, contour plots of air temperature are shown at a number of sections through the office. Figure 11 provides graphs showing the temperature profiles at a number of discrete locations. On both levels, there is a warm relatively well-mixed upper layer and a cooler relatively well-mixed lower layer separated by a stratified region. On both levels the mixed lower layer forms below approximately 1.2m and the well mixed upper zone forms above approximately 2.4m. Between the two mixed zones the space is stratified. This type of temperature profile is qualitatively similar to the classical UFAD and DV profiles shown in Figure 1, being somewhere between the two cases. On Level 2, there is an additional warm layer close to the soffit, which is due to the heat gains through the roof and the skylights.

The direction of air flow is predominantly vertical in the lower layer (in the plumes and fountains) and in the upper layer (away from the plumes) is approximately horizontal towards the atrium (Figure 12).

The pattern of the stratification is similar along the length of the office floor plate, with slightly more mixing occurring at low level near to the atrium than further away from it. Towards the end of the floor plate which is closest to the atrium, the thickness of the warm layer reduces as it is drawn upwards towards the extract at the top of the atrium. Further away from the atrium, the base of the upper mixed layer is starting to encroach into the occupied zone.

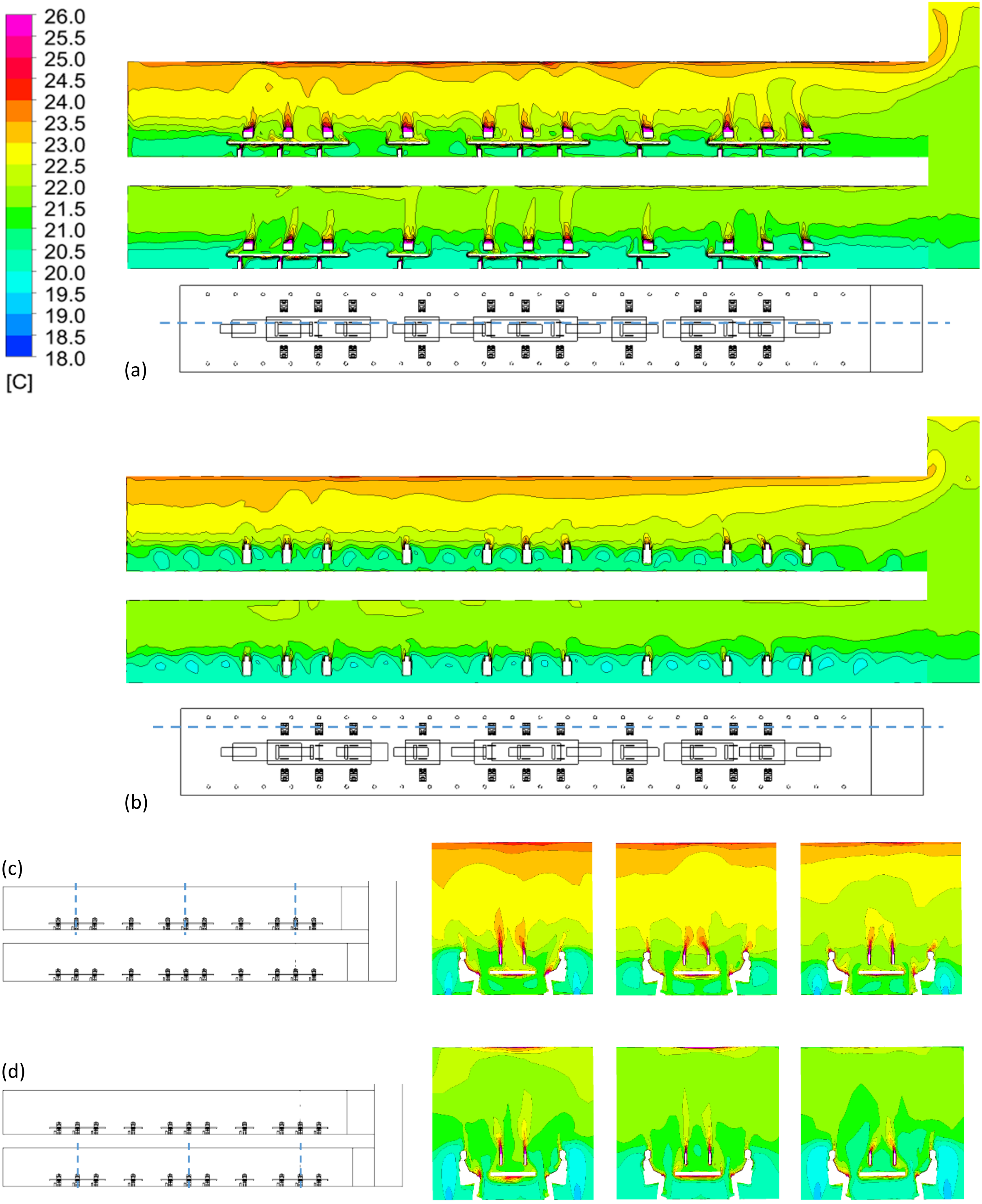

Figure 10: Air temperature at (a) a vertical section which cuts through the monitors; (b) a vertical section which cuts through the occupants. (c) Level 2 contours of air temperature through occupants (d) Level 1 contours of air temperature through occupants.

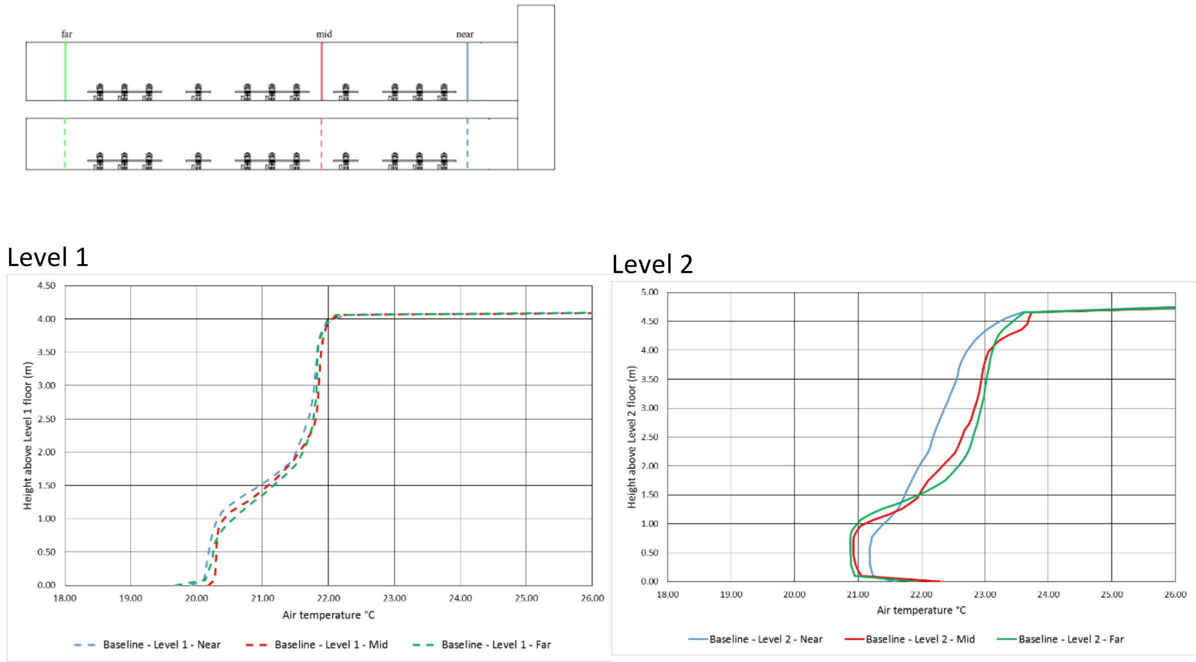

Figure 11: Vertical air temperature profiles for Baseline model on Level 1 and Level 2.

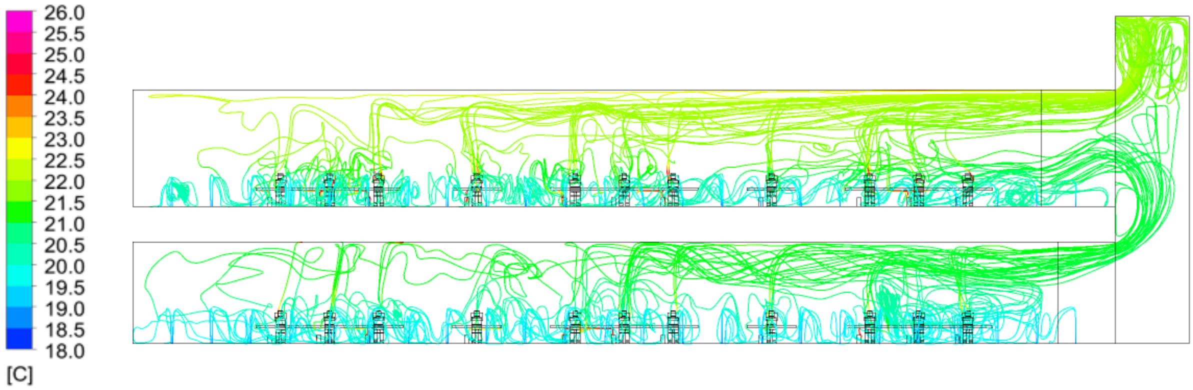

Figure 12: Streamlines, showing the approximate direction of air flow for the Baseline model.

3.1.2 Comparison with the theoretical model

A single storey office with a floor plate of the same area as in the CFD model was theoretically modelled using the model described in Section 2.1, with supply conditions, occupant and IT equipment heat loads, as detailed in Section 2.2 for the CFD model. The interface height predicted by the theoretical model was compared to that from the baseline CFD model.
The theoretical model predicted that the interface between the lower and upper regions would be 1.37m above the heat sources (2.12m above the floor assuming an average height of 0.75m for the heat sources). This implies that the warm upper layer will be above the head of the seated occupants.

Figure 13 and Figure 14 indicate where this interface level is predicted to be by the theoretical model in comparison to where it is predicted to be in the equivalent CFD model. It can be seen that they are similar, with the theoretical interface prediction being at the top of the intermediate stratified layer. These results gives some confidence that the CFD model is capturing the turbulent mixing processes in the plumes that determine the depths of the layers.

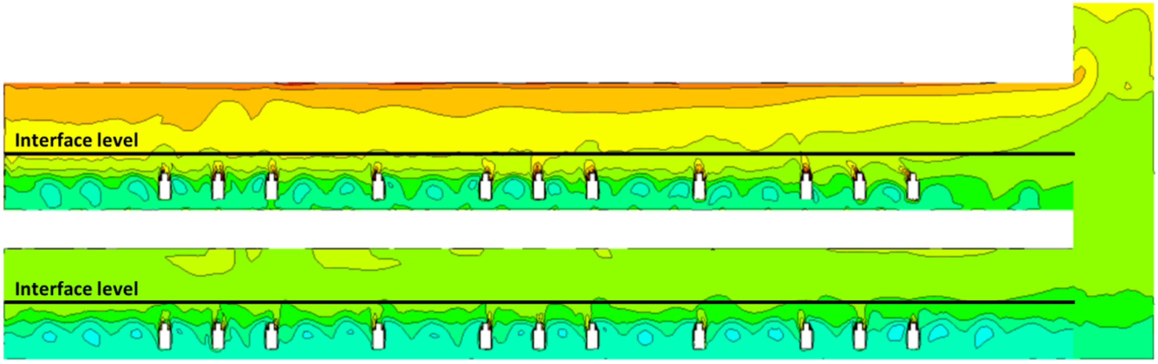

Figure 13: The CFD results together with the theoretical prediction for the interface level (the black line).

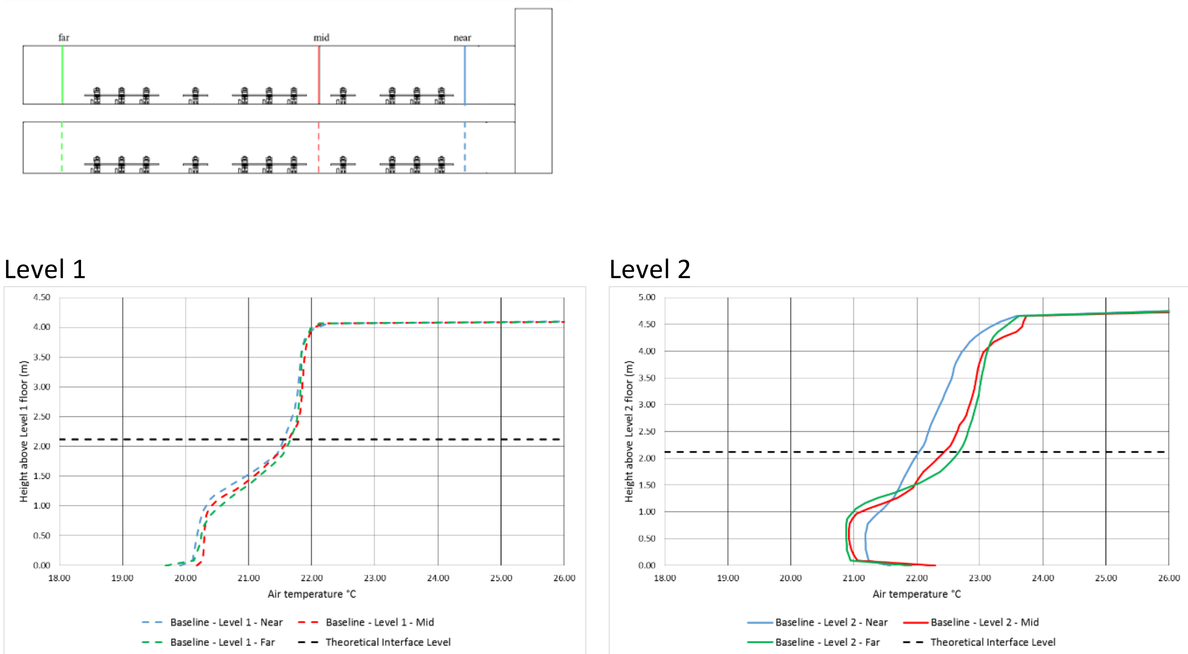

Figure 14: Vertical air temperature profiles for baseline model on Level 1 and Level 2, with the interface level predicted by the theoretical model shown by the black line.

3.1.3 Comfort assessment

On Level 2, the office is warmer than on Level 1 by approximately 1°C and there is also stronger stratification than on Level 1. Close to the atrium on Level 2 the vertical temperature profile more closely resembles a displacement ventilation profile than an UFAD profile, with stratification occurring between 0.6m and 4.0m above the floor. Immediately next to the floor, ceiling/skylights there is a sharp increase in temperature as these surfaces are relatively warm when compared to the air temperature next to them. The head-to-ankle temperature gradient is within acceptable limits (less than 3°C). The general conditions are also comfortable in terms of air temperature although slightly cool. This aspect together with the disparity in temperatures on the two floors can be addressed at commissioning stage by altering the supply air temperatures and flow rates to each floor.

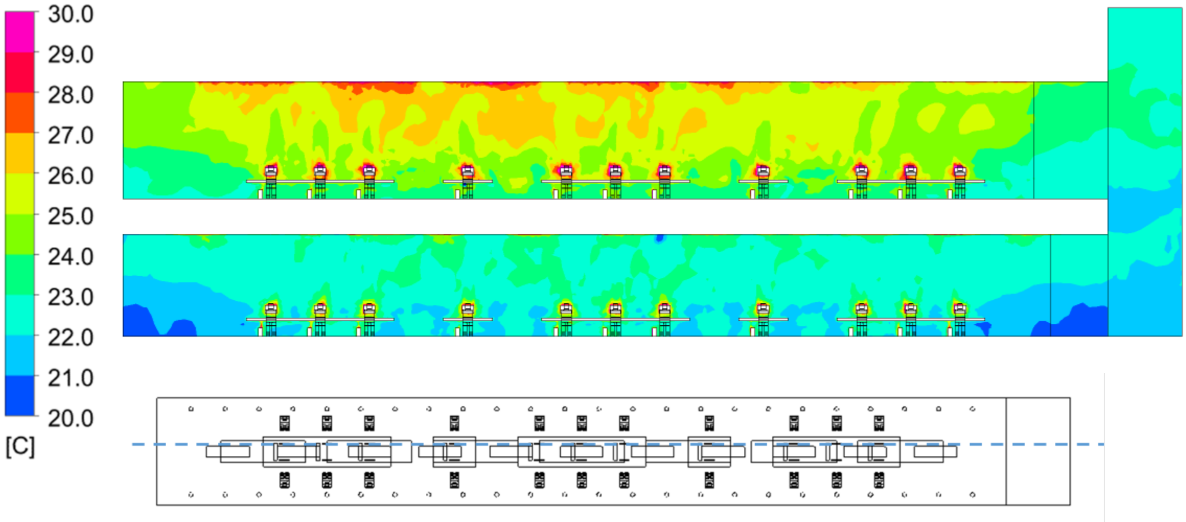

Figure 15: Operative temperature at a section which cuts through the monitors.

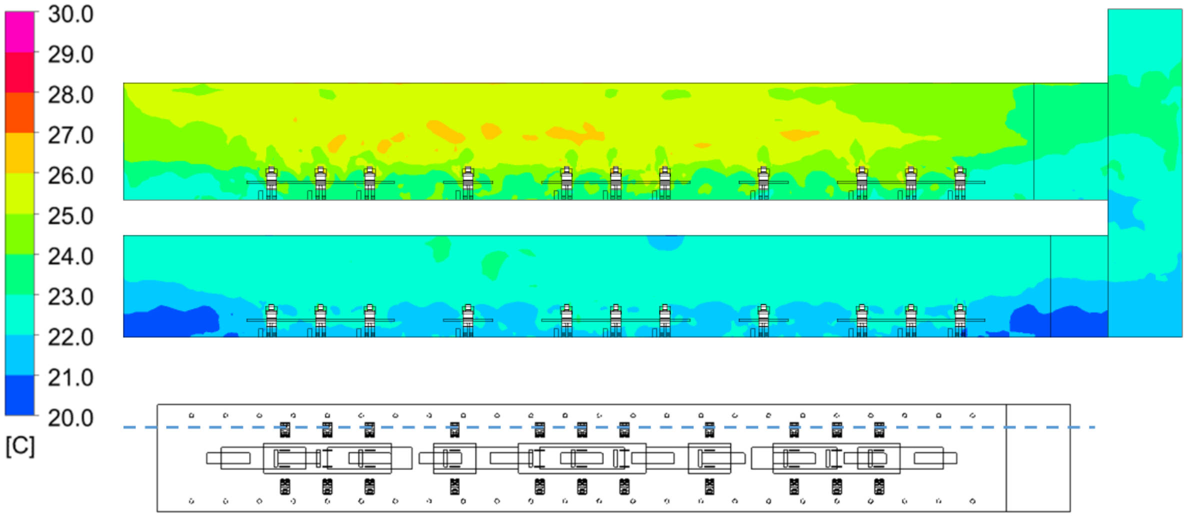

Figure 16: Operative temperature at a section which cuts through the occupants.

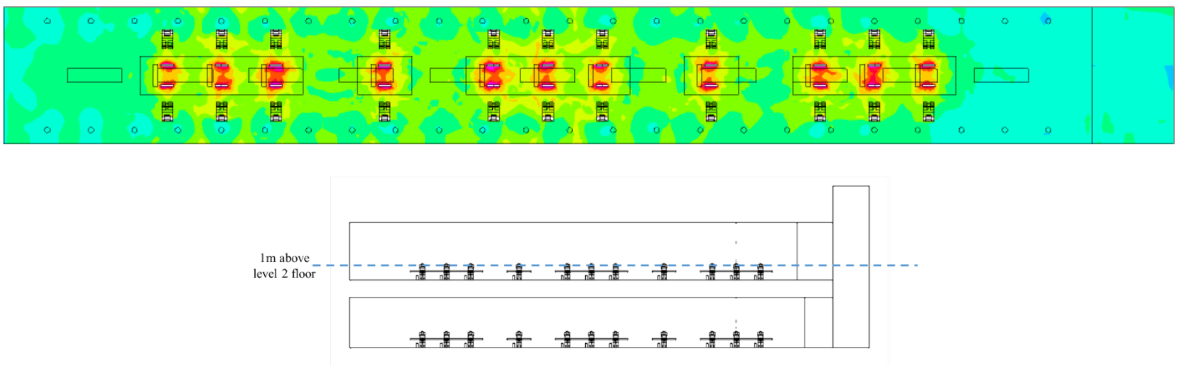

Figure 17: Operative temperature at 1.0m above Level 2 floor. (The temperature scale is as in Figure 15 and Figure 16.)

Operative temperatures at sections through the office are shown in Figure 15-Figure 16. On Level 1 the operative temperature is between 20-23°C and is quite similar to the air temperature. On Level 2, where there is solar radiation from the skylights, operative temperatures can reach 24-25°C in the occupied regions. This office space would meet the TM52 operative temperature criteria.

3.2 Effect of floor depth

As a rule of thumb, cross-ventilation – which might be taken to approximate the flow across the floor plate to the atrium – is viable for floor depths of around 5 floor-to-ceiling heights (CIBSE 2005). The floor depth of 40m in Case 1 is around 9 times the lowest floor-to-ceiling height (4.5m, on Level 1). A floor depth comparison was undertaken to assist the design team to position the atria into the building. The key criterion was the depth of the floor plate and the condition of the occupied space at the perimeter zones at the furthest points away from the atria. The base line (40m deep floor plate) was compared to an additional case Case 1b, which had a 20m floor depth.

Figure 18 shows a comparison of results for Case 1 and 1b. As the distance from the atrium increases the stratified layer encroaches into the occupied zone; however the air temperature is still maintained within acceptable levels (i.e. below 24^{o}C). The pattern of the stratification within the common distance in the two cases, i.e. within 20m of the atrium, is very similar. This because the flow in the lower layer is governed by the flow from the floor diffusers and in the convective plumes, this being essentially the same with distance across the floor plate, and the upper layer is sufficiently deep in the configurations studied to carry the total return volume flow across the space in the upper layer to the atrium.

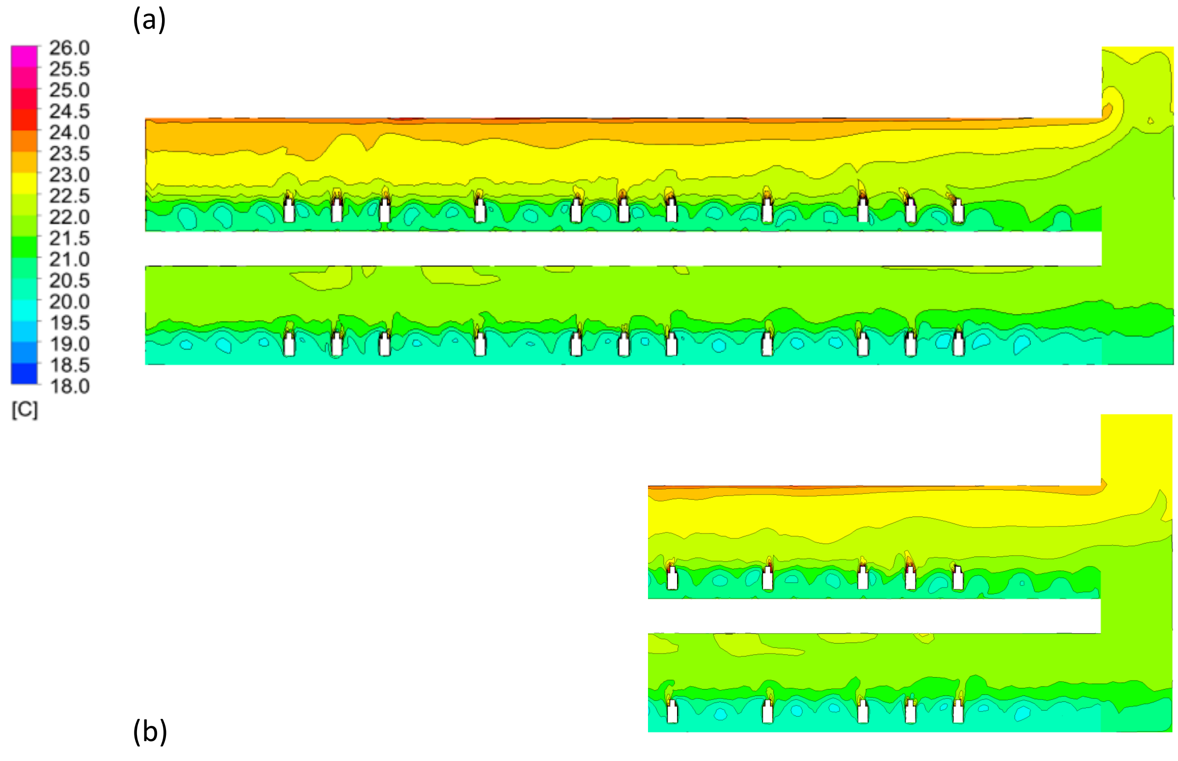

Figure 18 Comparison of air temperature results for a (a) 40m floor depth and (b) a 20 m floor depth.

3.3 Sensitivity studies

The impact of modelling assumptions on the prediction of the thermal stratification is explored with the following variations around the baseline CFD model:

- Case 2: As baseline but diffusers are not calibrated, only a supply flow rate and temperature are specified using the CFD software defaults;

- Case 3: As baseline but heat sources are evenly distributed across the floors and ceilings.

3.3.1 Un-calibrated diffusers

It is expected that the throw of the floor diffusers is important in determining the degree of thermal stratification. This hypothesis was tested by comparing the baseline model where some calibration of the turbulence properties at the inlet was carried out, to a model where the turbulence properties of the diffusers were unchanged from the ANSYS-CFX defaults (see Section 0). In both models the flow rate and temperature of the supply air was the same.

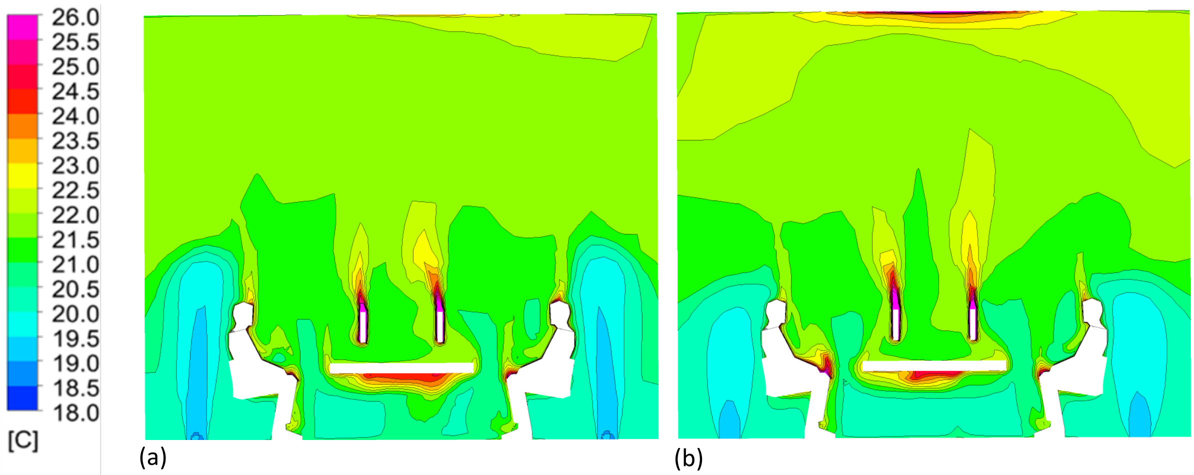

Figure 19: Level 1 contours of air temperature through occupants (a) un-calibrated diffusers and (b) calibrated.

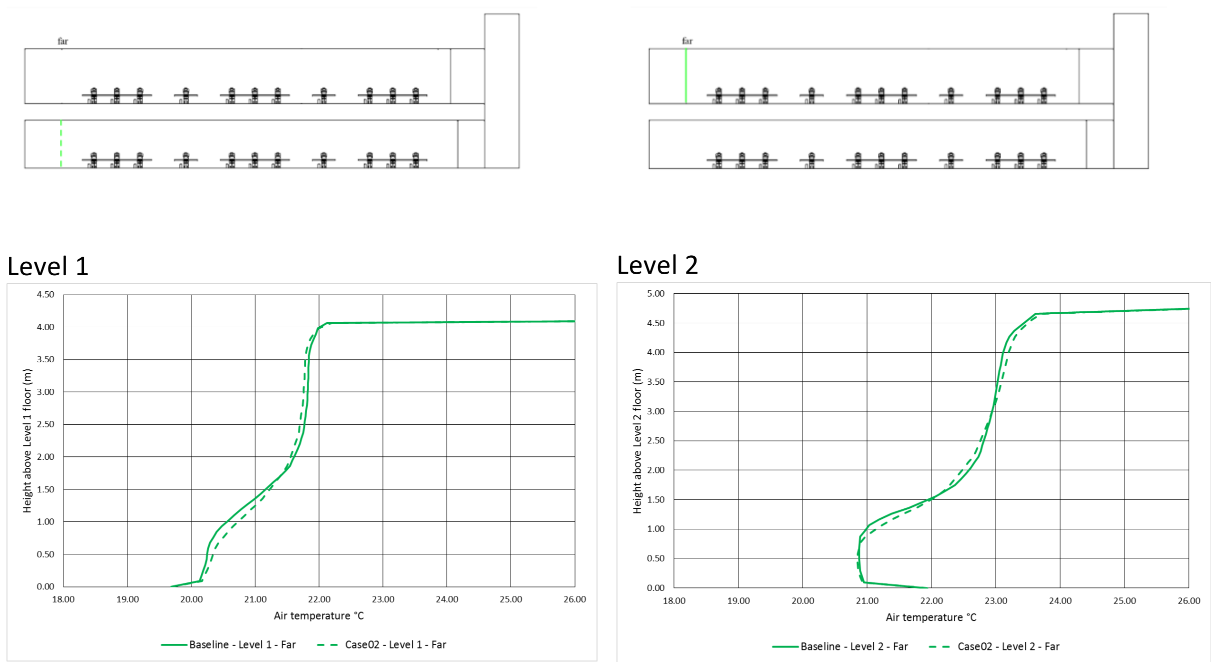

Figure 20: Vertical air temperature profile comparing baseline and Case02.

The impact on the stratification in the office is illustrated in Figure 19-Figure 20 comparing the vertical air temperature profile on Level 1 and Level 2. Although the change in air temperature in the occupied zone is not significantly different, the stratification pattern is altered slightly, with the space being slightly warmer and more mixed in the lower part of the stratification in the Case 2 model. It is noted that this relative insensitivity to the floor diffuser representation may be due to the low flow rate per diffuser studied; we do not expect this result to apply in general to all flow rates and floor diffuser types.

3.3.2 Distributed heat sources

In Case 3 all of the discrete heat sources were removed and their load was evenly distributed across the floors and ceilings. The occupant and IT equipment loads were distributed across the floor and the lighting and skylights loads were distributed across the Level 1 and Level 2 ceilings respectively. This is a default simplification sometimes used in CFD modelling studies.

From Figure 21 and-Figure 23 it is evident that the effect of evenly distributing the heat sources across the floor pate is to make the temperature profile relatively well mixed with height other than the immediate influence of the warm surfaces on the ceiling and the floor. This is compared with a more stratified temperature profile in the baseline model. The average space temperature is similar for the two models, but the temperature gradient predicted in the occupied zones differ quite significantly.

The operative temperature plot shown in Figure 22 show noticeable differences. These differences are predominantly due to the removal of the stratified conditions which results in a drop in the operative temperature at the top of the occupied zone and higher operative temperatures closer to the floor.

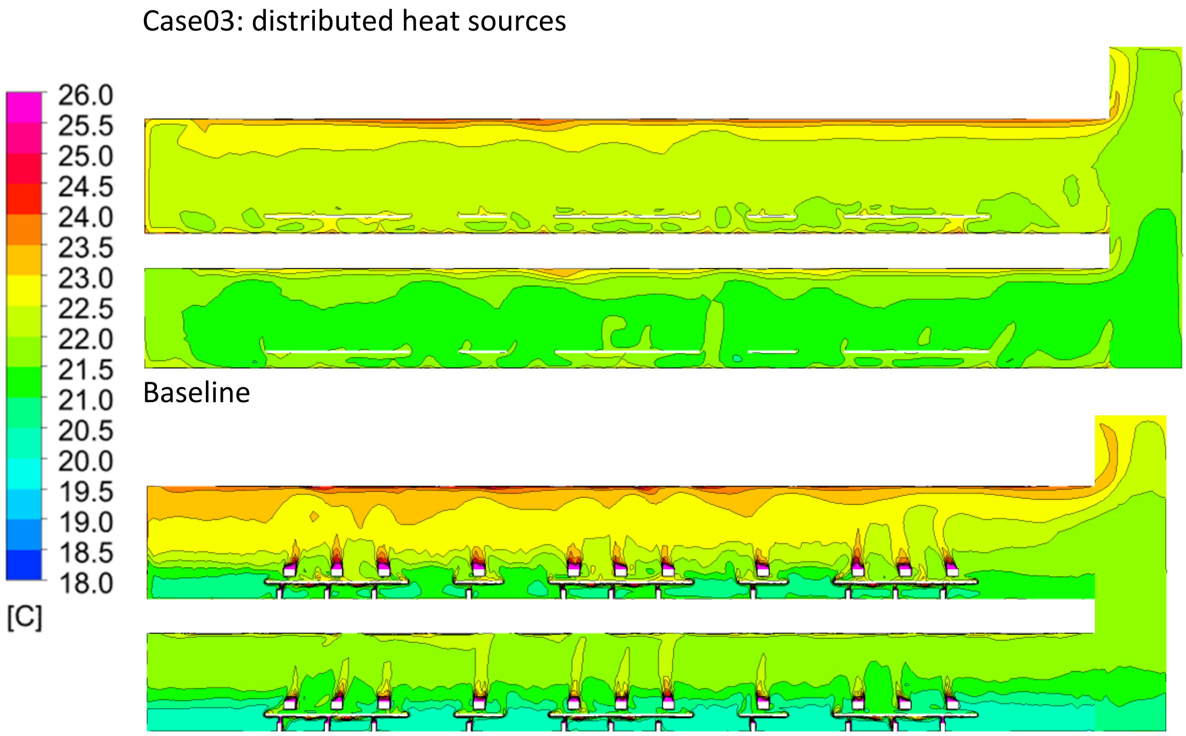

Figure 21: Contours of air temperature through monitors. Comparison is made of distributed heat sources (top) and baseline model (bottom).

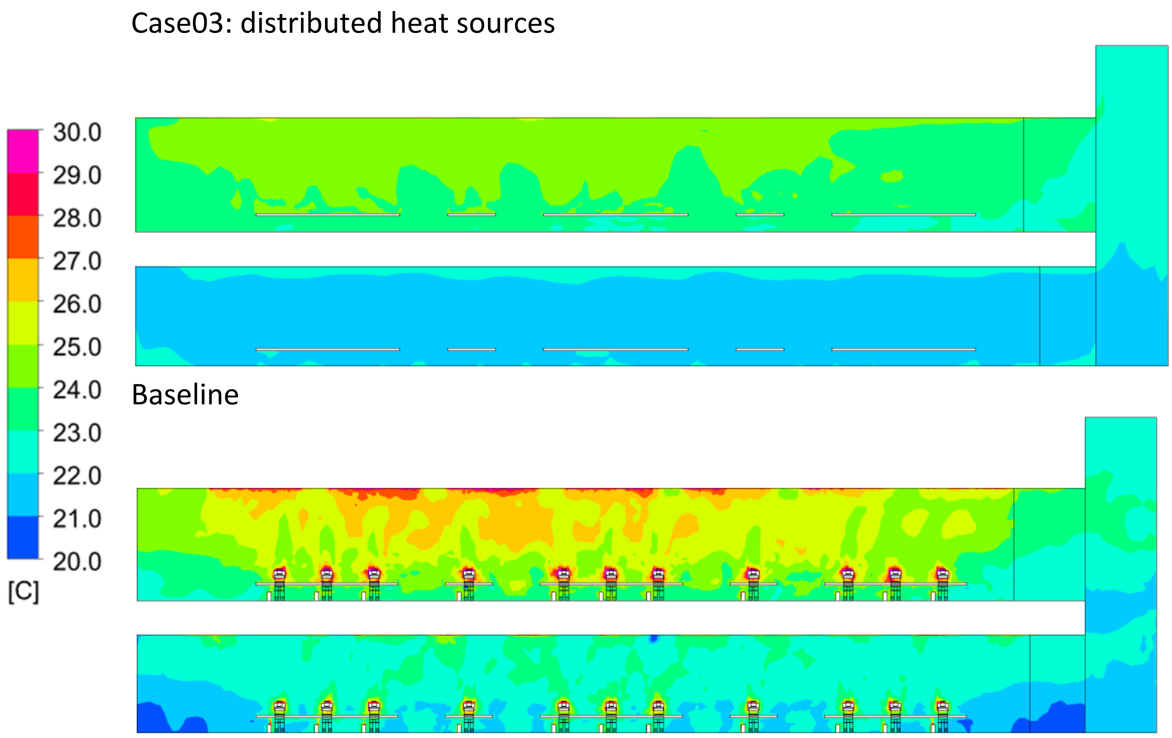

Figure 22: Contours of operative temperature through monitors. Comparison is made of distributed heat sources (top) and baseline model (bottom).

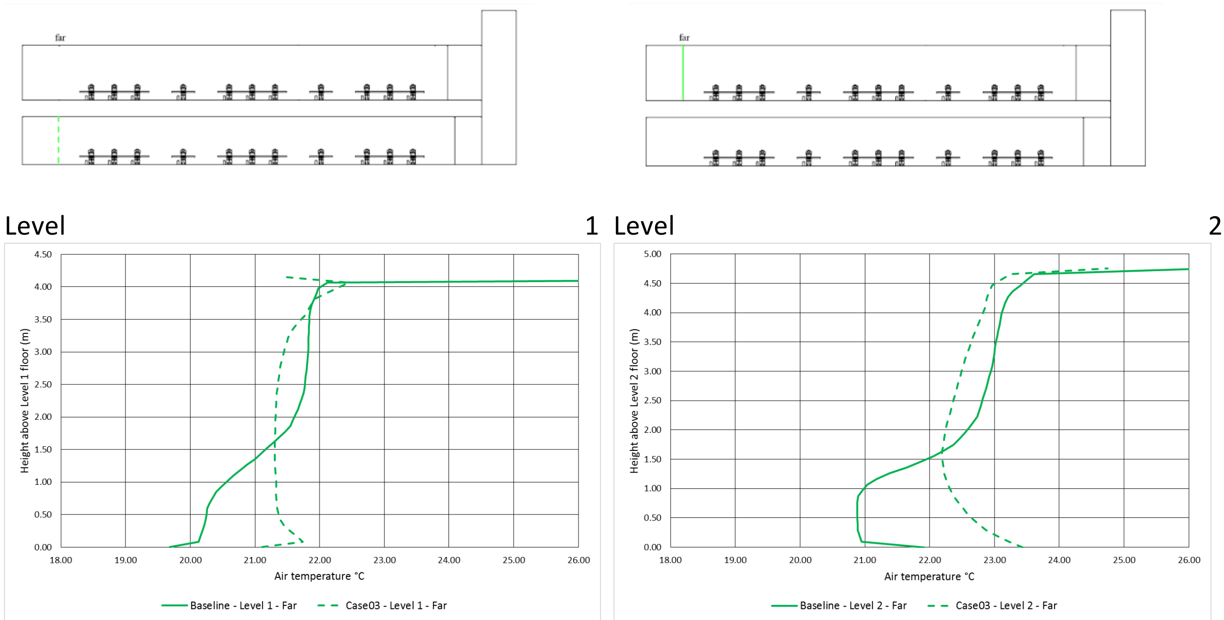

Figure 23: Vertical air temperature profiles on Level 1 and Level 2 comparing baseline and Case 3.

4 Discussion and conclusions

In this paper, we have shown how CFD models were used to assist the development of a novel displacement ventilation system for a large open plan office. The models developed show the salient features of a displacement ventilation system and provide results consistent with the results of theoretical models. The models were used to inform major design decisions in the real-world design case study reported, in particular the number and spacing of atrium-voids required to facilitate the ventilation strategy. The CFD models were used to examine the 3-dimensional variation of air temperature and other factors affecting comfort such as operative temperature and thereby determine if comfort targets could be met under different design options. Together, these aspects made the CFD models highly beneficial to the design team in informing the design development.

We have also shown in this paper how aspects of the modelling of the physics of an office space with an underfloor-supply displacement ventilation system using CFD models can be challenging. Two areas where the CFD model was sensitive to the modelling assumptions were examined. Through these studies, we have arrived at the following conclusions regarding the application of CFD modelling to this type of UFAD-DV system:

- It is essential to model the discrete nature of the heat sources in as much detail as possible in order to provide a prediction of temperature stratification.
- It was possible through calibration of the boundary conditions to match the throw profile of the floor diffusers modelled to available manufacturer’s data. In the current study this calibration proved to not greatly affect the results, but we expect in other circumstances this would not be the case.

A number of outstanding challenges remain with these types of models:

- The disparity of spatial scales, from the overall scale of the building down to the multiple individual heat sources and floor terminal diffusers, presents challenges of how to model the complete scale of such a large office within practical computation constraints. We have approached this challenge by modelling only a section of the office and exploiting lines of symmetry (Maroulas et al 2016).
- A significant proportion of the heat loads in the office studied are likely to be absorbed into the plenums and the high-mass ceiling slabs. These effects will tend to warm the air in the plenum, which in turn will need to be supplied to the plenum at a suitably low temperature to take account for this heat pick up. In the modelling reported here we represented these affects using a relatively simple approach of assigning adjacent boundary temperatures. In reality, these effects are essentially time-dependent and to be fully addressed in a CFD model would require a transient analysis of a least a day and ideally several days duration, which places further demands on computational resources.
- The steady-state Reynolds’ averaged turbulence models used here may be insufficient in some circumstances to fully capture the turbulent mixing and convection processes which determine the temperature stratification. The use of more advanced turbulence models may be beneficially therefore in some circumstances.

We are currently investigating further the use of CFD modelling to address these aspects. We are also in the process of comparing our CFD modelling results with the results of full-scale physical testing of the office design. We hope to report on these developments in future communications.

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The evaluation of the variables of domestic overheating in the UK under TM52 using a future climate model- Guidance for designers

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Abstract

The variables of the formulae used in TM52 (CIBSE, 2013) are not understood by designers who cannot evaluate potential overheating within concept stage designs. Guidance on how TM52 relates to usage and heat wave effects is lacking in current documentation. The paper evaluates occupancy profiles, level of control, level of insulation and Internal Heat Gains on overheating criteria. The base point temperature for bedroom usage is discussed and how TM52 can be modified to accommodate this condition. Previous studies have established overheating mitigation measures (ZCH, 2014) and within the study these have been evaluated on their effectiveness for the UK future climate.

Using available weather files a heat wave criterion is established and its significance on the TM52 protocol is explored. Simulation software is used to investigate sensitivity of key parameters within realistic bounds. Shading, thermal mass, air velocity and ventilation availability are the most important factors in the reduction of overheating events. Heat waves cannot be definitively categorised given current weather files and other factors require consideration. Overheating in bedrooms is mainly caused by heat wave instances. Buildings should consider overheating aspects at the design stage to ensure buildings are fit for purpose at the end of their lifespan.

Keywords: TM52, Future Climate, Overheating, Heat Wave

1 Introduction

The mechanics and the sensitivity of the formulae used in the Chartered Institute of Service Engineers (CIBSE) Technical Memorandum TM52 (2013) used to establish overheating in buildings are not understood by designers who cannot evaluate overheating effects within proposed concept stage designs. There is an increasing need to design buildings for robustness over the proposed design lifespan of buildings rather than using current regulations which assess designs with historic weather data. Some elements such as the different usages of rooms and heat wave risks are not covered by TM52 but requires user guidance and an investigation to the relative sensitivity to be established within the current framework.

BSEN 15251 (BSi, 2007), now interpreted by TM52, and provides operative thresholds and does establish such aspects as the weighted mean temperature overheating effects or heat stress definitions. TM52 uses adaptive cooling methodology based on acclimatisation to previous weather patterns. Using this methodology these standards are not accessible to designers requiring a range of specifications not normally considered at an early stage of building design.

Previous studies have established passive mitigation strategies but these have been crudely ranked with little explanation of how the results were obtained, the sensitivity of results or the inputs used for each of the variables. Aspects of the standards are not readily assessed using simulation software and such shortcomings require highlighting. TM52 has its boundaries and it is important to establish instances when it should not be used in its current format as a reliable measure of comfort levels in buildings.

2 Research aims

The main part of the study assesses the range of factors inputted to simulation software (Energy Plus v8.2.10) in varying the parameters of TM52 including sensitivity of occupation, passive ventilation control, construction specification and Internal Heat gains (IHG) within a range in the normal operation of building design specifications. The paper does not investigate personal variables such as clothing, activity and age of the domestic building occupants.

In the evaluation of the criteria for the identification of heat wave scenarios the significance of the TM52 protocol for a cooling season can be established. This requires the investigation of current definitions of heat waves and the identification of warm periods applied to available weather files.

The paper derives a ranking to identifying the factors along with the significance of previously used mitigation measures by quantifying their effects against a baseline building physics model.

3 Background

The evaluation of the robustness of building designs at a future date needs the consideration of how climate change will affect the built environment. Previous studies have established probabilistic weather for future years on established climate change models (Eames et al, 2012). Establishing the lifespan of a building taken from the Building Research Establishment life cycle analysis of a building being 60 years (BRE, 2014). The resultant end date of the building being in operation until 2076 and as a result a 2080 weather file used in this study. Given the slow rate of progress of the global tackling of climate change a high scenario (a1fi under IPCC modelling) was used with a 50% probability profile.

The climate output files are available in two forms of future weather files. Test Reference Year (TRY) which uses averages from the previous 20 years of data to produce a weather file and Design Summer Year (DSY) which uses 20 years of the peak summer condition to weight the weather file. As DSY data has been specified in TM52 as the file to be used in the assessment, these weather files were used for the basis of analysis in this paper.

3.1 CIBSE TM 52 2013

The evaluation of overheating is defined by the proportion of uncomfortable conditions that is experienced by building occupants. This is defined by TM52 which establishes a methodology to assess a naturally ventilated building which cannot be assessed simply on when a set internal temperature is exceeded and updates previous BS EN 15251 guidance. TM52 has more of a relationship between the outside temperature, the occupant's behaviour, activity and adaptive opportunities which affect comfort. Overheating in the standard is defined in three distinct criteria which has some interdependency in their calculation method:

1. The proportion of degree hours above 1K over the limiting comfort temperature. Assessed from 1st May to 30th September must be below 3% of occupied hours.
2. The higher the temperature the more significant the effect. This test quantifies the severity of temperature on a daily basis. Where the weighted excess of temperature must be less than 6K on any one day for comfort to be achieved.
3. Reports heat stress events 4K above the limiting comfort temperature.

Occupants are likely to experience overheating if two or more of these conditions are not met.

TM52 does not deal directly with more sensitive environments but categories have been stated on the grade of sensitivity in the building. Previous definitions of a sleeping comfort temperature have been stated as 2K lower than other occupied spaces (BSi 2007). Given the criteria above further investigation is conducted to the sensitivity of this temperature as a realistic update of the guidance given in TM52.

3.2 Overheating

The resilience of domestic buildings is in question and should be based on projected future climate to reduce the risk of the building not being fit for purpose over its lifespan (Jenkins et al, 2012). Rather than defining thermal comfort of occupants when buildings have been completed, under traditional post occupancy thermal comfort surveys, there should be a bias towards a future performance leading the specification of building designs.

Overheating has previously been assessed for living rooms and bedrooms but only on 2007 weather data using BS EN 15251 criteria (Beizaee et al, 2013). To some extent this only adopts part of the TM52 specifications to assess overheating. A PassivHaus single dwelling has also been previously assessed against the overheating criteria used in building regulation methodology (McLeod et al, 2013). However, this study is limited to a crude overheating assessment. Moreover, this regulatory tool assesses the building against historic climate, not its fitness for purpose in the future.

Current designer guidance for mitigation has been provided by The Zero Carbon Hub (2012) but this is presented as a simplistic bar chart showing the reduction in overheating percentage for a notional house with no explanation of the quantification or specification of factors. The impact of the significant overheating variables has been analysed by Mavrogianni et al (2014) but there is no clear statement of the significance of factors under the BS EN 15251 overheating criteria chosen. TM36 (CIBSE, 2005) is a large scenario based document covering a range of future climate scenarios. Whilst a good sensitivity study, it documents a range of graphs with no distinct outcomes or conclusions on the importance of inputs. This is of little use in the building design process.

3.3 Heat waves

Heat wave weather periods have been established to have a direct relationship to mortality events (Zhang et al, 2013). Many major urban centres have a trigger temperature when an increased emergency services plan is to be put in place (Diaz et al, 2015). Studies have been conducted to classify Inhabitants by location and social demographic to identify their venerability to heat wave events (Wolf and McGregor, 2012) for a trigger temperature of 28^{o}C. Heat wave definitions vary depending on geographic locations ranging in peak daytime temperatures from 26^{o}C to 40^{o}C (Scandinavia to Australia respectively). They also vary as a result of the duration these temperatures are experienced from a daytime single event to averaged over seven consecutive days. Other heat wave definitions include night time temperatures as part of the assessment occurring before or after the daytime threshold level to be classified as a heat wave.

Dense built up areas cause Heat Island Effect in major urban cities resulting in an average rise of night time temperatures (Lemonsu et al, 2014). This is the basis of the current heat wave plan for England (NHS, 2015) with a set point temperature for the day on condition that the night before breaks a specified differing threshold temperature. Previous heat wave studies show actual observed data from a historic viewpoint (Porritt et al, 2012). As heat waves are defined as extreme random events, historical data is currently the only methodology of analysing such events with no studies defining heat wave effects using future climate files.

4 Methodology

A 2 bed flat in a typical apartment layout was modelled in EnergyPlus simulation software. There are two main exposed walls south to the main living space and to the north for bedrooms, a midpoint entry on one of the flanking sides provides a dual facing apartment (see figure 1). Double glazed argon filled windows are of the same size for each habitable room and is representative in terms of size for natural lighting and ventilation. The model was placed in Islington a short distance from Central London UK to match the weather file used.

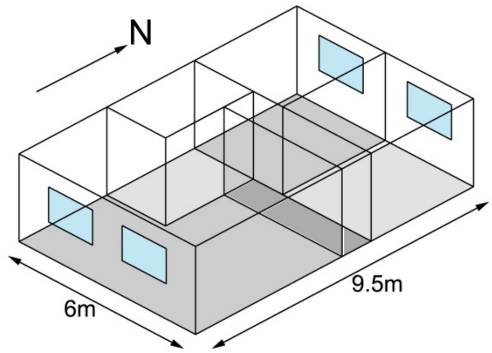

Figure 1. Two bed Flat configuration and dimensions

To simplify the comparison, default values were established for each of the parameters investigated. The weather file chosen is that for 2080, high scenario with 50% probability. Of the main parameters explored were broadly classified into the following groups:

The evaluation of the occupancy profile, including: full occupancy (model 1), one adult working with a child at home with other parent (model 2), one adult working and other part time with child at school (model 3), both parents working and occupying house only in evenings (model 4).

In order to establish the level of ventilation control by windows in the model, variants included: open all the time (model 5), completely closed (model 8) and two intermediates when the temperature outside is 2.5K higher than inside temperature (model 6) and 5K higher (model 7) before windows are closed as an upper limit to ventilation control.

The construction composition and heat transfer in the envelope is mainly determined by the level of insulation. In the model a zero heating U value the equivalent of 300mm of insulation was used (model 9), subsequently the specification of a PassivHaus: U value equivalent of 0.15 W/m^2K (model 10), current UK building regulations (model 11) and a minimal insulated building the lightweight equivalent to a solid wall building, such that no thermal mass effects were applied (model 12).

Internal Heat Gain (IHG) occurs from people and appliances which influences overheating criteria in relation to the efficiency of cooking, lighting and domestic appliances and are broadly aligned to zero internal load (model 13) A rated EU appliance labelling classification (induction hob LED lighting model 14), C rated (ceramic hob, compact fluorescent lighting, model 15) and D rated bands (electric resistance hob, halogen lighting, model 16) with appropriate wattages and usage determined for each appliance on occupancy.

The next range of variables considered mitigation approaches. The first is the fixing of internal ceiling fans with increasing internal air velocity applied to the model. The default value for the air velocity in the dwelling is $0.2ms^{-1}$ (model 17). This is raised in subsequent models to $0.4ms^{-1}$ (model 18), $1.6ms^{-1}$ (model 19) and an unrealistically high velocity of $3.2ms^{-1}$ (model 20). A sensitivity analysis of increasing air velocity was undertaken for a given operation profile when the dwelling was occupied, in line with TM52 guidance.

The shading on the south elevation was increased from a default of no shading (model 21) to a horizontal shade 1.5m deep for the width of window. This value was chosen as the maximum realistic structural depth not requiring excessive fixing details and shades mid day sun throughout the cooling season (model 22). This was subsequently increased to a full horizontal shade for the width of the facade (model 23) which over shades each side of the openings and a local horizontal shade with 1.5m deep vertical fins for the two windows on the south façade (model 24). Fixed shading is chosen rather than a bespoke user operated device which has a high risk of being operated incorrectly or an unrealistic number of user options determined within the building physics model.

A high thermal capacitance, through the use of high density materials (thermal mass) reduces peak temperatures within the building and dissipates the heat energy (Hacker, 2008) over a longer period of time when applied to the internal face. The density of material used was $2200kg/m^3$, in line with CIBSE recommendations. The default value of plasterboard (model 25) was increased to 12.5mm cement board (model 26). This was further increased to a realistic value a timber/steel structural wall could support at 40mm thick (model 27). Model 28 would require a different construction system with 100mm of concrete structure directly exposed as an internal face of the external walls.

A base case scenario is duplicated in some models (models 2, 7, 10, 15, 17, 21 and 25 have identical specifications) to facilitate the evaluation of results into distinct groups of variables. TM52 was used as a basis of the evaluation with the number of overheating events logged as overheating. This modifies criterion 1 reporting overheating events rather than the percentage of overheating. All events reported are during occupied hours. The use of a future weather file allows conclusions to be drawn as the amount of overheating events is higher than current or historic weather files. Each of these results was compared to the base case to evaluate if overheating is taking place. This is not a full Monte Carlo analysis but establishes individual events over threshold values rather than cumulative effects of overheating.

As stated bedrooms have a different set of comfort criteria which is not covered in TM52. An analysis was conducted in changing the variables in TM52. The first case being no change taken place. The second variation is that of the reduction of the sensitivity to a higher class (from level II to level I) reducing the upper temperature before overheating is perceived, this was the methodology used in the previous models to differentiate the living room specification from that of the bedroom. The third variation reduces this by a further 2K and is in line with the threshold stated in BS EN 15251. The fourth case reduces again by a further 2K and increases the time schedule of reporting on criteria 2 from a day interval to a week in which the 6K value is broken for each day in that week.

For establishing a heat wave effect, a 32^{o}C day temperature with a night temperature of 18^{o}C is used. The daytime temperature was varied to create a significant and realistic result. This was used on an Islington and Heathrow weather file for a historic value (Eames et al, 2012), the 2010 DSY data (CIBSE) and then the 2080 DSY data (Eames et al, 2012) in each case. This is to establish the influence of heat island effect on the results obtained.

The same models (1-25) are conducted for a heat wave period identified in July in the 2080 Islington data and the results evaluated against the proportion of overheating events for the whole cooling season.

5 Results

Consistency was important in the model and results were evaluated continuously to ensure robustness. The Heathrow weather file was used as an error control to compare different scenarios, as the weather station is 30km away, providing a realistic variance for the amount of overheating experienced.

5.1 Cooling Season

The living area was modelled over the 28 scenarios (including duplicates) showing the variance from the base model (model 2). See figure 2. Negative effects are aggravated solutions to overheating and higher the positive effects. The occupancy (models 1-4), thermal insulation values (9-12) and internal heat gains (13-16) show a low amount of variance to the overheating result.

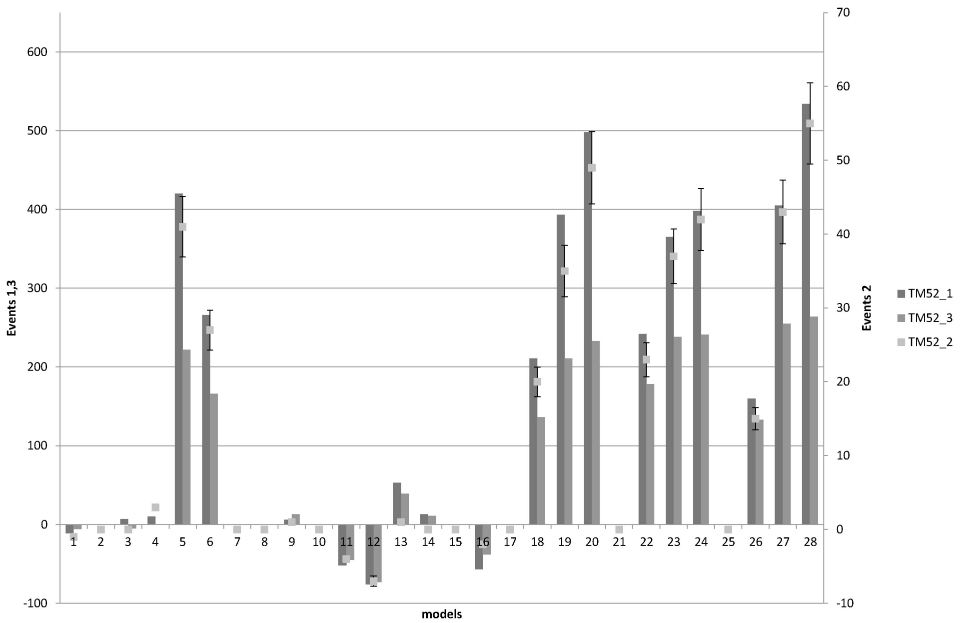

Figure 2. Living room overheating events by category and model

There is a high variance of the ventilation control options (models 5-8) with the best results obtained when windows are left open but this may cause discomfort due to low night time temperatures and also security/ noise concerns. Similarly, air velocity (17-20), results had to be recalculated as EnergyPlus under BS 15251 does not take into account air velocity. Once the error was recognised the results had to be calculated within a spreadsheet using the graph within TM52 for inside operative temperatures. Shading (21-24) and thermal mass (25-28) have a high influence. Again these should be considered realistic in terms of comfort for internal air velocity as well as nuisance factors (blowing papers), psychological issues regarding seeing the sun with passive solar gain in winter for the fixed shading of windows and structural issues for building mass.

It is worth noting that model 8 (building fully closed) had extremely high results that were omitted from the graph otherwise the other results would be dwarfed. As presented the results allow some conclusions to be drawn.

For bedrooms using a base temperature of 2K lower than the living rooms a similar pattern emerges during occupied night hours. Ventilation, velocity and thermal mass have high influences but unsurprisingly shading, being north facing rooms, had no influence on the night time overheating results.

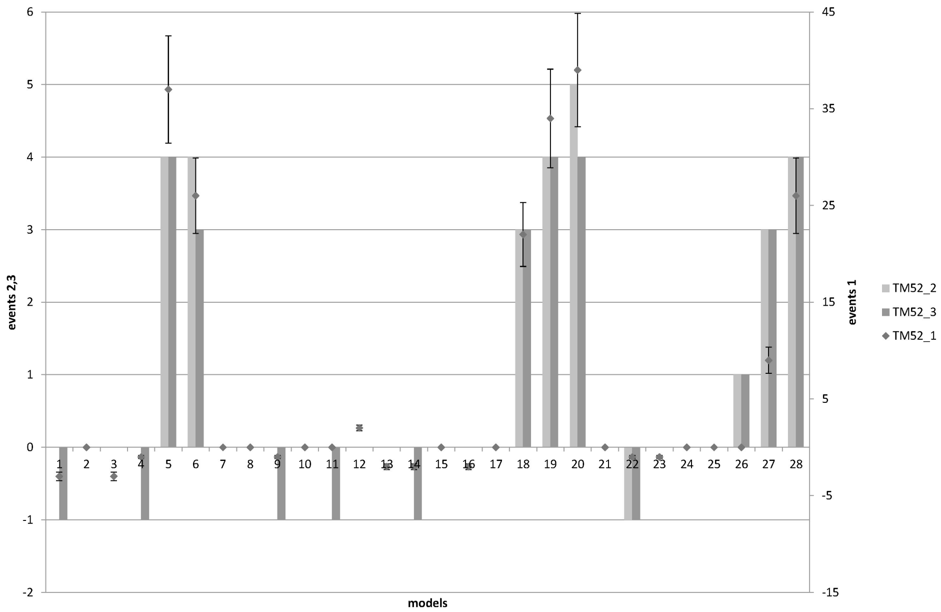

Figure 3. Bedroom overheating (2 occupants) by TM52 category

The relationships between criteria 1,2 and 3 is less consistent for the bedrooms than that of a living room with many cases criteria 2 and 3 being very similar indicating a direct relationship to outside temperature. Also Criteria 1, in the bedroom, is roughly a tenth the value in most cases compared to the living room overheating events. Again model 8 results led to excessively high overheating event values and were excluded from the graph. See figure 3.

When the base temperature for overheating of the bedrooms uses the same conditions as the living room (bar 1, in figure 4) a very low number of overheating incidences exist.

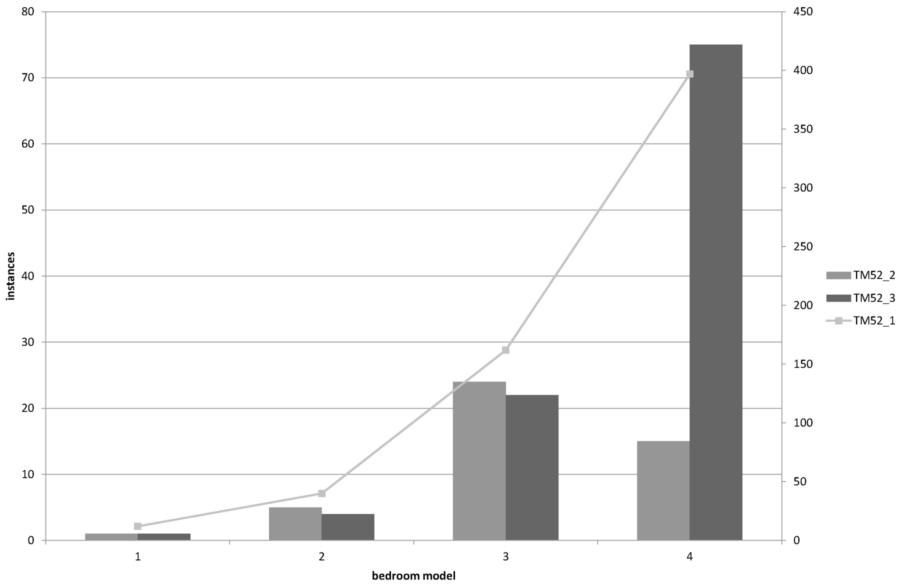

Figure 4. Bedroom variation of TM52 criteria

For each reduction of 2K the relationship for criterion 1 increases exponentially and the values for criteria 2 and 3 are fairly similar. In bar 4 the time period of reporting for criterion 2 is increased to 7 days, hence its significantly reduced value. This suggests that if longer term outside conditions are used, a correction factor is required to correlate with condition 3. However, this would need to be tested through physical thermal comfort surveys to indicate what factor should be used to match comfort levels.

5.2 Heat wave

A range of base point temperatures were used to check the sensitivity on the amount of heat wave events experienced. Realistic results were achieved with a 30^{o}C daytime and 18^{o}C night time temperature recording any day with a preceding warm night. The base points used pick up historical heat waves of 2007 and 2010 in the dates that were reported by the press. This compares to the NHS (2015) London trigger levels of 32^{o}C during the day and 18^{o}C at night.

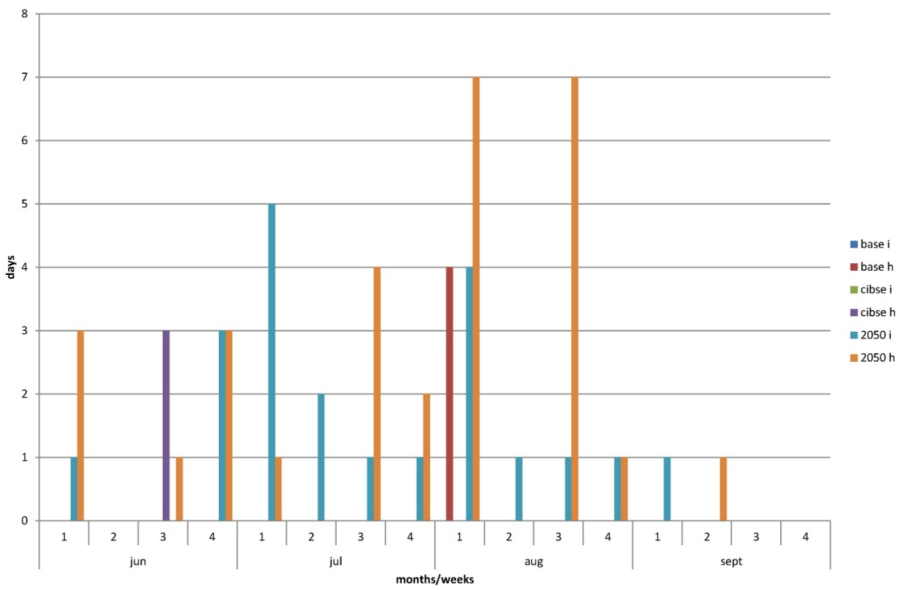

Figure 5. Time periods of heat waves

These air temperatures show that there is no account of heat island effect with Heathrow (h) bars being consistently higher than Islington (i) files. See figure 5. In all cases a day threshold had a corresponding preceding night threshold trigger of 18°C. This may indicate that a sensitivity analysis is required on the night time trigger temperature against a physical comfort survey data to evaluate the discomfort experienced.

To evaluate the heat wave effect on the living room previous model scenarios were used and proportionally evaluated against the whole cooling season. The heat wave in 2080 of 4th to 9th July was used as the specific building physics model time interval modelled.

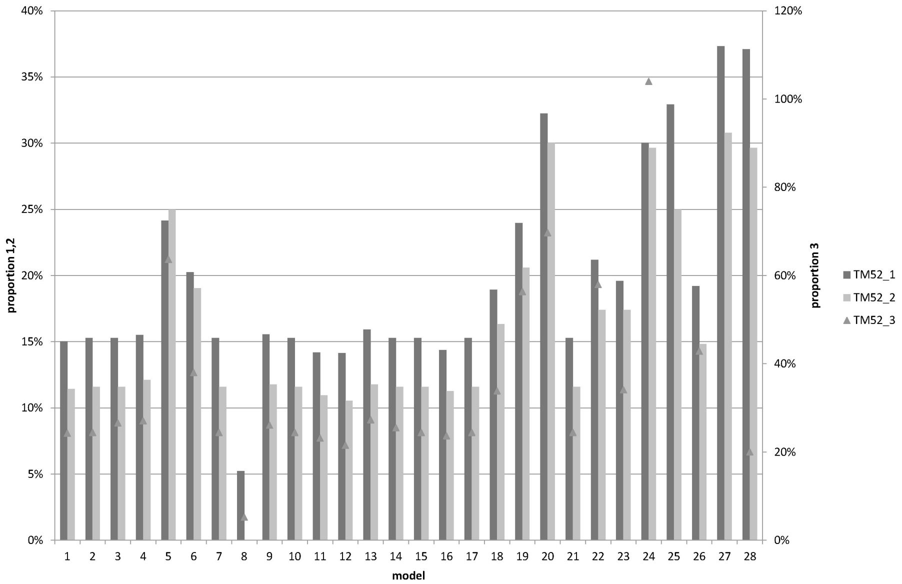

Figure 6. Living room proportion of overheating events over cooling season

With high levels of mitigation such as air movement and shading the heat wave is responsible for a large proportion of heat stress effects (condition 3) in living rooms (figure 6) and accounts for around 20% of occupied hours of overheating and daily weighted averages. Largely the same measures in the cooling season are applicable in a heat wave event.

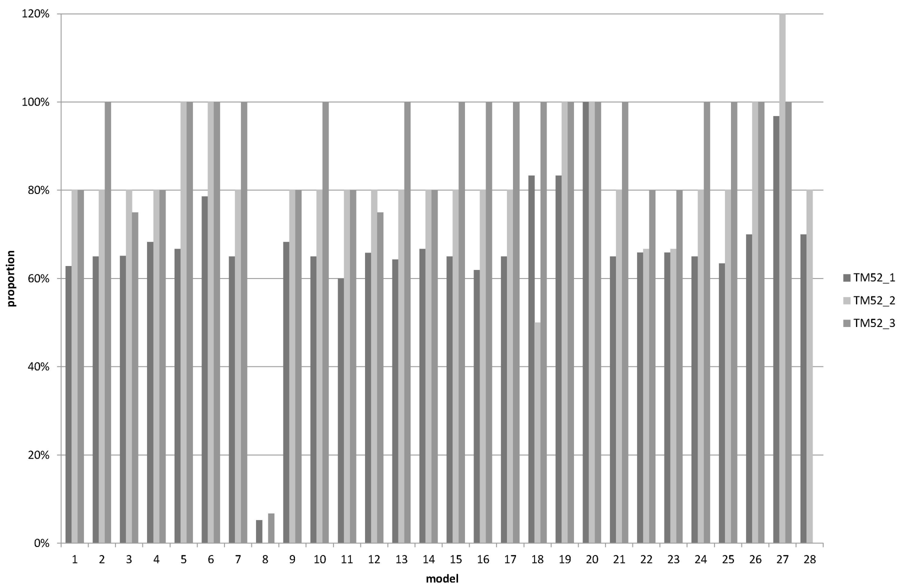

Figure 7. Bedroom proportion of overheating events over cooling season

Looking at the bedroom situation (figure 7) low figures are obtained from model 8. This is due to extremely high figures assumed in this scenario, that result in a reduced number of overheating events during this confined period of time.

The results show that the variation is lower between models and the heat wave event picks up most overheating incidents ranging from 60-100% of the cooling season. This indicates that bedrooms are more susceptible to heat waves, although mitigation strategies are limited due to highly consistent results across all model types. As the shading models report higher figures than the cooling season this was further investigated.

For models 23 (horizontal shading across windows) and 28 (high thermal mass model) the data was taken from those specific dates from the cooling season data (part of the data from earlier tests) demonstrating some variation exists.

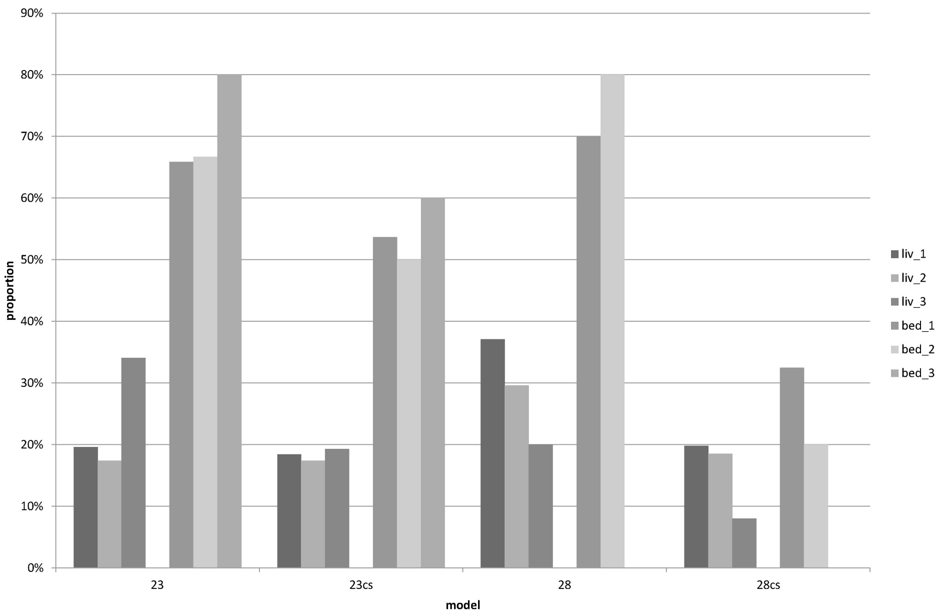

Figure 8. variation of EnergyPlus models given different run times

The results in figure 8 show the proportion of heating season for living rooms and bedrooms with 'cs' stating part data from the cooling season models, as the previous set of results. The part data (the heat wave) is consistently lower with marked changes in condition 3 (heat stress) in living rooms. This shows that the building physics model is highly influenced by the small number of days modelled and the 'warm up days' used to stabilise the internal temperatures in the model. For more accurate results, part data should be used as comparison whether the errors experienced would be consistent across all the models. This is still inconclusive given the results obtained.

6 Conclusion

Designers need to consider the building design in the order of shading, thermal mass, internal air movement, ventilation set points and availability. Some aspects of mitigation could be retrofitted such as ceiling fans but it is unclear whether given the choice, occupants would choose this solution due to the discomfort and inconvenience experienced in operation. Other aspects such as thermal mass need consideration on the outset of building design with regards to structural issues. If disregarded robust reasons should justify the exclusion of high density materials.

Many of the variants explored in the study are linear in their results, they achieve realistic specification boundaries and have little overlap between the factors considered, although this can only truly be established in a full Monte Carlo analysis. There is not enough data in survey modelling to suggest that the time constant for criteria 2 of TM52 to be changed but a 2K reduction and a classification to the sensitivity of sleeping occupants is a realistic recommendation for the overheating experienced in bedrooms. This is a 4K reduction in the limiting temperature which creates a similar number of overheating events at night compared to the living room during heat wave events. As part of this a new benchmark should be created and evaluated against thermal comfort surveys to check people's experiences match the findings in this paper.

Current weather data on heat waves is insufficient to assess extreme events. This should be a bespoke extreme data file for air temperature to include humidity and radiant effects to clearly demonstrate the influence of heat island of the results. This could be a synthetic data transformation based on the statistical risk from existing weather files. The differences between Heathrow and Islington data leads to questions on the reliability of future weather files and the significance of consistently hotter longer periods evidenced in the Heathrow projected data.

Bedrooms are at more risk of heat waves due to high night time air temperatures which result in the majority of overheating events in a cooling season. In living rooms this is around a third although the same mitigation strategies are applicable for both cooling overheating events in a cooling season and in a heat wave for living spaces.

Buildings have a realistic 10-fold susceptibility of increased heat wave effects at the end of a 60-year life and these should be considered by designers as an important upgrade strategy to ensure future fitness of purpose of buildings currently at design stage.

7 Further work

This paper could be expanded to include the lifespan of buildings should be evaluated against the mitigation measures used as major mitigation may not be necessary if a building is to last less than a certain number of years, each mitigation has its limit relating to the lifespan of the design building in question. A more comprehensive design guide is required showing the exact variables in EnergyPlus changed so that they can be scrutinised and peer reviewed for their realism with results replicated by others. More work would be beneficial on the influence of microclimate around a building that can influence overheating events and increase the reliability of the design tool.

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The Impact of factors unrelated to environmental quality on satisfaction with IEQ in green and common buildings in China

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Abstract
In China 3-Star evaluation standard is a semi-mandatory, consensus-based, government and market-driven program that provides certification of green buildings by third-party, contributing to maximize conservation of resources (including energy, land, water and materials), protect the natural environment and minimize pollution. Many previous studies analysed influence of green building certification on occupant satisfaction. Although occupant satisfaction with IEQ in office buildings has been closely related to the indoor environmental physical parameter, such as thermal, lighting, acoustic environment and indoor air quality, it can also be impacted by factors unrelated to conventional environmental quality. This paper follows the results of POE surveys within green and common office buildings in two climate zones of China. The aim of this paper is to investigate the impact on occupant satisfaction in green and common buildings in China of factors unrelated to environmental quality, taking consideration of spatial layout, gender, age, knowledge of green buildings, environmental attitude, type of work, time at workspace, and weekly working hours.

Keywords: Three-Star evaluation standard, Occupant satisfaction, Post-occupancy evaluation, Indoor environmental quality, Non-environmental factors

1 Introduction

Three-star evaluation standard, the first comprehensive green building evaluation standard, was developed by the Chinese Academy of Building Research in 2006 (MCPRC, 2014). Buildings that are certified by three-star evaluation standard are expected to maximize conservation of resources (including energy, land, water and materials), protect the natural environment, minimize pollution, provide people with healthy, adaptive and efficient spaces during its life cycle and coexist in harmony with the natural environment. There is no doubt that green buildings have a booming development in China since 2006. However, research needs undertaking to verify if three-star standard is effectively contributing to improved users' workplace experience.

There are various studies on occupant satisfaction, and its impact factors and relationship with green rating certification. Newsham et al (2013) reported that green buildings exhibited superior performance, including environmental satisfaction, satisfaction with thermal conditions, the view to the outside, aesthetic appearance, workplace image, etc. JG Allen et al (2015) found that the initial scientific evidence indicates better indoor environmental quality in green buildings versus non-green buildings. Baird's (2010) review concluded that, in general, image for visitors, furniture, cleanliness, availability of meeting room, meeting job demand, overall light and demand (overall) of green buildings were most satisfactory. However, Gou's comparative study of two LEED offices and a sample of conventional offices in the same city suggested no difference in overall satisfaction with IEQ (2011) (Gou, 2013). Altomonte S and Schiavon S (2013) conducted a study by evaluating occupant satisfaction with IEQ of 144 buildings (65 LEED certified), and concluded that there is not a significant influence of LEED certification on occupant satisfaction with indoor environmental quality, except air quality and amount of light. Schiavon S and Altomonte S (2014) in another paper showed that comfort and satisfaction could be statistically significantly influenced by other factors unrelated to environmental quality.

By contrast, although green buildings have been developing rapidly in China, very little studies have been reported, focusing on occupant satisfaction, especially from the point of factors unrelated to environmental quality. In this paper, the influence of the following non-environmental factors on the satisfaction of occupants in green and common buildings in China is analysed: 1) buildings feature: spatial layout (open space without partitions, open space with partitions, shared office); 2) occupants' personal characteristics: gender, age, knowledge of green buildings (none, basic, proficient), environmental attitude (positive, negative, whatever); and, 3) work-related variables: type of work, time at workspace, weekly working hours.

2 Methods

Description of questionnaire survey

The dataset for the analysis presented in this paper is based on the same questionnaire survey described in a previous study by the authors (Pei, 2015). The dataset features 598 individual responses from obtained from 10 green office buildings (360 responses) and 8 common office buildings (238 responses). A questionnaire about the users' habit and satisfaction of this building is distributed by hand to occupants in these buildings. To quantize the occupants satisfaction level on IEQ and general acceptability of the workplace, the questionnaire uses a scale model ranging from -1 to +1, representing the occupants' satisfaction from strongly dissatisfied to strongly satisfied, as shown in Fig 1.

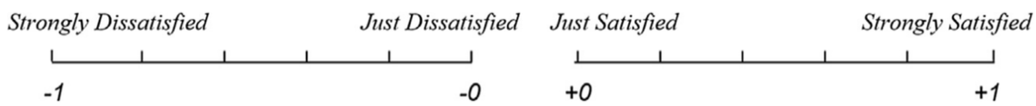

Fig 1. Scale Model of Satisfaction

For the aim of this paper, it is important that two kinds of office buildings are comparable in terms of distribution of occupants' responses according to: spatial layout, gender, age, knowledge of green buildings, environmental attitude, type of work, time at workspace and weekly working hours. Table 1 illustrates such comparison.

Table 1 Distribution of occupant's responses based on non-environmental factors

	Non-environmental factors	Number of occupants' responses					
		Green		**Common**		**Total**	
Spatial layout	Open space without partitions	140	39%	68	29%	208	35%
	Open space with partitions	142	39%	168	71%	310	52%
	Shared office	72	20%	2	1%	74	12%
	Private office	6	2%	0	0%	6	1%
	Total	**360**		**238**		**598**	
Gender	Male	166	46%	112	47%	278	46%
	Female	194	54%	126	53%	320	54%
	Total	**360**		**238**		**598**	
Age	<30	193	54%	101	42%	294	49%
	30-60	166	46%	134	56%	300	50%
	>60	1	0%	3	1%	4	1%
	Total	**360**		**238**		**598**	
Knowledge of green buildings	none	35	10%	48	20%	83	14%
	basic	236	66%	157	66%	393	66%
	proficient	89	25%	33	14%	122	20%
	Total	**360**		**238**		**598**	
Environmental attitude	positive	251	71%	155	65%	406	68%
	negative	36	10%	36	15%	72	12%
	whatever	69	19%	47	20%	116	20%
	Total	**356**		**238**		**594**	
Type of work	Administrative	41	11%	26	11%	67	11%
	Technical	13	4%	31	13%	44	7%
	Professional	127	35%	106	45%	233	39%
	Managerial	105	29%	42	18%	147	25%
	Other	74	21%	33	14%	107	18%
	Total	**360**		**238**		**598**	
Time at workspace	Less than 1 year	90	25%	43	18%	133	22%
	1-2 year	146	41%	51	21%	197	33%
	3-5 year	100	28%	59	25%	159	27%
	More than 5 year	24	7%	85	36%	109	18%
	Total	**360**		**238**		**598**	
Weekly working hours	Less than 10	42	12%	28	12%	70	12%
	11~20	14	4%	21	9%	35	6%
	21~40	172	48%	73	31%	245	41%
	More than 40	132	37%	116	49%	248	41%
	Total	**360**		**238**		**598**	

Note) Due to the lack of data, private office under spatial layout and more than 60 under age are not analysed.

Statistical methods

The mean and media values of satisfaction with overall building and 12 parameters of indoor environmental quality, including thermal environment, IAQ, lighting, acoustic environment, working efficiency, comfort of furnishing, colors and textures, amount of space, visual privacy, ease of interaction, cleanliness, operation and maintenance (O&M) are calculated for each of the eight non-environmental factors. In this study, the statistical significance of the differences in mean values of satisfaction (ΔM, green minus common) with the overall building and 12 IEQ parameters was also tested with the Mean-comparison test. And the spearman rank correlation (Rho) is used to estimate the standardized size of the mean difference in IEQ satisfaction between green and common buildings. All the statistical analysis is carried out with STATA software.

3 Results

The difference in mean values of satisfaction (ΔM, green minus common) with the overall building and 12 IEQ parameters for each of the non-environmental factors is shown in Table 2. A positive ΔM denotes a higher mean value of satisfaction given by occupants of green buildings and, on the contrary, negative ΔM values signal a higher satisfaction for users of common buildings. The data of Table 2 can illustrate potential of influence of non-environmental factors on occupant satisfaction in green and common office buildings. For example, a clear trend of decrease of efficacy of three-star certification in terms of satisfaction with the overall building in different level of knowledge of green buildings can be recognized when moving from none (ΔM=0.46; that is, higher occupant satisfaction in green buildings), to basic (ΔM=0.28), and finally to proficient (ΔM=0.09). Similar trends are also recognizable for satisfaction with other IEQ parameters such as thermal, lighting, acoustic, working efficiency, comfort of furnishing, colors and textures, visual privacy, ease of interaction, and cleanliness.

Table 3 presents the effect size (Spearman Rho) and the statistical significance of the difference in ΔM with the overall building and 12 IEQ parameters for each non-environmental factor. In Table 3, values marked in bold italic indicate a 'moderate' effect size (Rho>0.50). The effect size values of only four items calculated for the correlations considered in this study are equal or higher than 0.50, and therefore it can be concluded there are small effect sizes for most non-environmental factors on satisfaction with IEQ.

To represent the largest overall variation of mean value of occupant satisfaction between green and common buildings irrespective of analysis of non-environmental factors, the absolute variation (ΔV) of the ΔM with the overall building and 12 IEQ parameters is shown in Table 4, which means the 'spread' of the differences. Values marked in bold italic indicate an absolute variation of mean vote of satisfaction ΔV equal or higher than 0.40. For example, the absolute 'spread' of occupant satisfaction with overall building between green and common buildings based on consideration of the spatial layout is ΔV=0.45, resulting as the 'range' between a higher mean value of occupant satisfaction with overall building in green buildings of open space without partitions (ΔM=0.30, as per Table 2), and occupants more satisfied with this parameter of IEQ in common buildings of shared office (ΔM=-0.15). Table 4 can be used to suggest the potential 'weight' that each variable unrelated to environmental quality can have in influencing differences in occupant satisfaction in green and common office buildings. Based on the analysis of ΔV, it could be noted that the most interesting 'spread' of satisfaction can be found for spatial layout, type of work, and weekly working hours. The former factor can be directly affected by designers and building owners, and the latter two factors are often closely related to the office type and work schedule. Other considerable influences of non-environmental factors on the ΔV of satisfaction are noted for knowledge of green building and time at workspace, both of which are occupant's personal characteristics.

4 Discussion

Fig 2 presents the mean, median, first and third quartile; Differences in mean values (green minus common); Effect size (Spearman Rho) of occupant satisfaction with the overall building for seven non-environmental factors, including spatial layout, gender, age, knowledge of green buildings, environmental attitude, time at workspace and weekly working hours).

Spatial layout

According to Table 4, the spatial layout has a substantial influence on the absolute variation of mean satisfaction value between green and common buildings (ΔV). It could be found from Fig2 that for satisfaction with the overall building, there is a trend of increasing difference in satisfaction between green and common buildings when moving from shared offices to open spaces. This pattern is clearly identifiable in Table2 for thermal, IAQ, working efficiency, colors and textures, cleanliness, and O&M. This result is in line with the conclusion of study by Stefano Schiavon et al (Schiavon, 2014)

Gender and age

Table 4 suggests that gender does not substantially affect the absolute variation of occupant satisfaction in green and common buildings (ΔV always lower than 0.15). It is interesting to note that in China females tend to express a slightly higher mean satisfaction than males with all IEQ parameters, with the exception of working efficiency (Table 2 and Fig 2), which is different with the results of studies by Stefano et al (2014) and Kim et al (2013). Similarly, age does not considerably influence the satisfaction in green and common buildings, as indicated by an absolute variation ΔV always lower than 0.15.

Knowledge of green buildings

On the basis of Table 4, it can be noted that occupant' level of knowledge of green buildings does not entail a substantial variation in satisfaction with overall building and IEQ parameters between green and common office buildings, with the exception of working efficiency (ΔV=0.44). However, based on the data presented in Table 2, it is interesting that there is a trend of decreasing difference in satisfaction between green and common buildings when moving from none to proficient for most IEQ parameters, except IAQ, amount of space and O&M. This indicates that occupants who do not know green buildings have higher satisfaction than those who are proficient in green buildings.

Time at workspace

In terms of time at workspace, the difference in satisfaction with overall building between green and common buildings (ΔM) tends to drop at first from occupants having spent less than one year at their workspace (ΔM=0.24) to those of 1-2 years (ΔM=0.18), and begins to increase again, peaking at those having spent more than five years (ΔM=0.45). This pattern is clearly identifiable in Table2 for all IEQ parameters except cleanliness. These indicate that

Table 2 Difference in mean of satisfaction (ΔM, green minus common) with IEQ parameters for each non-environmental factor

		Overall building	**Thermal**	**IAQ**	**Lighting**	**Acoustic**	**Efficiency**	**Furnishing**	**Colors textures**	**Space**	**Visual privacy**	**Interaction**	**Clean**	**O&M**
Spatial layout	Open without	0.30	0.31	0.52	0.15	0.17	0.44	0.13	0.11	0.20	0.07	0.21	0.16	0.29
	Open with	0.27	0.29	0.34	0.15	0.18	0.33	0.29	0.10	0.15	0.24	0.07	0.08	0.25
	Shared office	-0.15	-0.16	-0.16	-0.08	0.14	-0.07	0.10	0.25	0.33	0.54	0.33	0.01	0.04
Gender	Male	0.24	0.23	0.39	0.12	0.13	0.42	0.18	0.07	0.11	0.16	0.08	0.06	0.22
	Female	0.30	0.31	0.41	0.18	0.21	0.27	0.24	0.13	0.19	0.19	0.15	0.14	0.30
Age	<30	0.25	0.24	0.37	0.18	0.19	0.36	0.25	0.12	0.13	0.22	0.11	0.01	0.28
	30-60	0.28	0.30	0.41	0.13	0.15	0.29	0.18	0.08	0.15	0.14	0.10	0.16	0.22
Knowledge of green buildings	none	0.46	0.36	0.42	0.29	0.24	0.65	0.32	0.21	0.14	0.28	0.16	0.23	0.27
	basic	0.28	0.28	0.45	0.13	0.19	0.32	0.23	0.10	0.18	0.21	0.12	0.09	0.32
	proficient	0.09	0.19	0.22	0.08	0.08	0.21	0.02	0.01	0.07	0.01	0.04	-0.02	0.07
Environmental attitude	positive	0.28	0.29	0.41	0.14	0.15	0.35	0.20	0.13	0.15	0.17	0.11	0.15	0.26
	negative	0.23	0.27	0.40	0.16	0.23	0.34	0.12	0.01	0.21	0.29	0.16	-0.10	0.23
	whatever	0.30	0.23	0.39	0.20	0.19	0.32	0.28	0.07	0.11	0.14	0.13	0.08	0.26
Type of work	Administrative	0.26	0.38	0.43	0.22	0.09	0.00	0.35	0.19	0.10	0.17	0.12	0.15	0.22
	Technical	0.50	0.53	0.71	0.36	0.30	0.85	0.12	0.15	0.21	0.57	0.21	0.08	0.22
	Professional	0.30	0.28	0.38	0.15	0.18	0.44	0.24	0.15	0.14	0.11	0.15	0.11	0.37
	Managerial	0.32	0.27	0.46	0.14	0.25	0.34	0.26	0.09	0.23	0.17	0.18	0.19	0.26
	Other	0.19	0.22	0.36	0.12	0.13	0.24	0.05	-0.05	0.22	0.23	0.05	0.02	0.04
Time at workspace (year)	Less than 1	0.24	0.32	0.46	0.22	0.17	0.32	0.28	0.18	0.22	0.14	0.18	0.13	0.26
	1-2	0.18	0.09	0.27	0.06	0.09	0.20	0.14	0.02	0.05	0.11	0.06	0.02	0.20
	3-5	0.22	0.18	0.34	0.17	0.16	0.37	0.29	0.05	0.18	0.24	0.06	-0.01	0.29
	More than 5	0.45	0.48	0.52	0.19	0.43	0.63	0.31	0.30	0.32	0.37	0.23	0.27	0.27
Weekly working hours	Less than 10	0.51	0.52	0.69	0.30	0.37	0.62	0.55	0.37	0.40	0.56	0.31	0.35	0.41
	11~20	0.23	0.28	0.35	0.22	0.25	0.38	0.15	-0.14	0.11	0.16	0.17	0.03	0.26
	21~40	0.17	0.12	0.24	0.11	0.15	0.21	0.14	0.01	0.20	0.16	0.04	0.03	0.13
	More than 40	0.30	0.35	0.46	0.13	0.13	0.41	0.19	0.13	0.05	0.06	0.11	0.10	0.32

Table 3 Effect size (Spearman Rho) and statistical significance of ΔM (green minus common)

		Overall building	Thermal	IAQ	Lighting	Acoustic	Efficiency	Furnishing	Colors textures	Space	Visual privacy	Interaction	Clean	O&M
Spatial layout	Open without	0.37	0.30	**0.50**	0.22	0.16	0.29	0.15	0.17	0.26	0.10	0.27	0.22	0.30
	Open with	0.34	0.32	0.35	0.22	0.18	0.23	0.34	0.16	0.18	0.27	0.12	0.12	0.33
	Shared office	-0.04	-0.04	-0.05	-0.04	0.07	0.01	0.05	0.13	0.13	0.19	0.18	0.01	0.03
Gender	Male	0.31	0.25	0.40	0.16	0.13	0.27	0.20	0.10	0.13	0.17	0.11	0.07	0.26
	Female	0.37	0.32	0.41	0.27	0.22	0.19	0.28	0.21	0.24	0.24	0.25	0.21	0.37
Age	<30	0.32	0.26	0.38	0.22	0.19	0.22	0.27	0.17	0.16	0.23	0.16	0.01	0.30
	30-60	0.35	0.31	0.42	0.21	0.17	0.21	0.21	0.12	0.19	0.18	0.17	0.24	0.29
Knowledge of green buildings	none	**0.51**	0.37	0.45	0.40	0.28	0.40	0.37	0.31	0.20	0.31	0.23	0.28	0.39
	basic	0.37	0.30	0.46	0.21	0.21	0.23	0.27	0.16	0.21	0.24	0.18	0.15	0.37
	proficient	0.10	0.17	0.18	0.06	0.04	0.12	0.01	0.03	0.09	0.02	0.10	-0.01	0.07
Environmental attitude	positive	0.34	0.30	0.40	0.20	0.15	0.23	0.24	0.19	0.18	0.19	0.17	0.20	0.32
	negative	0.34	0.27	0.49	0.19	0.26	0.21	0.13	0.03	0.24	0.32	0.20	-0.11	0.25
	whatever	0.40	0.26	0.42	0.29	0.21	0.21	0.29	0.11	0.15	0.17	0.22	0.14	0.35
Type of work	Administrative	0.35	0.42	0.46	0.28	0.11	0.01	0.44	0.30	0.15	0.17	0.17	0.20	0.28
	Technical	0.48	0.47	**0.55**	0.40	0.24	0.46	0.10	0.12	0.25	**0.53**	0.30	0.07	0.20
	Professional	0.40	0.30	0.40	0.21	0.17	0.34	0.30	0.25	0.20	0.15	0.24	0.19	0.43
	Managerial	0.36	0.24	0.42	0.21	0.25	0.20	0.25	0.13	0.23	0.17	0.21	0.27	0.34
	Other	0.20	0.22	0.35	0.18	0.11	0.12	0.05	0.03	0.24	0.24	0.08	0.03	0.08
Time at workspace (year)	Less than 1	0.37	0.38	0.52	0.33	0.18	0.20	0.33	0.29	0.23	0.14	0.25	0.14	0.34
	1-2	0.23	0.11	0.27	0.11	0.08	0.11	0.13	0.02	0.09	0.13	0.09	0.04	0.21
	3-5	0.25	0.17	0.33	0.19	0.17	0.27	0.28	0.08	0.17	0.27	0.09	-0.02	0.28
	More than 5	0.41	0.39	0.37	0.18	0.36	0.34	0.31	0.32	0.32	0.36	0.24	0.32	0.31
Weekly working hours	Less than 10	0.55	0.45	0.62	0.37	0.36	0.34	0.58	0.51	0.44	0.54	0.39	0.44	0.52
	11~20	0.28	0.34	0.40	0.37	0.29	0.29	0.17	0.16	0.17	0.15	0.21	0.06	0.33
	21~40	0.22	0.14	0.26	0.16	0.14	0.14	0.16	0.02	0.21	0.18	0.06	0.04	0.17
	More than 40	0.40	0.38	0.47	0.20	0.14	0.29	0.22	0.19	0.07	0.09	0.20	0.16	0.37

Table 4 Absolute variation of mean value of satisfaction (ΔV) with overall building and 12 IEQ parameters for each non-environmental factor

	Overall	Thermal	IAQ	Lighting	Acoustic	Efficiency	Furnishing
Spatial layout	**0.45**	**0.47**	**0.68**	0.23	0.04	**0.51**	0.19
Gender	0.06	0.08	0.02	0.06	0.08	0.15	0.06
Age	0.03	0.06	0.04	0.05	0.04	0.07	0.07
Knowledge of green buildings	0.37	0.17	0.23	0.21	0.16	**0.44**	0.30
Environmental attitude	0.07	0.06	0.02	0.06	0.08	0.03	0.16
Type of work	0.31	0.31	0.35	0.24	0.21	**0.85**	0.30
Time at workspace	0.27	0.39	0.25	0.16	0.34	**0.43**	0.17
Weekly working hours	0.34	**0.4**	**0.45**	0.19	0.24	**0.41**	**0.41**

	Colors and textures	Space	Visual privacy	Ease of interaction	Clean	O&M
Spatial layout	0.15	0.18	**0.47**	0.26	0.15	0.25
Gender	0.06	0.08	0.03	0.07	0.08	0.08
Age	0.04	0.02	0.08	0.01	0.15	0.06
Knowledge of green buildings	0.20	0.11	0.27	0.12	0.25	0.25
Environmental attitude	0.12	0.1	0.15	0.05	0.25	0.03
Type of work	0.24	0.13	**0.46**	0.16	0.17	0.33
Time at workspace	0.28	0.27	0.26	0.17	0.28	0.09
Weekly working hours	**0.51**	0.35	**0.50**	0.27	0.32	0.28

green office buildings in China may be more effective in providing higher satisfaction to occupants who have spent for a longer time at their workspace rather than to those having occupied their place for 1-2 years. These results are inconsistent with the studies by Stefano et al (2014) concluded that LEED certification on occupant satisfaction may tend to diminish with the time spent at the space of work.

Limitations of the study

The first limitation of this study is that the selection of buildings investigated in this study is not based on a systematic randomized approach, and the majority of the responses were obtained from buildings located in Beijing, Tianjin and Shanghai.

A further limitation is the small sample size, which is represented by the lack of data about private office under spatial layout and more than 60 under age.

A final limitation of this study is represented by the fact that no analysis has yet been performed, for each of the green buildings included in our dataset, on the potential correlation between satisfaction of occupants and the level of rating obtained by the buildings, such as 1-star, 2-star, 3-star.

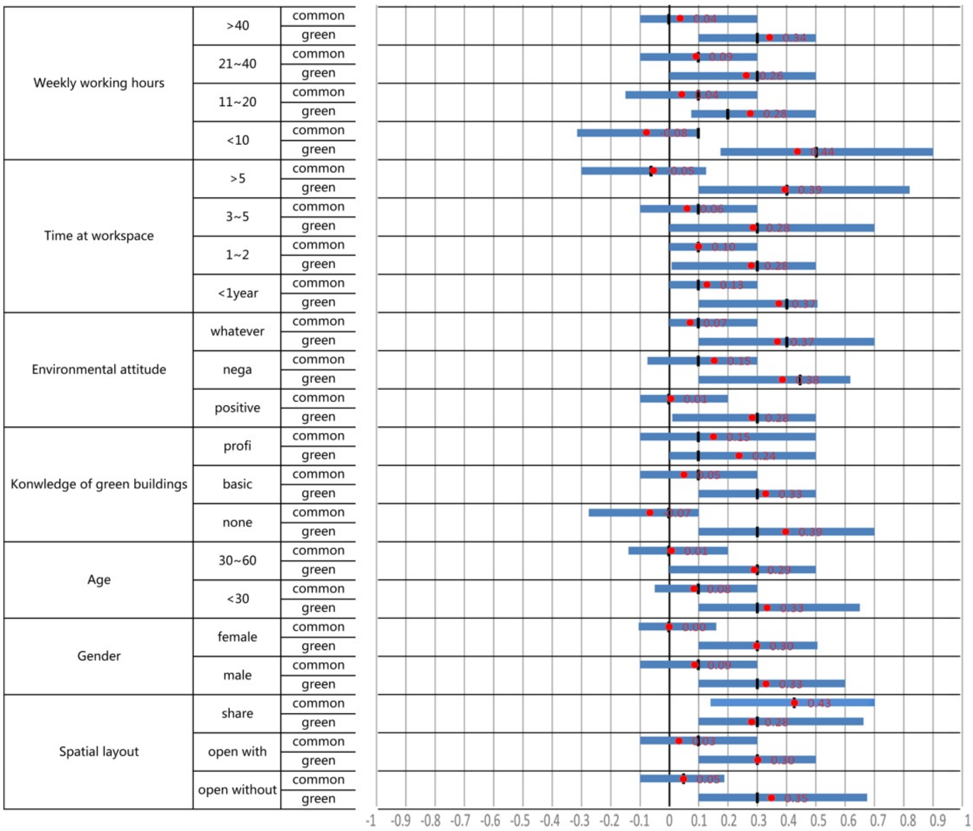

Fig 2(a). Mean, median, first and third quartile

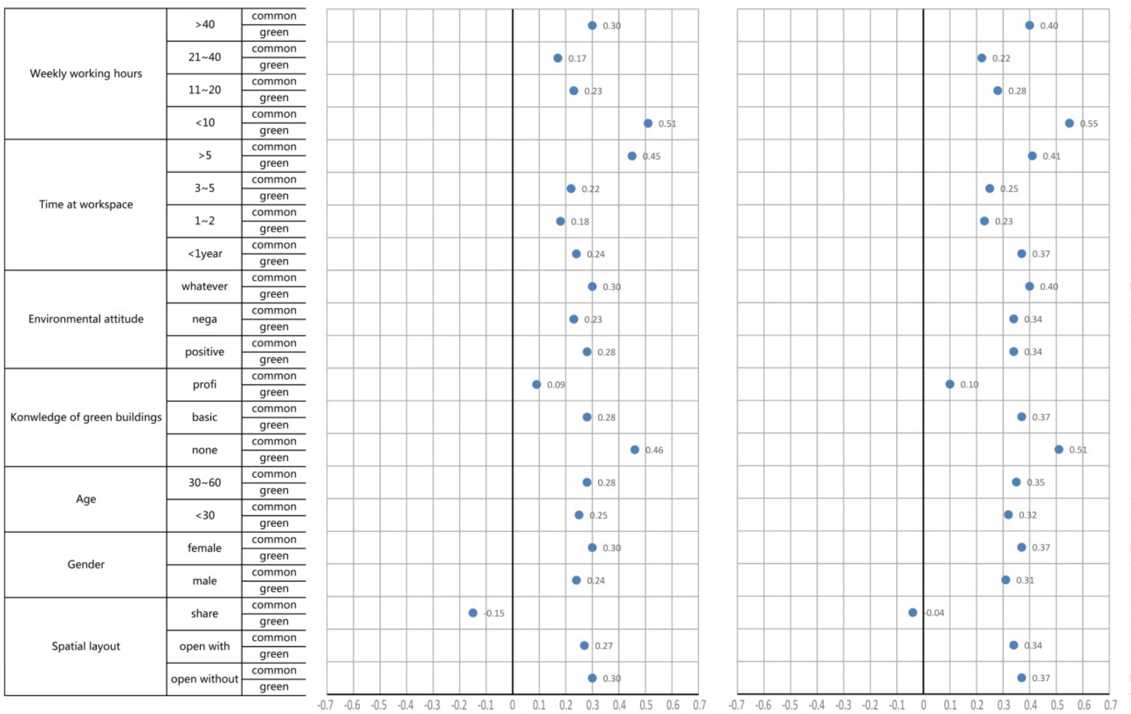

Fig 2(b). Differences in mean values (green minus common) (left); Effect size (Spearman Rho) (right) of occupant satisfaction with the overall building for seven non-environmental factors (spatial layout, gender, age, knowledge of green buildings, environmental attitude, time at workspace and weekly working hours)

5 Conclusion

Based on the methodology of POE on green and common buildings China, this study tries to explore the impact on occupant satisfaction in green and common buildings in China of factors unrelated to environmental quality, taking consideration of spatial layout, gender, age, knowledge of green buildings, environmental attitude, type of work, time at workspace, and weekly working hours.

The main conclusions that can be drawn from this study are:
There is a trend of increasing difference in satisfaction between green and common buildings when moving from shared offices to open spaces for overall building, thermal, IAQ, working efficiency, colors and textures, cleanliness, and O&M.

Gender and age do not considerably influence the satisfaction in green and common buildings.

Occupants who do not know green buildings may have higher satisfaction with IEQ than those who are proficient in knowledge of green buildings.

Green office buildings in China may be more effective in providing higher satisfaction to occupants who have spent for a longer time at their workspace rather than to those having occupied their place for 1-2 years.

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WORKSHOP 2.3

Thermal Physiology and Comfort

Invited Chairs: Wouter van Marken Lichtenbelt and Ken Parsons

WS2.3: Thermal Physiology and Comfort.
Chairs: Wouter van Marken Lichtenbelt and Ken Parsons

Thermal comfort and thermal physiology are linked to each other. In the last decennia much new information has been gained on thermal physiology. In the past ergonomic studies mainly focused on extreme temperatures. Gradually more information is being gathered on the effect of moderate temperature variations on our physiology, thermal sensation and comfort experiences. However, there remains a dearth of information on temperature drifts and temporal switches in ambient temperature. Another aspect that deserves attention is health as very little is known about the long-term effects of ambient temperature on our health. Are comfortable temperatures healthy? It is becoming apparent that excursions outside the thermal comfort zone can be beneficial. Cold or warm acclimated subjects are better able to cope with heat and cold waves and it has been shown that mild cold is beneficial with respect to the metabolic syndrome. The workshop intends to explore where we are in relation to such issues and discuss new directions for research on the link between thermal comfort and physiology and related health issues.

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

The effect of warmth acclimation on thermoregulatory behaviour and thermal physiology

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Abstract

Public and commercial buildings tend to overheat and a lot of energy is consumed by air-conditioning and ventilation. However, many occupants remain unsatisfied with the thermal environment. Energy use is significantly influenced by thermoregulatory behaviour (TRB). In the present study, we hypothesize TRB can be affected by warmth acclimation. 12 young healthy men visited the laboratory for 9 consecutive days. TRB was assessed by a so-called SWITCH protocol (90min) before and after acclimation (7days, 6h/day, ~35˚C). During SWITCH, participants could freely choose between a warm (37˚C) and a cold (17˚) condition. TRB was determined by total amount of switches and time spent in a specific condition. Mean skin temperature (14 ISO-defined spots) was measured to indicate behavioural thresholds. After acclimation, the upper critical behaviour threshold (UCBT) of the mean skin temperature significantly increased from 35.17±0.61˚C to 35.54±0.47˚C (P=0.050). Moreover, the range of mean skin temperatures at which no behaviour occurred (thermoregulatory behaviour neutral zone, TBNZ) significantly widened from 3.63±0.65 to 4.16±0.57 (P=0.027). The total amount of switches tended to decrease (P=0.059). Time spent in the respective conditions remained unchanged. The present study is the first one to show prolonged passive exposure to warmth without exercise extends the behavioural threshold.

Keywords: warmth acclimation, thermoregulatory behaviour, behavioural thresholds, building energy use

1 Introduction

In the Western world, public and commercial buildings tend to overheat due to, amongst other things, highly effective construction materials and high internal heat load. Moreover, global warming is progressing slowly but steadily (IPCC, 2013). Approximately one-third of the primary energy supply is used for the air-conditioning and ventilating of buildings, mostly to ensure occupant comfort. However, a great number of building occupants remain unsatisfied with their thermal environment.

In order to maximise thermal comfort and to improve satisfaction, building occupants influence their thermal environment by, for example, opening a window or increasing the air-conditioning. These actions, referred to as thermoregulatory behaviour (TRB), influence building energy consumption. Importantly, the indoor climate of a building can affect human metabolism and uncomfortable warm environments might cause sleepiness and restrict productivity (de Dear et al., 2013).

TRB is closely related to thermal physiology of the human body. Changes in core and skin temperature have previously been identified as being the main driving forces for TRB (Chatonnet et al., 1966, Cabanac et al., 1971). More recently, Schlader *et al.* (Schlader et al., 2013) have indicated that skin temperature may be the most important initiator of TRB, especially in mild thermal environments. However, the mechanisms, which actually control TRB and the thresholds that must be exceeded before behaviour is initiated, are unclear. The missing knowledge on the mechanisms regarding TRB makes it a rather difficult factor to predict, which is why most models fail to anticipate TRB properly.

Heat acclimation has been studied for many years, yet there is a distinct lack of information on the effect of (prolonged) warmth (mild heat) exposure on TRB. Traditionally, heat acclimation studies were designed to develop acclimation models for athletes or the military (Nadel et al., 1974, Nielsen et al., 1993, Regan et al., 1996, Pandolf, 1998, Cheung and McLellan, 1998). The majority of such studies used exercise-induced hyperthermia combined with high ambient temperatures to reach adjustments at various levels of the thermoregulatory system. These adjustments can include changes in core temperature, sweat rate, the cardiovascular system and other metabolic functions; they all result in a superior ability to dissipate heat. However, due to the frequent application of exercise as an additional heat stimulus, it is difficult to distinguish between temperature- and exercise-related adaptions.

Interestingly, information on the effects of prolonged (passive) exposure to mild warm ambient temperatures is very limited (Shvartz et al., 1973, Sareh et al., 2011). To the best of our knowledge, no information exists on the effect of such heat acclimation (neither active nor passive) on human TRB. To gain important insights for the built environment sector, it is desirable to enhance the knowledge on effects of milder, and thus more realistic ambient conditions on the human thermoregulatory system. It is hypothesized that prolonged passive warmth acclimation cause alterations in thermoregulatory physiology as well as behavioural set points. The present paper focuses on the effects of warmth acclimation on TRB and skin temperatures. It presents preliminary data, as the analysis is still ongoing.

2 Methods

The experiments presented in this paper are part of an extensive study, which was designed to evaluate the effects of passive warmth acclimation on thermal physiology, thermal comfort and thermoregulatory behaviour. In the scope of this paper, we focus on the behavioural part of the experiment.

All experiments were performed at the Metabolic Research Unit of Maastricht University (MRUM) between December 2014 and August 2015. During this period, twelve young, healthy male volunteers visited the MRUM on 9 consecutive days. Their characteristics are provided in Table 1.

Table 1. Participant characteristics

Participant characteristics	Mean ± SD
Age [years]	24.08±3.06
Height [m]	1.79±0.07
Body mass [kg]	73.64±9.68
BMI [kg/m2]	22.93±3.04
Body fat percentage [%]	19.78±2.89

All volunteers were healthy, normotensive, non-obese, non-smokers and not taking any medication that might have altered the cardiovascular system or thermoregulatory responses. Subjects refrained from food, alcoholic and caffeinated beverages as of 22:00h the evening before being measured. For the behavioural experiment, volunteers underwent 2 testing days (1 and 9) and 7 days of warmth acclimation (Figure 1). During days 1 and 9, the SWITCH protocol was performed.

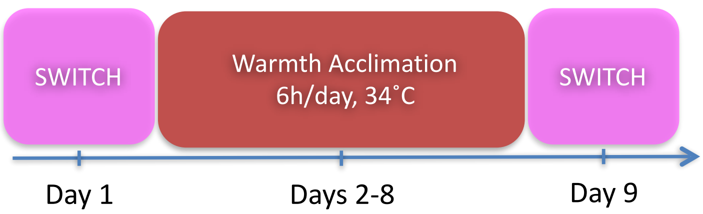

Figure 1. Time course of the experiment.

2.1 SWITCH protocol

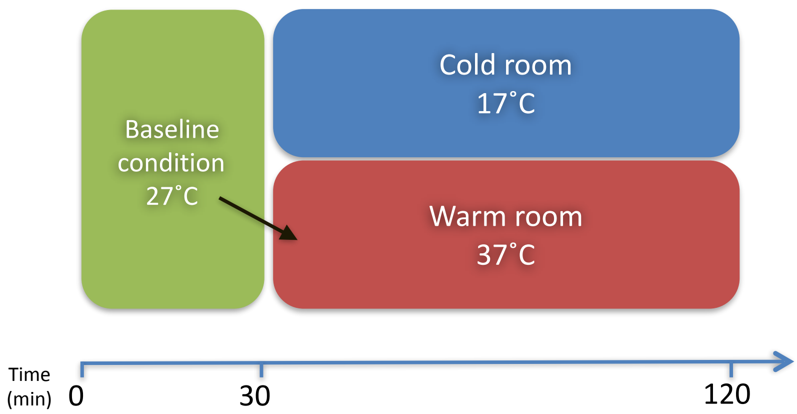

Figure 2. The SWITCH protocol: after 30min of baseline, participants were free to switch between a warm and a cold room; there were no limits with respect to frequency or time. The black arrow indicates the start condition.

The SWITCH protocol (Figure 2) was conducted to evaluate thermoregulatory behaviour (TRB). Upon arrival at the MRUM, volunteers were asked to change to standardised clothing, consisting of underwear, T-shirt, shorts and slippers/socks. During the experiment, volunteers sat on a chair. The total thermal resistance of the clothing ensemble plus the desk chair added up to approximately 0.41clo (McCullough et al., 1989, McCullough et al., 1994). 26 iButtons were attached to 14 ISO-defined (ISO, 2004) and 12 additional skin sites, to symmetrically measure skin temperature distribution. Skin temperatures were recorded at 1-minute intervals throughout the whole protocol. Air temperature and relative humidity were measured by means of wireless temperature/humidity sensors (Hygrochron iButton, DS1923, Maxim Integrated Products, USA), according to EN-ISO 7726 (ISO, 2001).

SWITCH was conducted in the climate chambers of the MRUM (Figure 3A). Volunteers started in the baseline condition (27˚C ambient temperature). After 30min, the participants were guided to a warm room (37˚C). They were instructed that from that moment onwards, they had the freedom to switch between the warm room (35˚C) and cold room (17˚C), without any limitation to the number of switches or time between switches. Moreover, participants were informed that they could switch between the warm and the cold condition without notifying the researcher, whenever they wanted, simply by opening the doors by themselves and walking into the respective room. The latter was considered to be of great importance in order to keep the freedom for thermoregulatory behaviour as great as possible. SWITCH continued for 90min. Participants were instructed to remain seated at a desk whilst remaining in the respective conditions (Figure 3B). They were allowed to perform reading tasks (1.2 METs).

A **B**

Figure 3A and B. *A* Two representative climate chambers at the MRUM. During SWITCH, participants commuted between two climate chambers (warm room, 37˚C and cold room, 17˚C). *B* Participant during SWITCH.

2.2 Warmth acclimation

After the first SWITCH on day 1 of the study, the warmth acclimation period commenced. Participants were exposed to approximately 35˚C ambient temperature for 7 consecutive days. During their stay, participants wore standardized clothing (underwear, T-shirts, shorts and slippers, ~0.36 clo (McCullough et al., 1989)) and they sat on an office chair (~0.05 clo, (McCullough et al., 1989)). They were asked to perform regular office work (1.2METs) and were allowed to leave the room for short toilet breaks. Participants were provided with food (sandwiches and crackers/cookies; 3 times in 6h) and water *ad libitum*.

2.3 Statistical analyses

TRB was evaluated by counting the total number of switches, by clocking the time participants remained in the warm and the cold room and by evaluating the course of their mean skin temperature, as the latter can represent an important predictor for TRB.

SPSS 22.0 for Mac (SPSS Inc.) was used for statistical data analyses. Preliminary data is presented since the analyses are still ongoing. Paired t-tests were applied to test for statistical differences between pre and post acclimation measurements. Statistical significance was assumed if $P \leq 0.05$.

3 Results

Before acclimation, participants switched 2 to 6 times and spent a total amount of 17-77min in the warm room and 12-74min in the cold room, respectively. After acclimation, participants switched 0 to 6 times and the total amount of time spent in the warm room increased to 35-90min, whereas the time spent in the cold room decreased to 0-56min (Table 2).

Table 2. Results of SWITCH pre and post warmth acclimation.

SWITCH results	pre warmth acclimation	post warmth acclimation	P-value
Switches	3.42±1.1	2.50±1.51	0.059
Warm room [min]	50.92±16.20	56.92±14.74	0.177
Cold room [min]	37.33±16.66	31.92±14.41	0.283
UCBT [˚C]	35.17±0.61	35.53±0.47	0.050*
LCBT [˚C]	31.59±0.87	31.38±0.84	0.585
TBNZ	3.63±0.65	4.16±0.57	0.027*

LCBT lower critical behavioural temperature, *UCBT* upper critical behavioural temperature, *TBZ* thermoregulatory behaviour zone. Data is presented as mean±SD. *P ≤ 0.05. N=12 (N=11 for 'Cold room', 'UCBT', 'LCBT' and 'TBNZ' post warmth acclimation as one participant did not switch during the post measurement of SWITCH)

During SWITCH, skin temperatures were measured at 1-min intervals. Mean skin temperature as measured just before switching from the warm room to the cold room (37˚C → 17˚C), indicated the upper critical behavioural threshold (UCBT), whereas mean skin temperature measured just before switching from the cold room to the warm room (17˚C → 37˚C) marked the lower critical behavioural threshold (LCBT). The range of mean skin temperatures between those two critical points can be described as the thermoregulatory behaviour neutral zone (TBNZ). Before warmth acclimation, participants revealed UCBTs ranging from 35.14˚C to 36.09˚C and LCBTs from 29.97˚C to 32.86˚C. After acclimation, UCBTs ranged from 34.50˚C to 36.31˚C and the LCBTs from 30.06˚C to 32.75˚C. As indicated in Table 2, UCBT's significantly increased post acclimation. The change in LCBTs was not statistically significant.

All individual ranges are presented in Figure 4. For participant 5, no TBNZ could be calculated since this subject did not switch post acclimation but remained in the warm room throughout the entire duration of SWITCH (90min after baseline). For participant 9, no LCBT could be recorded since this participant only switched once from warm to cold and remained in the cold condition until the end of SWITCH.

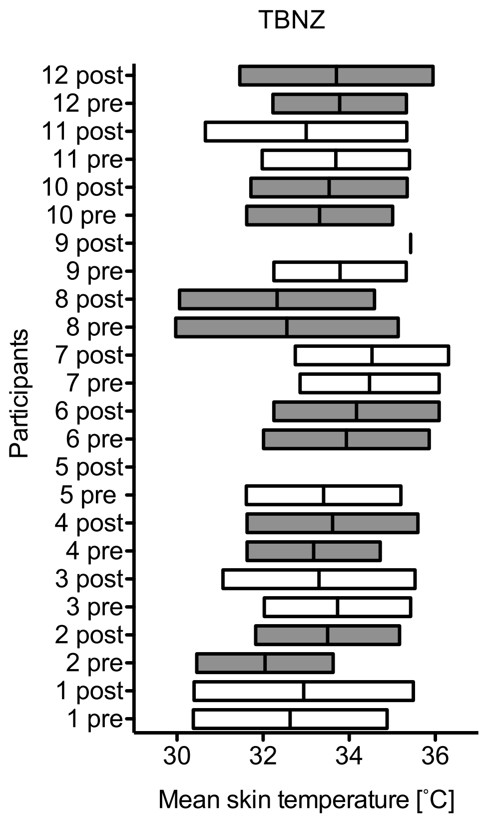

Figure 4. Individual thermoregulatory behaviour neutral zones (TBNZ) of all participants pre and post warmth acclimation.

As indicated in Table 2, the TBNZ widened significantly post warmth acclimation. The range of mean skin temperatures wherein no switch occurred increased from averagely 31.53±0.89˚C – 35.15±0.64˚C pre warmth acclimation to 31.38±0.84˚C – 35.5±0.47˚C post warmth acclimation.

4 Discussion and Conclusion

The present study has evaluated the effect of passive warmth acclimation on thermoregulatory behaviour (TRB) and thermal physiology. In accordance with our hypothesis, we have shown that 7 days of passive warmth acclimation significantly influenced thermal physiology (mean skin temperatures) and TRB. Post acclimation, participants switched at significantly higher mean skin temperatures (higher upper critical behaviour temperature, UCBT), thereby broadening the range of mean skin temperatures at which no TRB occurred (thermoregulatory behaviour neutral zone, TBNZ). Moreover, the total number of switches decreased post acclimation, although this trend was not statistically significant (P=0.059).

It had previously been suggested that core and skin temperature were the driving forces for TRB (Chatonnet et al., 1966, Cabanac et al., 1971) but more recently, Schlader *et al.* (Schlader et al., 2013, Schlader et al., 2009) have emphasized the importance of skin temperature in mediating behavioural thermoregulation, especially in mild thermal environments. Core temperature has been found to play a less important role, which might be due to the nature of the concept itself: the goal of both physiological and behavioural thermoregulation is to buffer (substantial) changes in core temperature and to ensure thermal balance (Schlader et al., 2010, IUPS-Thermal-Commission, 2003). We therefore decided to focus on skin temperature as the determining factor for TRB.

Generally, knowledge about behavioural thermoregulation in humans is limited, which is surprising given the important role that TRB plays in human thermoregulation. After all, thermal physiology (e.g. vasomotion, sweating and cold-induced thermogenesis) has relatively limited capacity, whereas the capability of TRB is virtually unlimited (Benzinger, 1969, Schlader et al., 2010). From our thermophysiological studies, we know that the individual variation in thermal responses is significant. Sex, age, body composition and metabolism (and acclimatisation) influence the range of preferred temperatures and thereby codetermine TRB (Schellen et al., 2010, Schellen et al., 2012, Jacquot et al., 2014). Our present results indeed reveal considerable individual variation in TRB. For example, the number of total switches between warm and cold ranged from 0 to 6. Moreover, the time spent in one of the respective conditions greatly varied between participants and as depicted in Figure 4, width and range of TBNZs notably differed.

To the best of our knowledge, the present study is the first to investigate the effect of warmth acclimation on TRB. Our findings indicate that prolonged passive exposure to warmth extends the behavioural threshold for warm conditions. Participants seem to tolerate higher mean skin temperatures before they feel the need to regulate their body temperature. This new discovery could be of great importance for the design of future indoor thermal environments; building energy expenditure could easily be decreased by the application of a less strict air-conditioning set-point, without affecting occupant satisfaction.

As indicated above, this study is part of an extensive study into warmth acclimation effects. We have measured many thermophysiological parameters and also thermal comfort and thermal sensation in different thermal environments. The next step is analysing physiological aspects such as cardiovascular function, core temperature, core-skin temperature gradient and subjective perception of the thermal environment (e.g. thermal comfort and thermal sensation) to gain greater insights into the relationship between behavioural and physiological thermoregulation.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Light intensity and thermal responses

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Abstract

Temperature and light are both major factors in the design of a comfortable indoor environment. Moreover, there might be an interaction between light exposure and human thermal responses. However, results of experiments conducted so far are inconclusive and current understanding of the relation between physiological and subjective thermal effects is poor. Therefore, we tested the effect of light intensity on thermophysiology, thermal comfort and alertness. In a randomized crossover design, 19 healthy female subjects were exposed to a dim light (5 lux) and bright light (1200 lux) condition. To assess thermal responses, each light condition was offered under three temperature conditions: a cold (26˚C), neutral (29˚C) and warm (32˚C) environment. During the experiments human energy expenditure, skin and core temperature and blood perfusion were measured under semi-nude conditions. Thermal comfort, visual comfort and self-assessed alertness were assessed using questionnaires. Preliminarily results show that both temperature and light influences self-assessed alertness ($p<0.01$). Additionally, a relation between thermal comfort and comfort of the perceived colour of the light condition was found ($p=0.02$). Knowledge on the interaction between temperature and light can be used to create healthy and comfortable indoor environments, thus allowing for extra energy savings.

Keywords: Thermal comfort, Thermophysiology, Alertness, Light intensity, Visual comfort

1 Introduction

The ambient temperature in a room is the most important determinant for thermal comfort. However, it also affects alertness of building occupants. Guidelines prescribe indoor temperatures to satisfy the needs of the building users. On top of that a variation of the indoor temperature outside comfort ranges may be beneficial for health (Hanssen et al., 2015) and may lead to building energy savings (Yang et al., 2014). The indoor temperature is not the only factor that influences thermal comfort and performance of building occupants. Light is also a factor that affects alertness, performance, well-being and visual comfort of building occupants (Cajochen, 2007, Sahin et al., 2014, Veitch et al., 1991). Therefore we are interested in the interaction between light and temperature, and how light can contribute to a comfortable and healthy indoor environment.

From literature it is known that light may affect human thermal responses (te Kulve et al., 2016). Experimental studies show that different light conditions in the evening can affect body temperatures (e.g. (Cajochen et al., 2005, Ruger et al., 2006)). For example: bright light in the evening supresses the decline of core body temperature (CBT). In the morning however, the opposite effect is found: dim light resulted in a higher CBT (Foret et al., 1993, Aizawa and Tokura, 1998). Additionally, some experiments report a lower skin temperature in the evening (Kim and Tokura, 1995) or afternoon (Ishimoto et al., 1998), after bright light exposure during the day.

But do these physiological effects influence thermal sensation and thermal comfort? The effects of light intensity on thermal sensation are reported in experiments and some found a lower thermal sensation after dim light e.g. (Teramoto et al., 1996, Ishibashi et al., 2010), another after bright light (Kim and Tokura, 2007) and a third did not find an effect on thermal sensation (Kim and Jeong, 2002). The different results could be caused by various timings, durations and intensities of the light exposure that were used. Since the results of the existing studies are still inconclusive and the relation between the effect the physiological effect and thermal sensation has not yet been described, we studied the effects of light intensity on thermoregulation, thermal comfort and alertness. In this paper we describe the results of comfort and alertness. Since we are interested in the link between the physiological and subjective effects of light, the experiments have been performed under strictly controlled conditions in which the subject is in rest. Otherwise, it would not have been possible to measure the physiological parameters as accurately. Extrapolation to daily living circumstances is anticipated in follow-up experiments.

2 Method

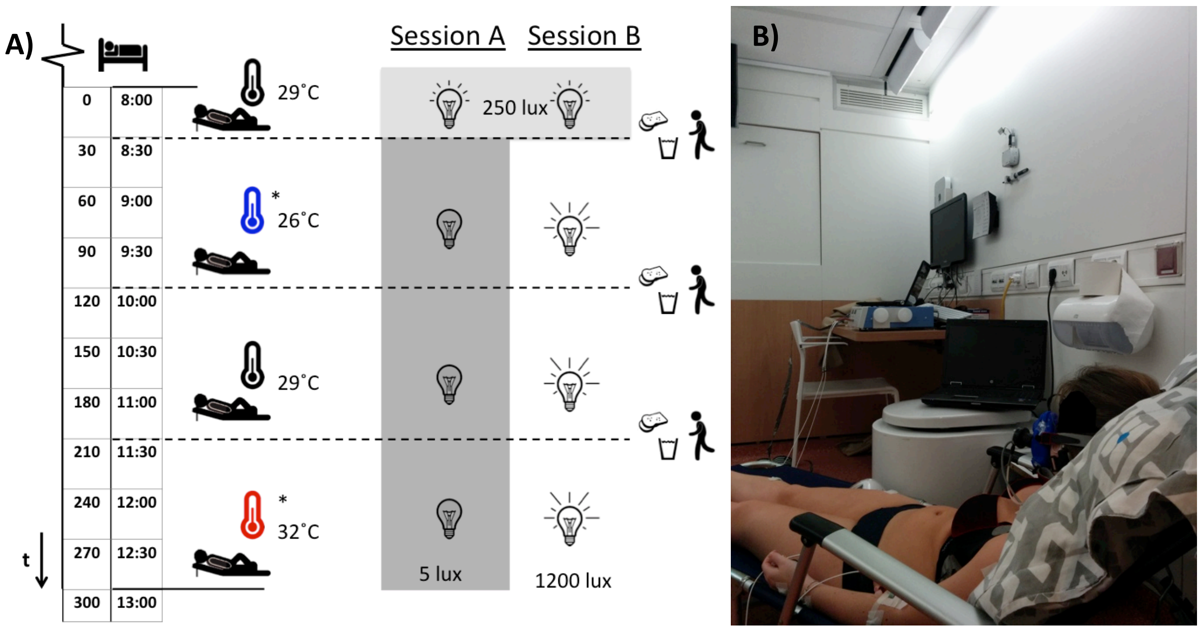

Figure 2: A) Schedule of the protocol. Each subjects participates in session A and B. B) Picture of a subject during the experiments.

In a randomized crossover design, 19 healthy female subjects participated in a dim light session (5 lux) and a bright light session (1200 lux). In each of these sessions experiments were conducted under three different ambient temperatures: cold (26˚C), neutral (29˚C) and warm (32˚C). Both sessions started with a baseline condition of 30 minutes with a light intensity of 250 lux and a temperature of 29˚C. The correlated colour temperature of all light settings was 4000K. All experiments took place during the morning. The night before the experiment, the subject slept at the university to control the temperature and light exposure, activity level and food intake before the experiment started. The protocol is illustrated in Figure 2A.

Subjects

All subjects were healthy females, age between 18-30 years of age, BMI 18-25 kg/m^2, using microgynon 30 or levonorgestrel/ehinylestradiol and of a normal chronotype. Participants did not use any further medication and did not have a feeling of illness on the experimental day. The subject characteristics are described in Table 1.

Table 1: Subject characteristics

Characteristic	Average (± SD)
Age (yr)	22.3 ± 1.9
Body mass (kg)	62.7 ± 5.5
Height (m)	1.70 ± 0.07
BMI (kg/m^2)	21.7 ± 1.8
Body fat (%)	30.2 ± 3.2

Study procedure

Each temperature condition lasted 75 minutes. During the exposure, the subject lay in a semi-supine position on a stretcher (Figure 2B). Between each condition there was a small break in which the subjects ate a cracker (53kcal) and was allowed to drink water as desired. During the experiments human energy expenditure, skin and core temperature, heart rate and blood perfusion were measured with an interval of 1 minute. Blood pressure was measured three times during each condition. Every 15 minutes, subjects filled out questionnaires about thermal comfort, visual comfort and self-assessed alertness. Thermal sensation was evaluated on the ASHRAE 7-point thermal sensation scale ranging from cold (-3) to hot (+3). Similar, the subject was asked how she perceived the light intensity on a scale from very low (-3) to very high (+3), followed by a question whether this was perceived as comfortable or not. Subsequently the same was done for the colour temperature: subjects could indicate how they perceived the colour of light from a very cool colour (-3) to a very warm colour (+3), and then indicated whether this was comfortable or not. After 55 minutes of each condition, a psychomotor vigilance task (PVT) was done to measure the reaction time to an auditory stimulus. Finally blood was drawn at the end of the session. The schedule of each temperature condition is illustrated in Figure 3.

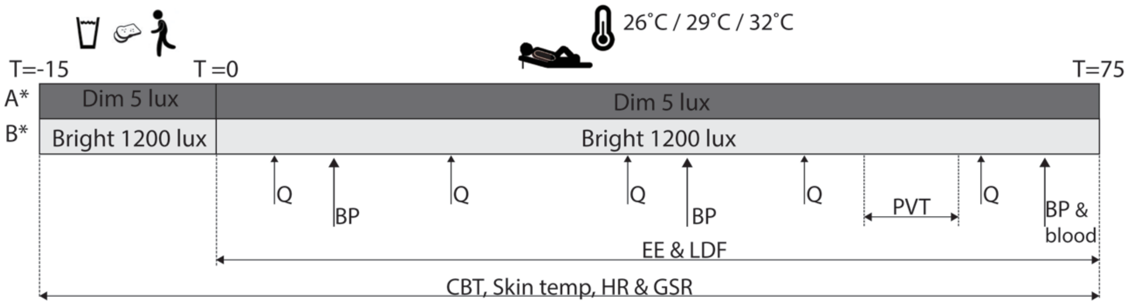

Figure 3: Schedule measurement during 1 temperature exposure of 75 minutes. Arrows indicate time and duration of measurements: Energy Expenditure (EE), Laser Doppler Bloodflow (LDF), Core Body Temperature (CBT), Skin temperatures (Skin temp), Heart rate (HR), Galvanic Skin Response (GSR), Blood Pressure (BP), Questionnaires (Q), Psychomotor vigilance task (PVT), Blood sampling (blood).

Statistics

Values are displayed as average ± standard deviation. To test the effect of temperature and light on the outcome variables, a mixed model was used in which the subject ID was included. Temperature, light and the interaction of light and temperature were used as fixed factors. For each temperature condition, the effect of light was analysed using a paired t-test. Statistical analyses were done using IBM SPSS statistics 21.0.0.1. $P < 0.05$ was considered statistically significant.

Approval

The Medical Ethical Committee of Maastricht University Medical Centre+ approved the study protocol. All subject provided a written informed consent previous to the experiments. Subjects were informed that the experiments were about light and temperature, but they had no information about the thermal conditions or lighting conditions in the room. All procedures were conducted according to the principles of the Declaration of Helsinki.

3 Results

Questionnaires

The first results show that there is no significant difference in thermal comfort and thermal sensation between the dim light and bright light condition for all three ambient temperatures. As expected, thermal comfort was significantly affected by temperature and best under the neutral condition (Figure 4A). Thermal sensation was, as expected, highest during the warm condition (1.60 ± 0.81) and lowest during the coldest condition (-1.28 ± 0.85). Perceived intensity and visual comfort of light intensity were significantly influenced by the light condition and perceived as most comfortable during the bright light session. However, temperature did not affect the perception of the light intensity. The subjects perceived the colour of the dim light condition as warmer compared to the bright light session (bright: -0.862 ± 0.67, dim: -0.02 ± 0.84 ($P<0.01$)). Though, this perceived difference in the colour of light did not result in an effect on visual comfort of the perceived colour of light (Figure 4B).

Interaction thermal comfort and visual comfort

However, when we calculate the difference in thermal comfort from the bright light to the dim light session for the cold condition, and the change in visual comfort of the perceived colour of light from the bright light to the dim light session for the cold condition, we find a correlation between these two variables ($r=0.57$ and $p<0.02$) (Figure 4C).

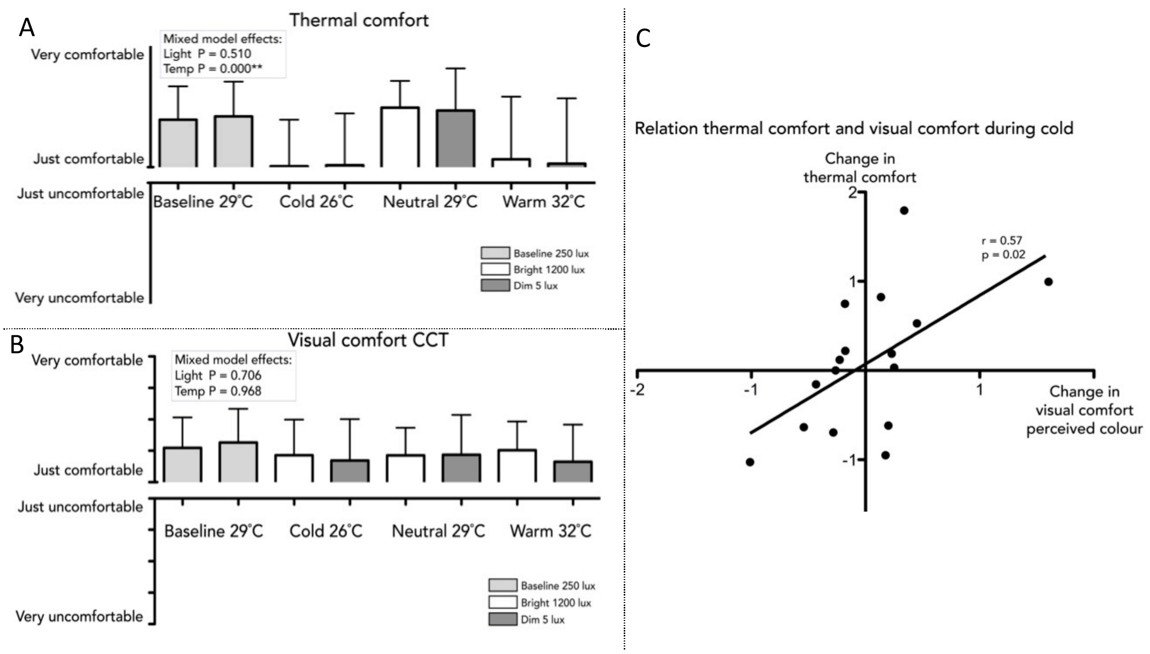

Figure 4: Results of (A) thermal comfort and (B) visual comfort of the perceived light colour. Average and standard deviation was calculated over the 2nd – 4th questionnaire of each temperature condition. The mixed model shows the fixed effects of light and temperature during the cold, neutral and warm temperature for the bright and dim condition. C) shows the correlation between the change in thermal comfort between the bright and dim light session and change in comfort of the perceived colour of light. The average over the 2nd – 4th questionnaire of the cold temperature was used.

Alertness

Subjects reported to feel most sleepy during the warm condition as compared to the neutral and cold condition (P<0.01). During the cold condition subjects were most alert. Light also affected self assessed sleepiness: during the bright light session subjects were more alert as compared to the dim light session (P<0.01). These results are illustrated in Figure 5A. Additionally, alertness was also tested using the PVT. Reaction time was best during the cold condition and worst during the warm condition. Light intensity did not significantly affect reaction time (Figure 5B).

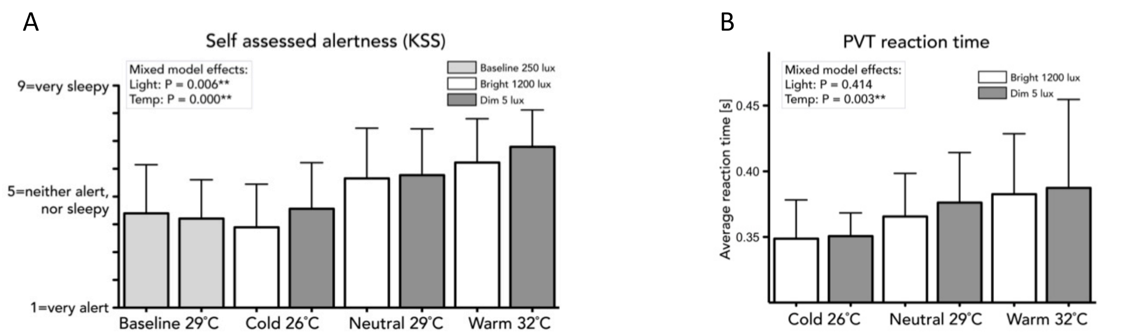

Figure 5: A) Results of self-assessed alertness: average and standard deviation was calculated over the 2nd – 4th questionnaire of each temperature condition. B) Result of PVT reaction time. The mixed model shows the fixed effects of light and temperature during the cold, neutral and warm temperature for the bright and dim condition for both variables.

4 Discussion & conclusion

In this study, we found that dim light exposure in the morning does not alter thermal sensation and thermal comfort as compared to bright light exposure. The timing of the measurement could be a reason for the absence of an effect. We did not find another study that measured the effect of light intensity on thermal sensation or thermal comfort in the morning. But two studies that evaluated thermal sensation in the afternoon, found that thermal sensation was cooler when it was preceded by dim light exposure during the morning (Teramoto et al., 1996, Kim and Tokura, 2000).

Light intensity was perceived as lower during dim light. Additionally, the intensity of the bright light condition was perceived as more comfortable. In contrast to a previous study in which no effect of the intensity on the perceived warmth of light condition was observed (Viénot et al., 2009), the colour of the dim light condition in this study was perceived as warmer than that of the bright light condition. In following experiments we will use different correlated colour temperatures to test the effect of a different light spectrum on thermal comfort.

Thermal comfort was not perceived differently during the two different light settings. Interestingly though, there was a correlation between the change in thermal comfort and the change in visual comfort of the perceived colour of light. According to Humphreys (2005), dissatisfaction with one or more indoor environmental aspects does not necessarily results in dissatisfaction of the overall environment. Nor does approval of one aspect lead to overall satisfaction of the indoor environment. However, a good aspect may compensate for a bad one. Laurentin et al. (2000) also tested the interaction between light and temperature conditions. They did not find an effect of ambient temperature on visual comfort, but they did find that colour temperature affected visual and thermal perception. In a follow up study, we will compare light with different correlated colour temperatures.

Self-assessed alertness was significantly influenced by both the temperature and the light condition. Bright light resulted in less sleepiness compared to dim light. This was also found in other studies e.g. (Chellappa et al., 2011, Smolders et al., 2012). In contrast to the effects on alertness, we did not observe an effect of light intensity on PVT reaction time. Besides the light effects, a cooler ambient temperature was associated with a higher alertness and also a faster reaction time. An experiment in office setting also found a reduced performance under a higher temperature (Lan et al., 2011). However, they did not test a cool environment, but they suggest that performance will decrease with thermal discomfort. To the best of our knowledge, not more is yet known about the interaction of light and temperature on alertness and performance.

Further analyses should reveal whether the intensity of light exposure during the morning affects thermo physiological responses and whether perceptions on light, temperature and thermal comfort interfere with each other.

In conclusion, we did not find a significant difference in thermal comfort between the dim and bright light setting. However, we did find that thermal comfort correlates with visual comfort of the perceived light colour. Also, light and temperature independently influence perceived alertness. Future research should be applied in an (artificial) office environment, to find out whether observed effects in this controlled setting, are also present in a more realistic environment. The results are important for the integral design of different indoor environmental parameters and efficient energy use in buildings.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

A preliminary study on the sensitivity of people to visual and thermal parameters in office environments

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Abstract
The evaluation of indoor comfort requires a thorough understanding of how human occupants perceive four indoor environmental factors: visual conditions, air quality, acoustic ambience and thermal conditions. Recent studies have found that overall comfort is more than the average effects of these four parameters. Beside their main effects, their mutual interactions play an equally important role in the *perception* of comfort. Thus, to progress regarding our understanding of global comfort, more effort is needed to further investigate the interactions between indoor environmental factors. For this kind of perceptual evaluation, it is necessary to conduct user studies. In these, subjects' evaluations need to be recorded in addition to the physical parameters that provoke them. Therefore, the sensitivity of people to their environment is the principal parameter around which the studies should be designed. This paper presents a first evaluation of the sensitivity of people to visual and thermal parameters in real office environments to establish a groundwork for future investigations. From this cross-sectional observational study, we concluded that possible effects of interactions between factors are difficult to see when the conditions are more or less comfortable. In that case people are not enough sensitive to environmental changes.

Keywords: visual sensation, thermal sensation, questionnaire, cross-sectional study, interactions.

1 Introduction

In recent decades, major efforts have been made to understand and control the factors that affect people's comfort, health and well-being inside buildings (WHO, 2000). These are influenced by physical and social factors such as age, gender, country of origin, working position, etc., but also by four indoor environmental factors: indoor air quality, acoustic ambience, visual and thermal conditions (Bluyssen, 1992). Over the last century, many studies have investigated the influence of such parameters on comfort, but only one at a time, which resulted in specific comfort models (e.g., thermal comfort) (Fanger, 1970), standards, guidelines (ASHRAE, 2004; ISO, 2005) and quantitative indices (Carlucci et al., 2015). Such models provide threshold values for light, temperature, noise and air quality when taken in isolation. However, all these indoor factors apply simultaneously and it is their combination that we experience and respond to (Bluyssen, 2013; Laurentin et al., 2000). It becomes clear that no single parameter of the indoor environment can be evaluated on its own. Thus, to improve our understanding of the influence of environmental parameters on human responses and perceptions in indoor environments, it is necessary to further study their combined effects and interactions.

Recently, the guideline ASHRAE 10P (ASHRAE, 2010) made an attempt to inventory these possible interactions, considering them exclusively as physical phenomena, e.g., that the visual radiation (both natural and artificial) produces heat which ultimately warms up the building and its occupants. However, interactions might also occur on a psychological and physiological level, implying that the environmental parameters could affect human beings indirectly, through not immediately recognisable ways. So, it is necessary to conduct user studies to investigate subjects' reactions and perceptions of particular environmental stimuli. In doing this kind of evaluation it is necessary to resort, at least to some extent, to methods from psychophysics. Psychophysics is defined as the quantitative branch of the study of perception, that examines the relations between physical stimuli and the sensations they affect (Baird and Noma, 1978). Psychophysics has been extensively used in both visual and thermal comfort studies (Hopkinson, 1963; Houser and Tiller, 2003; Nicol et al., 2012) and it has helped to understand the relation between people's sensations and the environmental parameters they are exposed to (e.g., apparent brightness and the light level). According to psychophysics literature, people are able to measure the stimuli they are exposed to and hence evaluate them with scales of sensation, discrimination tasks or detection tasks (Ehrenstein and Ehrenstein, 1999).

Therefore, it seems possible to study the effects of the interactions of indoor factors on comfort perception by conducting user studies. Subjects, exposed to a particular combination of environmental variables, should be able to grade them on a scale of comfort. By measuring the indoor environmental parameters and users' responses to them, it should be possible to determine the effects of indoor factor interactions on people's perception of comfort. To be able to set up and design proper user experiment, it is necessary to know in advance the parameters to study and how to measure them. Since users' perception is the means and the goal of studies on interactions, the sensitivity of people to stimuli in their environment can be a good indicator of how such studies should be designed. This implies that it is necessary to understand the ranges of values within which people are sensitive to environmental stimuli. In other words, what must be investigated is whether conditions in real environments are sufficient to provoke significant responses of users, or if studies must be run in more extreme environments.

Answering this question is the goal of this preliminary study. In particular, we will focus on the effects of visual and thermal parameters on comfort perception. Through a cross-sectional observational study, we will investigate if people are sensitive enough to visual and thermal stimuli in real conditions to be able to detect significant effects of indoor factor interactions on comfort perception.

In the next sections, the cross-sectional study will be described together with its scope and limitations. We will then report its findings, and finally provide some general observations about the shortcoming of the study and recommendations for future, more advanced research toward the evaluation of indoor environmental factors interactions.

2 Cross-sectional study

In building physics research it is possible to investigate people's response to the physical environment with two different methodologies: test room experiments and field studies. Some recent research has emphasized the need to conduct investigations in real spaces and specific context to achieve results that can be generalized outside the experimental setting into real architectural environments (Anter and Billger, 2010; Boyce, 2003; Humphreys et al., 2007). For this reason, as a preliminary study, we decided to conduct a field study to investigate the sensitivity of people to physical stimuli in real environments. In particular, a cross-sectional observational study was performed in late fall of 2015 in offices located at the Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland. The study was observational since it was not a real experiment where all the independent variables could be set or controlled. It was cross-sectional since the measurements on each subject were made at a given point in time without repetitions (Olsen and St George, 2004). The fact that neither the outcome nor the type of exposure are controlled by the researcher, and the entire population is under study, differentiate cross-sectional observational studies from cohort and case-controlled ones (Meirik, 2008). A cross-sectional study was chosen because it allowed to run a relatively quick and cheap study to look at prevalence in a population and identify associations (Mann, 2003). Moreover, fatigue or learning curve were not experienced by the subjects since they were tested only once (Coolican, 2014). As a downside, it was very likely to have confounding variables since the experimental environment was not controlled and many different subjects were tested (hence, there was a wide variation between subjective parameters). In addition, this kind of study may not provide information about cause-and-effect relationships since it offers a snapshot of a single moment in time without considering what happens before or after and it may lead to unbalanced groups of people to compare (Mann, 2003). For these reasons, the cross-sectional study can be just used as an exploratory study to determine the likelihood of a particular outcome of interest under exposure to relevant factors, which in our case were comfort perception and visual and thermal exposure respectively.

3 Research methodology

For the purpose of the study described above, three means of data collection were considered: (i) measurements of physical parameters, (ii) online questionnaire and (iii) observations of the researcher.

The thermal parameters taken into account were relative humidity, operative temperature and air temperature, while the visual variables were illuminance at the eye and task level, and glare. Figure 1 shows the devices used for measuring the physical parameters in offices. The air temperature and the operative temperature were recorded by two HOBO data loggers and one Tinytag Talk Thermistor Probe (with the pt100 probe placed inside the globe sphere) respectively, every minute. The two HOBO data loggers also recorded the relative humidity. The illuminance levels were measured with two LMT POCKET LUX 2A illuminance meters, one placed on the desk and the other one fixed on the lens of the camera used for taking HDR images. All sensors were previously calibrated against other reference devices.

People’s responses to the physical stimuli were recorded with an online questionnaire related to subjective responses (perception and personal control of the environment) and by direct observations of the researcher. Office conditions recorded at the moment of the measurements included office orientation, outside weather conditions, position of shading system, type of shading system, electric lighting (on/off), window (open/close), distance of subject from window and window position with respect to the subject.

Figure 1. Measurement devices for the preliminary study.

In this preliminary study the design of the questionnaire was particularly difficult since questions and scales from both the visual and thermal comfort points of view had to be considered and merged to give the same relevance and importance to the visual and the thermal part. For the design of the questionnaire the first decision to make was about the type of scale to use in the questions: semantic differential or Likert-type. The first category measures people's reactions to stimulus in terms of ratings on bipolar scales defined with contrasting adjectives at each end separated by empty spaces (Osgood, 1952). The second category includes five, seven or even nine pre-coded responses on a linear scale (Likert, 1932). This latter was selected for this study for two main reasons. First of all, the seven-point scale is the one traditionally used in the evaluation of comfort (e.g., the ASHRAE and Bedford scale). Secondly, the use of semantic differential scale may lead to misleading results since people interpret the empty spaces differently (e.g., they all represent comfort) (McIntyre, 1980). The second important decision for the design of the questionnaire was about its structure. The main constrains were the topics and the length. The focus should be on thermal and visual comfort, but overall comfort and personal control should also be investigated. On the other hand, the length of the questionnaire should not be too long, in order to allow participants to complete it in a maximum of 5-6 minutes. To respect these constraints, the questionnaire was structured in five main parts as following:

- overall comfort perception (including specific questions on noise, air quality and general questions on preferences for a comfortable environment);
- thermal comfort perception (including questions about thermal sensation, comfort and preference, but also about humidity and air movement);
- visual comfort perception (including questions about light intensity sensation, comfort and preference, but also about glare, quality and quantity of view to the outside);
- personal control (inquiring about actions that subjects took during the previous hour and that they would like to do at the moment of the questionnaire);
- personal information.

These parts were always presented in this order, except for the thermal and the visual sections that were randomised between subjects. Depending on scenario and users' responses, each questionnaire consisted of 24 to 30 questions. For example, if the light was on in the office, a question was asked to inquire about glare from electric light. In case an action was taken to improve comfort in the hour before the questionnaire, an additional set of 1-4 questions was asked to understand why the user did it. The same occurred if the user indicated that they wanted to do something to improve their comfort at the moment of the questionnaire, to inquire why they did not do that action until asked.

The first three parts of the questionnaire related to comfort were designed as Likert-type scale, while the last two related to personal control and information, were designed as multiple choice (with the order of the choices randomized within each question).

The sections about visual and thermal comfort were similar in order to be comparable. They began with three subjective measures for visual and thermal perception, i.e., sensation, satisfaction/comfort and preference. The questions about sensation were designed as a seven-point Likert-type scale. The ASHRAE scale was used for thermal comfort (de Dear, 1998) and a comparable one for visual comfort. The "sensation" questions were:

- Thermal: right now, how do you feel in this environment?
  Cold/ cool/ slightly cool/ neutral/ slightly warm/ warm/ hot
- Visual: how do you rate the current light level on your desk?
  Very low/ low/ slightly low/ just right/ slightly high/ high/ very high

The second category of questions regarding satisfaction was designed as a six-point Likert-type scale and referred to the general comfort scale from the SCATs project (McCartney and Fergus Nicol, 2002). The two "satisfaction" questions were:

- Thermal: how satisfied are you with the current thermal environment?
  Very satisfied/ satisfied/ slightly satisfied/ slightly dissatisfied/ dissatisfied/ very dissatisfied
- Visual: how satisfied are you with the current visual environment?
  Very satisfied/ satisfied/ slightly satisfied/ slightly dissatisfied/ dissatisfied/ very dissatisfied

Finally, the category about preference was designed as a five-point Likert-type scale and derived from the McIntyre thermal preference scale (used also in the SCATs project). The two "preference" questions were:

- Thermal: would you like the thermal environment to be:
  Much warmer/ a bit warmer/ no change/ a bit cooler/ much cooler
- Visual: would you like the visual environment to be:
  Much brighter/ a bit brighter/ no change/a bit dimmer/ much dimmer

The thermal comfort part also included questions regarding humidity and air movement (assessed with a seven-point Likert-type scale), whereas the visual comfort part also dealt with glare (Wienold, 2010), and the quality and quantity of view (assessed with a six-point Likert-type scale).

For the overall comfort part, a seven-point Likert-type scale was adapted to assess sound level and air quality (Levermore et al., 1999; Wargocki et al., 2000), whereas a general question on overall comfort was designed as a six-point satisfaction scale. Finally, the questions on personal control and behaviour were derived from Ackerly et al. (2012). At the end of the questionnaire, subjects were asked for demographic information (e.g., age and gender).

4 Results

27 offices were analysed in this study, with a total of 50 subjects. Of the subjects interviewed, 39 were men and 11 women. 19 subjects were between 21-25 years old, 26 between 26-30 years old and 5 above 30 years old. The majority of participants had lived in Switzerland for more than a year (41 subjects) and the rest for less than a year (4 subjects), or less than six months (5 subjects).

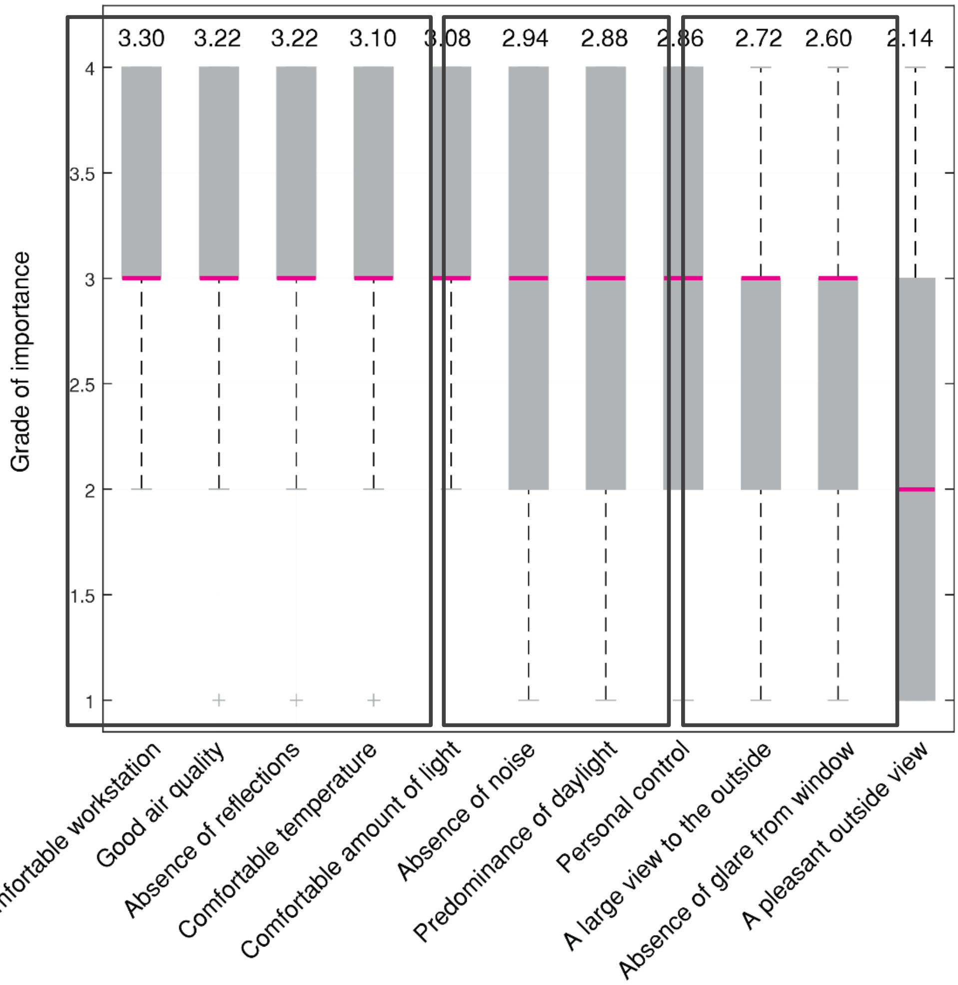

Figure 2. Box plot of the grades of importance of different factors influencing indoor overall comfort.

Within the overall comfort part, subjects were asked to grade the importance of different factors during working hours (4 = extremely important, 3 = very important, 2 = important, 1 = not very important). Figure 2 illustrates the results with a boxplot. The boxes are in order of importance according to the average score, indicated above of each box, with the most relevant factor being on the left hand side of the figure. It is possible to see that the factors can be grouped in three categories according to the spread of the boxes and prevalent grades. The first group includes high importance grades and small spread (factors 1-5), the second one refers to medium/high grades with a big spread (factors 6-8) and the last one illustrates factors with medium/low grades and a big spread (factors 9-11). Two visual and thermal parameters are graded almost in the same way and are in the first group of factors, namely, a comfortable temperature and a comfortable amount of light. Thermal environment and light are also considered the two most important factors in another question of overall comfort. Participants were asked to rank the four indoor environmental factors from the most important (first choice) to the least (fourth choice) in order to improve their comfort during their working hours. Figure 3 illustrates that thermal environment is the factor selected most often as a first choice, followed by light conditions as a second choice. Also, air quality was often chosen as the first factor to change, but still less than the thermal environment. Moreover, the sum of first and second choice votes for air quality is lower than the corresponding sum for light conditions.

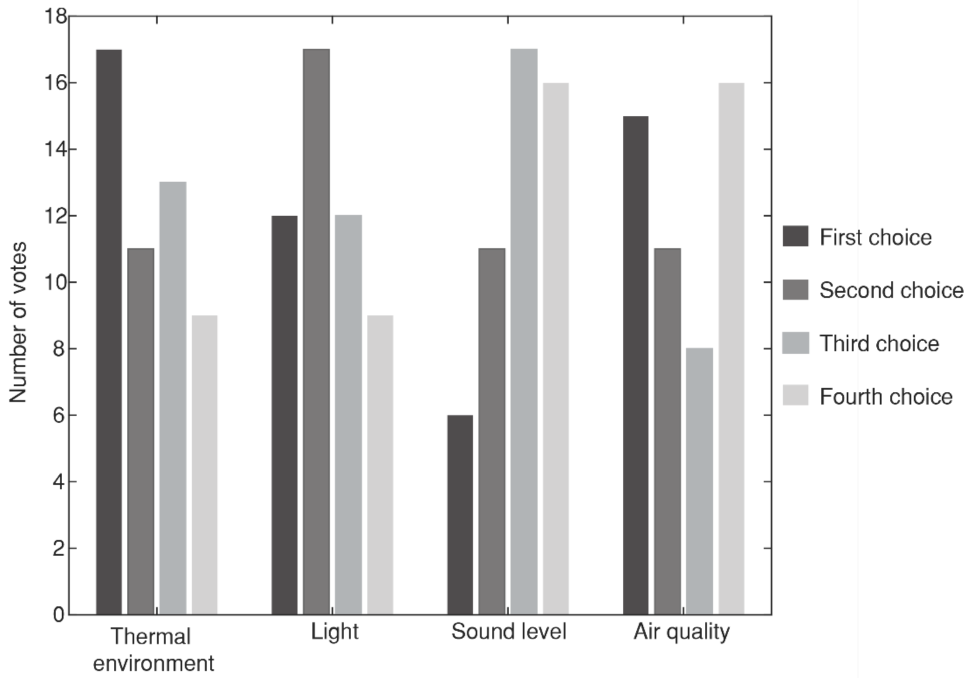

Figure 3. Bar plot of improvement choices.

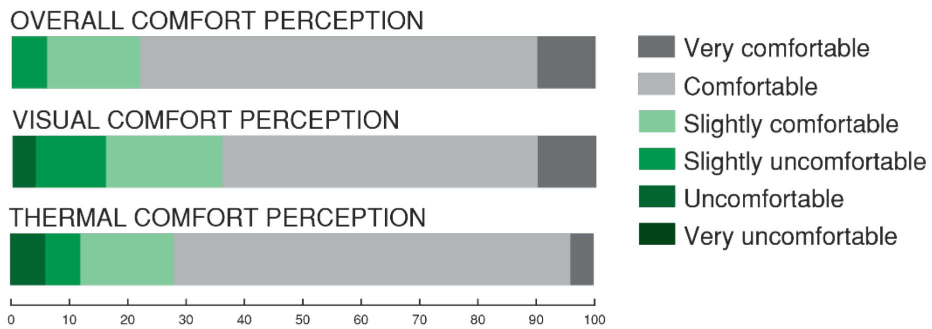

Figure 4. Stacked bar plot of comfort votes.

Figure 4 illustrates the comfort votes for overall, visual, and thermal comfort perception. In the three cases the grey part is the largest one, indicating that the majority of people was in comfortable conditions. This is due to the fact that both illuminance at the desk level and air temperature were in comfortable ranges and no other uncomfortable environmental factor was present. It is worth noting that some subjects expressed dissatisfaction with the visual and thermal environment (“uncomfortable” vote) but they did not always indicate overall discomfort, which was asked before. The relationship between visual and overall comfort perception as well between thermal and overall comfort perception was investigated with Spearman’s correlation coefficient. There was no significant relationship between visual comfort and overall comfort perception with ρ = -0.084 and p > 0.05. On the other hand, the two sets of scores of thermal and overall comfort perception correlated positively with ρ = 0.348 and p < 0.05. Assuming an effect size of 0.348 and a reduction due to the non-parametric test used, power was estimated at only 0.53. This means that the low effect size of the correlation must be balanced by a higher number of test subjects.

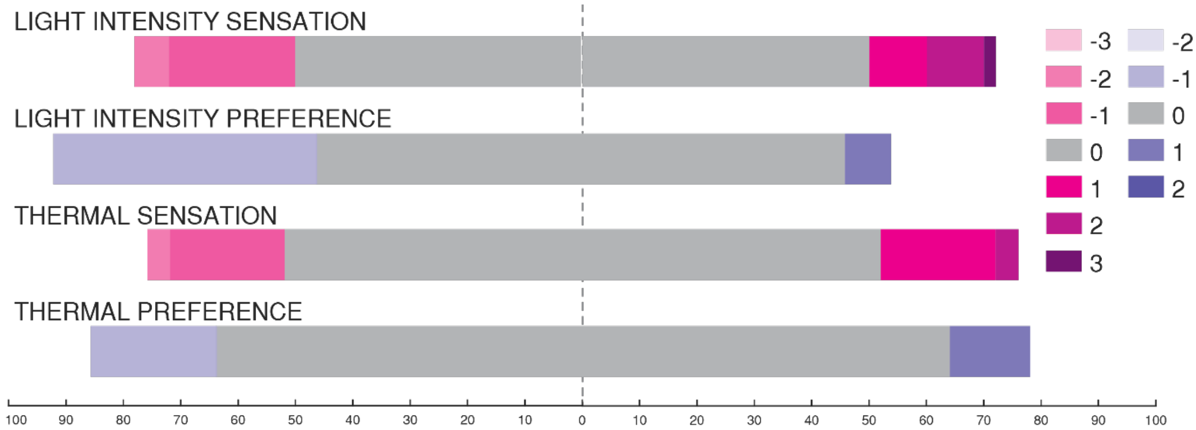

Figure 5. Stacked bar plot of sensation and preference votes.

For visual sensation (S): -3 = very low, -2 = low, -1 = slightly low, 0 = just right, 1 = slightly high, 2 = high, 3 = very high; for visual preference (P): -2 = much brighter, -1 = a bit brighter, 0 = no change, 1 = a bit dimmer, 2 = much dimmer; For thermal sensation (S): -3 = cold, -2 = cool, -1 = slightly cool, 0 = neutral, 1 = slightly warm, 2 = warm, 3 = hot; for thermal preference (P): -2 = much warmer, -1 = a bit warmer, 0 = no change, 1 = a bit colder, 2 = much colder.

Figure 5 shows the sensation and preference vote for both light intensity and thermal questions. In this case too, the majority of participants expressed satisfaction with the parameters, indicated by the grey part of the graph. Thermal sensation and thermal preference values are strongly positively correlated ($\rho = 0.68$ and $p < 0.01$). On the other hand, the correlation between light intensity sensation and preference is less strong (but still positive and significant with a $\rho = 0.315$ and $p < 0.05$). This can be also seen in figure 5, where more subjects wanted a brighter environment (left hand side of visual preference bar) compared to those that complained about a too low light level on their desk (left hand side of visual sensation). This result indicates that even if subjects were in comfortable conditions regarding the light level, they would have still preferred a higher light level on their desk. The importance of having different kind of scales to test subjects' perception is then proved, either for validating previous responses or for testing different perceptions.

Table 1. Spearman correlation analysis. * indicates significant result.

Independent variable	**Dependent variable**	**Spearman ρ**	**p**
Illuminance at desk level	Visual comfort perception	0.28	0.045*
	Light intensity sensation	0.45	<0.01*
	Light intensity preference	0.31	0.028*
	Overall comfort perception	-0.01	0.927
Air temperature	Thermal comfort perception	-0.06	0.675
	Thermal sensation	0.07	0.592
	Thermal preference	0.09	0.502
	Overall comfort perception	0.28	0.048*

Table 1 illustrates the correlations between the physical variables measured and the different evaluations of comfort. Only two variables are reported since they were strongly correlated with the other measures (illuminance at the desk level with illuminance at the eye level, and air temperature with operative temperature and relative humidity). The visual votes are positively correlated with the illuminance at the desk level (especially the visual sensation), whereas the thermal votes are not significant correlated with the air temperature. On the other hand, overall comfort is significantly correlated with air temperature (although with a small effect size) but not with illuminance.

Regarding the other environmental factors included in the questionnaire, participants were generally in comfortable conditions. They only complained about bad air quality (38% said it was slightly stuffy), not enough air movement (64% said it was slightly still or too still) and a bad quality of view to the outside (18% of participants were slightly dissatisfied and 14% dissatisfied). These results could have influenced the evaluation of overall comfort.

According to the personal control part of the questionnaire, 70% of the subject made at least one action during the hour before the questionnaire. Mainly, these consisted of opening the window to change air and to feel cooler (48% of the people who mad an action), turning on the light (28%), closing the window to feel warmer (25%), and removing a layer of clothing (20%). 54% of the subjects wanted to make and action during the questionnaire, mainly opening the window and increasing the temperature, but they did not do it because the level of comfort was still acceptable or they were too focused on their work. It is interesting to notice that not all the participants who took an action before the questionnaire expressed satisfaction with their conditions, whereas the majority of people who gave a high grade to the overall comfort did not want to take an action. In fact, there is a significant correlation between overall comfort and unwillingness to take an action, with $\rho = 0.471$ and $p < 0.01$.

Finally, we investigated the effects of the interaction of visual and thermal parameters. In particular, we conducted statistical analyses to see correlations between visual parameters and thermal comfort perception and thermal parameters and visual comfort perception. All the results were statistically insignificant. As illustrated in the previous section the majority of subjects expressed satisfaction with their conditions regarding overall, visual and thermal comfort independently of temperature and illuminance levels, which, in any case were mainly in a comfortable ranges (figure 6). The data points referring to subjects who expressed dissatisfaction with the environment were too few to draw significant conclusions about interactions.

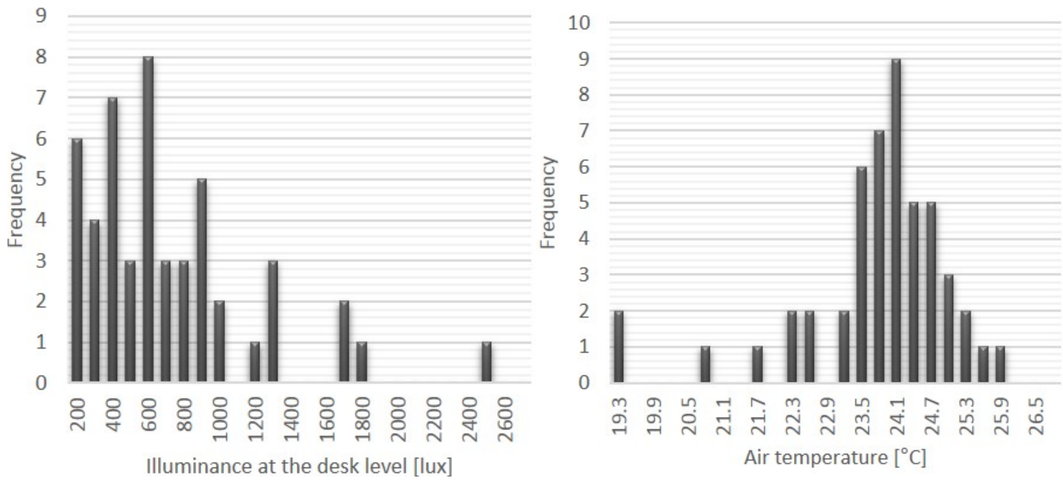

Figure 6. Recorded illuminance and temperature ranges.

5 Discussion

In the preliminary study we encountered some issues that were unexpected and that need more attention in future studies. The first set of issues are linked to the limits of a cross-sectional observational study. First of all, it allows to study just restricted ranges of parameters within which people are not sensitive enough to changes of those parameters, since they fall into comfortable values. Secondly, in a real office there are too many uncontrollable nuisance variables that make results difficult to interpret. A possible solution for these problems is to conduct experiments in a controlled environment, where the investigated variables can be changed until extreme limits (to provoke wider ranges of visual and thermal sensations) and the other variables can be kept constant or in limited ranges. Another solution is to conduct the same field study but in more extreme conditions (i.e., in summer, without cooling systems) and with more subjects to increase the power of the experiment (100 people is the number suggested by Nicol et al. for a transverse study).

The other problems were related to the questionnaire since it was difficult to analyse or some of the questions may have been confusing. For future studies on interactions we suggest the following changes:

- the order of all the questions need to be randomized. The majority of people expressed satisfaction with the overall conditions, but later complained about some other environmental factors when asked.
- The questions regarding visual and thermal perception need to be of the same type. In other words, according to the classification of Parsons (2014), they need to refer either to the environment or to the people (e.g. "how do you perceive the thermal environment?" or "how do you feel now?"). In our case, since personal questions regarding light cannot be asked, questions regarding the thermal aspect also need to refer to the environment and not to the personal sensation. We asked questions about personal perception *in* the environment that may have been misleading and may have resulted in the low correlation between air temperature and thermal votes (ref. table 1). In case of personal questions, physiological measurements may help the interpretation of data.
- Dependent variables need to be continuous in order to analyse the results with parametric statistical tests that are more powerful and provide more information than non-parametric alternatives. It is therefore necessary to transform the ordinal scale into a linear one.
- Different type of scales are necessary to be able to record comfort, sensation and preference, which makes it difficult to compare the results since those questions have different scales. It is therefore necessary to use comparable scales or to calculate a total index for each comfort (overall, visual and thermal).
- It is not sure that people understood all verbal descriptions of the environmental factors we wanted to be rated. It is therefore necessary to instruct participants on the meaning of the words, the scales used and how to apply them to rate a specific aspect of the environment (Houser and Tiller, 2003).

6 Conclusion

The aim of this preliminary study was to investigate people's sensitivity to physical stimuli present in real office environments. In particular, to understand whether users' responses were sufficiently different and strong to draw conclusions about indoor factors interactions.

The main finding is that, within the comfortable ranges of real spaces, people's perception of the indoor environment is mainly neutral. For this reason, a cross-sectional study does not allow the investigation of the interactions of indoor factors on comfort perception. Extreme conditions are needed to get significant results because people are somewhat oblivious to their comfort levels – except when asked specifically – in a large range of conditions around standard comfortable values.

The research conducted allowed to draw some other conclusions as well:

- rating scales must not be the only methodology adopted for the evaluation of subjects' perception. Physiological measurements, observations, adjustment and discrimination tasks should be implemented in the experiments.
- Thermal and visual parameters (especially temperature and amount of light) have been indicated to be among the most important factors influencing people's comfort in office environments. Hence, people are aware of their role and importance for achieving indoor comfort.
- The role of other parameters on comfort is not completely understood. For example, the "quality of the view to the outside" was rated as the least important at first, but was then among the parameters about which people complained the most.

The shortcomings and suggestions of this preliminary study will be taken into account in future investigations on indoor factor interactions. They are planned as test room experiments to have extreme visual and thermal physical conditions and, as a result, broader user responses. Moreover, it will be possible to have more control on the other nuisance variables and on the subjects (e.g., age, gender, clothes). Finally, besides questionnaires, different methods will be used to evaluate people's perception.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Indoor climate and thermal adaptation, evidences from migrants with different indoor thermal exposures

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Abstract

Previous adaptive thermal comfort research mainly emphasized the correlations between outdoor climate and thermal adaptation. In this paper, we explore the influence of indoor thermal experience on occupants' thermal adaptation, especially with regard to physiological adaptation. We also investigate whether people with distinct cold indoor exposures have different levels of physiological adaptation to cold environment. A comparative experiment, including both physiological measurements and subjective questionnaires, was conducted in China where winter indoor climates in the northern region (with pervasive district heating) are much warmer than the southern region (without district heating). Two subject groups were recruited, namely: (a) N-N group - subjects who had lived in the northern China with district heating all their life, and (b) S-N group - subjects who grew up in the southern region without district heating but recently moved to the north. The results indicate that S-N subjects who had lived their entire lives in cold wintertime indoor climates had slither physiological response and felt less uncomfortable in mild cold exposures than N-N subjects who lived in neutral-to-warm wintertime indoor climates. The findings suggest that indoor thermal exposures can also influence occupants' thermal adaptation, which can reserve as a reference to the future adaptive thermal comfort model.

Keywords: adaptive thermal comfort; physiological adaptation; thermal history; indoor thermal environment; thermal health

1 Introduction

Indoor environment quality is strongly correlated with people's comfort perception, wellbeing and work performance (Zhu and Luo, 2015). Questions such as 'what kind of indoor climate should be created' and 'how to create it' always capture building environment researchers' attention. Considering the increasing amount of energy that is consumed by HVAC services in large economic entities, it is essential to review the status of current indoor climate and shape its future roadmap.

1.1 The warming winter-time indoor temperatures

Since the application of HVAC technologies in buildings, people have the ability to control the indoor thermal environment freely. The rapid development of HVAC engineering technologies coupled with the increase in affordability enable us to create constant and uniformly neutral indoor thermal conditions easily by just pressing several buttons. A study from (Davis and Gertler, 2015) described the growing use of air conditioning in developing nations. Covering our homes, workplaces and transport, pervasive HVAC equipment seems to have become necessity for modern life. Not surprisingly, indoor climates in modern buildings are moving ever-closer to theoretically ideal conditions around thermal neutrality.

Figure 1 shows the temporal trends of wintertime indoor residential temperatures in countries such as the US, the UK, northern Japan and China. Compared with the situation a century ago, our wintertime residential temperatures were climbing and converging to the neutral comfort zone of about 20oC. Similar phenomena also happened in other developed countries like Denmark, France, Germany, Italy etc. (Mavrogianni, 2013). Some researchers even named this warming trend of wintertime indoor temperatures as 'homogenization of built environment' and 'comfort capsules' (Wilhite, 2009). Moreover, Figure 1 also reveals a 'knotty' problem in Chinese residential space heating. The wintertime residential indoor temperature gap between northern and southern China (refer to the Hot Summer and Cold Winter climate zone of China) is 'huge'. In recent years, more and more people in south part of China have been requesting space heating in residential buildings to improve their living standards. Many efforts have been made to deal with this problem.

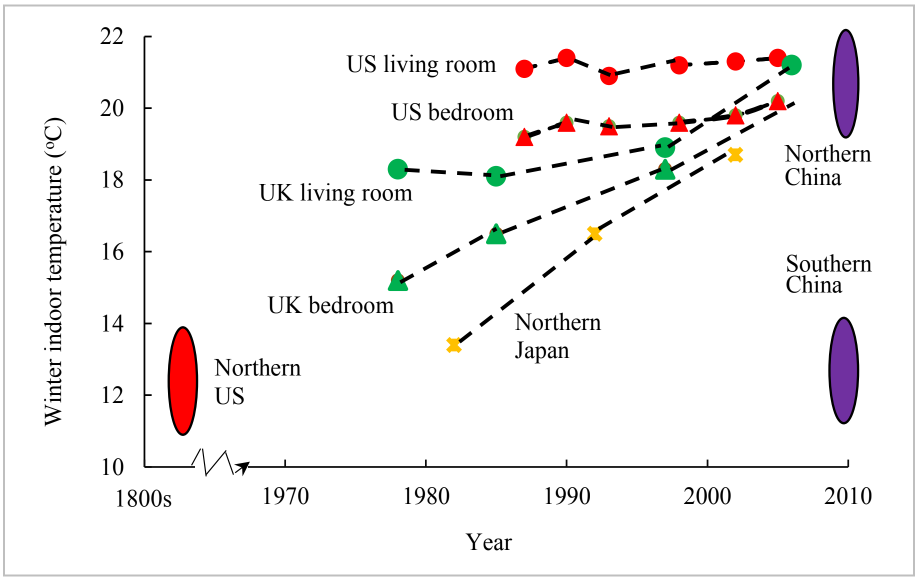

Figure 1 Long-term trends of wintertime residential temperatures in the UK, the US, northern Japan and China

1.2 Statement of the problem: indoor climate and thermal adaptation

Both the indoor warming drift posed in Figure 1 and huge wintertime indoor temperature gap between southern and northern China beg the question as to whether long-term indoor thermal experience would shift occupants' thermal comfort perception. Although previous adaptive research has managed to shed some useful light on how occupants adapt to thermal environments, the evidence relevant to the driver of thermal adaptation (indoor or outdoor thermal exposures?) has mostly been anecdotal. If we carefully look into existing adaptive models adopted in current standards, all of them simply utilized prevailing outdoor temperatures as the parameter to represent thermal history, which means they all regarded outdoor climates as the only adaptation driver. However, what about the influence of indoor thermal exposures on thermal adaptation? People spend most of their time living in indoors. There is no reason to ignore the influence of indoor thermal exposures.

1.3 Objective

This study focuses on the impacts of indoor thermal exposures on occupants' physiological adaptation, and ask the question whether people with distinct cold indoor exposures have different levels of thermal adaptation to cold thermal environment.

2 Materials/Methods

2.1 Subjects recruitment

Two subject groups with distinct indoor thermal histories were recruited on the basis of their wintertime indoor thermal exposures (Table 1). N-N group consists of subjects who had spent their entire life in the heated northern region with neutral-to-warm wintertime indoor climates (with space heating both at home and school dormitory). S-N group consists of subjects selected from those who grew up in the hot summer and cold winter climate zone without space heating facilities (no space heating both at home and school dormitory) and recently moved to north. Each group contains 15 healthy volunteers who did not know much about thermal comfort and had no smoking habit. All the subject were asked to do some physiological measurements and subjective response in a climate chamber. To exclude the influence of gender, age, weight and etc., all the subjects were male college students. Table 1 summarizes their profiles. Although the N-N subjects had slightly higher heights, their BMI indexes were controlled in normal range and were very close to S-N group.

Table 1 Subjects' profile

Group	Description	Sample size	Age (year)	Height (cm)	Weight (kg)	BMI
N-N	grow up in cold climate zone with district space heating	15	20.5±1.3	176.3±6.2	65.6±4.9	21.1±1.1
S-N	grow up in hot summer and cold winter climate zone without district space heating	15	18.8±0.7	171.9±3.3	63.3±4.5	21.6±1.2

2.2 Experimental protocol

Figure 2 shows the detailed experiment protocol. When the experiment began, subjects had 10 min to calm down, change clothes, learn how to vote, as well as to wear physiological sensors. All the subjects were required to wear uniform clothes (underwear, T-shirt, shorts, socks, and sport shoes) with a total clothing insulation of 0.42clo. The reason that we chose light dress mainly lies in the convenience to wear physiological sensors. Then, the subjects were asked to stay in a neutral temperature (26^{o}C) for 30 min. Both physiological measurement and subjective questionnaire were started from the beginning of this phase. Finally, the subjects moved to other cold cases (24/21/18/16^{o}C) for 60 min.

To ensure the validity of experimental data, subjects were reminded to avoid caffeine, alcohol, smoking and strenuous activities, and to sleep well in the day prior to the experiment. At the beginning of recruitment, voluntary subjects were informed that there would have some cold exposures and that they were free to interrupt the experiment at any time if they felt unwell. For each subject, the temperature cases were ordered randomly.

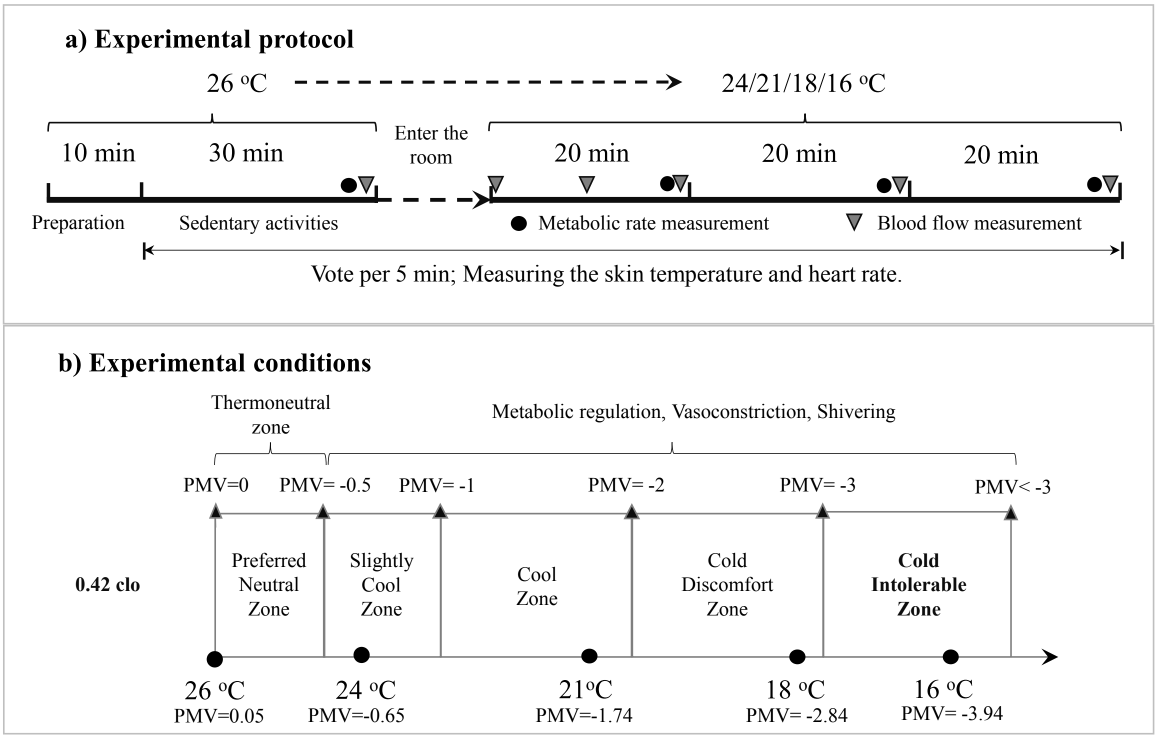

Figure 2 Experimental design

Physiological parameters such as metabolic rate, skin surface blood flow rate, skin temperature, and heart rate were monitored as well. The time to measure these physiological parameters has been illustrated in Figure 2. For metabolic rate determination, the Vmax Encore metabolic cart (SensorMedics, USA) was utilized to measure the oxygen consumption and carbon dioxide production of the human body. Heart rate was monitored by Equivital heart rate measurement (Hidalgo, UK) during the whole 90 min experimental period. Skin surface blood flow rate was measured by PeriFlux 5001 (Perimed, Sweden). Skin temperatures were measured during the entire 90 min exposure by Vitalsense Dermal Patch sensors with a precision of 0.1 oC (Respironics, USA). The sensors were attached at nine body areas: forehead, chest, back, upper arm, forearm, hand back, thigh, calf, and ankle. The mean skin temperature was calculated using the following equation:

$$T_{ms} = 0.07T_{forehead} + 0.18T_{chest} + 0.18T_{back} + 0.07T_{forearm} + 0.07T_{upper\ arm} + 0.05T_{hand\ back} + 0.19T_{thigh} + 0.19T_{calf} + 0.19T_{ankle}$$

To collect subjective responses, subjects were asked to vote every 5 min. The questionnaire includes a seven-point thermal sensation vote (TSV), a seven-point thermal comfort vote (TCV), self-reported shivering or sweating rate, and other miscellaneous information. To compare the data from different cases, Independent Samples T Test and Paired-Samples T Test were utilized. When the test result shows significance of difference, it is labeled as ‘p<0.05’ or ‘p<0.01’, otherwise, ‘p>0.05’ was labeled.

3 Results

3.1 Physiological response

Figure 3 compares the physiological response between N-N group and S-N group. The data includes results from the steady state of each temperature case. In general, when temperature dropped from 26°C to 16°C, the average metabolic rate increased nearly 14%, the mean skin temperature dropped from 33.8°C to 30.9°C, the average blood flow at left middle fingertip decreased from 350 unit to 213 unit, while the heart rate did not show significant changing.

Further comparing the differences between the two subject groups, it can be seen that no significant difference exists in metabolic rate and heat rate. However, the mean skin temperature and blood flow showed some differences between these two groups. Especially in mild cold conditions (21°C and 18°C), S-N subject group had higher mean skin temperature and higher blood flow. In conditions close to thermal neutrality (26°C and 24°C) and intolerable cold temperature (16°C), no significant differences were found.

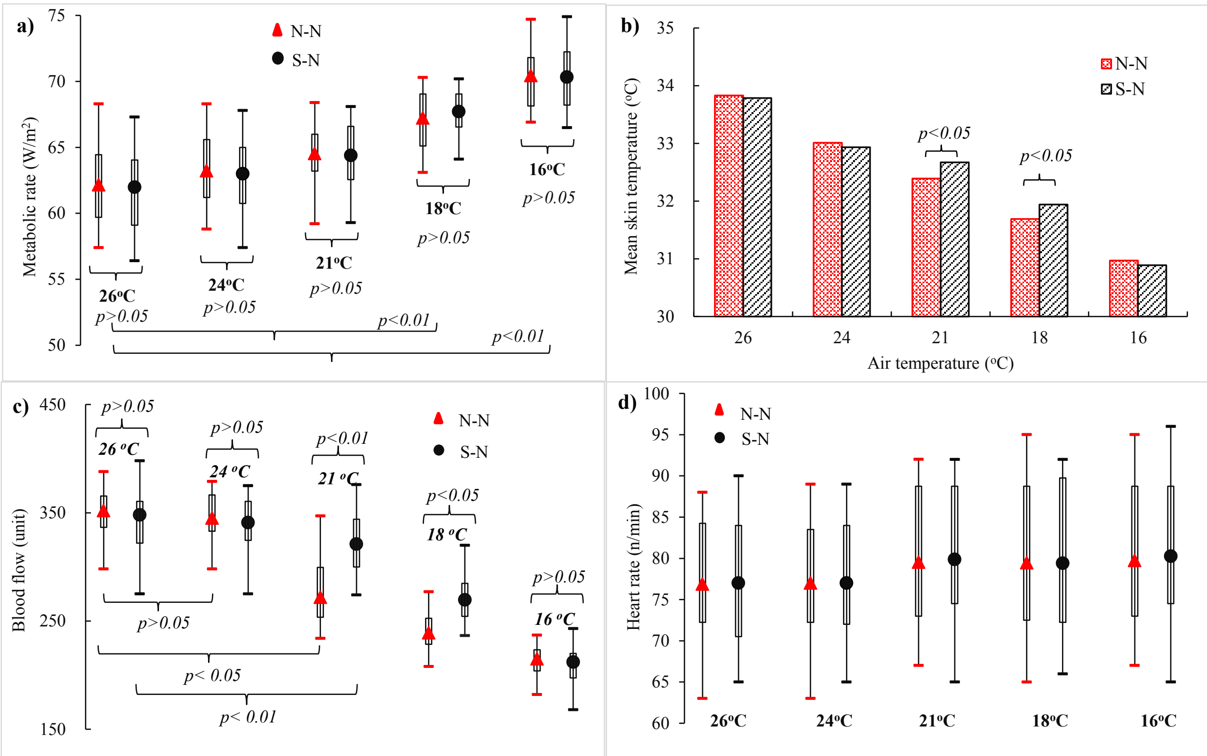

Figure 3 Physiological response differences between N-N group and S-N group: a) metabolic rate, b) mean skin temperature, c) blood flow at left middle fingertip, d) heart rate

Figure 4 illustrates the changing process of mean skin temperature in different experimental cases. Mean skin temperature decreased with the drop of ambient temperatures. In 21°C and 18°C cases, N-N subject group had slower skin temperature decreasing rate during the adjusting process and lower skin temperature after reaching steady state. Similarly, the differences only exist in 21°C and 18°C cases. No significant differences were observed in other temperature cases.

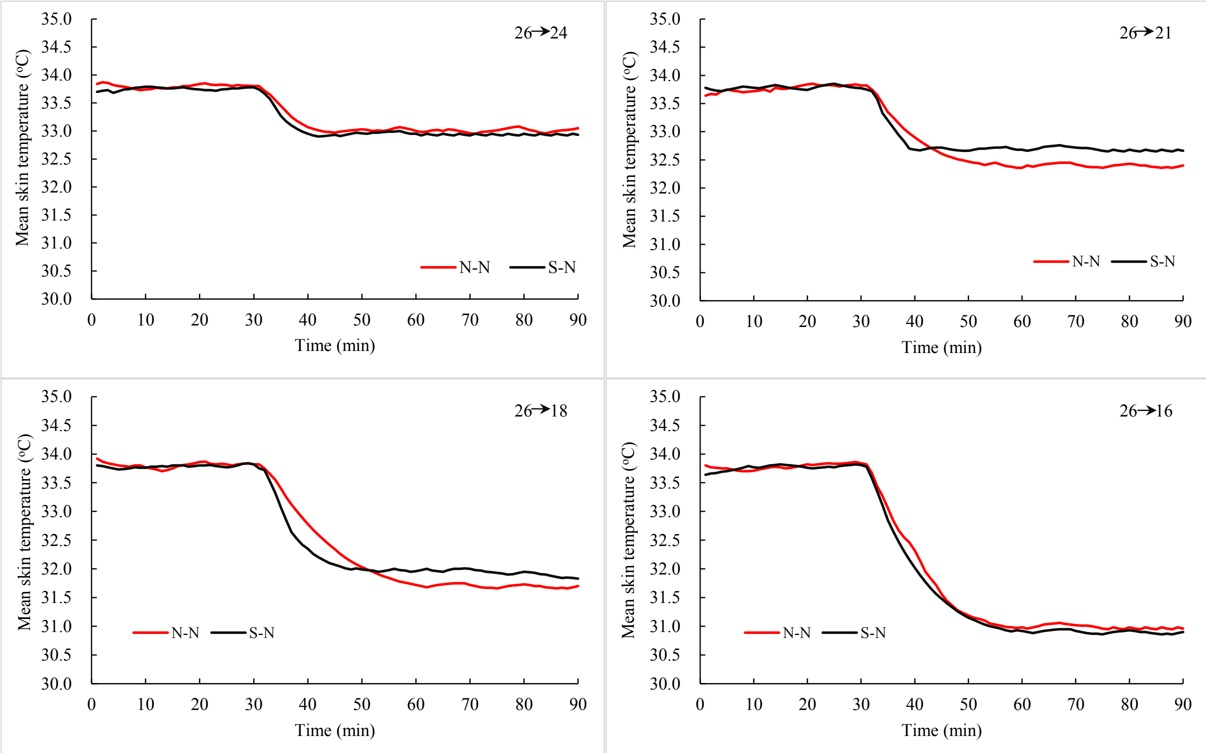

Figure 4 Comparison of mean skin temperature in different experimental conditions

3.2 Subjective perception

Figure 5 compares the subjective thermal sensations and comfort perceptions between N-N group and S-N group. The data includes results from the steady state of each experimental case. Compared with N-N group, S-N group felt less cold and less uncomfortable when they were exposed to mild cold conditions (21°C and 18°C). In other neutral temperatures (26°C and 24°C) and intolerable cold case (16°C), no significant differences between these two groups were found.

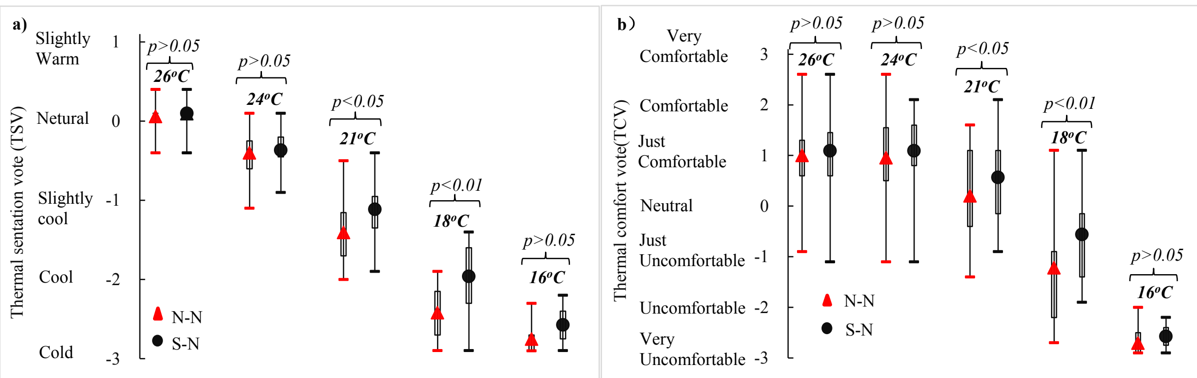

Figure 5 Subjective perception differences between N-N group and S-N group: a) thermal sensation vote, b) thermal comfort vote

4 Discussion

4.1 Physiological adaptation to cold

Figure 6 further summarizes the regression line of average metabolic rate and temperatures. The metabolic rate in 16oC were 13.6% higher than that in neutral case. And this increasing trend happened in both N-N and S-N group. It is noteworthy that N-N subjects reported higher shivering rate (which is closely related with human body heat production) in 21oC and 18oC, while there was no significant difference in metabolic rate between these two groups. What is the underlying mechanism behind this phenomenon? Some recent research conducted by van Marken Lichtenbelt's group reported a kind of fat called "brown adipose tissue" (van Marken Lichtenbelt, 2009). The brown adipose tissue is closely related with cold-induced non-shivering thermoregulation (thermogenesis in the absence of shivering) of human body. Their research results indicated that cold exposure would increase brown adipose tissue mass and activity (van Marken Lichtenbelt, 2009). According to their findings, S-N subjects may have increased brown adipose tissue mass and activity, because they lived in colder wintertime indoor temperatures. And this might be the reason why S-N subjects had higher shivering rate but the same metabolic rate with N-N subjects. However, it should be noted that this inference needs to be further confirmed.

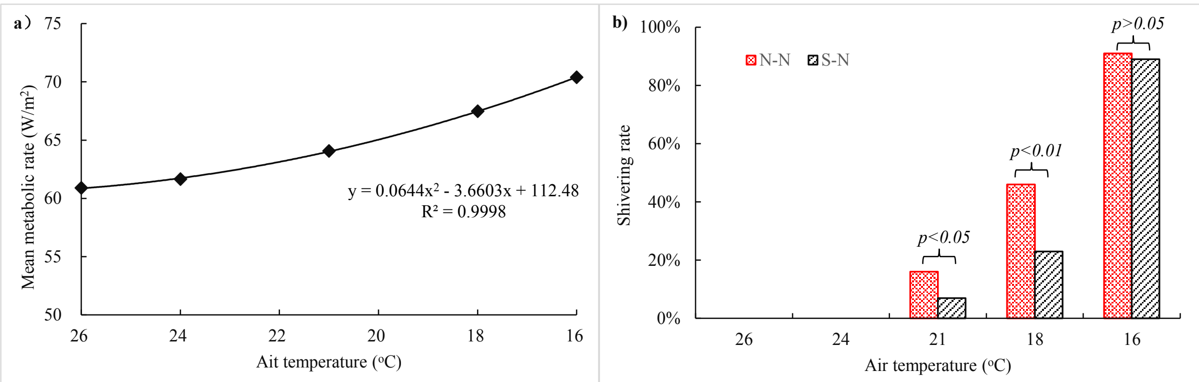

Figure 6 Increasing trend of average metabolic rate and self-reported shivering rate

4.2 Indoor cold exposure and comfort perception

Figure 7 further compares the regression lines of mean TSV and PMV. rPMV was revised PMV by using the measured metabolic rate in each temperature case. Firstly, the slope of TSV regression line for S-N group is slighter than that for N-N group, which indicates that S-N subjects felt less cold than N-N subjects did. This results is consistent with the physiological test introduced above. Normally, a colder TSV correspondents to lower skin temperature, lower skin surface blood flow rate, higher metabolic rate, and higher self-reported shivering rate. All this results collectively point to a conclusion that subjects with colder indoor exposures had slighter physiological response and felt less uncomfortable in mild cold conditions. Secondly, the "scissors difference" (different slopes of regression lines) between PMV and TSVs indicates that PMV overestimated subjects' cold sensations. This may be resulted from the inaccurately assumed metabolic rate (1.1 met). If the actual measured metabolic rates were utilized, the rPMV was quite close to the TSV from N-N group. This phenomenon reminds us to consider metabolic rate more carefully in future comfort studies. However, it should be noted that rPMV still overestimated the actual sensations of S-N group.

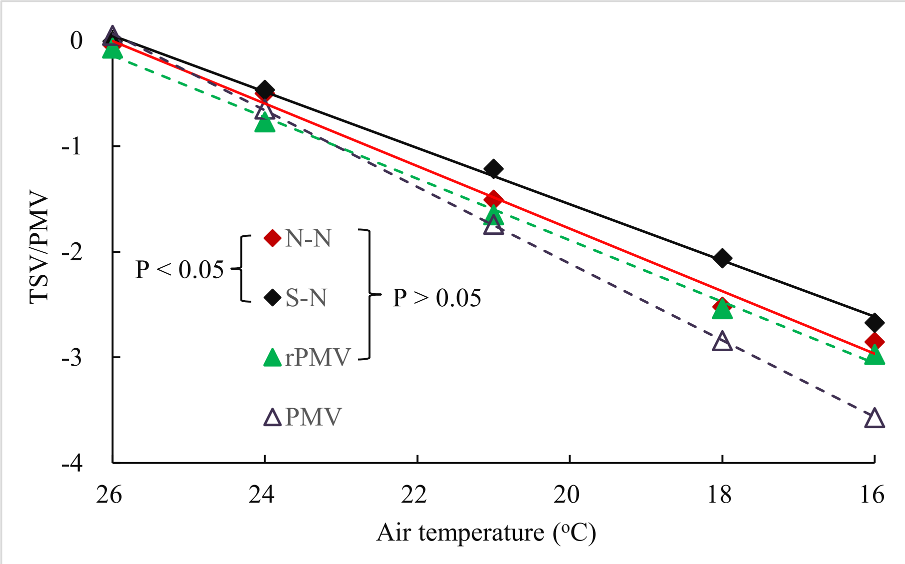

Figure 7 Comparison of TSVs, PMV and rPMV

5 Conclusions

Human body itself can adapt to cold environment to some extent. At 16°C, the metabolic rate increased 13.4% referring to the value at 26oC. The self-reported shivering rate also increased drastically in cold exposures. The skin surface blood flow and skin temperature decreased with the drop of ambient temperature.

Subjects acclimated to cold indoor climate had slighter physiological response and felt less uncomfortable during mild cold exposure. In 21°C and 18°C cases, S-N subjects had higher skin surface blood flow and higher skin temperature than N-N subjects did. And S-N subjects felt less cold and less uncomfortable.

Acknowledgement

This study was funded by Innovative Research Groups of the National Natural Science Foundation of China (51521005) and the Natural Science Foundation of China (51308396 and 51508300).

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WINDSOR CONFERENCE 2016

MAKING COMFORT RELEVANT

AFTER DINNER EVENT

Just Exactly How Cool are You?
The Clothing Quiz

Invited Chairs: Dennis Loveday and Susan Roaf

WORKSHOP 3.1

Comfort in Ventilated Spaces

Invited Chairs: Jarek Kurnitski and Adrian Pitts

WS3.1: Comfort in Ventilated Spaces.
Chairs: Jarek Kurnitski and Adrian Pitts

This workshop is dedicated to comfort in highly ventilated spaces. Such spaces are often in retail stores, where ventilation in high rooms may or may not be used for heating and cooling purposes (all air systems or other systems), or in transition spaces (foyers, lobbies, corridors, atriums, etc) in other non-residential buildings. In highly ventilated spaces there is normally a higher than average level of air movement; avoiding stagnant zones and controlling stratification are issues in varying conditions. Another common area is in comfort for warm humid climates where high ventilation rates are commonly used. In such circumstances the convective effect is much enhanced and will impact on the heat transfer from the body. Because of the high ventilation rate the amounts of energy required to maintain comfort can be high (both for heating and cooling); one option may be to compensate for lower (or higher) air temperatures by use of modified radiant temperature so as to balance the body heat flow. But such radiant impacts and asymmetries can have their own negative impacts. The workshop will discuss the occupant perception and other comfort parameters in highly ventilated spaces or in those where radiant temperature is used to attempt to compensate for the air temperature. Among parameters under interest, the impact of odours on occupant perception of ventilation needs will also be explored.

Proceeding of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
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Application of Wind Towers in the Australian Residential Context – A Wind Tunnel Assessment of Thermal Comfort Performance

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Abstract

This study explores wind tower applications for passive cooling in contemporary Australian apartment buildings located in subtropical Sydney, Australia. Wind towers have been used as a natural cooling system since 1300 BC in vernacular architecture throughout Persia and neighbouring countries and recently in modern constrictions in US and UK but to date, nothing in Australia. This research project investigates the comfort potential of wind towers as a substitute for mechanical cooling to reduce electricity demand and greenhouse gas emissions. The research method has two main components; first, wind-tunnel experiments derived pressure distributions around a sealed model of a four-story apartment building scaled at 1:100 in an isolated neighbourhood context. Secondly, internal occupied zone velocity coefficients were derived for calculation of indoor velocities throughout the six warmest months in Sydney. Results indicate that during Sydney's warm hours (>23°C) the elevated indoor air speeds resulting from the wind-catcher produced a cumulative total improvement in indoor comfort temperatures (ΣΔSET*) of 1368 degree hours compared with the default case of the same apartment building in through-window cross ventilation mode.

Keywords: natural ventilation, wind tower, wind tunnel, indoor air speed, thermal comfort

1 Introduction

The drive toward an energy efficient and sustainable built environment has been gathering momentum since the beginnings of postmodernism and eco-technology styles in the early 1970s. It presents challenges for the architects and engineers to simultaneously increase renewable energy consumption, decrease reliance on fossil fuels, and abate greenhouse gas emissions, all without adversely impacting occupant comfort, health and wellbeing. Enhanced exploitation of natural ventilation in tropical and subtropical buildings holds strong potential for meeting all these objectives.

The impact of air movement on the thermal comfort of building occupants has been extensively studied and it is generally accepted that enhanced indoor air movement can offset elevated indoor air temperature by removal of excess body heat through evaporative and convective processes (e.g. McIntyre 1978; Arens et al., 1986; Bauman et al., 1989; Tanaba and Kimura 1989; Ernest et al. 1992; Aynsley 1998; Nicol and Roaf 2007; Arens et al. 2009; ASHRAE Std 55, 2013).

Wind towers have been used extensively in Persia and the Persian Gulf region since circa 1300 BC as a traditional natural ventilation system (Roaf 1989, Foruzanmehr 2012; Saadatian et al., 2012). The wind tower, or "badgir" (translated to "wind-catcher" in Persian language) is a tower mounted on the roof of a building, reaching down into the living rooms, or sometimes to the basement of a construction. Being elevated above the roofline the tower is exposed to faster winds than is the fenestration on building facades. The exposed tower induces a large pressure distribution around the exterior surface of the wind-tower and the internal partitioning of the chimney channels the flow to the interior spaces below (Roaf 2008; Roaf 2009, Montazeri et al., 2010; Jones and Kirby 2010). Internal partitioning in the chimney using wet cloth, further cooled the air. Figure 1 shows various configurations of vernacular wind catchers in the city of Yazd in Iran.

Figure 1, Persian Wind Towers, sources: http://www.ichto.ir, http://www.yazdcity.ir/data/, http://www.nlai.ir/

1.1 Background of the research

Several studies have been carried out on the function and efficacy of the vernacular wind catcher. Bahadori (1985, 1994) reported that the indoor airflow rates generated by the wind catcher could be escalated by raising the tower's height. Karakatsanis et al. (1986) proposed that an adjoining courtyard in the building could improve the cooling performance of the wind catcher. The angle of wind and the configuration of the tower's openings were also proposed as important parameters influencing the overall efficiency of the badgir (Karakatsanis et al., 1986). Roaf (1989) reported field observations collected in the 1970s from Yazd in Iran's hot-dry climate region, regarding the thermal performance and the indoor temperature reduction potential of wind catchers.

Elmualim and Awbi (2002) found that the square cross-section wind catcher showed a higher efficiency compared to the circular ones when exposed to the same wind speed. Montazeri and Azizian (2008) and Montazeri (2010) concluded that the airflow rate inside the duct would decrease by increasing the number of wind catcher openings. Similarly, Khan et al. (2008) found that the one-sided wind tower performed better than a multi-sided one facing the same wind direction. Conversely, Hosseinnia et al. (2013) reported that the increase in the internal wet partitions of the tower could decrease air temperature by increasing the evaporative cooling performance of the tower. In another study Montazeri et al. (2010) noted that the efficiency of wind towers depended on the maximum pressure difference between inlet and outlet air.

The MacCabe and Roaf (2012) parametric study investigated impacts of wind tower height and cross-sectional area on the thermal environmental and adaptive comfort performance of three numerically simulated wind catchers. They concluded that changing the dimension of the towers directly influenced their thermal performance, while the whole house behaves as a self- regulating thermal system. Dehghan et al. (2013) modelled three detached, one-sided wind catchers and observed that an inclined roof on the wind tower enhanced the airflow inside the tower duct compared to flat-roof and curved-roof alternatives. Calautit and Hughes (2014a) reported that for a multi-directional commercial wind tower the wind angle of 45° could create the highest airflow rate in the duct compare with the other wind directions.

1.2 Gaps in the literature

Extensive published research has mostly been conducted on the efficiency of either detached wind-towers (i.e. no building underneath), or wind-towers attached to one single room, mostly to measure the airflow rate inside the duct of the tower or the induced airflow at the exit of the tower. The urban terrain context, external building design, building height, building width, building roof configuration and location of the wind tower on the roof of the building have not been investigated in extant research literature. Meanwhile, internal aspects of the building, configuration of rooms and other internal partitions, as well as characteristics of ducts, including the nature and number of direction changes in the duct-work and associated energy loss and have been ignored in the literature to date. Fundamental architectural aerodynamics literature emphasises pressure coefficients over the inlet and outlet openings in the building façade as the primary drivers of wind-induced ventilation. Therefore the external design of the whole building and its broader urban context, as well as the orientation and the location of the tower in relation to the base building are significant to the natural ventilation processes. Only a handful of wind tunnel experiments have been carried out up till now, and most of them set up a scale model of the badgir inside the wind-tunnel, but the model building to which it conducts ventilation air has usually been located underneath the wind tunnel's test section i.e. isolated from the flowing wind (Elmulim 2006; Montazeri et al, 2010; Montazeri and Azizian, 2008; Montazeri and Azizian 2009; Montazeri, 2011; Calautit and Hughes, 2014a; Calautit and Hughes 2014b).

On the other hand there are many studies on the wind driven natural ventilation of buildings through normal fenestration openings in the façade, and the impact of the enhanced indoor air movement on the thermal comfort of the building occupants (e.g. Ernest et al., 1991; Fountain 1991, Enest et al., 1992; Kato et al., 1992; Jiang et al., 2003). But, as with the badgir literature reviewed above, most of these investigations modelled a single room, ignoring urban terrain, morphology, and the building geometry effects on the pressure discharge and indoor air distribution have not been investigated yet.

There is also room in the badgir literature for a comprehensive comparison between ventilation rates induced by the wind-catcher, and the base-case of normal cross-ventilation through the building's fenestration.

1.3 Objectives

In response to the gaps in the research literature identified above, the present study aims to investigate a) the impacts of the external design and the orientation of the wind tower in relation to the base building, b) the effects of surrounding urban morphology on the surface pressure of the construction, c) the influence of the pressure gradient over the building on the indoor air movements, and d) the indoor thermal comfort performance of the wind tower compared with cross ventilation of the building in Sydney located in Australia's eastern seaboard, humid sub-tropical climate zone.

2 Wind tunnel experiments

2.1 Design Process

a) Building design

The apartment building design adopted in this study is typical of the medium–density, medium-height apartment development being widely forecast to increase in popularity in many Australian cities by 2030 (NCCARF, 2013). The National Climate Change Adaptation Research Facility (NCCARF) published a framework for adaptation of Australian households to heat waves in which the thermal performance as well as the energy consumption of five popular apartment developments were analysed; the model design of this study is based on one of the reported buildings. Each apartment spans two storeys and two apartments are stacked vertically, making the entire development four storeys in total. Each apartment has three bedrooms located on its upper floor, and the apartment total floor area is 159 m^2 while the total building height is 12 m.

The apartment's internal layout is open plan and the absence of internal zoning combined with a large west-facing area of glass contributes to a high cooling demand. Living room, kitchen, and dining room were demonstrably uncomfortable during the NCCARF four-day heat wave during which daytime temperature maxima exceeded 35^{o}C and negligible hours fell below 26^{o}C (NCCARF, 2013). Total cooling energy and peak demand for the four-day heat wave for the case study apartment located in Richmond, western Sydney, was reported to be 1018 MJ and 15.5 kW respectively.

Changing the orientation of the building to optimize the wind resource as well as installing a wind tower with two horizontally arranged wind catcher openings (one per apartment) in the south façade of the building are the main modifications to the NCCARF design for the present study. Changing orientation turned the apartment's living area towards the south, rather than facing west where high heat loads were gained through large glazed areas during the hottest time of the day. The latter change was effected by affixing the wind tower to the basic floor plan (Figure 2).

b) Wind catcher design

A physical scale model of a wind catcher rising above the general roof-line of the construction has been developed at the scale of 1:100. Wind-catcher orientation as well as its openings were optimised based on the a) wind climatology studies for western Sydney (inland), and b) research literature regarding the geometry of tower cooling performance. The result was two single-sided wind catchers with an inclined roof affixed to the south façade of the apartment development. Each apartment has its own opening in the wind-tower, arranged side-by-side. The openings of the towers (1.5m in vertical dimension) were tested in south, north, and east orientations. Three different wind catcher opening heights were implemented in the scale model for parametric study; the centre points of the three different openings were 0.75m, 3.0m, and 6.75m above roofline respectively (full-scale).

c) Urban landscape morphology

Three different scenarios were designed for analysing the wind catcher cooling performance in the boundary layer terrain wind tunnel; a) isolated building model located in a terrain with a boundary layer category 2 as defined in Standards Australia (2011), b) building embedded in a residential complex located in the corner of surrounding neighbourhood (heights of the neighbouring buildings vary from 10 to 16 m in the full scale, and c) the study building surrounded by buildings of various heights buildings (Figure 3). Comfort cooling performance of the wind catcher in scenario (a) is analysed and reported in this paper.

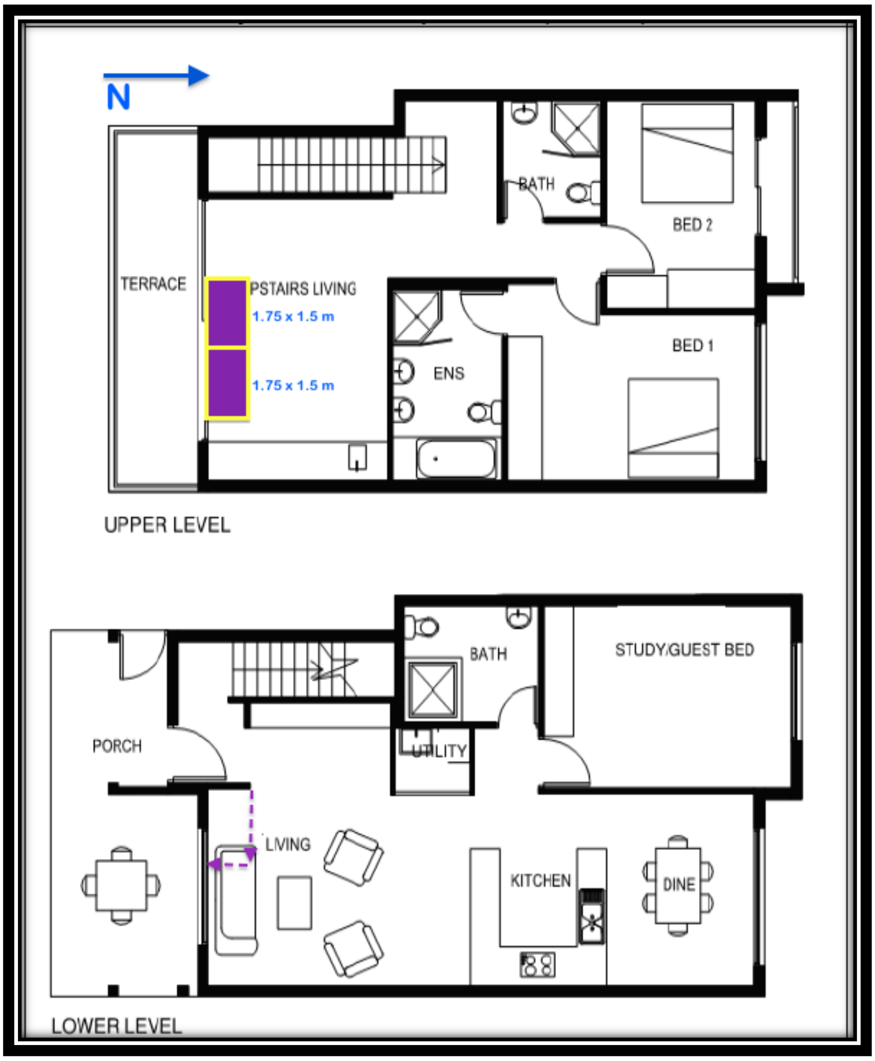


Figure 2, Upper and lower level Plan view demonstrating location and dimension of the towers, Basic plan source NCCARF 2013.

2.2 Boundary layer Wind tunnel

Aiming to calculate the wind-driven indoor air movement in the scale model apartment building, the surface pressure measurement experiments were conducted in the boundary layer wind tunnel located in Cermak Peterka Peterson laboratory in Sydney, Australia. The wind tunnel has a closed circuit configuration with dimensions of 20 m in length, 3.0 m in width, and 2.4 m in height with blockage tolerant roof. Wind tunnel fan is a variable frequency drive; boundary layer thickness is up to 1.5 m (Figure 4). The approach flow processing section is covered with a matrix of roughness elements on the floor and generating turbulence according to the desired terrain type (boundary layer category 2 for the this study (see Figure 3). The pressure sensors and velocity instruments were mounted below a rotating turntable with 3.0 m diameter in the working section. A PC-based data acquisition system located immediately outside of the tunnel test section was used to collect the experimental data

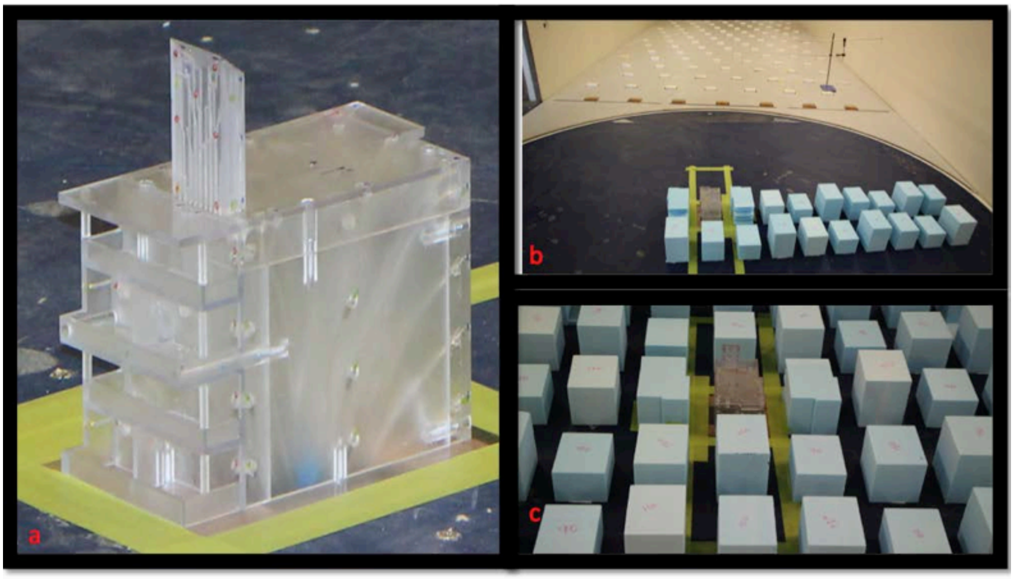


Figure 3, Boundary layer wind tunnel experiments. scenario a, scenario b, scenario c

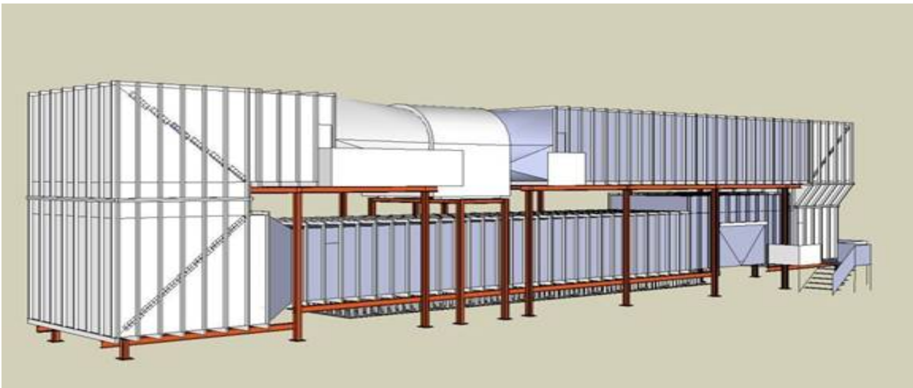


Figure 4, CPP closed-circuit wind tunnel

2.3 Model characteristics and construction

A 3D-printed stereo-lithography scale model of the apartment building was covered with 423 individual pressure taps over all external surfaces of the model. The 1:100 scale model was sealed so that the surface pressure could be measured over areas corresponding to fenestration locations on the base design. The overall dimensions of the model are H= 19 cm, L= 17 cm, and W= 10 cm for the height, length, and width respectively. For pressure tubing, first, the model was de-constructed to five planes; secondly each pressure tap on the model surface was connected to a manifold via pressure tubes allowing each tap to be sequentially connected to a single pressure transducer underneath the wind tunnel's working section turntable. Each manifold contained 64 individual tubes, each had a corresponding code number that was transferred along with corresponding pressure readings to the data acquisition system. Lastly, the scale model planes were re-assembled before the 423 ports were connected to the pressure transducer under the turntable (see Figure 5). Since the model had a blocked geometry and also since surface pressure measurement instead of internal velocities were of interest, Reynolds number similarity was relaxed (Aynsley et al. 1977; Lawson 1980).

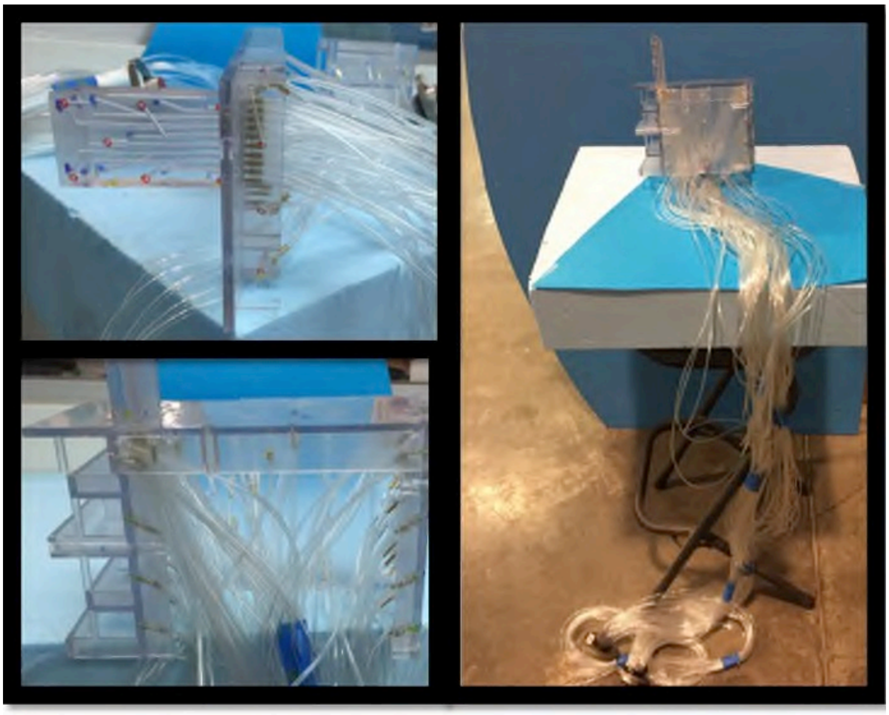


Figure 5, Model pressure taps and tubes

2.4 Pressure measurements

The pressure readings of each tap on the surface of the sealed model were conducted by a pressure transducer, after which the analog-to-digital conversions were performed by the data acquisition system. The upstream dynamic and reference static pressures were continuously monitored with separate devices. The mean reference wind speed up-wind of the model building was measured with a Pitot-static tube located upstream of the model at a height of 0.5m above the floor of the wind tunnel (50 m at full-scale).

Sixteen tests were performed corresponding to 16 compass azimuth angles of wind direction (North (N)= azimuth 0°, North North East (NNE) = 22.5°, North East (NE)= 45°, East North East (ENE)= 67.5°, East = 90°, East South East (ESE)= 112.5°, South East (SE)= 135°, South South East (SSE)= 157.5°, South (S)= 180°, South South West (SSW)= 202.5°, South West (SW)= 225°, West South West (WSW)= 247.5°, West (W)= 270°, West North West (WNW)= 292.5°, North West (NW)= 315°, North North West (NNW) = 337.5°). Data were sampled for 100 s, which is equivalent to one hour at full-scale.

For consistency with indoor air speed measurements, surface pressure measurements were converted into non-dimensional (n.d.) pressure coefficients relative to the upstream dynamic pressure at the reference height of 50 m above ground level (Aynsley 1974, Aynsley et al., 1977; Ernest et al. 1991; Ernest et al. 1992; Montazeri et al 2010):

$$Cp_{ref} = (Pm-Ps)/(0.5\ \rho V_{ref}^{2}) \qquad \text{(Eq. 1)}$$

Where,

Cp_{ref}= mean surface pressure coefficient at reference height (n.d.)

Pm = mean surface pressure (Pa)

Ps = mean static pressure at reference height (Pa)

ρ = density of air (kg/m^3)

V_{ref} = mean wind speed at reference height (m/s)

Then, pressure coefficients derived using the reference height (50 m) pressure were rescaled to correspond to the building height of 12 m using velocity profile for terrain category two in Standards Australia (AS/NZS1170.2, 2011).

For each configuration under analysis, the surface pressure was measured on the model at the inlet and outlet locations. For instance, the south façade has 7 pressure taps on the tower positioned to correspond to the height and width of the tower's wind catcher openings. Sixteen additional pressure taps were distributed over the four storeys of the scale building model to correspond with fenestration (see Figure 6). In this study, the opening related to the base building were defined as "windows", while for the wind catcher itself, the term "opening" has been applied.

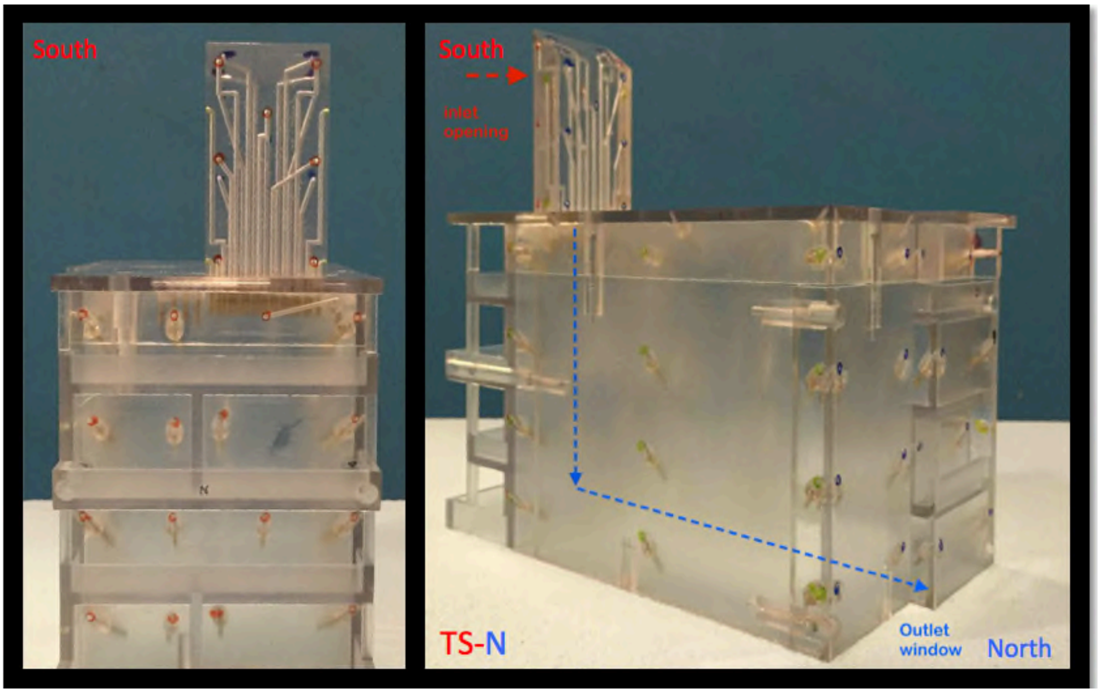


Figure 6, pressure taps over model façades to analyse various geometry and airflow pattern effects on the ventilation rate. TN-S: Tower inlet opening across South façade outlet window

3 Results and discussion

3.1 Pressure coefficient differential

The average surface pressure coefficient over the entire surface of each façade of the base building and the wind tower were calculated separately in 16 wind directions. To calculate the total energy lost by the wind in transmission through the wind tower duct and building, the average pressure coefficient of each façade was considered in relation to the other facades. This identifies the highest pressure coefficient difference through all facades and also makes it possible to compare wind catcher results versus the through-window cross ventilation benchmarks. Figure 7 shows the mean pressure coefficient difference (ΔCp) of each side of the tower (inlet area) against the opposite façade of the building (outlet area).

$$\Delta Cp = Cp_i - Cp_o \quad \text{(n.d.)} \qquad \text{(Eq. 2)}$$

where,

Cp_i = inlet pressure coefficient (n.d.)

Cp_o= outlet pressure coefficient (n.d.)

ΔCp for the cross ventilation between opposite windows of the base building is also plotted for comparison.

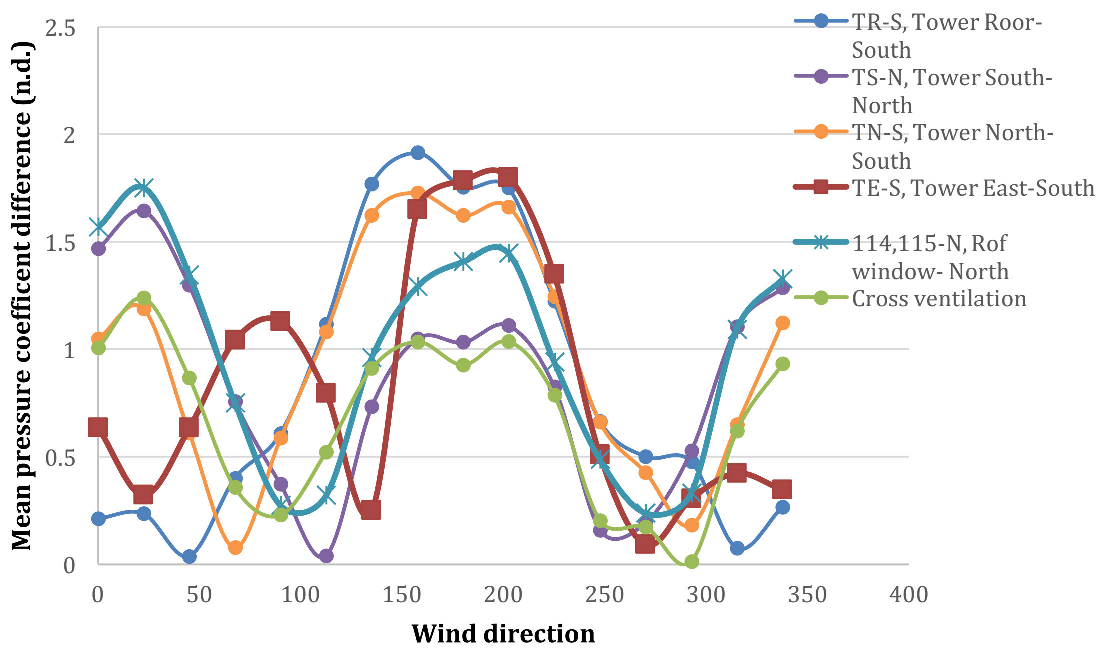


Figure 7, Mean Pressure coefficent difference between the facades of the wind catcher and the builing

Figure 7 indicates that the roof opening of the wind tower (TR-S) versus south building façade represents the highest mean pressure coefficient differential at 1.91 for the southern (S) wind direction; the average pressure coefficient differential of all directions in this case was 0.81. The east opening of the tower relative to the south façade (TE-S) still shows a considerable pressure coefficient differential with the average of 0.82 and a maximum of 1.8 for the south west (SW) wind direction. North wind catcher openings relative to south-facing windows (TN-S) indicate mean pressure coefficient differential of 0.97 with a maximum of 1.73 obtained during north north east (NNE) winds. Pressure coefficient differentials through the opposite windows over south and north façades (cross ventilation) averaged 0.68, with the maximum of 1.24 occurring under the same direction as TN-S, (NNE).

The analyses of the model building show that the windows at the roof of the building just beside the wind catcher delivers a notable mean pressure differential with the north windows (114, 115-N). The average ΔCp is 0.97 and it peaks at 1.75 along the same wind direction (NNE).

3.2 Indoor air speed calculation

To analyse the effects of the pressure difference between inlet and outlet window, on the indoor air speed, Bernoulli's equation is relevant. Notwithstanding friction losses through conduit and ventilation systems, the basic energy conservation equation is essentially applicable (Aynsley et al. 1977). There are a number of energy balance equations, however, for duct systems energy per unit volume is conventionally applied which has dimension of pressure,

$$\text{Energy/volume = Force/area = pressure} \quad \text{(Eq. 3)}$$

$$P= ½ρV^2 \quad \text{(Eq. 4)}$$

where,

P = dynamic pressure

P = density of air (kg/m^3)

V = mean outdoor speed (m/s)

The inlet energy must be equal to the outlet energy (Aynsley et al, 1977; Oke, 1978):

$$P1*V1=P2*V2 \quad \text{(Eq.5)}$$

Therefore, by reducing P2 on one side of the equation, V2 should have been increased to satisfy the above equation. Consequently, the higher the pressure differential (ΔCp) the higher velocity (indoor air speed) is generated. Meanwhile, the analysis takes into account the energy loss in the system; the length and the cross-sectional area are the key factors as they control the friction loss along the duct. Additional friction within the duct, duct bends, duct exit and entry, all have the effect of reducing the airflow rate; they are lumped together under the term Total Energy Loss in this study.

Total Energy Loss coefficient= entry loss + exit loss + bend losses + friction loss (n.d.)

Entry loss and exit loss are assumed to be 0.5 in this study, bend loss is equal to 1.2, and friction loss was calculated according to the duct length (Ld), area (Ad), and wetted perimeter of the duct (Pd). For the base-case analyses Ao= 2.63 m^2 (1.75m * 1.5m), Ad= 2.65 m^2 (1.75m * 1.5m), and Pd = 6.5m (1.5m + 1.75m)*2. The length of the duct depends on which floor of the apartment building is in question, therefore, for each floor a separate Total Energy Loss was calculated (Aynsley 1999).

Following the thermodynamic laws the equation applied for calculating the air change rate per hour can be expressed as (Aynsley ET AL, 1977):

(Eq. 6)

Air changes per hour= √ΔCp * Ve* Ao/Volume /√total energy loss coefficient * 3600

where,

ΔCp = pressure coefficient differential (n.d.)

Ve = mean exterior velocity at building height (m/s)

Ao = area of openings on windward building façade (m)

Then, the air flow rate has been calculated using equation 7:

Room airflow rate per hour= Air changes per hour * room volume (Eq. 7)

Once the airflow rate (m^3/hour) is calculated, the Vi is predicted via equation 8:

Vi = airflow/3600/Ar (Eq. 8)

where,

Vi = indoor air speed (m/s)

Ar = Room cross-sectional area (m^2)

3.3 Indoor velocity analyses

Figure 8 shows the mean indoor air speed (Vi) generated by the south-facing opening of the wind catcher venting out the north window of the first floor (TS-N,F1) and the third floor (TS-N,F3), where the living rooms, kitchen and dining areas of both apartments are located along the 16 wind direction. The green columns demonstrate the mean Vi presented by natural ventilation (NV) through opposite windows.

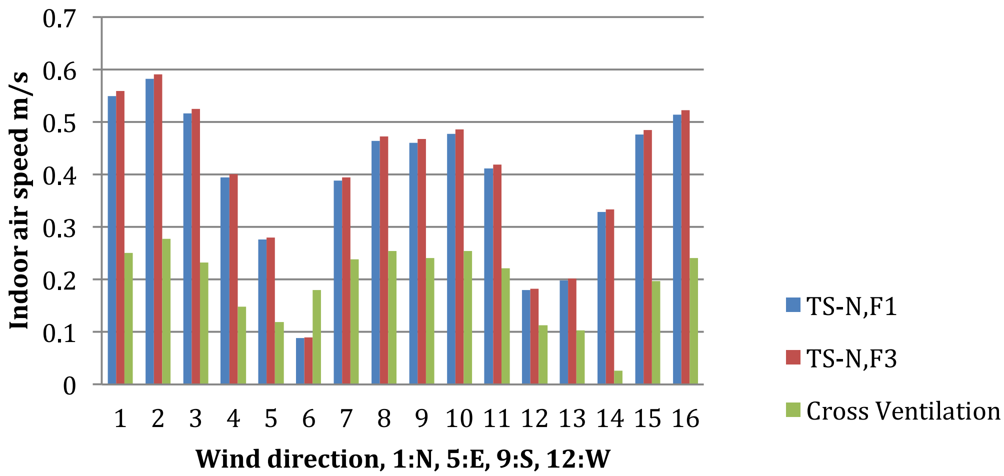


Figure 8, Indoor air speed for wind catcher ventilation with south opening and the outlet window on the north facade (TS-N) in first floor (F1) and third floor (F3), compared with cross ventilation.

The highest average indoor air speed, Vi, in the first floor (living area of the downstairs apartment) was 0.45 m/s for the NNE wind direction and this is mirrored in the third floor (living area of the upstairs apartment) with a peak of 0.6 m/s. The lowest Vi for both first and third floor was 0.09 m/s and occurred during the south east wind direction. The indoor air velocities in the upstairs apartment (F3) should be consistently higher than those downstairs (F1) for the same wind directions due to the shorter duct lengths and smaller Total Energy Losses, but the differences are negligible as seen in Figure 8.

The highest Vi in through-window cross ventilation mode was 0.28m/s and was registered during the same wind direction of the highest Vi in wind catcher mode, namely NNE. The lowest natural ventilation Vi was 0.03 m/s registered during the WNW wind direction. The openable area for the windows in the cross ventilation simulations was assumed to be $1m^2$ and its Total Energy Loss equal to 1 (0.5 entry loss + 0.5 exit loss), while in the wind catcher analyses total energy loss came to 2.24 (0.5 entry loss + 0.5 exit loss + 1.2 bend loss + 0.14 friction loss).

While the geometry of the wind catcher is not the focus of this paper, performance of various combinations of wind catcher opening orientation, wind catcher opening area, and wind catcher opening height above roof, have led us to an optimised design that will be used for all subsequent analyses in this paper. The final design included the following features;

- East opening of the wind catcher (inlet point),
- The lowest of the three vertically stacked wind catcher opening heights,
- Window on north façade of the building as exit (outlet point),
- One bend in the ductwork between wind catcher opening and the apartment's living area,
- Smallest of the three wind catcher opening areas (2.63m^2),
- Total volume of the apartment's living area under analysis (158m^3),
- For the analysis that follows the outdoor wind speed is assumed to be 3.0 m/s at 12 m above ground (building height).

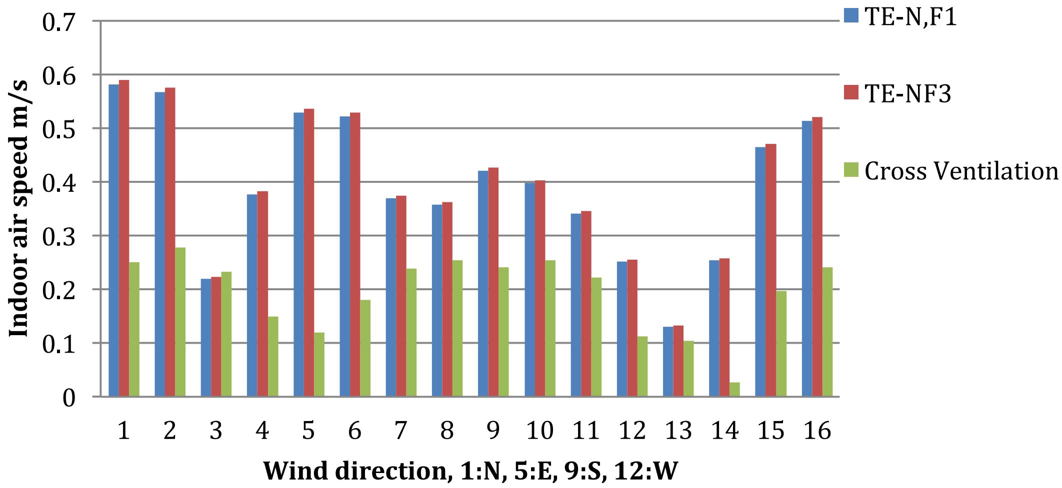


Figure 9, Indoor air speed for wind catcher with south opening and the outlet window on the north facade (TS-N) in first floor (F1) and third floor (F3), compared with cross ventilation .

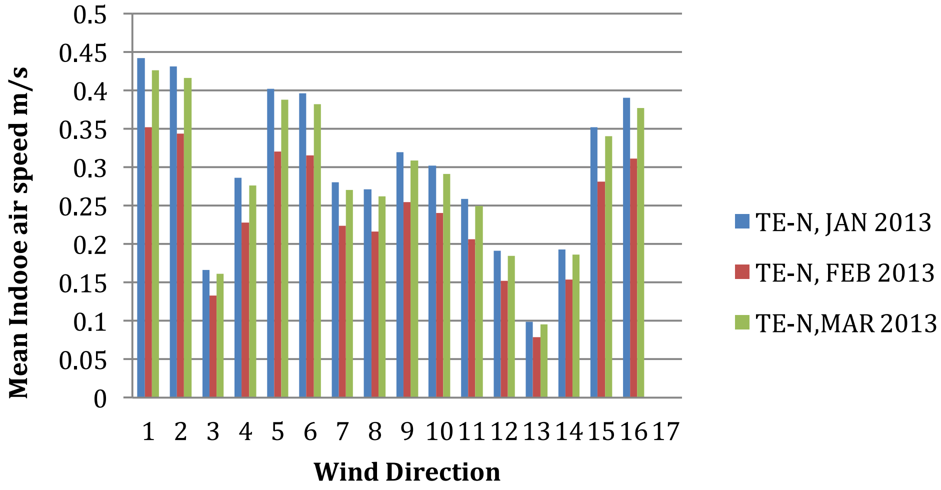
Figure 9 shows Vi in the first floor and third floor of the apartment building for a wind catcher with eastern openings and the outlet window on the north facade (TE-N). The cross ventilation through windows is also included for comparison across all 16 wind directions. In all but one of the sixteen wind directions it is clear that the wind catcher delivers significantly higher indoor air velocities than would be the case for conventional through-window cross ventilation. It is also clear that two of the 16 wind directions minimise indoor air velocities – NE and W. In the case of cross ventilation through windows the indoor air speed very rarely exceeds 0.25 m/s, barely perceptible, but for the majority of wind directions with wind catcher in use, indoor air velocities reach or exceed 0.4 m/s, peaking at 0.6 m/s for winds coming from the north and NNE.

4 Case Study: Sydney in present day climate

4.1 Climatology Study

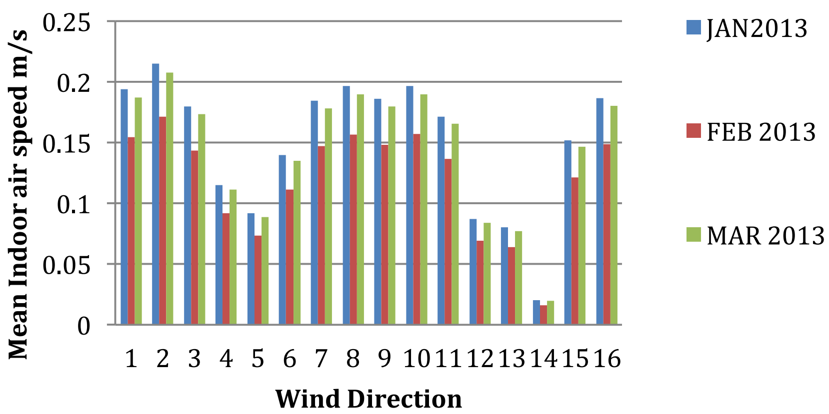
Sydney is located on the eastern seaboard of Australian continent (34°S, 151°E), and its climate is characterised as sub-tropical humid with warm-to-hot summers and cool-to-cold winters. The annual rainfall is about 1200mm (BoM, 1991). Being located in the southern hemisphere the warmest month is January, with a record maximum air temperature of 45°C, whereas, winters are relatively mild-to-cool, with air temperature rarely dropping below 5°C along the coastal regions. The coldest month is July, with an average daily minimum air temperature of 6°C (BoM 2011).

A Typical Meteorological Year (TMY) presents a data set for 8,760 hourly data of selective meteorological values corresponding to an average year. For the purpose of this study, 2013 TMY file developed by Ridley and Boland (2002) was applied to the wind tunnel analyses described above.



Figur 10, Mean Indoor Velocity, Sydney in January, February, and March 2013 with wind catcher ventilation for East oening and North outlet

Figure 10 compares the mean indoor air speed in Sydney's 2013 Typical Mean Year for the summer months of January, February and March (cooling season). Exterior wind speed (Ve) in each direction was collected from the TMY, at 10 m above ground, and up-scaled to building height, 12 m, using the wind profile for terrain category two in AS/NZS1170.2 (2011). Average wind velocity at building height was 2.32 m/s, 1.85 m/s, and 2.24 m/s for the TMY months of January, February, and March, respectively.



Figur 11, Mean Indoor Velocity, Sydney in January, February, and March 2013 with Cross Ventilation

The wind catcher delivered mean indoor air speeds (Vi) of 0.4 m/s for outdoor wind directions 1, 2, 5 (east), 6, and 16 (north) during January and February. These airspeeds were about twice those recorded for through window cross ventilation which rarely managed to lift air movement to perceptible speeds (Figure 11).

To facilitate comparisons between indoor air speeds for wind-catcher and through-window modes of ventilation, a delta indoor velocity (ΔVi) parameter has been defined. Figure 12 shows ΔVi for January 2013 when the mean outdoor wind speed was 2.32 m/s in the case TE-N, F3. It can be seen that the wind catcher increased indoor airspeeds by an average of 0.15 m/s above the values that were registered with through-window cross ventilation.

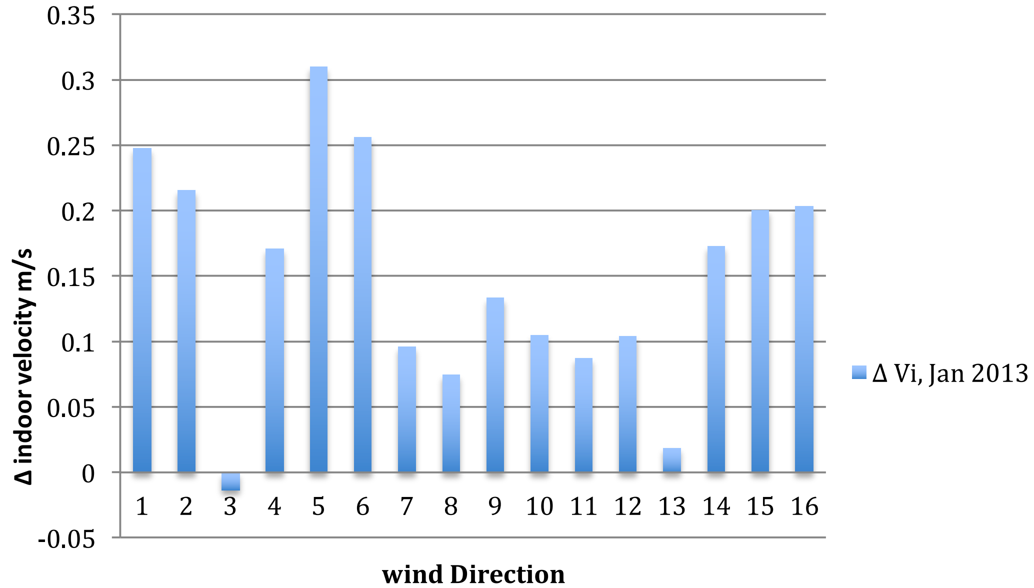


figure 12, Indoor air speed diffrence betweeb wind catcher ventilation and cross ventilation

In the next step of the analysis, an air speed coefficient (Vc), (n.d.) was calculated as the ratio of indoor (Vi) and external reference (Ve) air speeds. Vc was defined for each wind direction via this equation:

$$Vc = Vi/Ve \qquad \text{(Eq. 8)}$$

Indoor air velocities for the six warm/hot months of Sydney's 2013 TMY file (October, November, December, January, February, and March) were calculated hourly for both wind-catcher and through window ventilation by applying these velocity coefficients (Vc) to the hourly outdoor wind velocities in the TMY file. In the analyses the smallest opening area of wind catcher (Aow= 2.63 m^2) was used.

5 Thermal Comfort Analyses

According to ASHRAE-55 2013, Arens et al. 2011, Ernest et al. 1992, Arens et al. 1986, Arens et al. 1984, the elevated air speed will escalate the range of acceptable temperature and consequently, extend the thermal comfort zone. ASHRAE-55 2013, describes the Standard Effective Temperature (SET*) as a suitable model for assessing the cases of comfort under elevated air speed above 0.2 m/s. The impact of the hourly increased Vi of the wind catcher performance has been computed with the ASHRAE Thermal Comfort Tool (Fountain and

Huizenga, 1997). Data analyses and visualisation have been accomplished using MATLAB software.

Two series of The SET* simulations for both modes of ventilation, wind catcher and through-window cross ventilation, for the six warm/hot months of the year 2013 have been carried out hourly for Sydney. Air temperature and humidity has been collected from the NCCARF 2013 report, indoor radiant temperature has been considered equal to the air temperature, metabolic rate and clothing insulation were 1.1 met (almost sedentary), and 0.5 clo (typical summer residential clothing) respectively. The difference between wind catcher SET* and base cross ventilation SET* is defined as the Cooling Potential (ΔSET*) of the wind catcher in this study.

For the six warm/hot months in Sydney's TMY 2013 weather file there were 1,548 hours registering air temperatures greater than our nominal threshold of 23^{o}C. During those warm hours the elevated indoor air speeds resulting from the wind-catcher produced a cumulative total improvement in indoor comfort temperatures (ΣΔSET*) of 1,368 degree hours compared to the default case of the same apartment building in regular through-window cross ventilation mode.

6 Conclusions

Wind tunnel experiments have been carried out to measure the surface pressure around a model of a typical Australian apartment building at 1:100 scale, with the aim being to assess the performance of Persian vernacular wind catcher technology in the Australian medium density residential context. A series of equations were developed to transform pressure readings taken from scale model building exterior into the mean airspeed within the occupied zone of the full-scale building. The indoor velocity calculations for a several different duct configurations between inlet and outlet, wind tower geometries, and wind catcher opening orientations have been performed to optimise the wind catcher design. Using the optimised wind catcher design, the model building was exposed to the current climate of sub-tropical Sydney (2013 TMY file) and indoor thermal comfort analyses were performed using ASHRAE's predictive thermal comfort tool. Standard Effective Temperature (SET*) simulations were used to predict the comfort cooling potential (ΔSET*) of the wind catcher by comparison with default case of through-window cross ventilation scenarios under identical meteorological summertime meteorological conditions.

The major findings of this study are as follows:

a) Exterior design of the building, as well as the wind-catcher tower, significantly affect the wind-generated surface pressure. The height of each floor, as well as the height and orientation of each opening of the tower, are the other factors which should be considered in the application of the wind catchers in terms of the pressure differential which is the main factor in the wind driven naturally ventilated buildings.

b) Interior design of the duct (the number of bends and its length) certainly impacts on the interior air speed. The area of the opening and duct cross section has been found as the most significant parameter influencing the indoor air speed. Increasing the width from 1.75 m to 3 m can raise average Vi from 0.4 m/s to 0.7 m/s. Equation 6 can predict average indoor air speed taking into account ΔCp, outdoor wind speed, opening area, and total energy loss through the flow path

c) Thermal comfort analyses (ΔSET*) indicate that wind catcher in its smallest cross sectional area (1.5*1.75 m) can reduce SET* at the maximum of 7°C and average of 1°C during the six warm/hots months of the year 2013 in comparison with the base cross ventilation. This SET* reduction is called cooling potential of the wind catcher. The basic analyses of other landscape designs, in which the development has been located among the neighbourhoods show the higher cooling potential of wind catcher compared to the cross ventilation.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Evaluation of indoor air quality in classrooms equipped with different methods of ventilation

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Abstract

Natural ventilation through windows is the main source of air supply in the majority of UK schools.. Designing a window that enhances the air flow into a space in order that fresh air and thermal comfort are provided without compromising daylight and attenuating background noise level is very challenging. The aim of this study is to evaluate the impact of using different ventilation methods on classroom air quality and assess how different ventilation methods can also affect other comfort factors. In this study CO_2 levels of eight classrooms equipped with different methods of ventilation are recorded in four primary schools located in the West Midlands, UK. Pupils' perceptions about classroom air quality, speech intangibility and the level of light on the working plan were also established. Results confirm that classrooms equipped with cross, stack and mixed mode ventilation perform better compared to those that have single sided ventilation due to a higher satisfaction rate and lower CO_2 level. Mixed mode ventilated classrooms perform better acoustically and in terms of providing thermal comfort in winter. Pupils from stack ventilated classrooms are more satisfied with the level of light on their working plane compared to other classrooms.

Keywords: Single side ventilation, Cross ventilation, Stack ventilation, Mixed mode ventilation, Air quality, Thermal comfort, Acoustic comfort, Primary School, Classroom

1 Background

The health and performance of students and teachers are influenced by the internal environment of school buildings such as air quality (Haverinen-Shaughnessy et al., 2015), noise levels (Shield and Dockrell, 2008), indoor temperature (Parsons, 2014) and light levels (Heschong et al, 2002). One of the main reasons that schools fail to provide high quality learning environments is the lack of optimisation of different internal environmental factors and design features that could respond to all comfort factors holistically (Montazami et al, 2015).

For example, the majority of UK schools are naturally ventilated through windows and in some cases this approach can lead to significant problems (Montazami et al, 2012). This is related to the fact that windows act as a source of heat gain and heat loss, transfer daylight into the building, remove hot air, maintain levels of fresh air and also attenuate background noise levels. Furthermore, windows are an architectural element which allows the occupants of a building to experience the external environment, interact with it and also add an identity to a building.

Montazami et al (2015) introduces the Environmental Circle (Figure 1) which shows a close relationship between comfort factors.

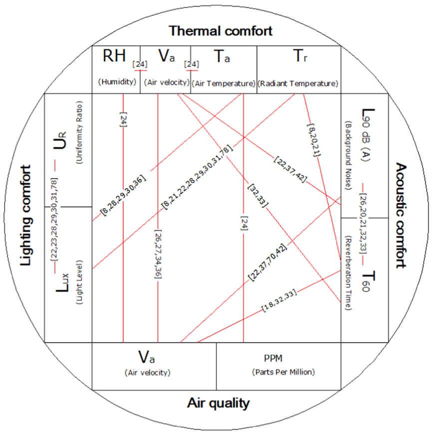

Fig.1 Environmental circle and relation between comfort factors (Montazami et al, 2015)

The lines on this circle represent the conflict between comfort factors through the history of UK schools since the Victorian era. One of the main reasons for this conflict is poor ventilation through single side windows. Ventilation is one of the key parts of school design as it has a direct effect on the indoor air quality and thermal comfort as well as an indirect link with other comfort factors. Consequently, it is important that innovative techniques are used in designing windows in order to maintain the relationship between comfort factors and minimise potential conflicts.

The concentration of CO_2 can be used as a good approximation of indoor air quality (IAQ) in learning spaces (Mendell and Heath, 2005). High CO_2 levels in classrooms in primary schools can have a negative impact on academic performance (Bakó-Biró et al, 2012) and long exposure can impact health and development.

The aim of this study is to compare the performance of conventional single side ventilation to cross, stack and mixed mode ventilation and understand how these different methods affect our ability to maintain the relationship between air quality and acoustic comfort, lighting comfort and thermal comfort.

2 Methodology

This paper is a part of a large case study assessing the indoor environmental quality of primary schools located in the West Midlands, UK. In order to evaluate the impact of different ventilation types on indoor air quality, this study uses both objective and subjective data from 8 classrooms of four primary schools which were equipped with different means of ventilation system during the cooling and heating seasons of 2014. The indoor CO_2 levels were recorded every ten minutes with EXTECH CO210 CO_2 monitors and data loggers (Accuracy: ± 5% of reading + 50 ppm). In these classrooms, pupils' air quality sensation was evaluated by asking them to vote if a classroom is *'Stuffy, Ok, Fresh, Very Fresh'* or *'Smelly, Ok, Not smelly, Not smelly at all'*. In both cases pupils have an option to vote *'I can't tell'* if they do not have any idea about the indoor air quality. 192 pupils participated in this study.

Some classrooms were selected to evaluate the impact of ventilation method on visual and acoustic comfort. In these classrooms, pupils' perceptions about acoustic comfort are evaluated by asking them to rate speech intangibility and how well pupils hear their teacher and vote to '*Very difficult, Difficult , Ok, Easy or Very easy'.* The sources of background noise that pupils may hear when they are inside the classroom were also questioned.

The visual comfort was also evaluated by asking pupils how well they can see their working plane and to vote '*Very difficult, Difficult , Ok, Easy or Very easy*'.

Schools, classrooms and the number of pupils who participated in this study and the ventilation types are presented in Table 1.

Table 1 Summary of all the collected data

School	Classroom	School year	Ventilation type	Number of respondents
1	1.1	4	Single sided ventilation	23
	1.2	5	Single sided ventilation	23
2	2.1	5	Cross ventilation	26
	2.2	6	Cross ventilation	24
3	3.1	3	Stack ventilation	20
	3.2	6	Stack ventilation	26
4	4.1	5	Mix mode ventilation	26
	4.2	6	Mix mode ventilation	24

The characteristics of each school equipped with different methods of ventilation are explained below.

Single sided ventilation: School One is a 1970s conventional single sided, naturally ventilated school building using a fan heater in winter. Two classrooms of C1.1 and C1.2 are selected from this school. C1.1 has a north-west orientation, and C1.2 has south-west orientation with secondary window wall facing south west. C1.1 has large glazing areas with no internal or external shading but has anti-glare filters fitted on the glass panes. C1.2 has internal blinds and rather small windows. Figure 2 shows internal and external view of the school building. As it can be seen, the internal blinds that protect the inside from glare may reduce the classrooms potential for having natural ventilation.

Fig 2. Single side naturally ventilated school

Cross ventilation: School Two naturally, cross ventilated building built in 2009 . Two classrooms of C2.1 and C2.2 are selected from this school. Both of these classrooms face north and are located on ground and first floor respectively, one on top of the other. Both have cross ventilation through the roof vents that can be operated through a switch and also windows that can be operated manually. Stack affect helps the cross ventilation. Windows consist of small top-hung windows and a larger window (or door on the ground floor), narrow safety ventilation panels, and large areas of fixed glazing inside the classroom. Both classrooms have movable wall partitions to adjacent classrooms.

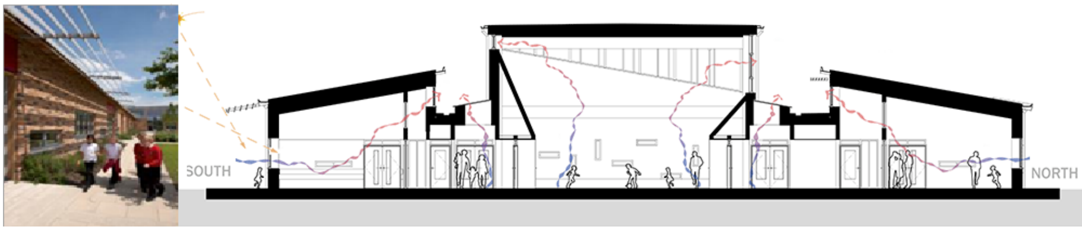

Fig 3. Cross ventilated school through roof vents and windows

Stack ventilation: School Three is naturally cross ventilated through stack affect and was built in 2011. Two classrooms C3.1 and C3.2 are selected from this school. Each classroom has a large window facing south and high level windows facing north that facilitate the stack ventilation and increase the lighting level. High-level windows are automatically operated and there are override switches in each classroom. An overhang with horizontal louvres offers partial external shading. Both classrooms are on the ground floor and have doors with glazing to the playground.

Fig 4. Stack ventilated school through windows on both side

Mixed mode ventilation: School Four is a Passivhaus building constructed in 2013, run on mixed mode ventilation in the cooling season and mechanical ventilation with heat recovery in the heating season. Two classrooms of C4.1 and C4.2 are selected from this school. In summer fresh outdoor air is provided in the classroom via the mechanical ventilation system, but users open the windows as needed, to cool down. In winter, the MVHR supplies pre-heated air in the classroom. All windows are manually operated, both classrooms have large ventilation panels and small bottom hung windows at desk level. Both classrooms are on the first floor. The orientation of the classrooms' window wall is south and north respectively. There is no external shading to the north. The roof eve projects out by about 80 cm offering shading in summer. C4.1 receives light from both sides through fixed high-level windows and the main window. One of the south side windows is replaced by a panel in order to facilitate air flow without introducing excessive solar gains as well as providing secure night time ventilation.

Fig 5. School equipped with Mixed mode ventilation

3 Analyses

3.1 Impact of different ventilation systems on classroom indoor air quality

In this part the impact of different methods of ventilation are compared through objective and subjective surveys. The pupils' perceptions of different comfort factors as well as recorded CO2 levels are compared in different classrooms equipped with different methods of ventilation.

Objective survey: Figure 6 shows the range of CO_2 levels in different classrooms equipped with different methods of ventilation. As can be seen, the range of CO_2 level in classroom with single side ventilation is significantly higher compared to the CO_2 level in other classrooms equipped with other means of ventilation. The range of CO_2 level in classrooms equipped with mixed mode ventilation is significantly lower compared to others.

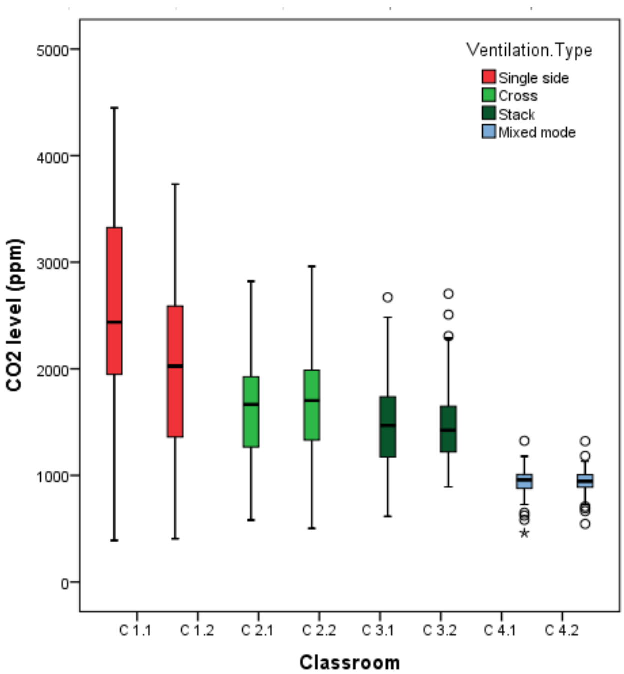

Fig 6. Range of CO_2 level in different classrooms equipped with different methods of ventilation during the cooling season

Figures 7 and 8 show the CO_2 concentration profiles for two weeks in summer and winter. The levels of CO_2 in both summer and winter generally are higher in single sided ventilated classrooms compared to the classrooms with other means of ventilation.

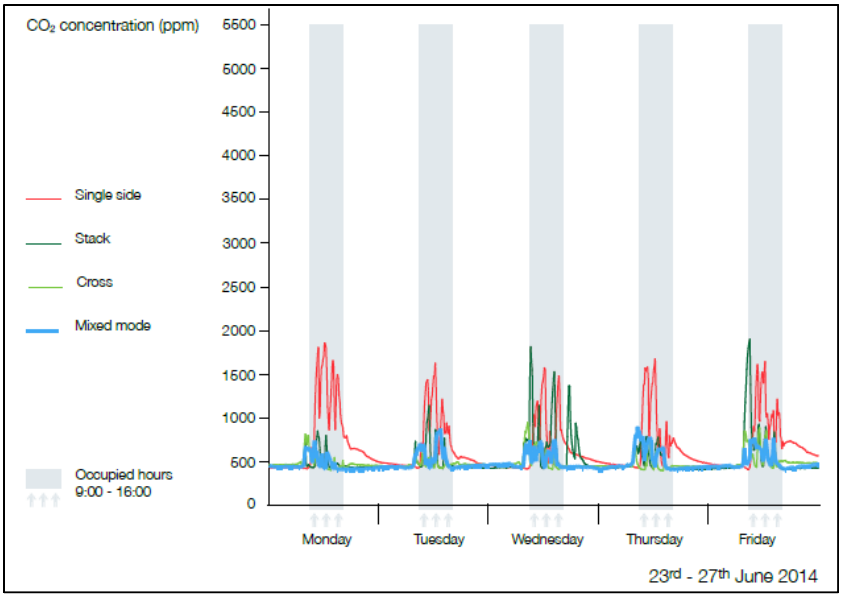

Figure 7. CO_2 concentration profiles for a week in summer

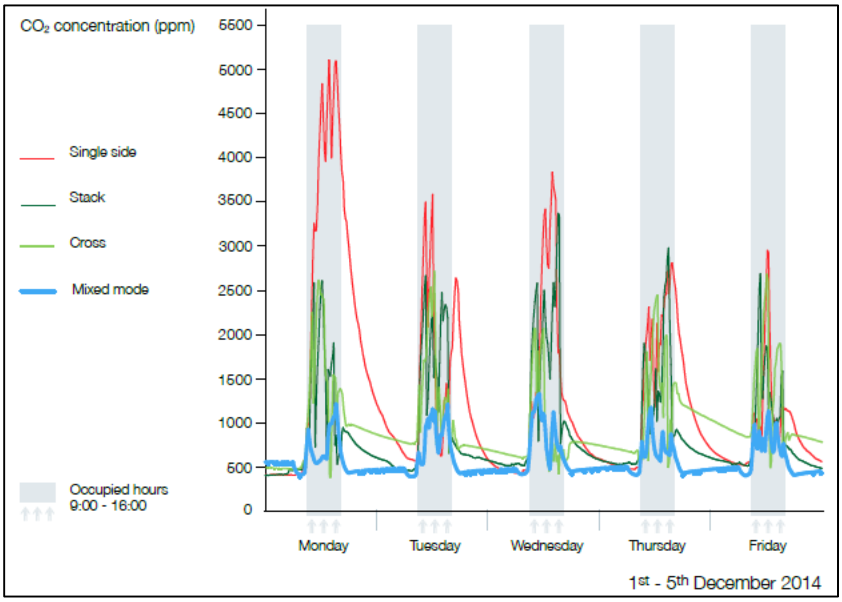

Figure 8. CO_2 concentration profiles for a week in winter

Subjective survey: Pupils' perception is evaluated by asking them to vote about freshness and the smell of the classroom. According to the regression analysis carried out between the pupils' perception about freshness/smell of the classrooms and the daily average CO_2, perceptions in terms of freshness ($P<0.05$, R^2 = 0.05, Freshness) better represent the quality of the classroom compared to the perception relkated to smell ($P<0.05$, R^2 = 0.01, Smell). However, pupils have a better understanding about the smell of the classroom rather than freshness of the classroom and it is easier for pupils to vote about smell rather than freshness.

Figure 9 shows the distribution of pupils' perception about the freshness of their classrooms according to the method of ventilation. In the classrooms equipped with cross, stack and mixed mode ventilation, less than 14% of occupants feel stuffy while this figure reaches 50% in single sided ventilated classrooms. As an example, unusually primary school classrooms have around 28 students. According to this finding in single sided naturally ventilated schools it is likely that 14 pupils feel the classrooms is not fresh while this figure can be reduced significantly to 2 pupils in classrooms equipped with other means of ventilation.

This figure also emphasis that the numbers of pupils who are satisfied with freshness of the classrooms are around 80% in stack and mixed mode ventilated classroom.

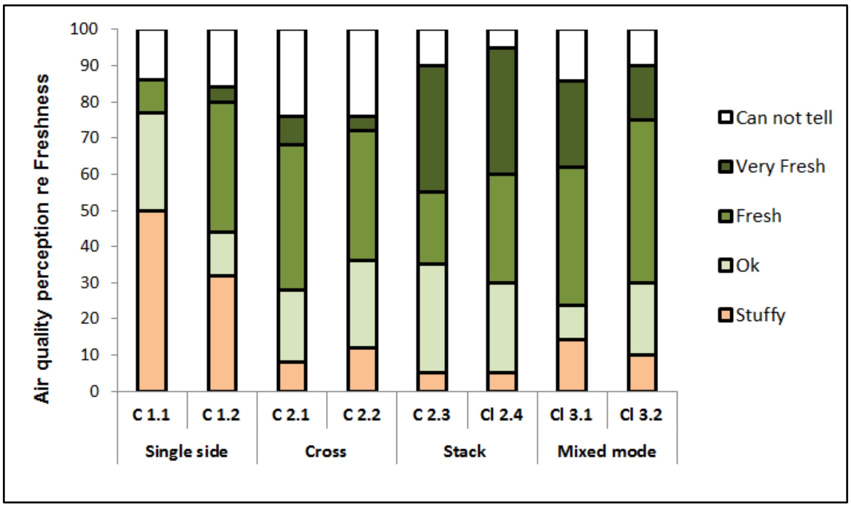

Fig 9. Pupiles perception about indor ar quaily based on freshness scale

Figure 10 shows the distribution of pupils' perception about the smell in their classrooms according to the method of ventilation. All the classrooms equipped with cross, stack and mixed mode ventilation are not smelly and pupils who voted *Not smelly* to *Not smelly at all* are significantly higher in these classrooms compared to the single sided ventilation classroom.

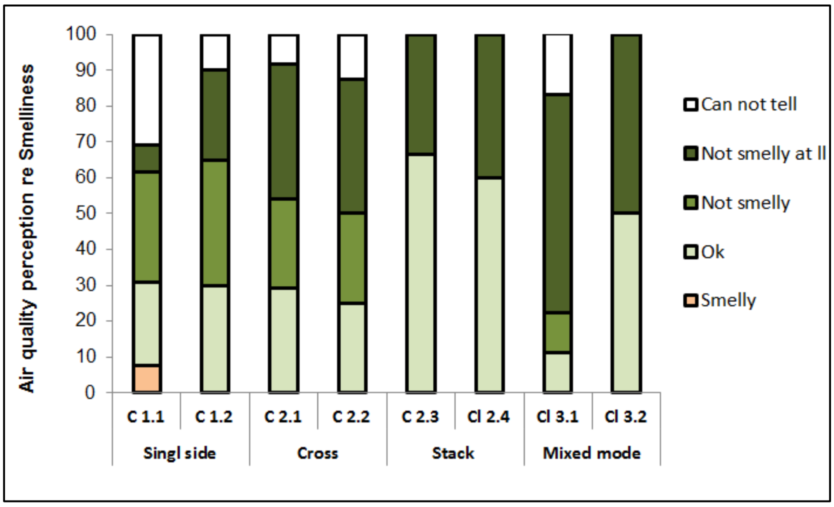

Fig 10. Pupil's perception about indoor air quaily based on smell

Pupils' perception about the freshness and smell of classrooms which are represented in Figures 9 and 10 correlate the range of CO_2 in classrooms equipped with different method of ventilation.

3.2 The impact of method of ventilation on lighting and acoustic comfort

This part highlights how innovative methods of ventilation may have a positive impact on other comfort factors such as acoustics, lighting and thermal comfort.

3.2.1 Mixed mode ventilation and acoustic comfort

In order to assess the impact of having mixed mode ventilation on acoustic comfort in classrooms, pupils are asked to vote how easy they can hear their teacher. Both of the schools have a considerable distance to the road with heavy traffic.

In classrooms with mixed mode ventilation systems all pupils can hear their teacher without any difficulty while in classrooms that have single sided ventilation 10% of pupils have difficulty in hearing their teacher (Figure 11). In addition, in the classrooms equipped with mixed mode ventilation nearly 80% of pupils found communication Easy to Very easy while this percentage drops to 40% in the single sided ventilated classroom.

In single sided ventilated classrooms around 90% of pupils hear noise from outside (i.e. car and people taking) while this reduces to 20% in schools equipped with mixed mode ventilation system

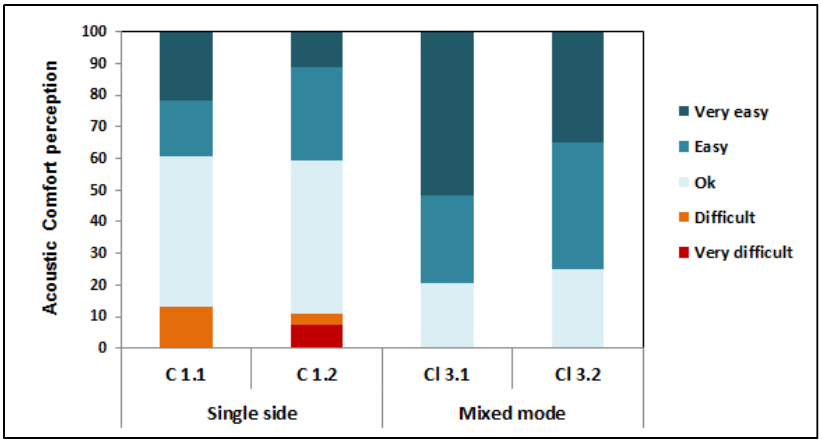

Fig 11. Acoustic perception in single side and mix mode ventilation system

This result suggests that classrooms equipped with mixed mode ventilation have a better acoustic comfort due to the lower background noise level as it is not necessary to open the window for ventilation purposes.

3.2.2 Mixed mode ventilation and thermal comfort in winter

Using the mix mode ventilation not only has a positive impact on acoustic comfort but also has a positive impact on indoor air quality during the heating season.

When the outside temperature is decreasing the level of CO_2 is increasing in single side and stack ventilated classrooms while it is not the case for classrooms equipped with mixed mode ventilation (Figure 12). This result confirms the fact that in classrooms equipped with mixed mode ventilation, there is not any conflict between achieving indoor air quality and thermal comfort as there is no need to open the window to maintain indoor air quality.

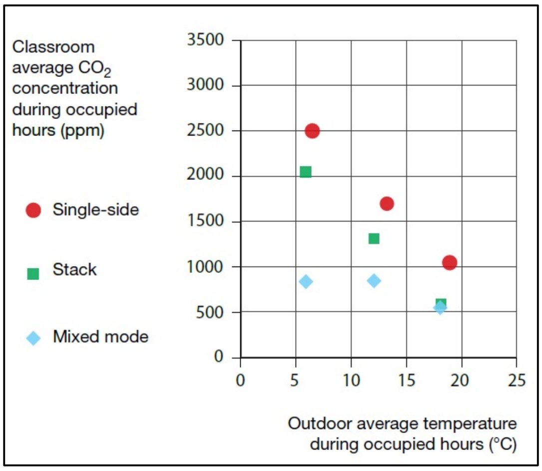

Fig 12. CO2 level in relation to outdoor temperature during heating season.

3.2.3 Stack ventilation and lighting comfort

In order to assess the impact of stack ventilation on lighting comfort, pupils are asked to vote about how easy they can see their working plane. In the stack ventilated classrooms, two windows at both sides let light in from both sides. Although classroom 3.1 is equipped with a mixed mode ventilation system, it is designed to receive light from both side (Figure 5- right).

Pupils from the classrooms equipped with stack ventilation or mixed mode ventilation (that have windows on both sides of the classrooms) do not have any difficulty to see their working plane while nearly 10 % of pupils from single side ventilated classrooms which receive light from one side have difficulty to see their working plane (Figure 9). In addition the number of pupils who find their working plane is either *easy* or *very easy* to see are less in single sided ventilated classrooms compared to other classrooms.

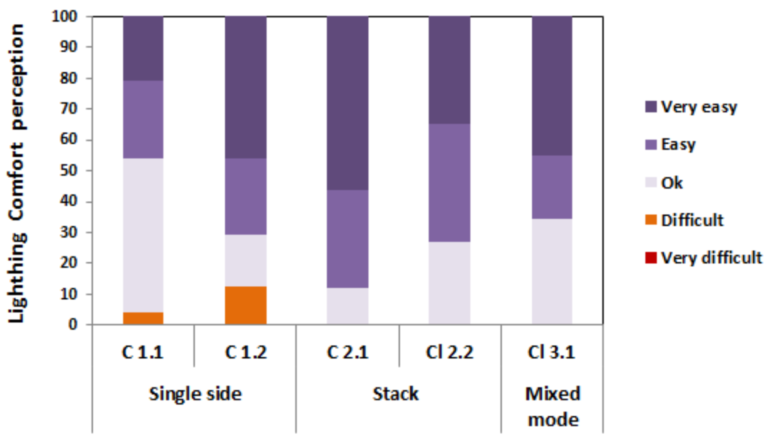

Fig 9. Lighting perception in stack and mix mode ventilation system

4 Discussions

The results indicate that CO_2 concentration and pupils' perception about the quality of indoor environment is significantly better in classrooms equipped with stack, cross and mixed mode ventilation system compared to single side ventilated classroom. Results also suggest that although pupils have a better understanding about the classrooms' smell compared to the freshness, asking about their perception of freshness is a better indicator of a classroom's indoor air quality.

Results also suggest that stack ventilated classrooms perform better with regard to lighting comfort compared to single sided ventilation systems as they receives light from two sides. In addition, classrooms perform better with regard to acoustic comfort and achieving thermal comfort for both winter and summer and also lighting comfort with some amendment.

5 Conclusions

Designing and delivering a classroom that is resilient to future climate change and uncertain future requires innovative solutions that could response to various needs. This paper is a part of large case study assessing the quality of indoor environment in primary schools located in West midlands, UK equipped with different methods of ventilation. Studies show that one of the main reasons attributed to the poor indoor environment in the history of UK schools is the lack of optimisation of different internal environment factors of thermal comfort, lighting comfort, acoustic comfort and indoor air quality.

The focus of this study is examine that how different methods of ventilation influence the air quality in learning environments and also help balance the often conflicting requirements of thermal, acoustic and lighting comfort.

Results suggest that single side ventilation is less likely to deliver good indoor air quality and also it is very challenging to satisfy all the comfort factors through a simple window design solution. The other methods of ventilation that should be considered in the future of school designs are stack, cross ventilation or mix mode ventilation.

Acknowledgments

This study is part of the Knowledge Exchange and Enterprise Network (KEEN) project between Architype and Coventry University, led by the University of Wolverhampton and funded by the ERDF and Architype. We are grateful for the assistance from the head-teachers and staff of the case study Primary Schools. External weather information was kindly provided by the Met Office.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
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The Role of Air Motion for Providing Thermal Comfort in Residential / Mixed Mode Buildings: a Multi-partner Global Innovation Initiative (GII) Project

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Abstract

As the climate changes, global use of air-conditioning will proliferate as solutions are sought for maintaining thermal comfort in buildings. This rises alongside increased purchasing power as economies grow, harbouring the potential to unleash an unprecedented growth in energy demand. Encouraging higher levels of air movement at warmer temperatures to maintain thermal comfort may offset the risk of increased air-conditioning use. Whilst laboratory studies have quantified air motion effects on the human body, it remains unclear as to how best to incorporate higher air motion in the design and operation of residential / mixed mode buildings to offset air-conditioning use. The project reported is developing a better understanding of thermal comfort in residential /mixed mode buildings and is identifying the potential for higher air movement for providing energy-efficient comfort. Co-ordinated field surveys in British and Indian residences of thermal conditions, sensations and air motion practices have been conducted. The data generated will contribute to a worldwide database, and will inform validation of a coupled thermal comfort / airflow model for designing comfortable, energy-efficient indoor environments that exploit higher air motion. This paper describes the overall project, and presents preliminary findings from the British residential field survey.

Keywords: Thermal Comfort, Residential/mixed mode, Field Studies, air motion, database

1 Introduction and Background

A growing body of evidence has established links between climate change and the carbon dioxide (CO2) emissions that arise from energy production and consumption. In 2010, annual CO2 emissions from the building sector were 9500 Mt, equating to one-third of the world's total CO2 emissions (IEA, 2011). Amongst the top 10 emitting countries in 2010, the US was second, India was third and the UK was tenth. The energy used for space cooling and heating accounts for the majority of CO2 emissions from buildings; up to 43% in the US (Levine et al 2012), 50% in India (Kapoor et al, 2011) and 60% in the UK (Palmer and Cooper, 2011). Demand for this energy is driven by the basic human need for thermal comfort and good indoor air quality (IAQ), supplied via a suitable ventilation strategy to maintain the health and wellbeing of occupants. The evidence is clear that it is critically important to address buildings if we are going to make a difference in global energy use and its subsequent effect on climate change and the environment.

With people typically spending 90% of their time indoors, the qualities of the indoor environment, such as thermal comfort and IAQ, can have a significant impact on people's health and well-being. With a changing global climate, current energy-intensive paradigms for conditioning indoor environments have the potential to unleash an unprecedented growth in energy demand in the next few years. The challenges and potential solutions are somewhat different in the residential and commercial building sectors, but both are critically important for affecting society at large. The combination of global warming and increase in purchasing power by growing economies bring forward a serious threat that air-conditioning will proliferate throughout the global residential sector, with potentially disastrous consequences for further energy demand and climate change. The global electricity consumption for home cooling is predicted to rise eightfold by 2050 (Isaac and Van Vuuren, 2009). Within India alone, a 20% annual growth rate in air-conditioning for the past decade has been reported, and it is estimated that by 2030 nearly 200 million air-conditioning units will be in service – an increase of almost 40 times the current number. Part of the solution for minimizing residential air-conditioning is likely to include encouraging higher levels of air movement at warmer temperatures, but although there are enough laboratory studies to quantify its effect on the body, it is still not clear how to best incorporate it in the design and operation of residential buildings in order to reduce air-conditioning use. An important reason for this lack of understanding is the inherently dynamic qualities of indoor air motion and the human response to it, which have been difficult to quantify.

To date, global understanding of thermal comfort and IAQ is well developed for commercial buildings that use air-conditioning (the most energy-intensive method of providing indoor comfort). Since the 1950s, such buildings have predominantly had sealed envelopes and require continuous mechanical conditioning. Natural ventilation, in which operable windows allow one to harness the forces of wind and temperature difference to provide comfortable indoor conditions, can deliver significant energy savings for many types of buildings when operated in conjunction with properly controlled air-conditioning. This arrangement is known as mixed-mode. However, the building industry lacks information on how to design these buildings in a contemporary context so that they perform well.

Existing building standards are very limiting in their guidance towards this approach. The current Adaptive Comfort Model in ASHRAE Std. 55 (ASHRAE 2013) incorporates findings that occupants perceive warmer and cooler indoor air temperatures as comfortable when the building allows them to adapt to outdoor weather conditions, and defines an expanded comfort zone for naturally ventilated buildings. However, this standard does not apply to mixed-mode, severely limiting our industry's ability to use this energy-conserving strategy in building design. The evidence is clear that people are accepting of wider temperatures in naturally ventilated buildings, and the analysis to date suggests that this is only partially due to higher air movement and more adaptive clothing patterns. The other part is likely due to shifting thermal expectations and preferences resulting from having a degree of control over one's thermal environment, and having a more variable thermal history that is more closely connected to the natural swings of the outdoor climate. However, compared to naturally ventilated buildings, there has been relatively little comparable data collected in mixed-mode buildings that combine both operable windows and mechanical cooling.

Without this information, it is difficult for standards to provide adaptive design guidelines for mixed-mode buildings.

Hence, the aim of our GII project is to develop a better understanding of human thermal comfort in buildings across the globe, and to identify and exploit opportunities for natural ventilation, mixed-mode strategies and other low-energy techniques that provide air movement, such as evaporative cooling, to reduce energy demand.

Field work is vitally important for capturing 'real world' behaviour that in turn supports modelling at the individual building and wider scale. It is the combination of field monitoring plus simulation that will finally enable us to better understand the unique transient and dynamic conditions in these low energy buildings that may very well be at the heart of how we can simultaneously achieve reduced energy consumption with enhanced thermal comfort. These two goals must be achieved in concert if we are going to have a real impact on mitigating climate change without sacrificing occupant well-being. These are the principal research approaches being adopted in this project, for the purpose of reducing global energy demand and carbon impact.

2 Aims and Objectives

To date, literature on thermal comfort field-based investigations in residential settings is relatively limited compared to the significant volume currently available for non-residential buildings (Attia and Carlucci, 2015). This is to some extent understandable, given the challenges of trying to work in such private and personal environments as people's homes (Limbachiya et al, 2012). Nevertheless, such work is vital given the significant energy consumption of the residential stocks in many countries. The comprehensive review by Rupp et al (2015) discussed thermal comfort field studies in residential buildings in a number of countries, highlighting differences between reported thermal sensations and those predicted by the PMV approach, and the role played by adaptive behaviours. The paper also reports work by Zhang et al (2011) that proposes wider ranges of indoor temperature in HVAC (mixed mode) buildings achievable through the use of ceiling and personal fans. Peeters et al (2009) suggest that a wider range of conditions than those of the adaptive model might be considered acceptable in residential environments. With regard to the use of air motion, Huang et al (2013) report survey and chamber work in China. Whilst no residential field work was conducted, it suggests that thermal neutrality could be achieved in residential buildings at temperatures up to 32C. However, Wang et al (2010) report survey work involving air movement sensation and preferences with families in naturally-ventilated residential buildings in Harbin, China, showing that air motion has a positive effect on thermal sensation. Indraganti (2010) also describes use of air movement and diverse adaptation mechanisms for providing comfort in Indian apartment buildings. As far as the authors are aware, no studies to date have specifically investigated air motion practices in UK residences, in relation to thermal comfort.

Given the preceding background, funding was secured from the British Council for a research project of 30-months duration (April 2014 – September 2016) bringing together an international partnership to investigate thermal comfort, and the potential for higher air motion, in residential / mixed mode buildings within an international comparative context.

The overall aim of the project is to develop a better understanding of human thermal comfort in residential buildings in an international comparative context, identifying and exploiting opportunities for higher air motion (natural ventilation, mixed-mode and other approaches) to reduce energy demand.

The specific objectives of the project are as follows:

- To gather data for understanding thermal conditions, thermal comfort and occupant responses in residential/mixed mode environments internationally, for contributing to a world-wide field study database to be made public for use by other researchers and students.
- To conduct field surveys in residential buildings in India and the UK, and utilise an existing coupled thermal comfort/air flow model alongside dynamic thermal simulation to assess the ability of a range of low energy techniques that employ higher air motion to deliver comfort and energy savings.
- Using the outcomes from the preceding objectives, to develop new insights and data for an international database that can lead to approaches and guidelines for such environments on conditions for thermal comfort so as to promote lower energy approaches for heating, cooling and ventilation, minimising unnecessary use of air conditioning.

In terms of partnership roles, residential field studies are being conducted by CEPT, De Montfort and Loughborough Universities, the latter two partners also responsible for coupled thermal comfort / airflow model development and dissemination. Database compilation and analysis is being conducted by UC Berkeley, with overall project management by Loughborough.

3 Methodology

Field studies were designed to gather data about thermal sensations, environmental conditions and air motion practices, in order to understand availability of, and occupant utilisation of, opportunities for use of air motion within buildings. The additional purpose was to supply data for the UC Berkeley database. The field studies were conducted in two countries, India and the UK, allowing coverage of both natural and mixed-mode ventilation strategies within a residential context. At the same time the arrangement afforded the opportunity to compare behaviours and responses in two different climates and in an international context. The approach adopted combined detailed subjective data gathering alongside objective monitoring of indoor and outdoor thermal conditions in people's homes.

3.1 Recruitment of Participants & Residences

Participants were recruited initially for a six-month study (with the possibility of extension), via the use of leaflets and 'word of mouth'. Family members comprised of adults and children across the age range 7-75 years, with consent from adults and assent from children being gained in line with full ethical requirements. An information leaflet, and a screening survey to obtain preliminary information about the homes and occupants, were designed and helped support sample selection. For the UK, the sample of residences for the study were located in the East Midlands within a fifteen-mile radius of the town of Loughborough, with two additional households located in Yorkshire. Climatic conditions experienced are 'temperate oceanic' as described in the Koppen Climate Classification (Wikipedia 2016). For India, the sample of residences were located in the city of Ahmedabad, Gujarat, a 'hot semi-arid climate region' (Wikipedia 2016)

3.2 Residences Description

Twenty residences were recruited for the India part of the study, comprising sixteen apartments (mainly 2-3 bedrooms) and four independent houses (two-storey, with three or more rooms per floor). These represent the typical housing typology prevalent in most cities in India. As preferred in most Indian residences, the approach for ventilation is mixed-mode, involving natural ventilation and the availability of air-conditioning (split units) to manage summer peak outdoor conditions. The UK study was made up of fifteen residences composed of a mixed sample of housing types giving a reasonable reflection of the national stock composition, though with some under-representation of terraced housing when compared to recent UK Government stock profile figures (DCLG 2013). However, this was not considered to unduly affect the study. More importantly for this study, in UK homes natural ventilation via windows and doors is the dominant mode, though there is some growth of mechanical ventilation with heat recovery (MVHR) and occasional instances of whole house or localised room air conditioning. The UK sample has attempted to capture this range of air motion capabilities. Table 1 summarises details of the residences and participants.

Table 1: Residences and participants summary, India and UK field studies

Country	India	UK
Total residences surveyed	20	15
Residence type and storeys, floor locations	4 houses (2-storey) 16 apartments (9 on ground to 3rd floor; 4 on 4^{th} and 5^{th} floors; 3 on or above 6^{th} floor)	1 terrace - (3-storey) 6 semi-detached - (5 are 2-storey and 1 is 3-storey) 6 detached - (5 are 2-storey and 1 is 3-storey) 1 flat (non-ground floor) 1 bungalow (ground floor)
Modes of ventilation	Mixed: natural via windows, doors, ceiling and pedestal fans, supplemented as required by evaporative air coolers and split-unit air conditioning	Natural: via windows, doors, worktop and pedestal fans. Instances of: MVHR (whole-house); air conditioning (whole house or conservatory-only); mechanical ventilation (no heat recovery)
Numbers of participants	42	31
Age ranges	16-74 years	7-75 ears

3.3 Data Gathering

Central to this was the design, trialling and evaluation of an advanced questionnaire and associated delivery / response mechanism. The questionnaire, titled the 'Home Thermal Comfort and Air Motion Survey' differed from those of previous field studies in four important respects: i) by asking about activities and behaviours immediately prior to, as well as at the time of, completion; this allowed estimation of closeness to thermal steady state at any given time, and related to activity, clothing and location within or outside the home; ii) by gathering details about availability and usage of air motion devices, and proximity (distance and direction) of the participant to those devices (includes windows, doors and equipment); iii) by gathering details about the presence or absence of any solar radiation incidence upon parts of the participant’s body; iv) by remotely delivering and then collecting participant responses using digital media, important for minimising disruption for people in their own homes (though paper-based versions can be used where acceptable). In other respects, the questionnaire was similar to standard field study approaches (seeking participant responses on features that included thermal sensation, acceptability, preference, air movement and local discomfort).

It is essential to strike a balance between the level of detail that one might like from such a survey, and the level of inconvenience that this might impose upon participants, especially given the challenging nature of the environment in question – the participant’s own home. We therefore devised a method for remote delivery, completion and collection of the survey using on-line techniques via home computer, ‘tablet’ and smartphone. This balance was achieved following rigorous pilot trials with volunteers (not study participants) aged 8-80 years, who provided feedback that enabled the survey tool to be finalised and rendered capable of completion in less than 10 minutes, thus encouraging retention of participants throughout the study. The survey can also be completed in paper format, if appropriate technology is not available.

Following an initial home visit by members of the research team, participants thereafter completed the survey on a (generally) weekly basis over a period of up to 9 months, commencing April 2015 and ending January 2016, capturing late spring, summer, autumn and early winter periods in the UK, and late summer, monsoon (rainy season), autumn and winter periods in India. At the time of writing, UK data gathering has been completed and the homes de-commissioned of sensors, with the Indian homes still engaged in the field study. All discussion and results that follow relate to the UK field survey.

The visit allowed for a full thermal comfort survey to be conducted using a Dantec Dynamics ‘ComfortSense system (compliant with EN 13182, ISO 7726 and 7730, and ASHRAE Standards 55 and 113). Calibrated sensors (HOBO U10 and Pendant 64K) were positioned and left in households for the duration of the study, to record air temperatures and relative humidities in living rooms, bedrooms and conservatory (where applicable). Specific measurements with the Dantec system confirmed similarity of air and mean radiant temperatures, and very low values for airspeed indoors in each home. At the end of the field study period, researchers again visited the homes, and carried out a 30-minute interview with the participants to ascertain the representativeness of their on-line responses over the study period to their residential living behaviour in general.

4 Preliminary Results & Discussion

The majority of the UK participants completed the Home Thermal Comfort and Air Motion Survey online, with only two participants preferring to use paper versions. In India, reliable access to the internet or mobile technology could not be guaranteed for all participants, and so all completions were paper-based. Consequently, Indian survey data are still being processed and reported on later, and so results presented here are the preliminary findings from the UK field study only, with analysis continuing of the ‘cleaned’ data gathered.

The online method for delivery, completion and collection proved to be very successful, with all 31 UK participants in 15 homes, resulting in 509 individual responses between April and December 2015. Of the 509 responses, 47% were completed by females, with 53% completed by males. In terms of ages of respondents, 100 completions (approx. 20%) were from participants in age range 7-16 years, and 409 completions (approx. 80%) from participants in age range 18-75 years. Table 2 shows house type, household make-up and ventilation category against identification number allocated.

Table 2: UK households participant composition, house type and ventilation category

House number	House type	Participants	Ventilation
1	Detached	2 adults (1m, 1f) 1 child (f)	Natural, plus air-conditioning of whole house
2	Semi-detached	2 adults (1m, 1f) 1 child (m)	Natural, plus air-conditioning in conservatory
3	Detached	4 adults (2m, 2f) 1 child (m)	Natural
4	Semi-detached	2 adults (1m, 1f)	Natural
5	Detached	2 adults (1m, 1f) 2 children (2f)	Natural
6	Detached	1 adult (m)	Natural
7	Semi-detached	2 adults (1m, 1f)	Natural
8	Semi-detached	2 adults (1m, 1f)	Natural
9	Flat	1 adult (f)	Natural
10	Detached	2 adults (1m, 1f) 1 child (m)	Natural
11	Semi detached	2 adults (1m, 1f)	Natural
12	Terraced	1 adult (m)	Natural and MVHR
13	Detached bungalow	1 adult (f)	Natural and MVHR
14	Semi detached	1 adult (m)	Natural and MV
15	Detached	1 adult (m)	Natural and MVHR

At the time of writing, it must be emphasised that the field data campaign in the UK ended only in the last few weeks (with India still continuing). This has generated a large, longitudinal, rich dataset gathered over a 9-month period, and comprised of reported thermal sensations and related factors. Analysis is in its early stages, but here we present a descriptive statistical overview of several key facets from the total of 509 responses to the survey. Thus, for the UK sample of 31 participants, for the period April-December 2015, at the instant of completion, findings to date are as follows.

4.1 Participant behaviours

In the majority of cases, survey completions took place in the living room and in the evening. Figure 1a and 1b show that the main and other activities taking place during the 15-minute period prior to survey completion were largely of a sedentary nature, the remainder illustrating a wide range of other residential activities. With respect to clothing, very little change (addition or removal) of items of clothing was reported during the 15 minute-period prior to survey completion (94% of the 409 adult responses showing no change). Clothing ensembles data gathered are extensive, but selecting one item from this (footwear), Figures 2a and 2b illustrate a predominant lack of any footwear in the home (slippers, shoes or socks) during the summer period, with an increase in socks-only during the autumn / winter period.

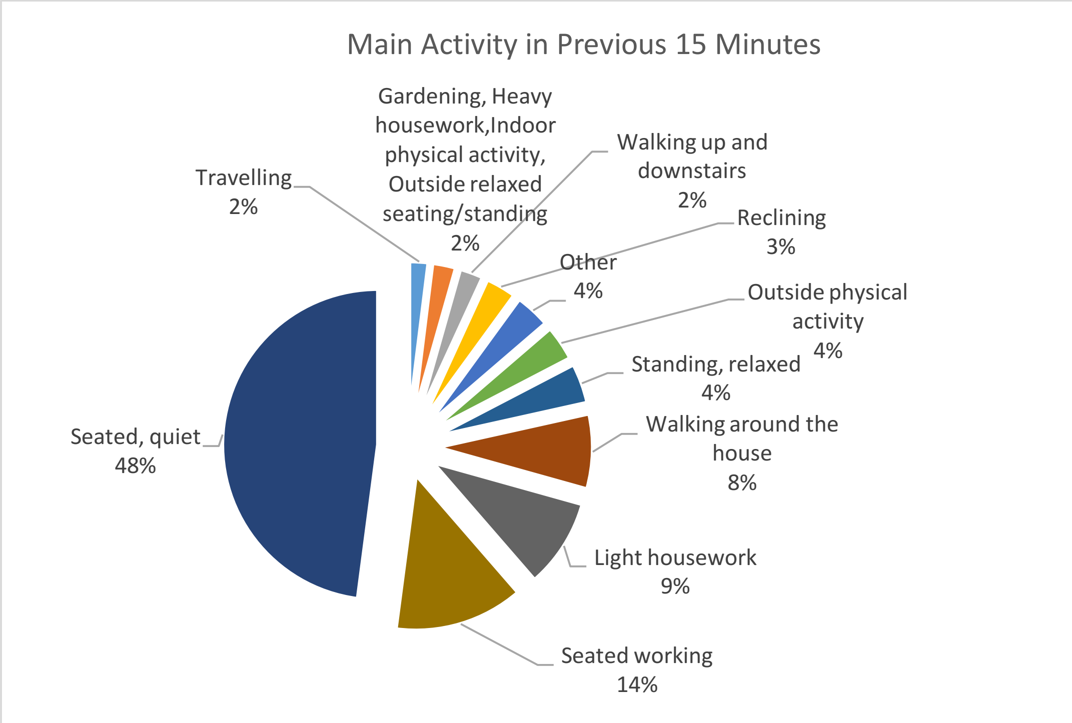

Figure 1a Main activity during 15 minutes prior to online survey completion based on the total of 409 adult responses) ('other' ranged from bathing to eating/drinking to DIY / car washing to opening windows)

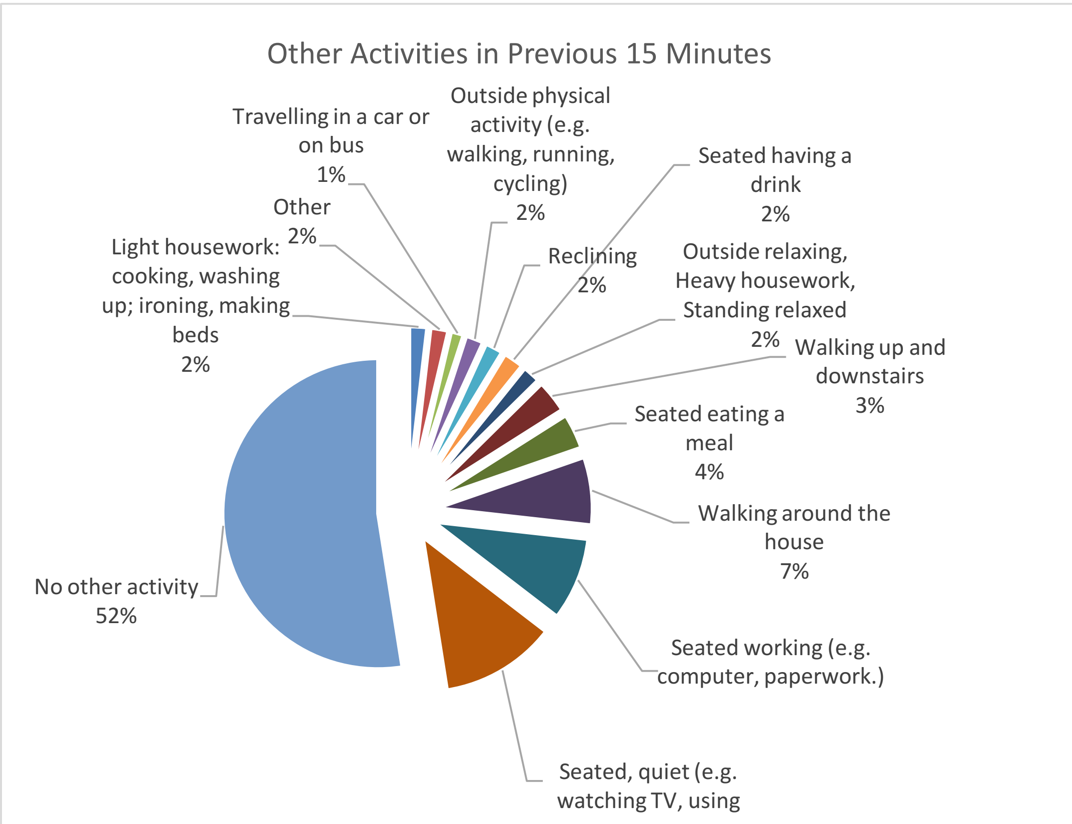

Figure 1b: Other activities during 15 minutes prior to online survey completion based on the total of 409 adult responses.

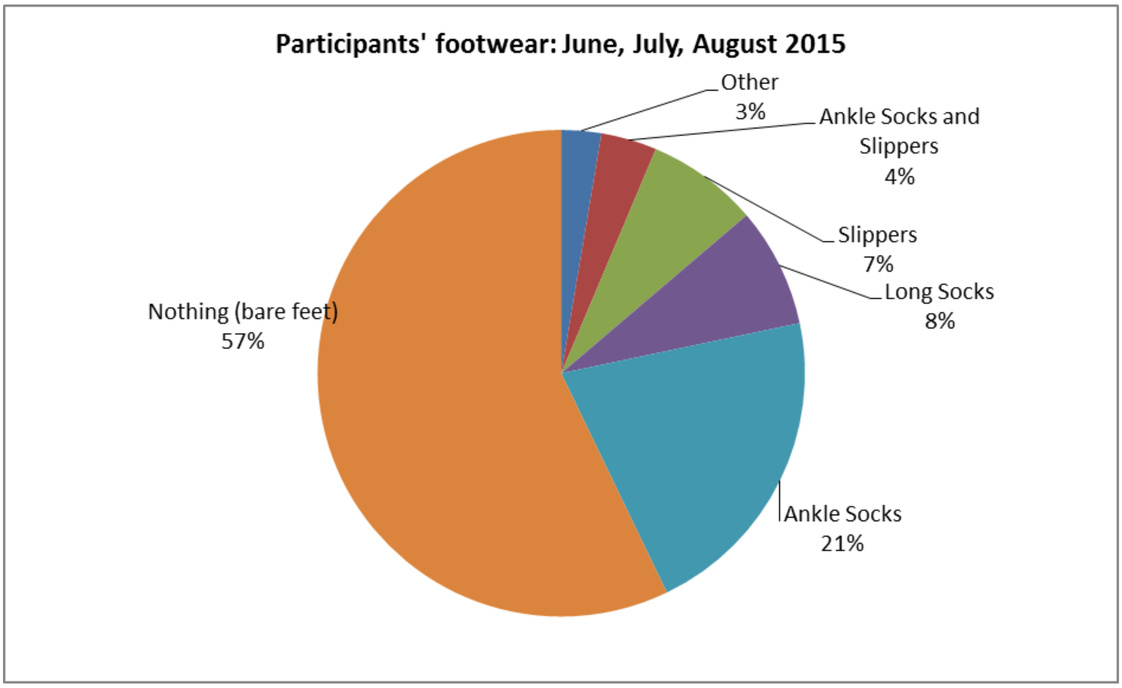

Figure 2a: Participants' footwear at home, during summer period (June-August)

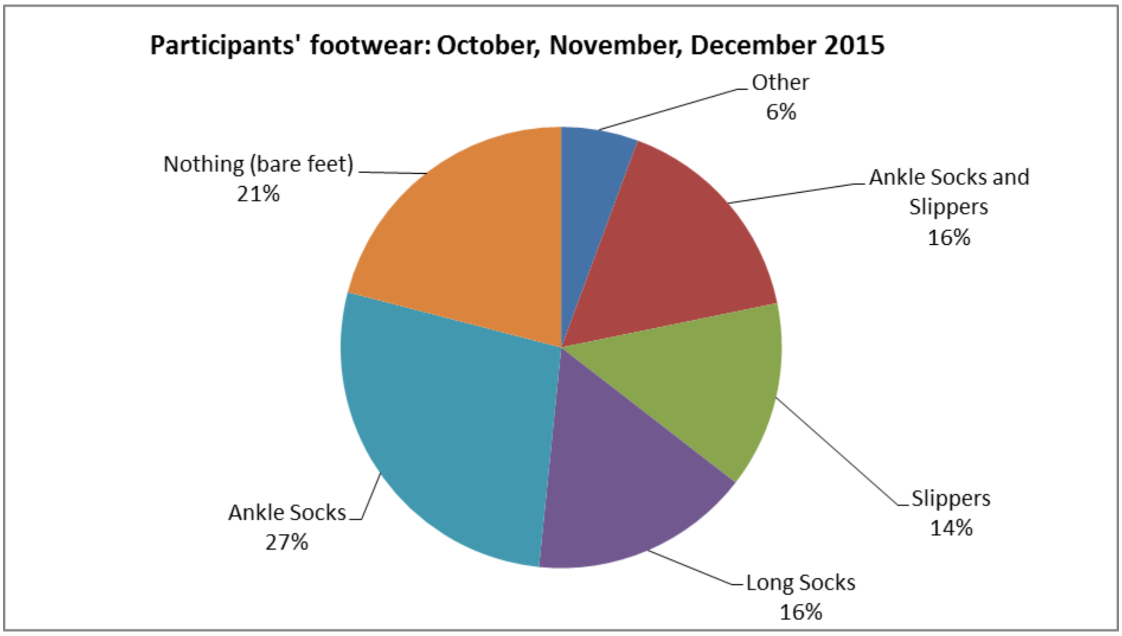

Figure 2b: Participants footwear at home during autumn / winter period (October-December)

4.2 Air motion practices

For responses from adults, Figures 3a and 3b present the reported usage of windows (as percentage of responses) in the room being occupied by the participant at the time of online completion for the summer period (June-August) and autumn/winter period (October-December) respectively. Figures 4a and 4b present the reported usage of external doors (as percentage of responses) in the room being occupied by the participant at the time of online completion for the summer period (June-August) and autumn/winter period (October-December) respectively In the autumn/winter months Little or no use of fans was reported. Where devices (includes air-conditioning as well as those that promote higher air motion) are reported, Figure 5 gives the percentage distribution of usage of these devices. It is clear that there has been little reported usage of means to promote higher air motion in the sample of homes during this period. It should be noted that the UK summer period of 2015 had relatively mild steady temperatures, with the only hot spells in late June / early July and in mid-August (see section 4.3 for further details). This might have inhibited air motion use for maintaining comfort, and further data is required.

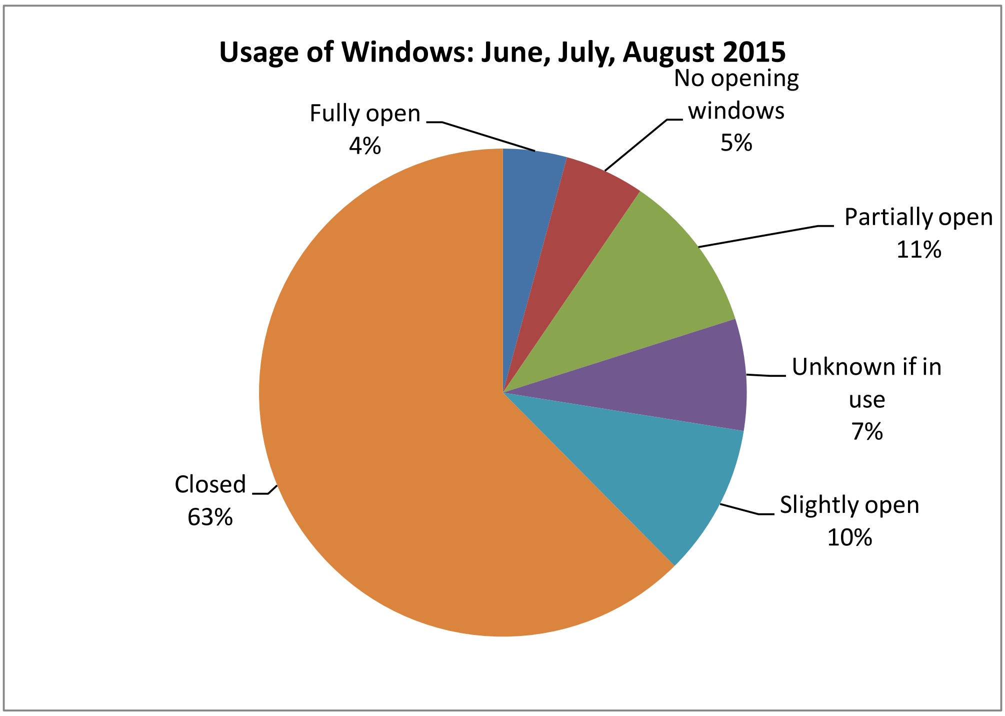

Figure 3a: Reported usage of air motion devices (windows) at time of online survey completion during summer period (June-August)

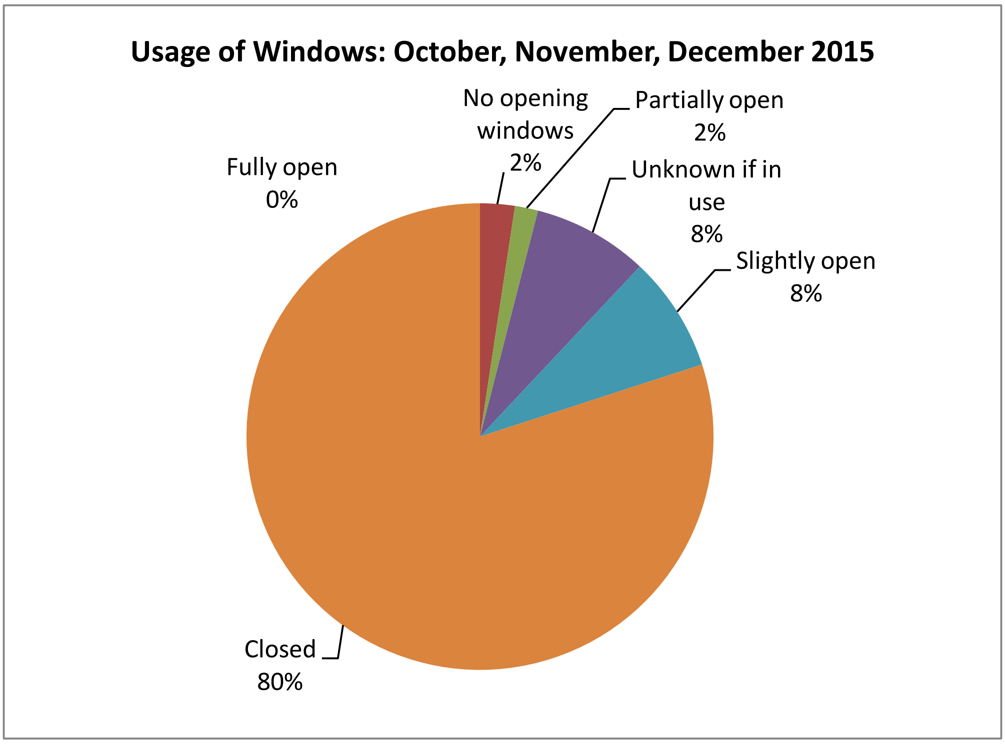

Figure 3b: Reported usage of air motion devices (windows) at time of online survey completion during autumn / winter period (October-December)

Within the scope of this GII project, it was not possible to gather quantified airspeed data on a continual basis local to the participant. However, it was possible to determine details regarding the location of a participant in relation to the principal air motion device(s). This will be important for subsequent detailed airflow and sensation investigation currently in progress and scheduled to continue beyond the GII project funding period.

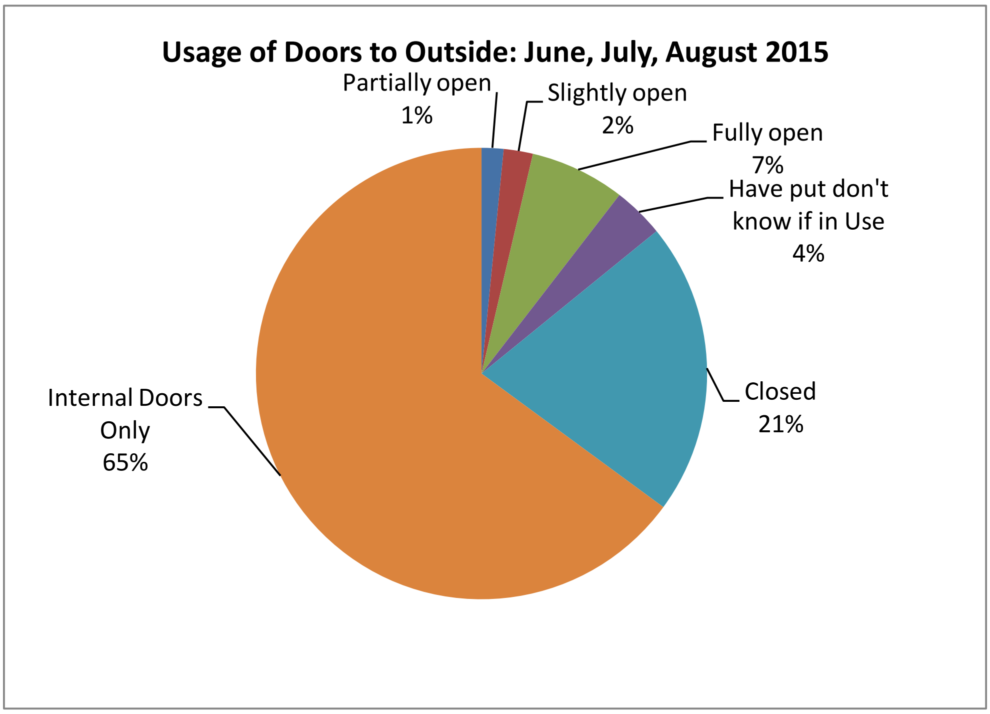

Figure 4a: Reported usage of air motion devices (Doors) at time of online survey completion during summer period (June-August)

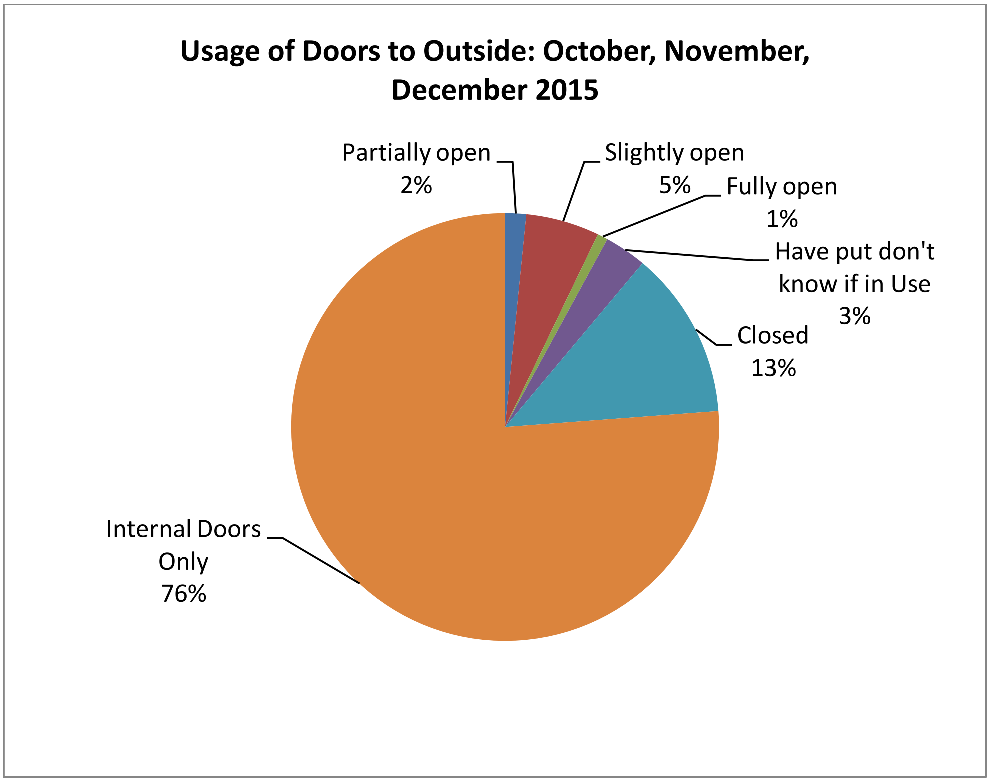

Figure 4b: Reported usage of air motion devices (Doors) at time of online survey completion during autumn / winter period (October-December)

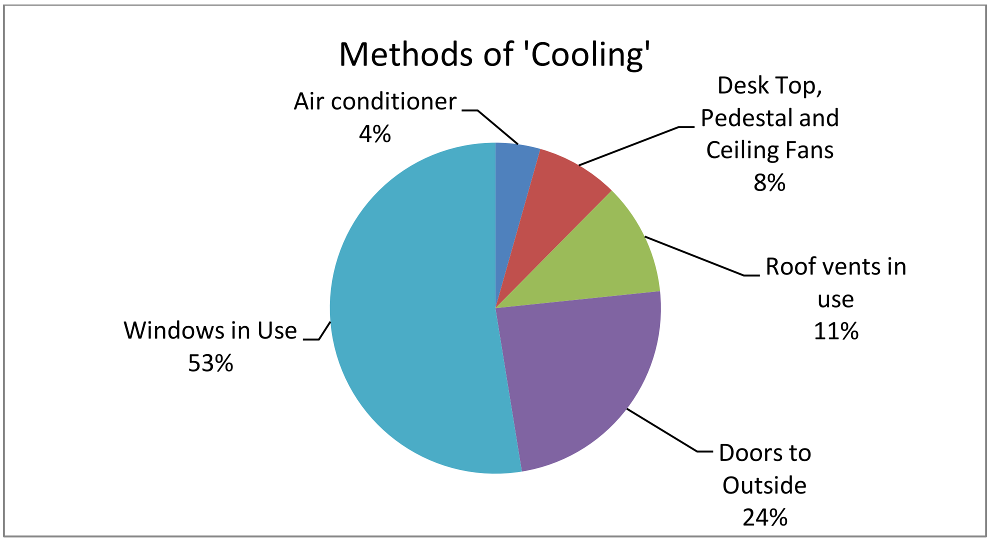

Figure 5: Where devices are reported as being used for 'cooling' (includes air motion and air-conditioning), percentage distribution of usage of devices

4.3 Actual thermal sensations

Figure 6 presents actual mean votes (AMV) of all participants aged 18-75 years reported over the entire period April-December 2015, expressed as a time series. Figure 7 shows a similar time series of the AMVs of participants aged 7-16 years, while Figure 8 presents a histogram of average adult household AMV for each house (as identified by its allocated number - refer to Table 2) for the 'warmer' (June, July and August) and the 'cooler' (October, November and December) periods. Preliminary inspection suggests that the majority of responses lie within a range +1 to -1 AMV, and outside this range there are more 'warmer' than 'cooler' responses. The range in the outdoor temperatures measured hourly in Loughborough for the period April-December 2015 was approximately 5-20C, with an average around 12C, a period popularly noted that year for its fairly consistent 'mildness', except for a 'hot' spells in late June to early July, and around mid-August (measured peak temperatures of 33.6C on 1 July, and 28.1C on 22 August).

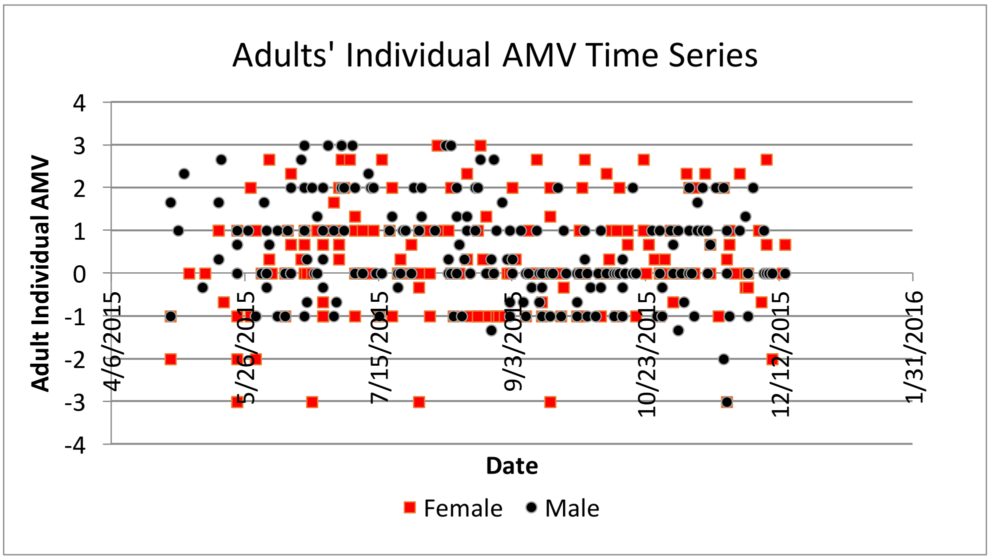

Figure 6: Actual mean vote (AMV) responses of all adult (18-75 years) participants (409 survey responses in total), expressed as a time series from April-December 2015. Sensation scale: -4 (very cold), -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm), 3 (hot), 4 (very hot).

Monitored data from the sensors placed in rooms in the 15 UK houses is currently being collated with the subjective data gathered for analysis. A similar process is underway for the data gathered in the Indian field survey. These will be supplied to the UCB database for overall analysis alongside other field studies. A significant dataset has been generated from the UK and India residential field studies, and this will be analysed in detail over coming months and beyond the GII project.

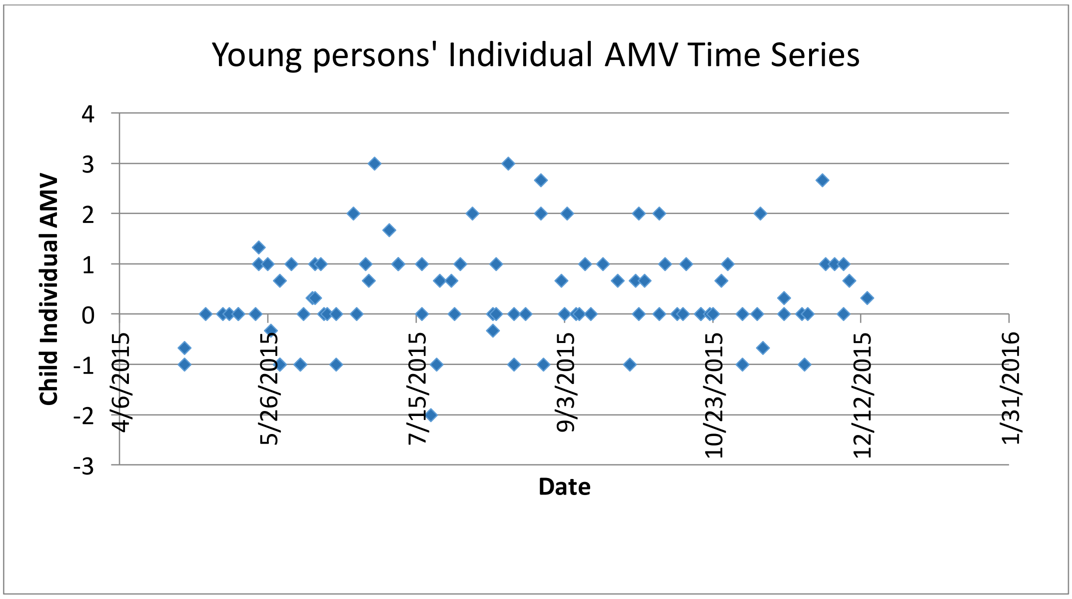

Figure 7: Actual mean vote (AMV) responses of all participants (100 survey responses in total) aged 7-16 years, expressed as a time series from April-December 2015. Sensation scale: -4 (very cold), -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm), 3 (hot), 4 (very hot).

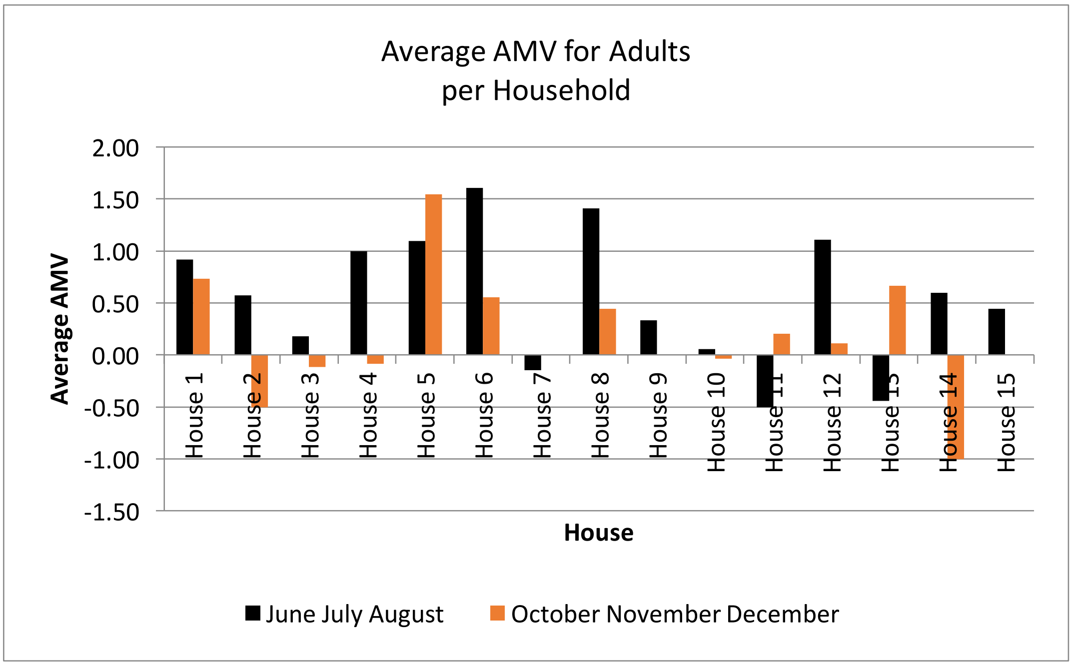

Figure 8: Average adult AMV per household for all houses, for 'summer' and 'autumn/winter' months. Sensation scale: -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm), 3 (hot).

5 Next Steps for GII Project

5.1 Database Contribution

The field survey data gathered will be entered into a global database being developed at CBE. We have identified approximately 36 thermal comfort studies that were conducted in mixed-mode and residential buildings, meet scientifically rigorous standards, and contain data usable for the GII project, and we are continuing to expand this search. To date, we have received positive replies from researchers willing to contribute their data from thermal comfort studies carried out in 13 different countries (Mexico, Finland, Estonia, Belgium, Italy, Slovakia, Portugal, Israel, Tunisia, China, Malaysia, India, Japan). Their data have already been received and we are currently working on data processing. We are simultaneously continuing with data gathering since more authors are being constantly invited to collaborate.

We are also working to expand and use two interactive visualization tools that allow users to look at all data, or subsets that are most interesting to them, based on building type (such as MM, NV, or HVAC), location, etc. The tools were described in Pigman et al (2014). The tools are built with the statistical package R, and the current user interface has dropdown menus, sliders, and input fields that allow users to filter the overall database based on the building location, cooling strategy, and program. Users can choose the metrics for the axes and for calculating satisfaction, the width of the bins, and the minimum number of votes that are required in a bin for it to be displayed. The screen then gives them immediate feedback, visualizing the results based on the input parameters and filters. In addition to the graph, there is a data table that indicates the sources of the data and the mean values of the basic physical and survey responses for each city that is included. This tool uses probit analysis to display the percentage of dissatisfied votes as a function of a variety of metrics - thermal sensation, PMV, or indoor temperature - and plots the corresponding probits. The four metrics for calculating satisfaction (or conversely, dissatisfaction) are acceptability, thermal sensation, comfort, and preference. The second tool, "Satisfaction mapping tool", provides a new way of analysing and representing data in these datasets that calculates satisfaction percentage directly, and visualizes the results directly in a form of the ASHRAE adaptive model.

5.2 Modelling

The UK and Indian field study findings about air motion practices are helping to inform experimental validation of a coupled thermal comfort / airflow model (Cropper et al, 2010). Knowledge transfer and training using the model is being arranged for all project partners, thereby building capacity at international level to tackle the problems posed by climate change. The model comprises a dynamically coupled model of human thermal comfort and physiology with computational fluid dynamics (CFD). The advantage of this modelling approach over existing thermal comfort prediction methods is its spatial resolution and two-way data transfer between the model of the human being and the CFD model of the occupied space. This enables accurate, time-dependent boundary conditions to be applied to each of the two models resulting in simulation of the evolution of occupant comfort as well as prediction of the steady state condition (where one exists). The types of scenarios being investigated involve localised air movement effects such as air flow through windows and those generated by fans. The model being used comprises 59 body segments which facilitates spatially-varying boundary conditions and so will enable such phenomena to be captured.

Once a set of viable ventilation/air movement scenarios has been identified, dynamic thermal simulation will be used to predict the likely energy consumption of each. These energy saving predictions of individual dwellings can be scaled up to building stock levels to give an overall prediction of the likely energy savings that could result from higher air motion in comparison with air-conditioning solutions.

6 Conclusions

The field studies in the UK (15 residences) and India (20 residences), whilst not being a particularly large sample, is nevertheless significant in two respects. Firstly, they have generated a large and very rich dataset, allowing a detailed picture of everyday family life as it might influence residential thermal comfort. Secondly, the work has successfully demonstrated a methodology that is suitable for residential application, can be replicated for subsequent national and international studies, and is capable of modification to suit particular circumstances and data requirements. Conclusions are as follows.

i) Residential dwellers will co-operate in surveys involving subjective and objective components if suitably approached and the surveys conducted carefully and sensitively. Online data gathering via mobile technology is an effective mechanism in this context.
ii) An advanced questionnaire, designed to align with the online approach, can be used to capture detail of air motion practices and configurations, together with information on other related factors.
iii) The method provides a rich and unique insight into residential practices that influence thermal comfort, and can be used in other such investigations elsewhere.
iv) The data generated will be made available to the UCB database, and will be analysed in more detail in coming months. Remaining tasks of the GII Project will be completed, and will be reported on in due course.

Acknowledgements

The research teams at UC Berkeley, USA, CEPT University, India, De Montfort University, UK and Loughborough University, UK express their gratitude to the British Council and UK Government Department of Business, Innovation and Skills, for funding this international partnership work under their Global Innovation Initiative Projects scheme.

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Evaluation of Indoor Environmental Quality – Case study of Lagos Offices

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Abstract

In order to mitigate the adverse effects of climate change, there has been a sustained focus on the provision of green or sustainable buildings and development over the years. To justify the added cost of green construction, the green indoor environment is often marketed as being responsible for increased worker comfort, satisfaction and productivity. This study uses both qualitative and quantitative means to evaluate this claim. The outcome is that the level of importance of the IEQ parameters varies across societies and cultures.

Keywords: IEQ, Comfort, Satisfaction, Productivity

1 Introduction

> "Man is a funny creature. When it's hot he wants it cold. When it's cold he wants it hot. Always wanting what is not. Man is a funny creature" (Nagengast, 1999)

Studies in the some industrialized countries have shown that the populations spend about 90% of the time indoors (US EPA, 1989; Leech et al, 2002). As such, the quality of the indoor environment becomes important in how it impacts the health and wellbeing of the occupants. Based on an 8-hour workday, about 50% of an adult's waking period is spent indoors within an office environment. This implies that the indoor environment should be conducive for work performance. This paper presents the findings of a pilot survey carried out to evaluate the indoor environmental quality (IEQ) factors in office buildings in Lagos, Nigeria.

In order to mitigate the adverse effects of climate change, there has been a sustained focus on the provision of green or sustainable buildings and development over the years. The major approach has been to minimize the impact of developments on the environment with major emphasis on energy use and material resources. However, the approach does not take full cognisance of the comfort perceptions of the occupants.

The indoor environment has had varied levels of importance through the ages. In ancient past, buildings were constructed for both security and comfort. Designs of the modern era placed emphasis on the building expressions and impressions. However the energy crisis of 1973 and the climate change revelation of the mid 1980s put focus on energy efficiency and conservation. In commercial buildings in the tropical climate, air conditioning has the highest percentage of energy use with lighting usually a distant second.

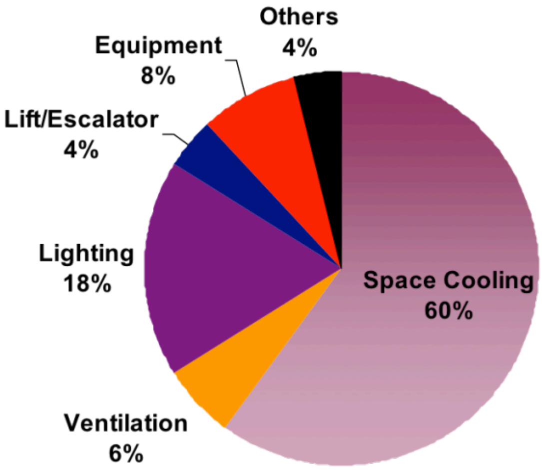

Fig 1 - Typical Annual Energy Usage for Commercial Buildings in Tropic Climate (UWCSEA, 2013)

Unfortunately these two services, airconditioning and lighting, contribute to the physiological comfort within the indoor space and, therefore, are the main focus in a quest for energy conservation. Consequently, ventilation rates were lowered and the buildings became more airtight. Office lighting levels which were 300lux prior to the 1960s, and that had climbed to 700 lux with the affluence of the 1960s, was dropped to 400 – 500 lux following the oil crises in the early 70s (Levin, 2000). There is continuing advocacy that it can and should be lowered further.

However, there was an implication of the lower ventilation rates on the health of building occupants. The consequence was that buildings became damper and the indoor pollution increased as a result of the volatile organic compounds (VOC) which were prevalent in the modern furnishing and finishing (Hobday, 2011). The inadequate ventilation resulted in complaints of headaches, nausea, fatigue and asthma. The ailment or feeling became known as the sick building syndrome or tight building syndrome. The World Health Organisation (WHO) linked indoor air pollution to over 2.8 million deaths annually (Hoskins, 2003). Tuberculosis and legionella are frequently mentioned as ailments of bad indoor air quality (IAQ). It is therefore not surprising that focus had to go back to the indoor environment.

> "During the 19th and into the 20th century... Energy efficiency was secondary to health. Improvements in ventilation, lighting and crowding are credited with helping to reduce the prevalence of tuberculosis. Today the position is reversed. The focus is now more on carbon emission savings and less on high standards of IEQ" (Hobday, 2011)

With the advent of the sustainable building certifications, due emphasis has been put on the quality of the indoor environment. For the LEED (Leadership in Energy and Environmental Design) certification, the quality of the indoor environmental ranks second behind energy and material considerations.

Much research is being carried out to evaluate the IEQ of residential and office developments. Unfortunately, a greater percentage of the research work is being carried out in the Western Industrialized economies with Asia following but at a distance. Studies carried out in Africa arerelatively very low. Sustainability is now a major consideration in the built environment and guidelines are based on research work carried out in the industrialized economies. Thus, there is a compelling need to evaluate the IEQ of office buildings in Lagos, Nigeria with the objectives of examining its relationship with comfort, satisfaction and productivity.

2 IEQ and Comfort

The functional value of a building, residential or commercial, cannot be truly assessed without considering the impact of the indoor environment on the occupants or users. The indoor environmental quality (IEQ) of a space has been given various definitions thus lending to the complex nature of the state or condition.

The Dictionary of Construction (2016) refers to IEQ as “an important criterion for green, or sustainable, building design (that) refers to (the) general overall building occupant comfort.” The dictionary includes humidity, ventilation/air circulation, acoustics and lighting as parameters of IEQ.

Coyle (2014), writing in Green Building 101 which is a USGBC publication, stresses the impact of IEQ on the health and wellbeing of the occupants. She did not mention comfort though this can be assumed to be inferred. Compared to the listing by the dictionary, she omitted acoustics but included ergonomics.

The NIOSH (National Institute for Occupational Safety and Health, 2015), in line with its core function, relates IEQ to the health and wellbeing of the occupants. The highlighted parameters were limited to lighting, air quality and dampness. The air quality has to do with air-borne contaminants and volatile organic compounds (VOC).

The Sustainable Facility Tool (2016), a resource of the U.S. General Services Administration (GSA), considers the following parameters: air quality, access to daylight and views, acoustics, occupant control over lighting and thermal comfort, work-space layout and sufficient area. They took the IEQ consideration beyond the physiological parameters to encompass the issue of personal control and workspace elements.

The Green Building Council of Australia affirms that IEQ is an important aspect of the overall sustainability of the building. The rating tool of the association identifies the core parameters as temperature, lighting and acoustics and these are believed to affect the occupants’ health, happiness and comfort.

The Whole Building Design Guide notes that the occupants’ wellbeing and productivity are affected by the common physiological factors as well as factors of aesthetics (light and colour, window views) and psychological (sense of enclosure, privacy and control, connection to nature). This view was supported by Ouwelande et al (2014) who listed six components of psychological comfort as self-acceptance, personal growth, purpose in life, positive relationship with others, environmental mastery and autonomy.

Bean (2012) added vibration to the five common physiological factors of indoor air, temperature, lighting, acoustics and odour.

Wargorcki et al. (2006) gave a comprehensive review of the physical factors as indicated in the figure below.

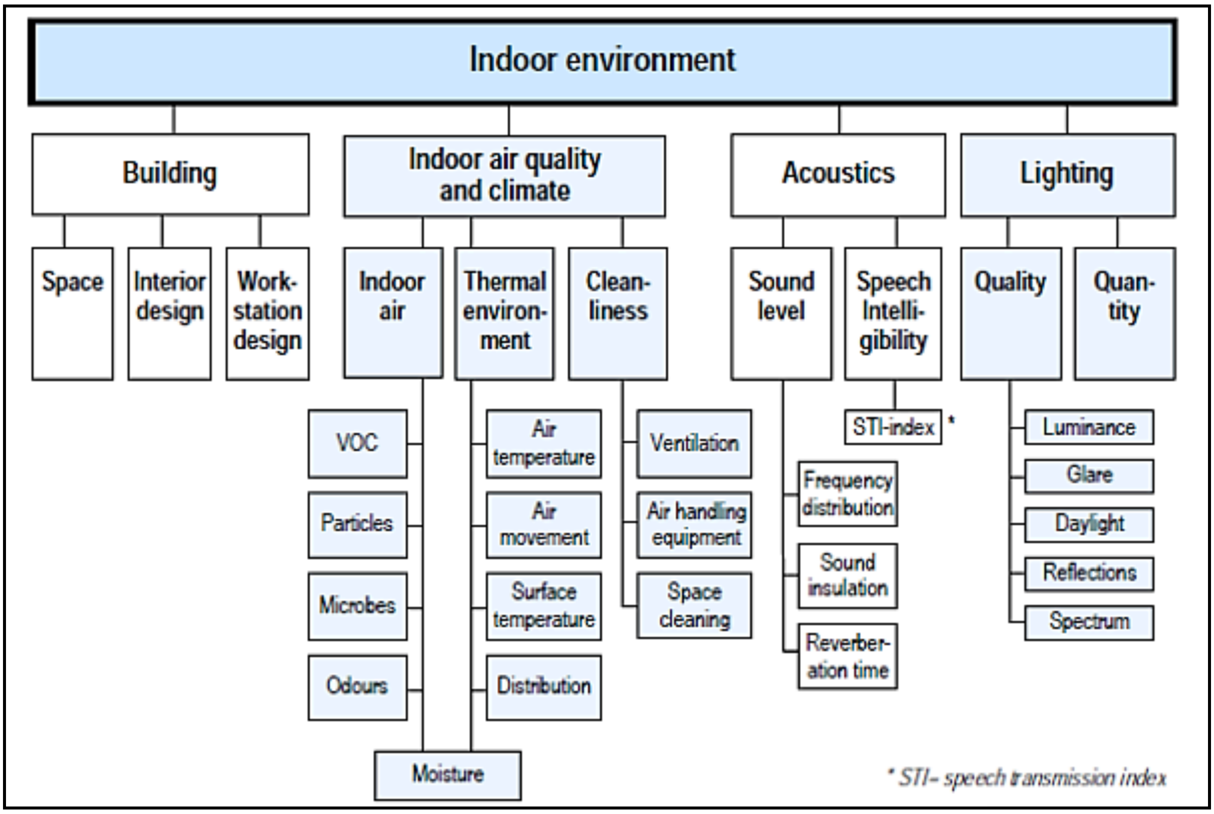

Fig 2 - The indoor Environment (Wargorcki et al., 2006)

The definitions above are not exhaustive but do confirm the complex and extensive nature of the indoor environment.

It is noted that the qualities of comfort, satisfaction and performance are influenced by both physiological and psychological parameters. The study by Frontczak et al (2011) showed that there are variations in the impact of the physiological parameters. As such, the conclusion has been that perceptions of comfort and satisfaction as impacted by IEQ may be dependent on the occupants' awareness (or knowledge) and culture (Chappells et al, 2004). In an earlier study, Wilhite et al. (1996) had indicated that 'Western' standards were becoming predominant in perceptions of comfort. Can this be due to the fact that researches in other regions were not as advanced? Or is it the case of 'globalization'?

It is important that practitioners in the built environment of Nigeria know or are aware of the perceptions of comfort of the Nigerian – especially whether it aligns with that of the 'West' or not. This will have significant impact on what is built and managed. How do workers in the Nigerian workplace perceive the concepts of comfort and satisfaction in relation to the quality of the indoor environment? How do their perceptions compare to the established measurements of their counterparts in the industrialized Western nations?

IEQ features prominently in all the sustainable building accreditation and assessment tools. LEED (Leadership in Energy and Environmental Design – by the U.S. Green Building Council) and BREEAM (Building Research Establishment Environmental Assessment Method – by the U.K. Building Research Establishment) are the two well-known tools in Nigeria. Certification is an assurance that the indoor environment will be comfortable and healthy.

Now both energy use and the IEQ of a space are inevitably linked to the sustainability of the space. A sustainable workplace is one that optimizes and conserves the use of natural resources and which also meets the needs of the people working there (Dwilson, 2014). The dread of climate change has pushed the topic of sustainability to the fore-front of political and professional discussions in the built environment. However, while sustainability has been legislated in most developed countries and by most international organizations, Nigeria still lags behind in this respect. This scenario may not hold for long.

Presently Nigeria does not really have a home-grown sustainability guideline. In Africa, only South Africa is believed to have such guidelines through the Green Building Council of South Africa that was established in 2007. Nigeria is still a potential member of the World GBC. The building industry in Nigeria has had to rely extensively on the international guideline which was principally developed by and for the developed western economies. Examples of such standards and guidelines include those of the American Society of Heating, Refrigeration and Airconditioning Engineers (ASHRAE), Chartered Institute for Building Services Engineers (CIBSE), Royal Institute of British Architects (RIBA), etc.

Green developments are in the forefront of environmental policies in the developed economies but there is still a problem with acceptability in the developing nations. Snushall et al (2005) reported that the "property industry will not sacrifice profit for the environment if it is not forced to do so by the planning bodies or its end users". As concern increased, sustainability was legislated in the developed countries and it has also been branded. The 'Green' brand is now a marketing tool or asset. Companies have adopted green/sustainable policies because of improved reputations, publicity and increased investor concern.

In debating the future of comfort, Chappells et al (2005) quoted Cooper (1982a, p.270):

> "Comfort standards are social constructs which reflect the beliefs, value, expectations and aspirations of those who construct them."

In other words, comfort and satisfaction can be impacted by awareness and culture. This may explain the global variance of the relative importance of the physiological factors of IEQ highlighted by Frontczak et al. How do Nigerians perceive comfort?

Most dictionaries define comfort as a state in which one is free of physical pain caused by pain, heat, cold, etc. Adebamowo (2007) defined it as a state of thermal rest devoid of heat or cold stress. It is also freedom from worry. Satisfaction is defined as the fulfillment of a desire, need or expectation. Comfort deals more with the physical but satisfaction is more perceptual in nature. This may explain why occupants' feelings vary over time even though the physical environmental conditions were similar. In the survey conducted by Gossauer et al (2008) of 16 German offices, 54% of the respondents were satisfied in winter and 30% in summer despite the fact that the temperatures were at 23-24^{o}C for both times. The researchers believed it had to do with a sense of control. Thus, perception and ultimately workplace satisfaction may vary across societies, generations and personalities.

3 IEQ and Satisfaction

The LEED buildings are marketed as being "competitive differentiators and make for happier employees and occupants". It is in this respect that the linkage between the physiological parameters of indoor environmental qualities (IEQ) – thermal comfort, lighting, acoustic and indoor air quality (IAQ) – and the satisfaction, comfort, wellbeing and performance of the worker is getting more attention. There are many studies to support this school of thought e.g. Seppanen et al. (1999), Heschong (1999), Milton et al. (2000) and Fisk (2002). But just as controversy has trailed the debate on the claims of the apocalyptic consequences of climate change, so is the linkage between IEQ, comfort, worker wellbeing and satisfaction generating its own controversy.

Kumar et al (2002) wrote on behalf of the IEQ linkage proponents:

> "Research into the indoor environmental quality (IEQ) and its effects on health, comfort and performance of occupants is becoming increasingly essential. Facility managers are interested in IEQ's close relationship to energy use. Employers hope to enhance employee comfort and productivity, reduce absenteeism and health-care costs, and reduce risk of litigation. The rising interest in the field has placed additional pressure on the research community for global guidelines on creating a safe, healthy and comfortable indoor environment".

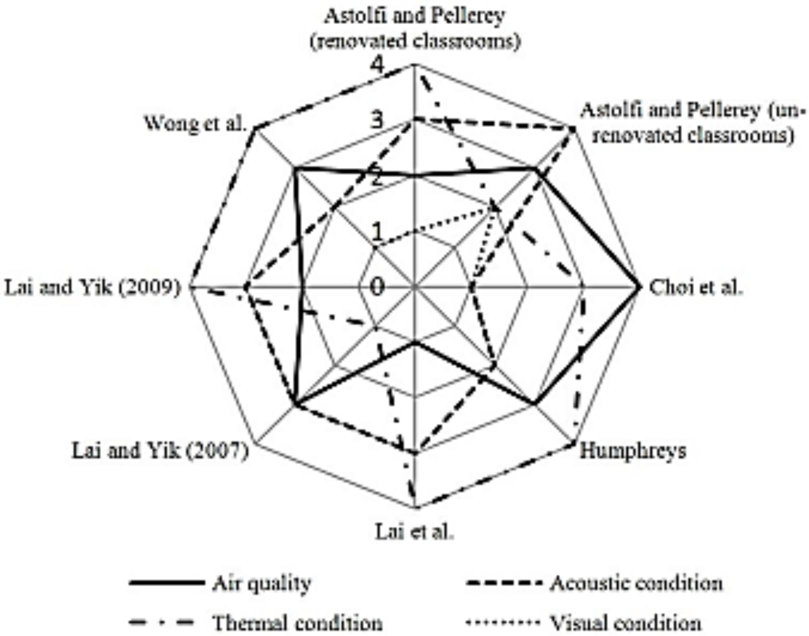

Fig 3 Previous researchers' attempts at ranking (higher number indicates higher ranking) of importance of IEQ factors for overall satisfaction (Frontczak et al, 2011)

On the other side of the divide, there is no consensus on the relative importance of the IEQ parameters to occupants' satisfaction. In their literature survey of different studies on IEQ, Frontczak et al (2011) highlighted the differences in the degree of influence of the physiological factors – see figure 3.

In their analysis of the survey database of the CBE (Centre for the Built Environment) of the University of California, Berkeley, Kim et al (2012) concluded that IEQ factors have both positive and negative impacts on the occupant overall workspace space satisfaction (Fig 4).

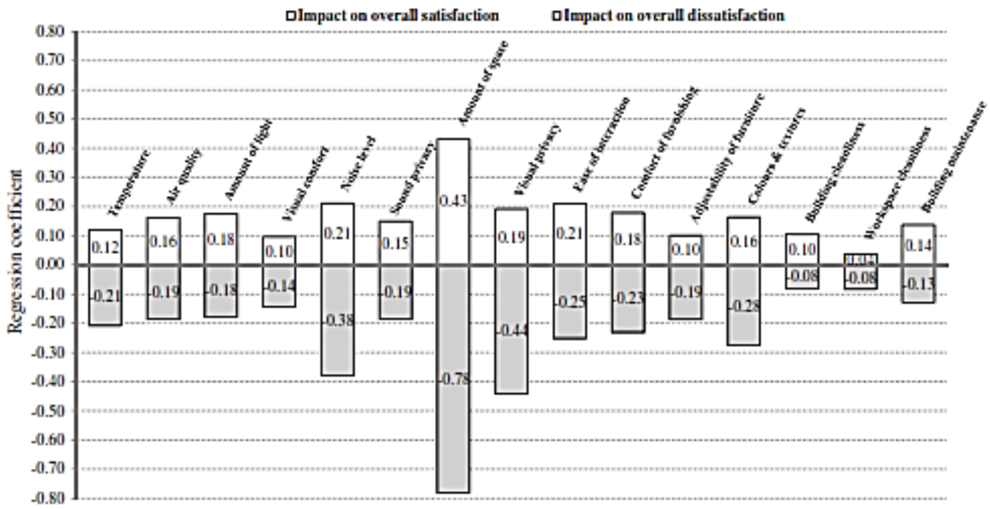

Fig 4 - Positive/negative impact of IEQ factors on occupant overall workspace satisfaction.
The values attached to each bar represent regression coefficients for each IEQ factor's satisfied occupants (white bar) and dissatisfied occupants (grey bar) (Kim et al, 2012)

Leaman et al (2007) concluded that that there are numerous confounding factors that can impact and distort the relationship between IEQ and satisfaction. Bhyssen et al (2011) confirmed Humphrey's (2005) finding that overall satisfaction does not depend on individual IEQ physiological factors but on a collective whole. The question of which is the predominant factor is yet to be answered.

4 IEQ and Productivity

> "It should be noted that good IEQ is a necessary, but not sufficient pre-requisite for enhanced productivity, since other factors, specific to individual contexts, and not directly related to IEQ, can also have a significant impact." (Paevere, 2008)

Linn et al (2011) noted that for the measurement of the worker's productivity to be comprehensive, the following factors needed to be considered:

1. Personal factors (e.g. motivation, satisfaction)
2. Organizational factors (e.g. quality of management, payment/salary and reward system).
3. Social factors (e.g. relationship with others)
4. Indoor physical environmental factors (e.g. accessories, work environment).

They confirmed that the study of the performance of the office worker or office productivity is a complex topic and that to measure productivity in a quantitative way was difficult. Thus subjective productivity measures was generally acceptable

In essence, the qualities of comfort, satisfaction and performance go beyond the physiological factors. Linn et al (2013) further noted:

> Businesses are becoming aware of the financial implications of occupying poor performing buildings in regards to energy, water and waste but their understanding of improvement process is still developing. ... Optimizing employee productivity is a complex science. It needs to be considered more broadly taking into account the organizational and management context, an individual employee's job satisfaction and the social work environment. …. There is no doubt that future research will need to expand its analysis from purely physical

parameters to a more holistic assessment. This more comprehensive analysis should also address technology enablers, such as IT, communication equipment, connectivity and cloud computing.

5 Methodology

The study consists of a survey of 10 offices on the Island and Mainland of Lagos. The offices were selected randomly. As expected, some offices declined permission on grounds of security and distraction of workers. No public building is included in the survey because of the bureaucratic delay in securing government approval.

There were 3 parts to the survey:

1 Physical measurement of the indoor environment parameters of temperature (dry bulb), relative humidity (RH), lighting lux level and the sound level for the work spaces. All measurements were taken by meters from PCE Instruments UK Ltd

2 A quantitative survey using questionnaires sent online to the workers in the 10 offices. The target was to get at least 5 completed questionnaires from each office. There were better returns in a number of offices. One did not respond at all. One limitation is that the questionnaires were not returned on the same day as when the physical measurements were taken.

3 A quantitative survey in which at least 3 employees would be questioned about their workspace and the issues of IEQ. The survey also included presenting 9 different office layouts and asking for the preferences of the workers. Pictures were used so as to standardize the survey.

The CBE IEQ instrument has the highest usage internationally (Peretti et al, 2011) and it was adopted for the quantitative study. This decision was also to justify the validity and reliability of the study. The instrument covers the IEQ parameters of office layout and furnishing, thermal comfort, air quality, lighting, acoustic, cleanliness and maintenance. It uses a 7-point Likert scale that measures the satisfaction of the workers for the aspects of the parameters as well as the overall satisfaction for the space. There were also questions of how the parameters enhance or interfere with getting the job done.

Another set of questions was added to measure the relative importance of the factors that impact productivity. This was based on the studies by Onyeizu et al (2013) who had identified the five factors as:-

1. Personal factors (e.g. motivation, satisfaction).
2. Organizational factors (e.g. quality of management, payment/salary and reward system).
3. Social factors (e.g. relationship with others).
4. Indoor physical environmental factors (e.g. accessories, work environment).
5. Convenience.

The results were then compared. Onyeizu et al covered offices in green buildings in Auckland, New Zealand. How will workers in Lagos, Nigeria compare?

The quantitative survey had a set of questions to gauge satisfaction with the work environment and to compare the measured parameters with acceptable building standards. Since satisfaction with the aesthetics was a measure of psychological satisfaction, the workers were to pick from the nine pictures what their ideal workplace would look like. The pictures are pasted below.

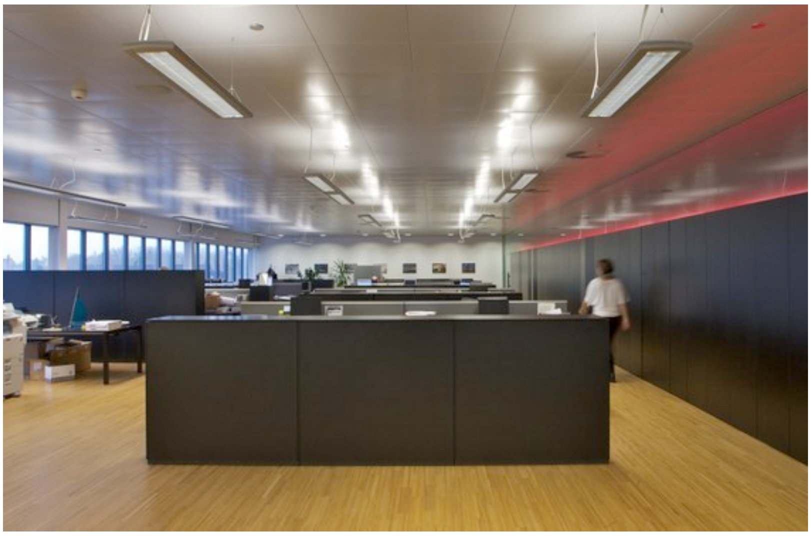
Fig 5 - Workspace Sample A
http://www.thornlighting.co.nz/en-nz/solutions/application-advice/office/office-lighting/office-3.jpeg/@@images/44756782-73cc-4eff-898b-9e5813051bb7.jpeg


Fig 6 - Workspace Sample B
http://cdn.shopify.com/s/files/1/0002/0948/files/led-t8-office.jpg?100902


Fig 7 - Workspace Sample C
http://www.genlight.com.sg/products_main_clip_image002_0001.jpg

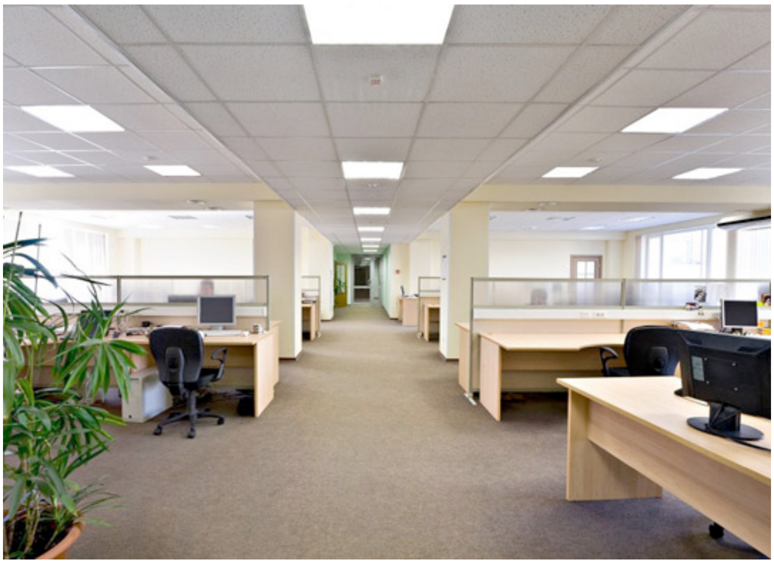

Fig 8 - Workspace Sample D
http://www.electricianschristchurch.net/wp-content/uploads/2013/12/Commercial-Installations.jpg

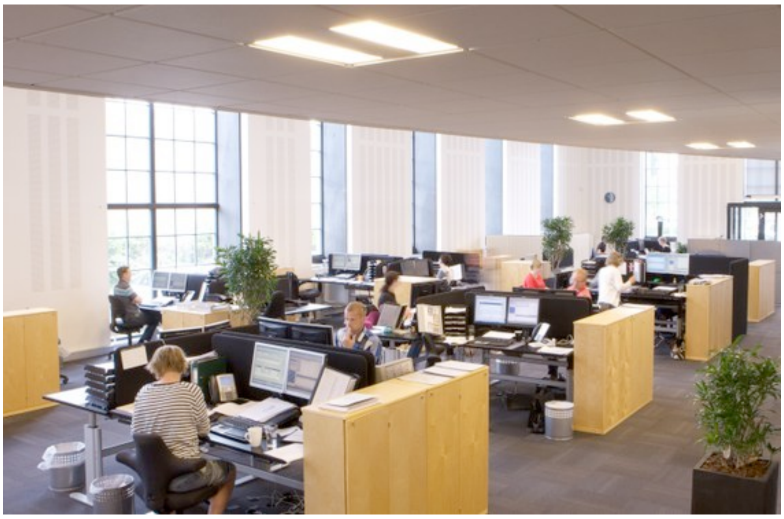

Fig 9 - Workspace Sample E
http://www.thornlighting.co.nz/en-nz/solutions/application-advice/office/office-lighting/office-1.jpeg/@@images/78d6845c-b274-49ee-a9ac-f51da382fdfb.jpeg

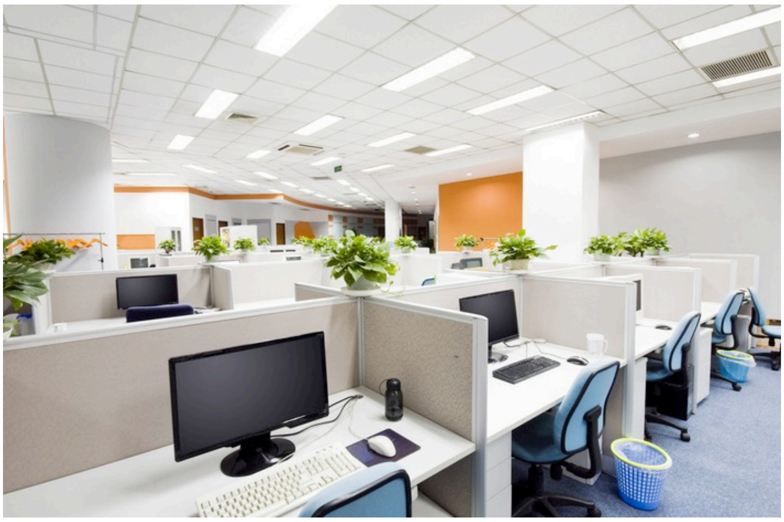

Fig 10 - Workspace Sample F
http://www.heston-wto.com/imageRepository/175c1716-a66b-4a00-a0c7-8b45c673aadb.jpg

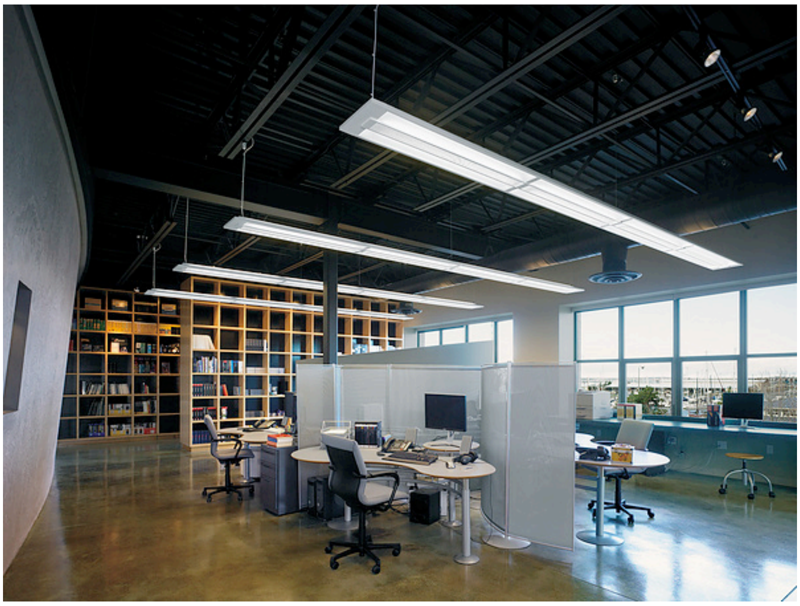

Fig 11 - Workspace Sample G
http://cdn.decoist.com/wp-content/uploads/2013/04/office-light-ideas.jpg

Fig 12 - Workspace Sample H
http://1.bp.blogspot.com/d89MXHg4c3k/T8xfQCbwpjI/AAAAAAAAOFI/9rwau4tquFY/s1600/Office_lighting.jpg

Fig 13 - Workspace Design I
http://ele-mec.com/el/wp-content/uploads/2012/09/5.gif

6 Results and discussion

A brief description of the 10 offices is presented in the table below

Table 1–Description of surveyed offices

Office reference	Type of business	Description	Question-naires returned
1	Architecture	Converted residential apartment. The large former living room serves as the main studio. Airconditioning is by mini-split units.	2
2	Architecture	Floor of purpose built office with central airconditioning	7
3	Pension Fund Management	Purpose built office with DX cassette units	9
4	Architecture	Converted residential building but remodeled as office. The attic is also used as studio. Airconditioning is by mini-split units.	8
5	Fund Management	Purpose built office with mini-split airconditioners	5
6	Financial Market	Floor of purpose built office with central airconditioning	0
7	Architecture	Floor of purpose built office with mini-split units	6
8	Architecture	Floor of purpose built office with central airconditioning	11
9	Engineering - MEP	Floors of purpose built office with central airconditioning	21
10	Engineering - Structures	Converted residential building. Airconditioning is by mini-split units.	6

Of the 75 questionnaires returned, 3 were invalidated and removed from the data analysis.

The table below gives the measurements of the parameters for the offices. Mostly, the survey was restricted to the main open office or the smaller rooms as in the cases of the converted residential buildings – offices 1 and 9.

Table 2–Measurement of parameters and comparison with code requirements

IEQ FACTORS		OFFICES									
	Building Codes	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Temperature (^{o}C)	**24 ± 2**	27.2	25	26.2	26.8	25.2	24.6	26	26.5	26	25.2
RH (%)	**50-60**	49	58	61	59.4	56	53	49	61.5	57	62.3
Sound Pressure (dBA)	**35-45**	50-60	65	58-65	58-62	49-55	50	56	60-66	60-65	60-64
Light level (Lux)	**300-500**	309-660	317-660	360	180-360	350	322-480	428	200-950	280-450	180-280
Occupancy rate (m^2/worker)	**10**	5.2	3.5	2.5	4.5	4.1	7.8	5	8	6	4

From the table, only 30% of the spaces meet the temperature comfort range. The workers in the spaces with central airconditioning cannot adjust the temperatures and usually put on their jackets when they feel cold.

30% of the spaces are outside the humidity range.

No space meets the acoustic requirement. The reason for this may be that most of the offices are located on busy roads. The windows are all single glazing except for office 6. The internally generated noise is also appreciable.

For the light levels, the higher figures are for spaces near the windows. There is no daylight saving switches to take advantage of the high illuminations near windows but very few of the workers switch off the lights. Also most of the offices have the window blinds closed either because of glare or to avoid distraction from the street scenes. The views were generally not interesting except for offices 2, 6, 7 and 8. There was no consequence with the low lux levels as most of the workers were using computers and they could adjust the monitors as desired. The non-uniformity of the lighting was not noticed by the workers. It is assumed that they had adapted.

The occupancy rates fall short of the optimal of $10m^2$/person and only two offices meet the minimum $8m^2$/person.

Very few of the offices made any attempt at energy conservation. Those who occupied offices in large buildings confirmed that they paid fixed charges for infrastructure. Whether they use the energy or not they pay. Therefore there is no incentive to conserve energy.

The workers that were interviewed were asked to assess the indoor environment as it impacted performance. The response is given in the table below.

Table 3 – Workers qualitative assessment of indoor environment and performance.

	OFFICES									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
What does your daily work performance in the workspace environment feel like?										
Very dissatisfying										
Dissatisfying										
Neutral			X							
Satisfying	X	X		X	X		X	X	X	X
Very Satisfying						X		X		

Generally the feeling was satisfactory except for office 3 where the workers complained of the congestion and lack of privacy. Office 6 had a very satisfying assessment. When the workers were questioned, they mentioned the relational factor amongst the workers as being the major contributory factor. There was no consensus for office 8.

The workers were asked to choose an office layout that conformed to their dream or expectations. Workspace design sample D had the highest score followed by workspace sample E. Workers in office 6 did not see any that was better than what they have.

Table 4–Workers preferred workspace design.

	OFFICES									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Please tell us about your dream working environment and your desires in terms of space, furniture, ambience, layout and lighting.(Respondents' preferred workspace sample)	D	E, A, G	D, E	B, E, F	D, E	none	D, E	D, E, F	D, E	D, E

For the quantitative study, 74% of the 72 respondents that had their questionnaires analysed were professionals – Engineers, Architects, Accountants, Lawyers, etc. 48% of them were under 30years of age. Of the lot, 43% worked in offices with closed window blinds with 24% actually confirming that the outside view was not interesting.

Respondents were asked to score the 35 parameters of the five factors that influenced productivity (Onyeizu et al, 2013). The parameters are:

1. **IEQ factors**: Daylight, Glare, Too hot/too cold, Artificial lighting, Too noisy/too quiet, View, Air quality
2. **Social factors**: Relationship at work, Relationship outside work, Distraction/disturbance
3. **Personal factors**: Injury, Loss of sleep, Life experiences, Other financial stress, Medication effects, Health/wellbeing, Transport to Work, Relationship outside work, Relationship at work, Distraction/disturbance.
4. **Organizational factors**: Job security, Access to health care, Workload, Refreshments at work and Poor management.
5. **Convenience factors**: Overcrowding, Inadequate equipment, Uncomfortable furniture, Position relative to equipment, Cleanliness, Office décor, Personal storage, Privacy, Positive relative to colleagues, Poor Equipment and Furniture arrangement.

The respondents were asked to measure the impact using a scale of 'indifferent', 'slightly important' and 'very important'. The responses were weighted from 0 to 2. Fig 4 above shows that the parameter of health/wellbeing was the most important. Air quality was the highest IEQ factor and ranked 7th. Outside view, another IEQ factor, was ranked the lowest. The result was compared to that of Onyeizu et al.

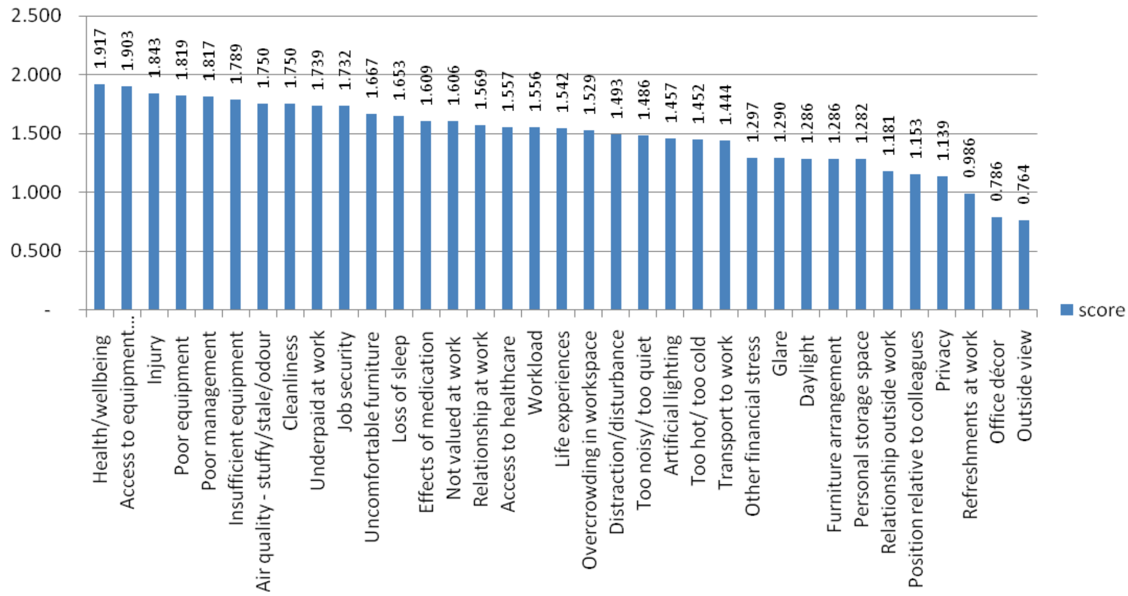

Fig 14 – Importance of factors that impact the perceived productivity of the Lagos office worker

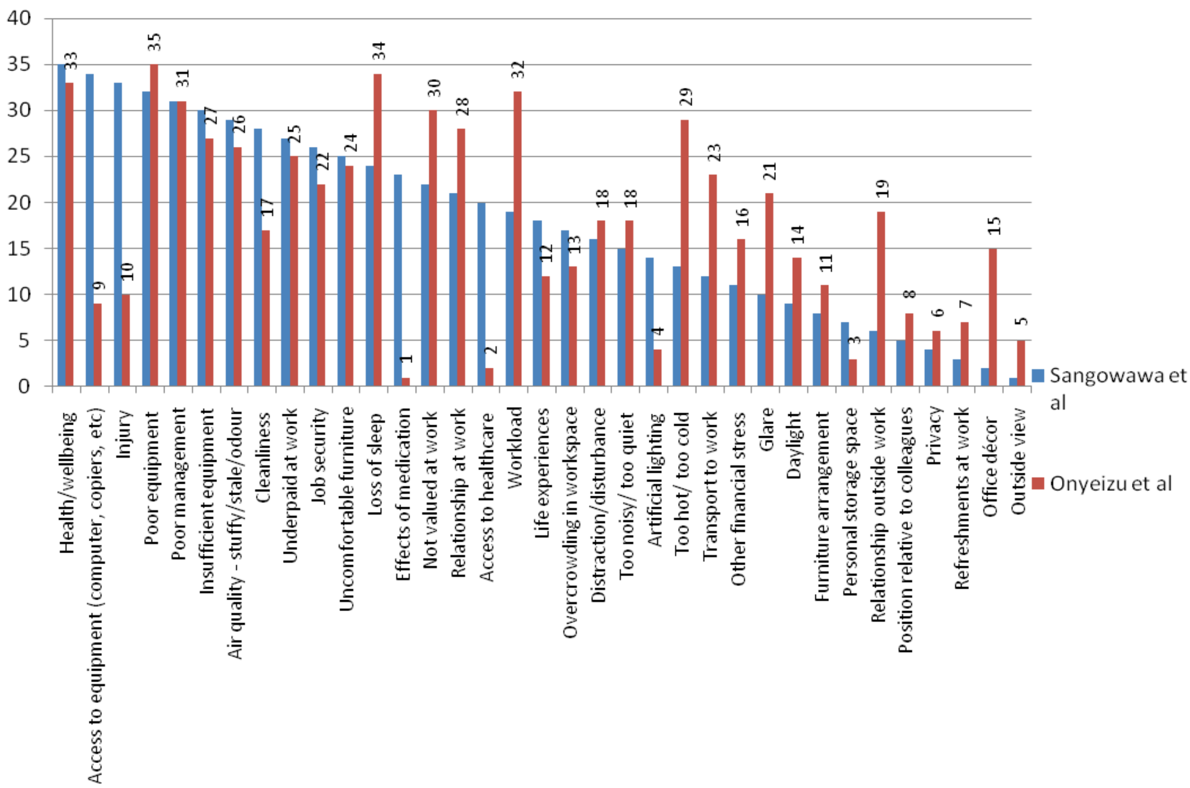

Fig 15 – Rank comparison of parameters that impact the perceived productivity of the Lagos and Auckland office workers

The comparison gives valuable insight. What is important in Auckland is not necessarily so in Lagos. Health/wellbeing is critical for the Lagos worker but it came in at 33rd in the Auckland ranking. Poor equipment was the highest in Auckland but came in 32nd in Lagos. Effect of medication was lowest for Auckland but the lowest for Lagos was outside view.

Some of the differences can be explained by knowledge of the local environment. Injury was 33rd for Lagos but only 10th for Auckland. In Nigeria, the public healthcare system is not commendable and the private ones are expensive. Also there is no disability allowance for the workers. Thus the risk of injury is taken seriously.

The IEQ parameter of temperature (too hot/too cold) was ranked 29th for Auckland and 13th for Lagos. Airconditioning is a common feature of most offices in Lagos. The external environment is dusty, warm and humid and the use of airconditioners is mandatory for comfort in most offices. It is assumed that it will be present and no longer features as a variable.

The parameters were grouped into their respective factors and the weighted averages were compared.

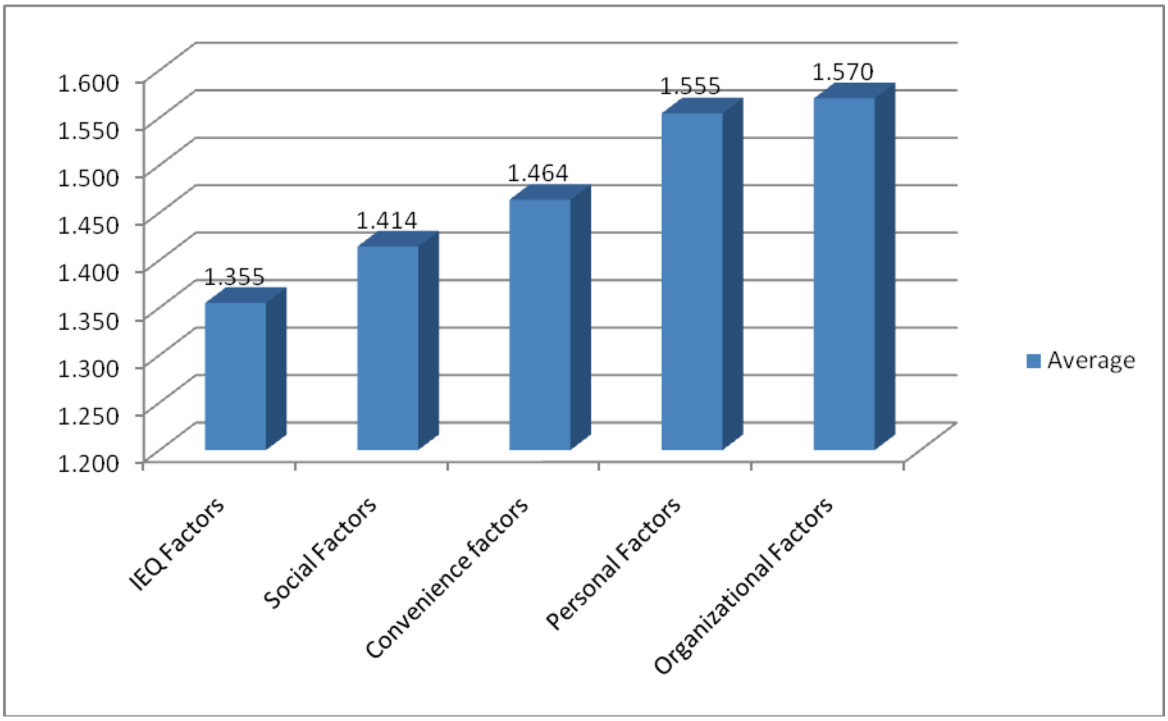

Fig 16 – Comparison of factors that impact the perceived productivity of the Lagos office workers

A comparison of the means shows that the IEQ factors were the least important while organizational factors were the most important factors of productivity for the Lagos worker. However the Anova test of the means did not return a significant difference at 95% level of confidence. The P-value was 0.601 and $F_{critical}$ was greater than F.

Onyiezu et al (2013) had concluded that:

> "The concern of this paper is whether or not the method by which worker productivity in 'green' certified buildings is measured is sufficient to prove that green accreditation increases productivity. These claims are based on results that appear to be extremely precise and can measure the percentage increase in productivity to two decimal places. This paper has shown that when compared with other factors, IEQ is of less significance to productivity".

The Lagos study has the same conclusion.

The analysis of the CBE instrument indicates that 81% of the respondents reported that they are satisfied with the indoor environment. A lower number of 72% believes that the quality of the indoor environment positively influences their productivity. Thus even though the IEQ factors were not the most important, they still contributed to the productivity of the worker.

Table 5 – Workers satisfaction with the indoor environment.

All things considered, how satisfied are you with your workspace as relates to the environmental parameters (- thermal, lighting, acoustics, air quality)	%
Very much interferes	0.00
Moderately interferes	0.00
Slightly interferes	5.79
Neutral	3.86
Slightly enhances	17.36
Moderately enhances	25.08
Very much enhances	55.94

Table 6 – Impact of IEQ parameters on productivity.

Overall, how is your productivity enhanced of interfered by the environmental parameters (- thermal, lighting, acoustics, air quality)	%
Very much interferes	1.39
Moderately interferes	4.17
Slightly interferes	5.56
Neutral	16.67
Slightly enhances	15.28
Moderately enhances	33.33
Very much enhances	23.61

The respondents were asked to measure how the different factors affected their ability to get there job done. A comparison of the weighted means is given in fig 17.

The Anova test was carried out on the difference between the means. The P-value was 0.006 and $F_{critical}$ was less (though close) than F. This indicates that there was a significant difference between the means. Some parameters were more influential than the others. Lighting affected productivity more than any other factor followed by office layout. Quite a number of the participants in the qualitative survey indicated their desire for spacious workspaces. Overcrowding was ranked 17th in the importance of parameters.

The data was tested to confirm if there was a regression in the parameters. The R-square was 0.534. However, the P-values for 4 of the 7 factors were too high (>0.05). A regression could not be established.

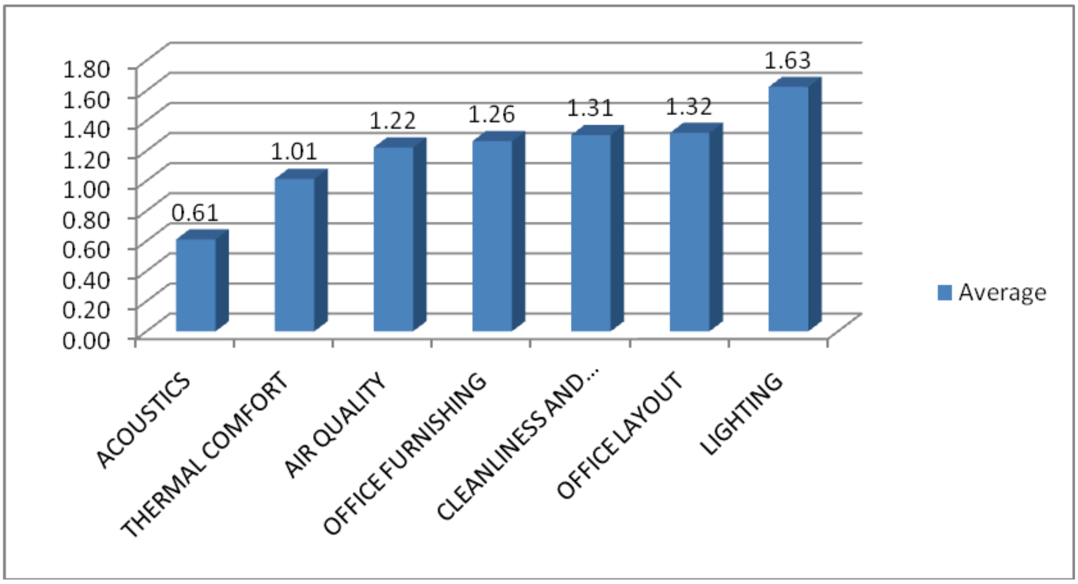

Fig 17 – Comparison of the impact of the IEQ parameters' on productivity

7 Conclusions

More than 60% of the offices that were surveyed did not meet the international standards for the indoor environmental parameters of temperature, humidity, acoustics and lighting. Yet, the subjects indicated satisfaction of their workspaces. This implies that comfort studies would need to be conducted for Lagos and that the international standards should only be a guide.

The study also showed that there is a variation in the relative importance of the IEQ parameters that impact productivity. This supports the view of Chappells et al (2005) that comfort and satisfaction have social and cultural connotations. One cap does not fit all.

For the Lagos worker, there is no significant difference in the impact of the five factors – IEQ, social, personal, organizational and convenience – even though IEQ was shown to be the least important. This finding corroborates that of Onyiezu et al (2013) in their study of green offices in Auckland, New Zealand.

We all still have a collective ecological responsibility and the goal of the architects and engineers in the built environment is achieving optimal comfort for the occupants while not forgetting their health and wellbeing.

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WORKSHOP 3.2

Using Statistics Correctly to analyse Comfort and Behaviours

Invited Chairs: Jane and Rex Galbraith

WS3.2: Using Statistics Correctly to analyse Comfort and Behaviours.
Chairs: Jane and Rex Galbraith

We shall open the workshop with an introduction to summarising and displaying thermal comfort data and a discussion of how such data might or might not provide answers to questions of interest. Participants will be invited to join in the discussion with questions and alternative solutions where appropriate in a wide ranging, expert and open debate on the challenges of applying statistics to comfort research. We request that participants send examples, with questions and comments, of issues that they have encountered in the analysis and interpretation of thermal comfort data to Jane Galbraith j.galbraith@ucl.ac.uk by 7th March. As well as using appropriate examples in the workshop we hope to provide statistical support to those who contribute examples.

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

A Study on Probabilistic Thermal Acceptability Evaluation

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Abstract

This study aims to establish a new thermal comfort index for evaluating air-conditioning systems, and introduces a new thermal comfort index for the provided and required temperatures. The authors performed comparison verification experiments on the temperature distribution of radiant air-conditioning and convective air-conditioning systems. The results showed the temperature provided by the convective air-conditioning system to have a wide distribution, unlike that of the radiant air-conditioning system. Based on these results, the authors propose a probabilistic thermal acceptability evaluation using the concepts of "provided temperature" and "required temperature". The authors consider this evaluation method to be applicable for non-steady thermal environments as well as uniform high quality indoor thermal environments using radiant air-conditioning systems, and personalized air-conditioning systems.

Keywords: Thermal acceptability, Thermal comfort, Provided temperature, Required temperature, Evaluation method

1 Introduction

Radiant cooling systems do not create an uncomfortable air draft, unlike conventional convective air-conditioning systems. Therefore, such systems are expected to improve thermal comfort. However, an index evaluation method for assessing the thermal comfort of radiant cooling systems has not yet been established. Evaluation using the conventional thermal comfort indices considers the comfort of an individual staying in a room to be the same as that of a group of people with common characteristics. However, some individuals complain that when they sit under the air outlet, or at the cold spot in an actual working space, they do not feel the thermal environment to be comfortable. Therefore, the thermal environment should be evaluated from the point of view of such individuals. Moreover, conventional indices are used for the evaluation of a steady environment. Therefore, they are not suitable for use in the evaluation of thermal comfort in non-uniform unsteady environments of personal air-conditioning systems.

2 Concept of provided temperature and required temperature

This study deals with each case individually when accounting for the human problems of physiological quality and physical quantity in the indoor thermal environment. A few basic suppositions are necessary in order to discuss these concepts. The authors named the index of physical properties of the indoor thermal environment "provided temperature", and the index of human physiological needs "required temperature". The concept of provided temperature and required temperature are further elaborated as follows:

(1) Provided temperature

Provided temperature is a quantitative index of the indoor thermal environment. Provided temperature is defined as the temperature of an imaginary uniform thermal environment equivalent to the real environment. The conventional index of thermal comfort is derived from air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation. However, provided temperature is derived from four elements of the environment because the authors want to regard provided temperature as the pure indoor physical thermal environment. Therefore, the authors consider that provided temperature is an index similar to equivalent temperature. Equivalent temperature is defined as the temperature of a uniform enclosure in which a human body loses heat at the same rate as it would in the actual environment.

(2) Required temperature

Required temperature is defined as the provided temperature at which a person in a room feels neutral in terms of thermal sensation. Therefore, the required temperature is derived from the metabolic rate and clothing insulation of the person staying in the room.

3 Comparison verification of the provided temperature distribution of a radiant air-conditioning system and a convective air-conditioning system

3.1 Summary of measurement

This measurement aimed to compare the characteristics of the indoor thermal environment between a radiant air-conditioning system and a convective air-conditioning system, using provided temperature as an index. Moreover, this measurement was performed in order to gain fundamental data toward establishment of this new index.

This measurement was taken in an environmental test chamber where it was possible to set the temperature to the same level in both the radiant air-conditioning system and the convective air-conditioning system. In this experiment, the authors measured a detailed distribution of the indoor thermal environment in these test chambers. The conditions for each measurement are shown in Table 1. The summary of results in the environmental test chamber is shown in Fig. 1. A photograph of the supply opening used for the conventional air-conditioning system is shown in Fig. 2. In the case of the convective air-conditioning system, a deflection plate was attached to an anemostat type diffuser. This experiment reproduced airflow characteristics in the common office room by using a line diffuser. In the case of the radiant air-conditioning system, cold water was supplied to a radiant ceiling panel. Outside air was introduced through a floor-supply displacement ventilation system.

Table 1. Conditions for each measurement

	Convective air-conditioning system	Radiant air-conditioning system
Air-conditioning system	Anemostat type diffuser on ceiling	Ceiling radiant air-conditioning system Floor-supply displacement ventilation system
Preset temperature	26 [ºC]	
Air volume	1000 [m^3/h]	230 [m3/h]
Sampling points	90	

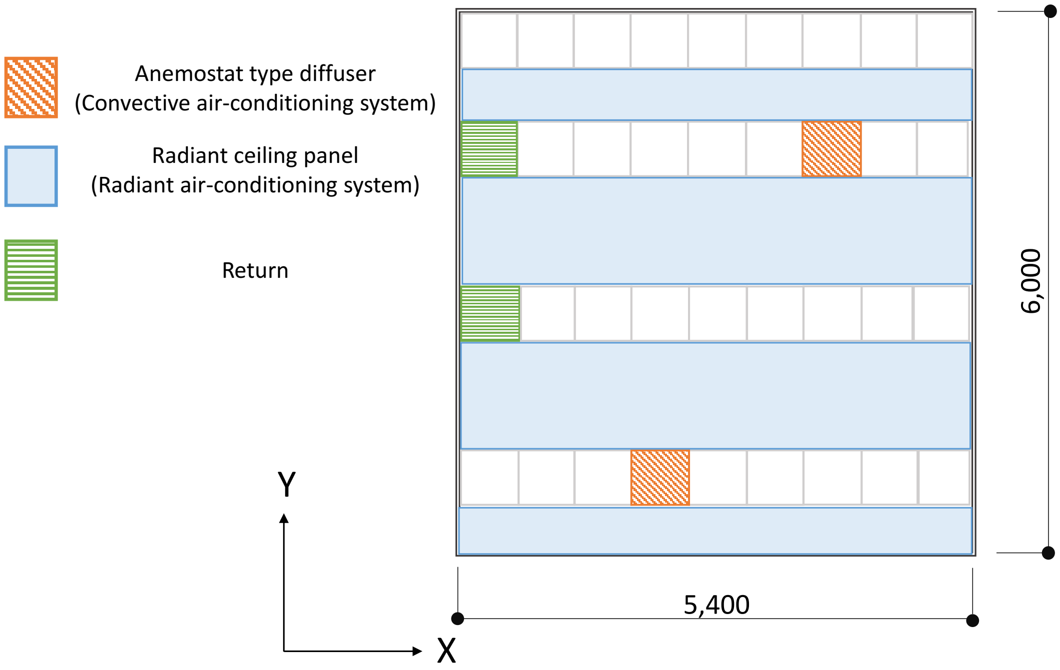

Figure 1. Summary of environmental test chamber

Figure 2. Photograph of supply opening used for convective air-conditioning system

3.2 Sampling points

The summary of sampling points is shown in Fig. 3 and Fig. 4. Air temperature and air speed on FL+1100 mm were measured at 90 points (600 mm) apart. The chamber was left to stabilize for 3 hours before measurements were taken. Measurements of air speed used a trestle with an 8-point non-directional probe hot-wire anemometer. These measurements were taken while the trestle was moving for a duration of 1 min at 5 s intervals.

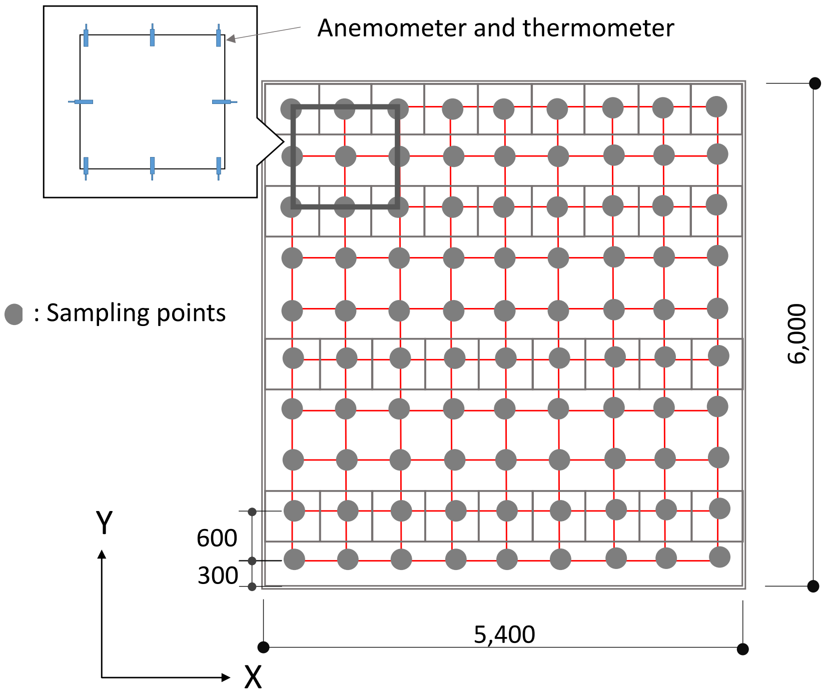

Figure 3. Summary of sampling points of floor plan

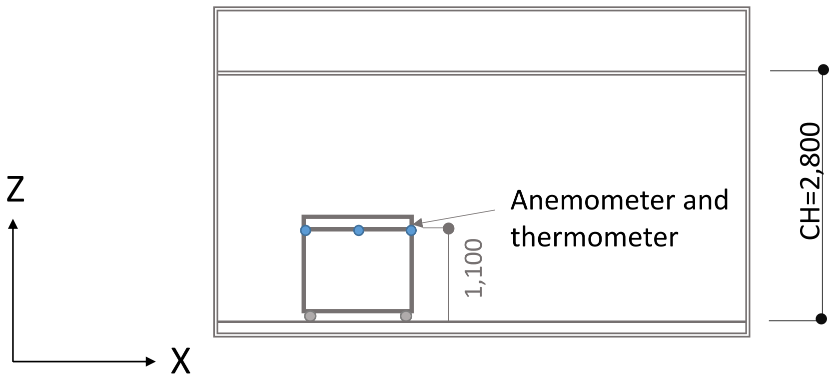

Figure 4. Summary of sampling points of cross section plan

3.3 Results of the experiment

(1) Planar distribution of air speed

Figures 5 and 6 show the planar distribution of the average scalar value air speed in the environmental test chamber for each air-conditioning system. Table 2 shows the maximum, minimum, and average in the planar distribution of the air speed for each air-conditioning system. In the case of the convective air-conditioning system, the average air speed was 0.14 [m/s]. These results also confirmed there was a noticeable difference in air speed between the maximum and minimum. In contrast, in the radiant air-conditioning system, difference in the air speed distribution was low. Moreover, the average air speed was 0.06 [m/s]. Therefore, the radiant air-conditioning system can provide a more stable environment compared to the convective air-conditioning system.

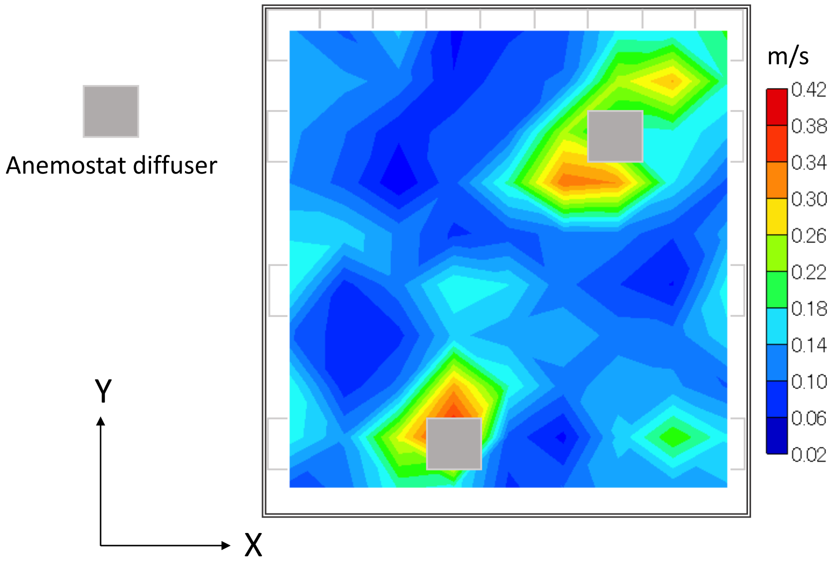

Figure 5. Planar distribution of air speed in the case of convective air-conditioning system

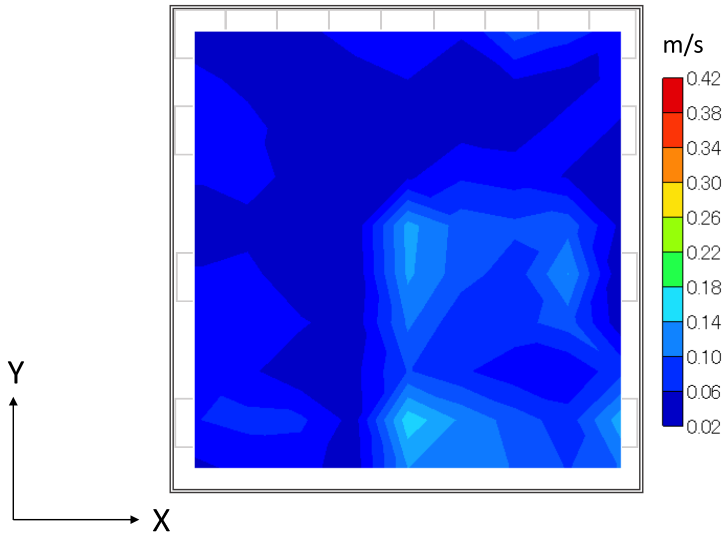

Figure 6. Planar distribution of air speed in a radiant air-conditioning system

Table 2. Results of air speed

	Convective air-conditioning system	Radiant air-conditioning system
Maximum [m/s]	0.40	0.15
Minimum [m/s]	0.04	0.02
Average [m/s]	0.14	0.06

(2) Provided temperature

For the evaluation of the provided temperature, the authors used Bedford's technique for evaluating equivalent temperature (Equation 1) on a trial basis. This can be easily calculated from the indoor physical thermal environment. Further, while we know the importance of the measurement of radiant temperature, it was not possible to measure it because of time constraints. Therefore, the mean radiant temperature is given as air temperature.

$$t_{eq} = 0.522t_a + 0.478t_r - 0.21\sqrt{v_{ar}}(37.8 - t_a) \qquad (1)$$

where

t_{eq} : Equivalent temperature by Bedford [ºC]

t_a : Air temperature [ºC]

t_r : Mean radiant temperature [ºC]

v_a : Air speed [m/s]

Figure 7 shows the occurrence frequency of the provided temperature and air temperature in each air-conditioning system. The equivalent temperature was used to determine the provided temperature, confirming a noticeable difference between provided temperature and air temperature in the case of convective air-conditioning systems. Therefore, it is difficult to precisely understand thermal environmental distribution using the conventional evaluation, which relies mainly on air temperature. Moreover, the radiant air-conditioning system appeared to create a uniform thermal environment compared to the convective air-conditioning system because the distribution of provided temperature was narrow. However, Bedford's equation is open to the criticism that it treats convection as measured from the body core temperature (37.8 ºC) rather than from the mean surface temperature of the clothed body, which can be much lower. In addition, the convective part of the equation rests on a multiple regression equation whose accuracy is questionable, to say the least. Further consideration will be needed to confirm any findings about the provided temperature.

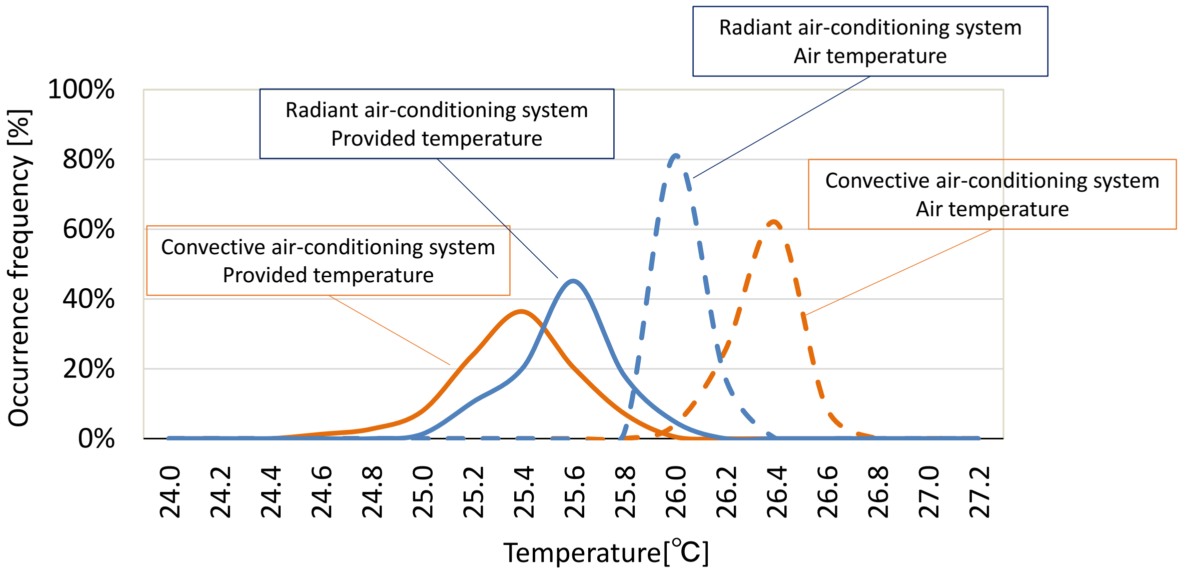

Figure 7. Occurrence frequency of the provided temperature and air temperature

4 Evaluating thermal environmental acceptability using a P-R chart

The authors designed a new means of evaluating thermal environmental acceptability based on the results from comparison verification of the provided temperature distribution between the two air-conditioning systems. The authors named this a P-R chart, after "provided temperature" and "required temperature". In this concept, all the values used are assumed. The conceptual diagrams are shown in Fig. 8 to Fig. 10. This theory applies probabilistic evaluation to thermal environmental acceptability. The thermal neutral line, which appears white on the charts, shows the points where provided temperature and required temperature are the same. Therefore, anyone on the white line area feels neither too hot nor too cold, meaning that they feel the thermal environment is acceptable. On the other hand, for example, we considered a case where 20% of the workers had a low required temperature because their metabolic rate and clothing insulation were high. If it is assumed that provided temperature in the indoor thermal environment is 20% maldistributed on the hot side, in evaluating the indoor thermal environment using this concept, we can probabilistically determine that 4% of the workers feel that the thermal environment is too hot. Moreover, in the case of an indoor thermal environment using a radiant air-conditioning system, the probability of worker complaints decreases, because the maldistribution of provided temperature becomes lower. In addition, if workers can use personal air-conditioning systems, worker complaints decrease further, because workers can adjust the individual provided temperature.

Two indices are typically used to evaluate thermal comfort: the predicted mean value (PMV) and standard effective temperature (SET*). However, these indices cannot evaluate the advantages of using radiant cooling systems over convective air-conditioning systems, because these indices are unsuitable to evaluate the uniformity of the indoor thermal environment. Moreover, they are not suitable for the evaluation of the thermal comfort of personal air-conditioning systems. However, it is believed that the aforementioned P-R chart can be used in thermal comfort evaluation for all air-conditioning systems. Radiant air-conditioning systems and personal air-conditioning systems are attracting attention now. However, these air-conditioning systems are not popular yet, because it is not clear to what degree do they increase the thermal comfort. Therefore, the development of the P-R chart will contribute to the widespread use of these air-conditioning systems.

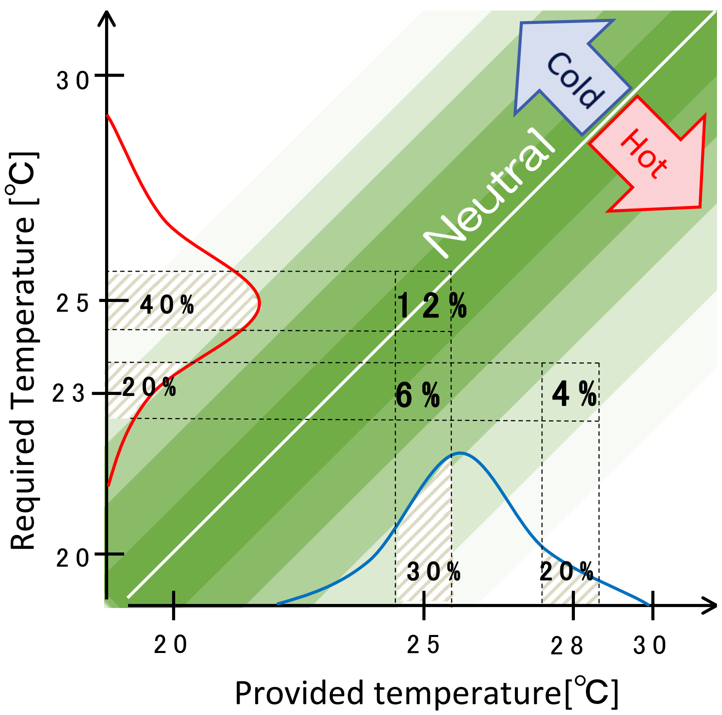

Figure 8. Conceptual diagram of P-R chart (Convective air-conditioning system)

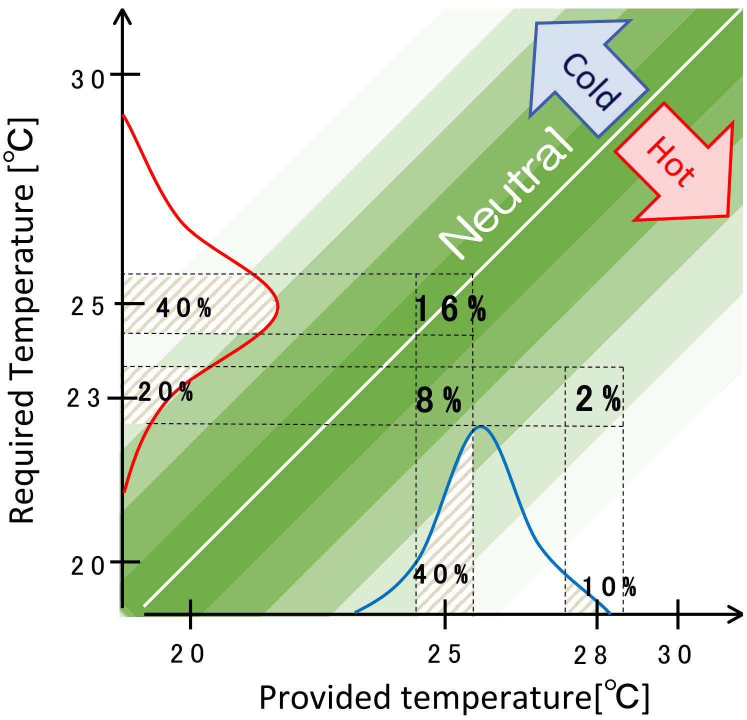

Figure 9. Conceptual diagram of P-R chart (Radiant air-conditioning system)

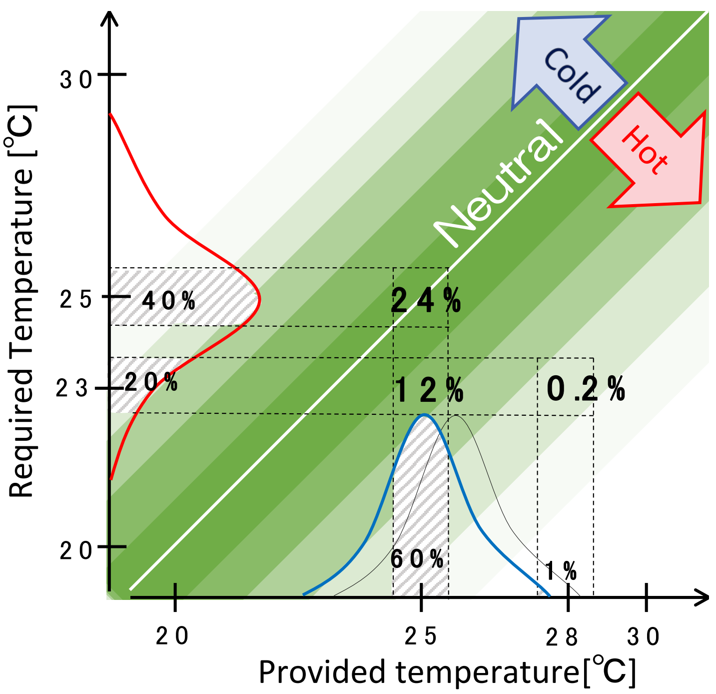

Figure 10. Conceptual diagram of P-R chart
(Radiant air-conditioning system + personal air-conditioning system)

5 Conclusions

This study aims to establish a new thermal comfort index for evaluating air-conditioning systems, and introduces a new thermal comfort index for provided temperature and required temperature. The results are summarized as follows:

1） The authors performed comparison verification experiments of the provided temperature distribution of a radiant air-conditioning system and a convective air-conditioning system.

2） In the case of the convective air-conditioning system, the average air speed was 0.14 [m/s]. It was also confirmed that there was a noticeable difference between maximum and minimum air speed. In contrast, in the case of the radiant air-conditioning system, the air speed distribution was low and the average air speed was 0.06 [m/s].

3） The narrow distribution of provided temperature indicated that the radiant air-conditioning system created a uniform thermal environment compared to the convective air-conditioning system.

4） The authors designed a means of evaluating thermal environmental acceptability based on the results from comparison verification of the provided temperature distribution of radiant air-conditioning systems and convective air-conditioning systems. The authors consider that this is an applicable method for evaluating non-steady thermal environments as well as uniform high-quality indoor thermal environments using radiant air-conditioning systems and personal air-conditioning systems.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

A survey of evaluation methods used for holistic comfort assessment

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Abstract
The complexity of a subject such as indoor comfort has encouraged the development of evaluation methods and scoring systems aimed at presenting either multiple indicators in a reduced set of results, a score, or a single classification, which can be more comprehensible for all the stakeholders involved. This paper examines these existing indoor comfort assessment models, taking into consideration both objective and subjective methods. Their aggregating, weighting and rating systems are summarized and compared. Important issues have risen with such formalizations. A multilevel hierarchical structure seems to be most suitable for a structured evaluation but weightings need to be used to show the relative importance of the four commonly considered main criteria, namely thermal and visual comfort, acoustic and indoor air quality. There are numerous weights assignment techniques, some of the most common are the Analytical Hierarchy Process (AHP) and multivariate linear regression of occupant responses. However, weighting factors may vary between geographic regions, cultural conditions, and individual circumstances. In addition, there is the need to find a model that offers a formal and logical way to include qualitative values in the analysis. Furthermore, the interactions of factors or parameters at different levels are not all known and are not considered in the models here reviewed, although regarded as important. A survey of techniques for sorting and presenting performance values such as scorecard models, radar diagrams or overall indices, is also presented. The framework drawn from this review provides the basis for the formulation of a comprehensive formal evaluation model.

Keywords: Comfort, indicators, benchmark, assessment models, indoor environmental performance

1 Introduction

In order to evaluate indoor comfort in a building, research studies and practice procedures have mainly focused on the optimization of single components of the indoor environment (thermal, luminous and acoustic comfort and air quality), trying to identify objective relationships between parameters and resulting occupants reactions. This component-related approach focused on dose-response relations has led to well-known models, such as for thermal comfort (Fanger, 1982) and to regulations and guidelines (ISO, 2005; ANSI/ASHRAE, 2013). Only recently, an alternative concept has become established, approaching the indoor environment in a holistic way (Bluyssen, 2014). The European standard EN 15251 for the first time takes into consideration a range of different aspects, and others are also following this path (CEN, 2007; Nordic Standard, 2014). These regulations suggest an approach to classify and certify buildings using levels of individual environmental components, without however providing information about how to combine them into one index that can be used to classify indoor conditions. This scientific methodology toward the assessment of comfort has tried to combine the different components, into a compound measure of the built environment, its indoor environment and occupant responses as a complex system. In order to assess the occupants' wellbeing, meaning health and comfort, several research methods have been developed. These models attempt to correlate the different indoor environmental factors with respect to the overall comfort or rather, as defined by Heinzerling et al., they take quality performance data and produce an evaluative numerical summary of the data (rating or score) (Heinzerling, et al., 2013). Two fundamental approaches can be distinguished – quantitative and qualitative – in which indoor environmental aspects are monitored directly via measurements or indirectly via questionnaires, respectively. The two typologies can be alternative or complementary: often both can be used in one study. In a review, Fassio et al. have classified two different main methods in assessing the indoor comfort: subjective-objective methods, which are a combination of qualitative and quantitative measurements, and objective methods, based only on quantitative measurements to be compared with a fixed set of criteria (Fassio, et al., 2014). However, a uniform measurement protocol has yet to be established and the individual models follow their own rules about space (sensor location) and time (measurement execution period). Organisations in the United States are attempting to standardise such a procedure with the development of a measurement protocol intended for commercial buildings (ASHRAE/USGBC/CIBSE, 2010), but an equivalent European document is still missing. Moreover, weighting schemes differ one to another, and it has yet to be established if and how it is possible to agree on a shared weights assignment. Furthermore, little agreement can be found between assessment scales and class thresholds, whose establishment is not properly justified. Additionally the impacts of the interactions between factors have not been considered yet by researchers and these are still addressed independently.

Research into ways of understanding how single factors contribute to, and interact with each other to result in a comprehensive comfort response from individuals is being actively developed, despite the complexity of the subject. Consensus is emerging that there is a need to improve assessment procedures and further research into them is required. To this end this paper aims to provide an understanding of how different existing comfort assessment models are constituted and a comparison of their aggregating, weighting and rating systems.

2 Comfort assessment models

A remarkable amount of variables and factors has an influence on the indoor environment. Commonly four main aspects of comfort are considered: thermal comfort, visual comfort, acoustic comfort and, of more recent interest, due to its health implications, indoor air quality. This is consistent with investigations showing that these four parameters are considered by occupants to be the most important in determining comfort (Frontczak, et al., 2012). Aesthetic quality and spatial and ergonomic quality, although significant, are not be considered in this review. This emerging definition of comfort can be seen as having a hierarchical structure composed by four levels (Figure 1). At the top level, the main strategy or fundamental goal is located, followed by four categories that are defined by a number of criteria, each one of them specified by one or more indicators. In this kind of formalization, it is usually recommended to go down until a measurable goal is reached. In this study, indicators are precisely defined as the measurable control parameters.

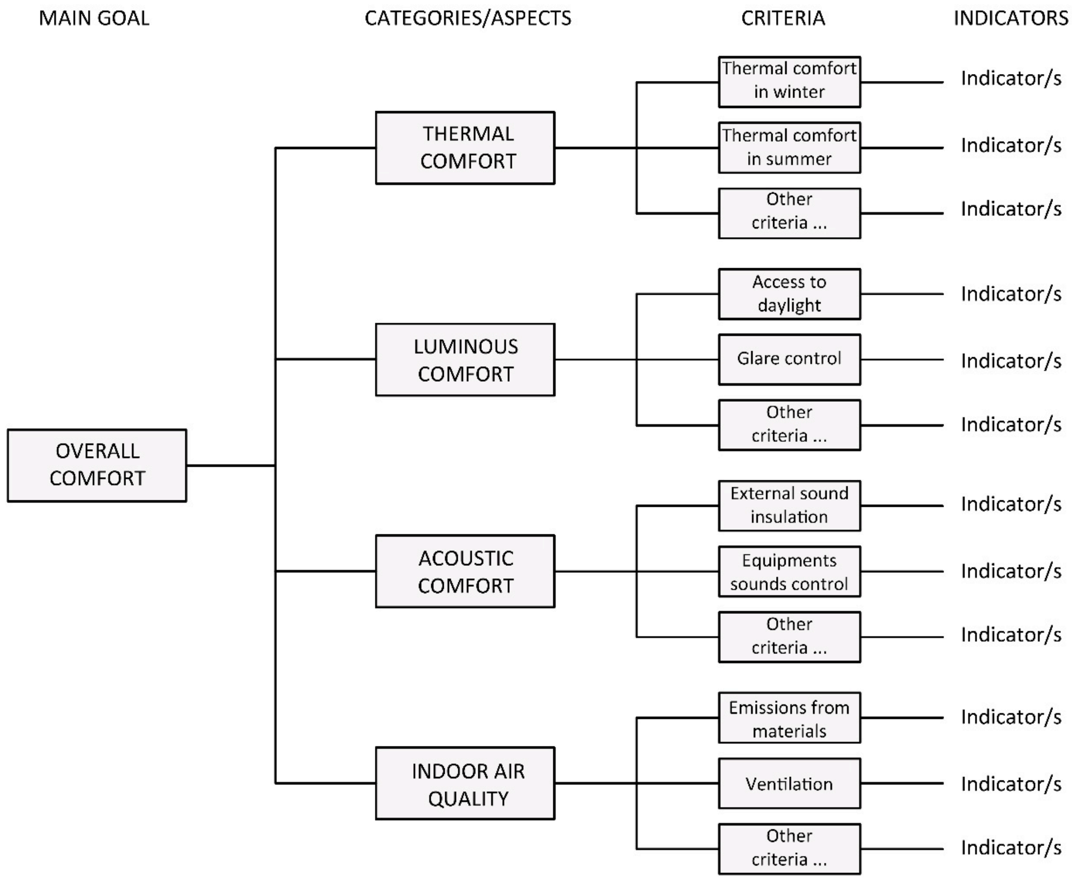

Figure 1. Comfort buildings performance hierarchical structure.

This formalization allows the complexity of the subject to be reduced, resulting in enhanced comprehensibility for different stakeholders. Comfort itself is divided into smaller parts which are individually analysed in order to better understand their contribution to the whole problem. Thomas L. Saaty claims that a hierarchical structure simulates the innate method of operation of the human mind. When facing a complex situation with a multitude of elements, the mind aggregates them into groups according to certain properties they share (Saaty, 1972). The main purpose of structuring the criteria is to form a basis for a formal evaluation process, taking into account all relevant objective and subjective factors.

In order to examine in depth different interpretations of this structure, a literature review was undertaken for papers presenting comfort assessment models or indoor environmental categories weighting scheme, using electronic database as Sciencedirect or Google Scholar, and a dozen research studies have been found and classified on the basis of aggregation methods.

2.1 Aggregation methods

In the examined subjective-objective methods, equations that attempt to predict occupant satisfaction based on objective measurements for each comfort category are provided. Satisfaction results represent the score ("sub-index") for each individual comfort category. A linear relationship between perceived comfort and contributing categories is established and the overall index is expressed as a multivariate model, function of the sub-indices of each category multiplied by the weighting coefficients derived from regression results of questionnaires (Ncube & Riffat, 2012; Cao, et al., 2012). A similar procedure, but with a non-linear relationship using multivariate logistic correlation, can be found in other studies (Lai, et al., 2009; Wong, et al., 2008; Mui, et al., 2015).

In the examined objective methods, a simple additive weighted method is used as aggregation method, where the parameters are measured on a common scale, multiplied by their respective weights, and added into an overall measure of quality (Chiang & Lai, 2002; Marino, et al., 2012; Reffat & Harkness, 2001). Objective measurements are compared with a fixed assessment class structure in which each range has a corresponding attribute score and the overall index is the combination of these sub-indexes through weighting process. Most of the green building certification tools use this kind of approach. Their protocols are structured in a similar manner as those in the cited comfort assessment models and are usually composed of the following elements: criteria or categories and indicators, which describe the performance of the defined criteria. They are also provided with an assessment scale that defines the requirements with which performance is designated as good or bad, using an allocation of scores and a weighting scheme to define the relative importance of criteria. In these models subjective measures can be taken but are not part of the assessment process. The data collected can be undertaken for validation and control purposes.

2.2 Weighting

To show the relative importance of the different criteria, weightings are used. Their assignment procedure is a crucial step in the multi-attribute analysis. Weightings can be elicited using hierarchical or non-hierarchical methods (Häkkinen, 2012). In the latter only bottom level weightings (indicator levels) are assigned, and upper levels (criteria) are derived as sums of weights of the indicators of which they are composed. More commonly, with a hierarchical method, weightings are established at all levels of the value tree and the weights at the bottom level are obtained by multiplying weights vertically. At all levels of the hierarchy the sum of the weights is expected to be equal to 1 (or 100%). A number of studies have attempted to prioritise indoor environmental categories. For the definition of the weighting factors, various possible methods have been applied. Some studies used regression coefficients of regression models obtained from subjective measurements to indicate the relative importance of the four categories to the overall comfort value (Lai, et al., 2009; Wong, et al., 2008; Ncube & Riffat, 2012). Other procedures harvest assumptions from expert forums or alternative structured methods. One example of formal weighting process is the Analytic Hierarchy Process in which the factors are judged by a panel of experts through pairwise comparisons: is thermal comfort strongly, slightly or equal important than indoor air quality? Paired comparison method and AHP are used in several studied models (Chiang & Lai, 2002; Liu, et al., 2012; Reffat & Harkness, 2001).

Among the analysed studies, thermal comfort has shown to be the most influential factor, slightly more important compared to indoor air quality and considerably more important compared to acoustic and visual comfort (Figure 2).

The advantage of AHP is first of all the possibility to include qualitative values in the analysis in a formal and logical way. The shortcoming of this well-known method is that AHP assumes that trade-offs between factors are linear functions and that there is no dependency among them, which is hardly true in the indoor environment. The criteria interact with each other rather than being independent. For example, interactions occur between thermal conditions and indoor air: odours are more annoying with higher temperatures and humidity than when the indoor climate is cool and dry.

In addition, the subjective judgment and preferences of decision makers have a great influence on the final adopted elicitation. To check the consistency of the judgments, an important part of the weighting assignment procedure is sensitivity analysis, which consists of studying how changes in weightings affect the results. In the case of assessment of building performance, this also helps to determine which are the most influential factors and how much the performance level of an indicator must be improved so that the building achieves a certain desired level of comfort. This element is present in most of the analysed models.

Figure 2. Summary of attempts at ranking indoor comfort categories (rank 1 = higher importance, rank 4 =

minor importance).

2.3 Indicators

Quantitative indicators in general define the indoor performance of a building. Examples are temperature, ventilation rate, lighting intensity or pollutant concentration. The definition of these parameters occurs with the traditional “bottom-up approach” (Bluyssen, 2014), establishing threshold values after having defined dose-effect relationships. These dose-related parameters are frequently used in standards and regulations and in green building assessment tools, both national (such as ITACA, DGNB or HQE) and international (such as BREEAM, LEED, CASBEE or WELL). In Table 1, an analysis of the indicators used in different protocols is presented, considering several green building assessment tools and a number of the investigated models.

Table 1. Overview of indicators concerning indoor comfort among existing tools and protocols.

		Green buildings rating systems														Stand.		Research models				
	Indicators	**ActiveHouse**	**Arca**	**BREEAM**	**CasaClima**	**CASBEE**	**DGNB**	**GBC Home**	**HQE**	**ITACA**	**LEED**	**MINERGIE**	**PassivHaus**	**TQB**	**WELL**	**EN 15251**	**Nordic stand.**	**Marino et al.**	**Chiang, 2001**	**Chiang, 2002**	**Heinzerling**	Total
Thermal comfort	Operative temperature	●					●			●	●		●	●	●	●	●	●	●	●	●	**13**
	Humidity					●	●						●		●	●			●	●	●	8
	Air velocity																	●	●	●	●	4
	Room temperature					●						●	●									3
	Room thermal capacity											●		●								2
	Temperature differences btw walls					●	●							●								3
	PMV/PPD			●			●				●		●	●		●				●	●	8
	Givoni comfort zone								●													1
	Sunlight penetration ratio					●																1
	Thermal control	●		●							●				●		●					5
Visual comfort	Daylight factor	●		●	●	●	●	●	●	●	●			●			●			●		**12**
	Daylight uniformity			●																		1
	Daylight illuminance			●																		1
	Sunlight availability	●					●					●		●	●							5
	Illuminance			●		●			●		●				●	●		●	●	●	●	**10**
	Illuminance ratio										●									●		2
	Equivalent Melanopic Lux														●							1
	View out			●			●				●											3
	Glare control			●		●																2
	Lighting control					●					●						●					3
	CRI						●				●	●			●							4
Air quality	CO2 concentration	●					●				●				●	●	●	●	●	●	●	**10**
	Air ventilation rate					●	●				●	●	●			●	●					7
	Formaldehyde conc.		●	●			●		●		●	●		●	●		●		●	●		**11**
	TVOC		●	●			●		●		●	●		●	●					●		9
	Low emitting materials		●	●	●	●		●			●	●		●	●							9
Acoustic	Sound insulation		●	●	●	●	●	●	●	●	●	●	●	●	●							**13**
	Indoor ambient noise level		●	●	●	●	●		●	●	●		●	●	●	●	●	●	●	●	●	**17**
	Reverberation time			●							●	●			●							4

As shown, some protocols make use of a considerable range of indicators distributed over all the four main categories. Some indicators are very common among the examined assessment models, such as daylight factor, CO_2 concentration and background noise level. An attempt to review and select the most important indicator has been made within the European project Perfection (Performance Indicators for Health, Comfort and Safety of the Indoor Environment), focusing on the implementation in an indicator framework for the assessment of building performance (Huovila, et al., 2010).

2.4 Assessment scale and categories

Some studies refer directly to occupant satisfaction. Others, however, present a breakdown in assessment classes, categories or sanitary levels. Especially for objective models, comfort ranges for each performance criterion are determined and a corresponding attribute value assigned (Figure 3). Indeed, a quantitative evaluation makes sense only if thresholds can be defined. Marino et al. present a breakdown in four quality classes for each category, using qualitative attribute and colours (I = green, II = yellow, III = orange, IV = red), while other studies assign to five categories a corresponding numerical value of 10, 8, 6, 4 and 2 (Chiang & Lai, 2002; Ncube & Riffat, 2012; Reffat & Harkness, 2001).

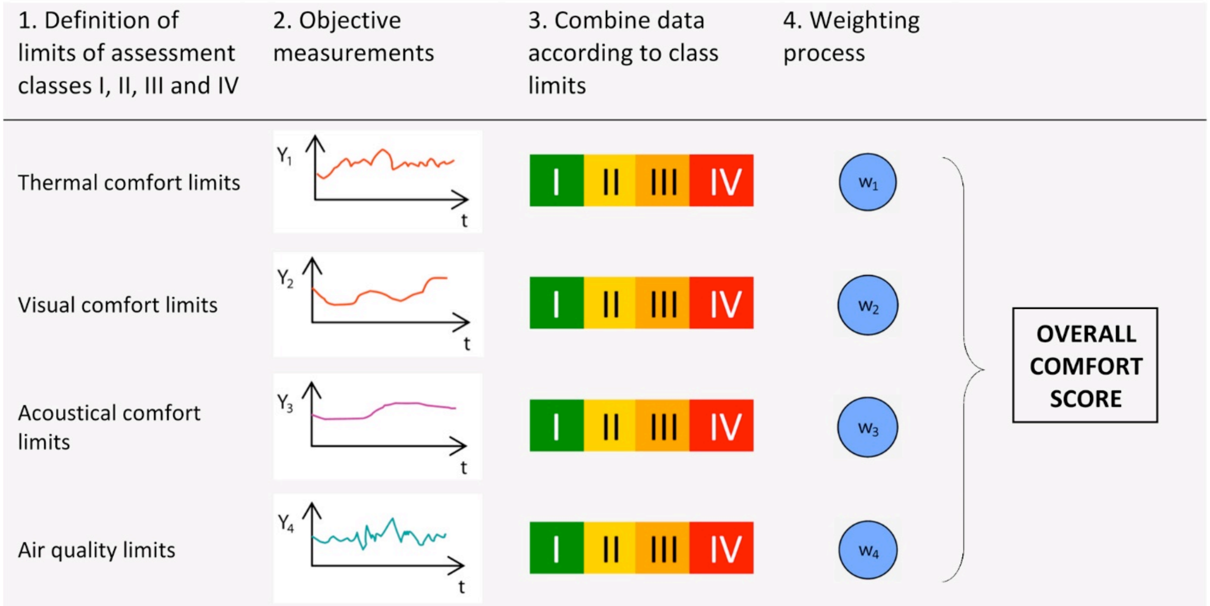

Figure 3. Determination procedure of overall comfort index through assessment classes, adapted by Marino, et al., 2012.

As seen for the previous weighting schemes, there is a high disagreement and variation between studies regarding these categories themselves and their limits and thresholds. Some indicators have ranges that vary widely between studies and categories not always reflect perceptible changes in occupants' satisfaction (Heinzerling, et al., 2013).

2.5 Presentation of results

The results of a performance measurement may be presented in different ways. One of the most common representations consists of a matrix structure or scorecard to facilitate side-by-side comparison. The matrix could contain numerical score or qualitative attributes (e.g. high, medium and low quality) or the impacts are presented in its natural units, rather than being converted into a single measure of worth. In the latter case, the comparative rankings for a single impact can be indicated by colour coding. In this type of representation the table is showing both the rank-coding and numeric outcomes for the different impacts. The advantages of using also colour coding is the possibility of conveying an overall impression of how rankings change readily that can other ranking schemes. Scorecards can present some difficulties in identifying the general trends in performance.

Another appreciated graphical presentation of the results is a radar chart, also called star or spider diagram**,** which shows the individual categories scores providing an axis for each variable. The results can be presented in natural units showing the individual category scale on each axis. It is important to clarify that the scales are not directly comparable and comparison across variables is pointless in this case. When communicating results – this is also valid for other kinds of representation – it is advisable to provide both normalized indices and the original raw data. It is then recommended to normalize the results in order the criteria to be commensurate. An example of radar diagram with common scale between axes is the one presented in Figure 2.

An advantage of radar diagrams is that referenced performances (least acceptable, standard/mean or best practice) can be also indicated in the chart. However, despite this kind of representation that gives an immediate picture of the overall score through the polygonal shape area, no weighting of the criteria is included in it and comparison between buildings with similar overall performances but different individual category scores can be cumbersome.

The ultimate goal of many assessment models is to provide a single index. The advantages of presenting one score is that it can be tracked and analysed allowing building comparison and benchmarking, as easily as for energy consumption. The weakness of such approach is that inaccuracies in individual scores and assumption may be compounded during the process of combining multiple attribute ratings. Additionally, one can criticise the need to quantify quality, pointing out a contradiction in terms. However, a such a symbolic score is a good way to immediately scope out a situation (Peña & Parshall, 2012). Moreover, it helps to raise the profile of comfort in relation to the importance attributed to energy consumption in buildings. To this end, graphical representations inspired by typical energetic efficiency rating bars (a seven point scale, from A to G), as used by Marino et al., may contribute also to enhancing the perceived importance of the subject.

3 Discussion and emergent models

The reviewed related research indicates that the hierarchical structure is most suitably applied to the case of evaluating comfort since it enables multiple interdependencies to be tracked at different levels of detail, while at the same time providing a holistic overview of the system being analysed. Hierarchies or value trees are also flexible scheme for such studies, where additions and reductions may be easily implemented if they are well-structured. However, many questions are raised about these frameworks. Firstly, it is still not univocally established which weightings shall be best given to the different variables or if equal consideration should be given to each of them. Some research demonstrates that not every factor has the same importance, but questions remain on how to assign respective weights in a meaningful way. Some authors are sceptical about this framework and claim that it is impossible to attempt to introduce an index of overall satisfaction, based on different factors, since these factors would acquire different weightings under different circumstances (Humphreys, 2005; Bluyssen, 2014). The relative weightings of individual attributes change significantly over time, from culture to culture and from country to country. Both authors state that it seems prudent to continue consider each aspect separately instead of relying on an overall evaluation that cannot be stable or reliable. At this point in the discussion, it is important to point out that the purpose of the comfort assessment models being reviewed here is to provide a simplified classification method of the indoor comfort quality in order to enable comparison between individual buildings in terms of their overall environmental performance. This aim is argued here to be adequately served using a conventional hierarchy of comfort undertaken with reference to what the intended use of the environment might be.

Another issue requiring more work relates to the fact that no dependency between factors has been taken into account in these methods. Interactions inevitable occur not only between light and thermal comfort, or between thermal conditions and indoor air, but also even within one comfort category, for example, between different air compounds like VOCs or CO_2. Perception of comfort is also influenced by these interactions since our senses are more sensitive to certain indoor environmental stressors than others. How can this interconnectedness be practically or accurately included in a model? In order to answer to this question, further and more detailed research studies are needed, before being able to develop the required framework with indicators and interactions.

The third open-ended question comes from the observation that when such a method is applied in reality, reported satisfaction responses do not always work as expected. Satisfaction with the thermal environment within space depends as much on the space itself as on personal variables people bring to the area with them, such age, sex, gender and cultural conditioning. These parameters are still described with quantitative dose-related indicators, expressed in numbers, or ranges of numbers, assumed to be acceptable and healthy for people. However, these indicators are describing sensations of comfort, based on research directed merely at the detection of a stimulus in the environment. Perception of comfort, instead, refers to the way in which one interprets the information received from the environment. Subjective factors need to be taken into better account in further models, linking also psychological factors and influences.

Additionally, the assumption that the trade-offs between factors are linear functions is not fully accepted. Some researchers have suggested the use of Kano's model to assess the level of human comfort and individuals' satisfaction (Fekry, et al., 2014; Kim & de Dear, 2012; Martellotta, et al., 2016). Developed as model to evaluate consumer satisfaction in marketing and product development fields, Kano's model starts from the assumption that the relationship between the performance of a product (or a space) and a user's satisfaction with it is nonlinear and asymmetric (Figure 4). Using this model in the building context, indoor comfort factors can be classified into three categories: basic factors, bonus factors and proportional factors. The first ones can be seen as minimum requirements and can affect comfort perception in a negative way; the second ones are those beyond minimum expectation and can increase satisfaction; the latter ones change satisfaction levels proportionally to their own performance. Through multiple regression with dummy variables on subjective measurements, some basic and proportional comfort factors have been identified.

What emerges from the above-mentioned papers is that some factors have a "veto power" since when occupants show dissatisfaction towards one of them no combination of the other parameters can lead to satisfactory results in terms of overall comfort. This conclusion is particularly interesting as it stands opposite to theories based on a sort of trade-off between different indoor comfort aspects, or as called by Humphreys the *forgiveness factor* (Humphreys, 2005). In these authors' opinion, the application of Kano's model is of notable interest and further research needs to be done.

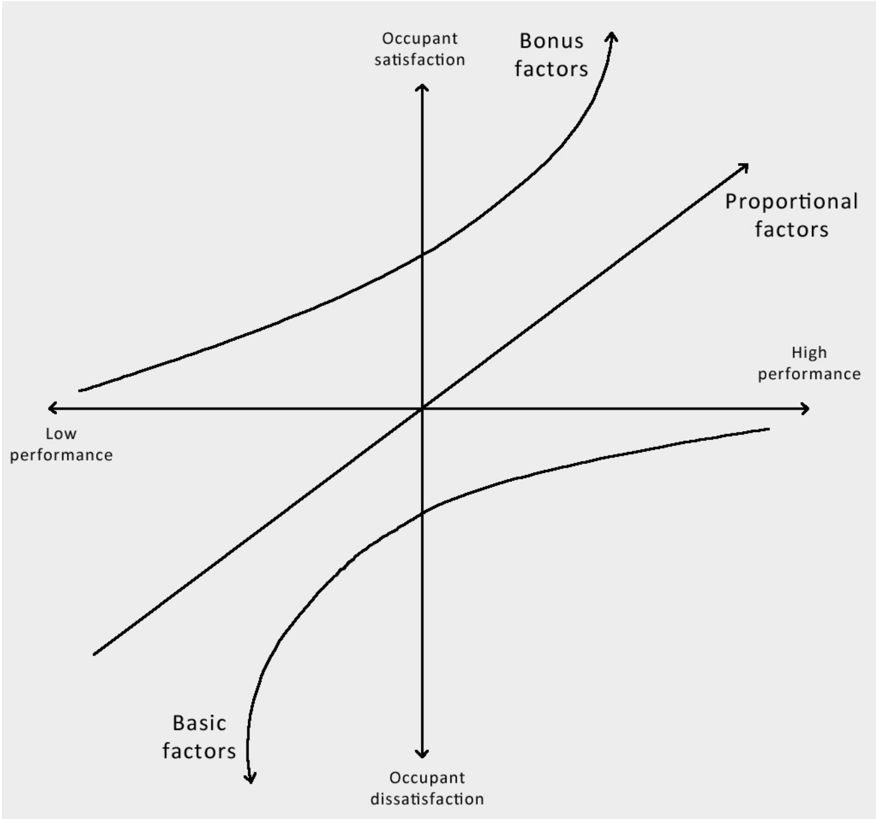

Figure 4.Kano's model of occupants' satisfaction (Kim & de Dear, 2012).

An alternative promising approach to describe correlations could be found in the implementation of artificial neural networks (ANN), a non-linear statistical data modelling tool. Inspired by the biological neural structure of the brain, this method can be used to model complex relations between inputs and outputs and can be suitable to simulate the changeable human decision-making process. So far the method has been applied as control strategy to HVAC system (Ari, et al., 2006) but a more useful (for this review purpose) application, with an ANN model fitted on objective measurements, have linked concentrations of pollutants in office with the observed number of workers presenting building-related symptoms (Sofuoglu, 2008). Durmisevic & Ciftcioglu (2010) also tried to predict the overall design performance of a large number of parameters in a healthcare environment. A similar approach could be implemented aimed at correlating the single attribute indoor comfort parameters to the overall comfort level perceived by the occupants with the use of a sufficient range of objective measurements.

4 Conclusions

When approaching a problem from a holistic point of view, the main risk is to get overwhelmed by an abundance of information. Comfort is a rather complex phenomenon, influenced by many factors involving both objective and also subjective issues, which may tempt many people to abandon the idea of measuring it. Moreover, the indoor environmental quality of a space, as perceived by its occupants, is often reported as not being acceptable even if standard quantitative requirements are met. However, it is possible to measure those factors that impact more significantly on comfort and to obtain a reasonable index, which, even if not perfect, is certainly much better than no comprehensive evaluation at all. The need to present an indicator for the overall indoor environment has been recognised also by a number of authors who suggest to take into account all physical parameters, which should be weighted opportunely, based on how they are ranked in importance differently by different building users. Furthermore, the development of a holistic comfort classification system for use in certain building assessments could be required to be produced and presented along with the energy certification, to give comfort the visibility and significance it should be accorded when compared to energy consumption performance in summary reports used in building evaluations.

Many attempts have been studied in this review, showing that there is a need to align benchmarking, weighting and aggregation methods with the definition of an assessment protocol for the selected indicators, making use of a range and combination of measurement techniques to successfully evaluate the buildings indoor environments, based not only on external stressors but also on personal factors. The basis for the formulation of a comprehensive formal evaluation model should start from what emerged from these previous studies. By developing such a holistic model, it could be finally possible to present indoor environments in a more realistic way and to understand why certain environments perform better than others. In addition, such a tool could be used to support decision makers/designers in improving the performance of buildings in this respect or in assessing the outcome based on inputs for new design planning. In conclusion, a new approach is required, based on users' satisfaction being measured comprehensively instead in terms of single components only, bringing back the focus in good design onto the primary goal of architecture, which is to create comfortable environments for building occupants.

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Investigating the overheating risk in refurbished social housing

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Abstract
Global average surface temperatures are predicted to rise from 1 to 5°C by 2100. Also, extreme events such as heat waves are expected to increase in intensity, frequency and duration. In most of Europe and other developed countries, existing buildings are projected to form from 70% to 80% of the built stock by 2050. Investigating the risk of overheating in the existing building stock is therefore crucial in order to adopt measures which can help to mitigate what it can be a lethal effect of global warming: prolonged exposure to high temperatures in buildings. By collecting measured data, this study investigates indoor temperatures and thermal comfort in bedrooms, kitchens and living rooms of 46 newly-retrofitted free-running social houses in Exeter, UK during the summer 2014. The overheating risk was evaluated using the CIBSE TM52 adaptive benchmark. It was seen evidence of 10 out of 86 rooms overheating in 9 dwellings. It was found that kitchens and bedrooms are the rooms with the greater overheating risk among the monitored spaces. It was also found that old and vulnerable occupants are at a higher risk of being exposed to high indoor temperatures due to fact that they spent most of their time indoor and also because of poor indoor ventilation.

Keywords: Overheating, thermal comfort, social housing, environmental monitoring

1 Introduction

Heatwaves are periods in which high outdoor temperatures persist for several consecutive days and night temperatures do not drop enough to allow buildings to cool down. Sadly famous is the heat wave of August 2003 which is estimated to have caused over 35000 deaths in Europe, including 2000 in UK, with the majority of the victims being among the elderly and long-term sick people (Stott *et al.*, 2004; Johnson *et al.*, 2005). Global average surface temperatures are predicted to rise from 1 to 5°C by 2100 (IPCC, 2013) and heat waves are expected to increase in intensity, frequency and duration (Meehl and Tebaldi, 2004; Jones *et al.*, 2008). In dense urban environments their consequences will be exacerbated by the urban heat island effect. The unusual warm summer of 2003 is expected to become usual by the 2050s and will be considered unusually cool by the 2080s (Coley *et al.*, 2012).

At the same time, climate change concerns and related mitigation strategies are driving the need of a more energy efficient built environment. As a result, super-insulated and airtight houses are currently being built or refurbished in order to reduce winter heating demand and associated greenhouse gas emissions. An attempt to reduce energy consumption for space heating has been seen in both newly-built and refurbished UK social dwellings, which are supposed to be driving the change in the British built environment.

There is already evidence of overheating happening in UK and Northern European homes which have been refurbished or newly built in order to comply with the new energy efficiency and zero carbon standards such as, for example, passive social housing flats in Coventry, UK (Tabatabaei Sameni *et al.*, 2015) and passive houses in Linköping, Sweden (Rohdin *et al.*, 2014). The evidence is so clear that a UK national report has been written, describing interventions to improve energy efficiency that can prevent overheating in the future (Dengel and Swainson, 2012).

A plethora of studies have used dynamic thermal simulation in order to see how different energy refurbishments would affect building overheating in current and future weather scenarios (Mavrogianni *et al.*, 2012; Tillson *et al.*, 2013; Porritt *et al.*, 2011; Porritt *et al.*, 2012; McLeod *et al.*, 2013; Oikonomou *et al.*, 2012; Ji *et al.*, 2014). However, little is still known about the current situation of retrofitted "energy-efficient" buildings (Vardoulakis *et al.*, 2015) and the literature only offers a limited range of monitoring studies, the most relevant found for this work were: (Tabatabaei Sameni *et al.*, 2015; Lomas and Kane, 2013; White-Newsome *et al.*, 2012; Beizaee *et al.*, 2013; Sakka *et al.*, 2012).

This implies that there is little empirical evidence in order to inform retrofit decision-making and there is still little knowledge on the way energy efficient homes reacts to high outdoor temperatures (Dengel and Swainson, 2012). Monitoring and investigating the risk of overheating in the existing building stock is therefore important in order to adopt measures which can help to mitigate the worst effects of global warming. This is especially important for households with elderly people who spend most of their time indoor and that are particularly vulnerable to high temperatures.

Furthermore, the majority of the monitoring studies have measured indoor temperature conditions in living rooms, see for example (Sakka *et al.*, 2012), while there are only few studies which have monitored environmental parameters in other rooms such as kitchens and bedrooms.

Another problem is that existing standards used for quantifying the severity and frequency of overheating have not been derived from direct assessment in homes. The BS EN15251 adaptive thermal comfort model (Nicol and Humphreys, 2010), upon which the overheating recommendation of the UK Chartered Institution of Building Services Engineers (CIBSE) is based, has been deduced from data predominately obtained during field studies in office buildings where people have less opportunity to adapt than in their homes. This fact suggests that the BS EN15251 comfort standards might be applicable for the residential stocks but it also reveals that its applicability and validity needs to be tested with thermal comfort field-studies in homes.

In order to address the gaps seen above, our study uses data from more than 60 newly-retrofitted (i.e. reasonably well-insulated) social housing dwellings in Exeter in South West England (Figure 2). Temperature and humidity of living rooms, kitchens and bedrooms (Figure 3) were measured every 5 minutes during the summers of 2014 and 2015. Occupancy was inferred from multiple motion sensors. Additionally, during the summer 2015, CO_2 levels were monitored in living rooms. Occupant thermal comfort was surveyed through a paper-based questionnaire distributed at the end of the summer 2014 and through telephone interviews carried out throughout the summer 2015. This paper reports the results for summer 2014, as the authors are still performing the analysis for the summer of 2015.

Different housing design characteristics (roof exposure and façade orientation) and occupant variables (vulnerability, occupant ventilation patterns) are used to conduct the meta-analysis of the 86 monitored rooms. The adaptive overheating criteria of CIBSE TM52 (based on the European Standard EN15251 adaptive model of thermal comfort) are used to assess overheating in the different monitored rooms.

2 Factors affecting overheating

Occupants' behavioural thermal adaptation refers to all the conscious or unconscious actions that a person can take in order to modify the building indoor environment, their personal situation or both of these. In reducing temperatures and hours of overheating, Coley et al. have found that occupants' behavioural adaptation (night cooling done by opening of windows, closing window when the external temperature is greater than the internal, reduced electrical gains by better housekeeping) is equally important in order of magnitude to common structural adaptations (increased thermal mass, night cooling done by additional vents, external shading above windows, solar-control glass, reduced electrical gains by using more efficient items) (Coley *et al.*, 2012). Behavioural adaptation is related to the specific characteristics of the occupants; for example, elderly and people with compromised health might have a limited control of ventilation due to restricted possibility of movement.

Since overheating depends on both occupants and dwelling characteristics, social and behavioural factors interweave with structural aspects making it particularly difficult to assess its causes.

The following has been seen about factors that can affect the severity of overheating:

- Urbanization and the associated urban heat island effect increases ambient temperatures and prevent the cooling of the buildings at night. It also influences occupant ventilation patterns especially night cooling due to outdoor pollutions, noise and security reasons (Mavrogianni *et al.*, 2012).
- Floor level, orientation of the dwelling (Porritt *et al.*, 2012) and glazing to wall ratios affect the severity of solar gains (McLeod *et al.*, 2013).
- The absence of window shading (fixed external shading devices or external shutters) also affects solar gains (McLeod *et al.*, 2013; Porritt *et al.*, 2012).
- The dwelling rate of overcrowding affects internal heat gains while their insulation and air-tightness prevents the release of the accumulated heat (Beizaee *et al.*, 2013).
- The building thermal mass influences heat amortization by absorbing heat gains during the day and releasing them during the night. This strategy is efficient if there is a drop in night temperatures and a sufficient night ventilation of the building.

Figure 1 Location of the city of Exeter in South West England (Source: Google Maps ©)

The evidence shows that properties with a particularly high risk of overheating are:

- flats (Lomas and Kane, 2013; Beizaee *et al.*, 2013) and, especially, top floor flats (Beizaee *et al.*, 2013),
- dwelling built after 1990 (Beizaee *et al.*, 2013),
- any dwelling when occupied by vulnerable tenants (e.g. old people) (Tabatabaei Sameni *et al.*, 2015),
- bedrooms of any property when compared to living room (Firth and Wright, 2008).

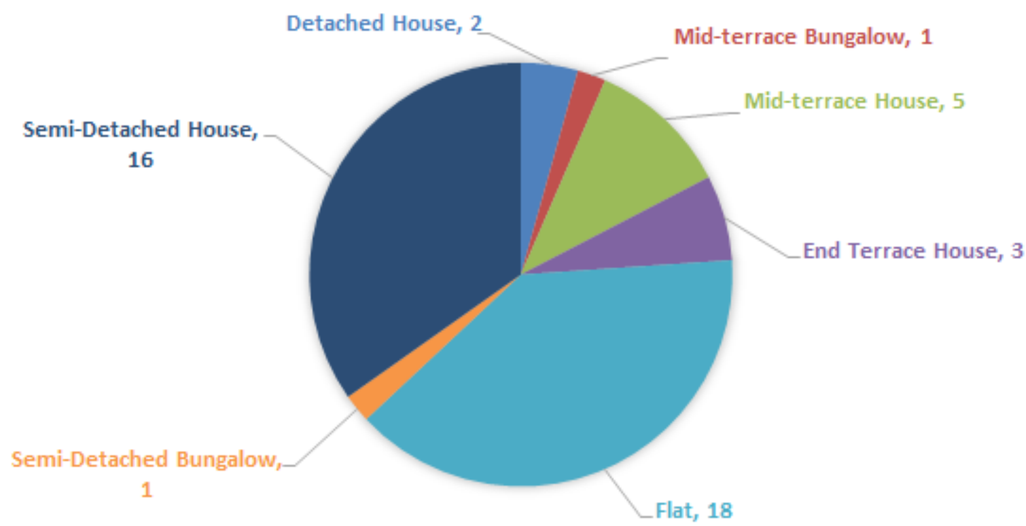

Figure 2 Distribution by built type of the 46 monitored dwellings.

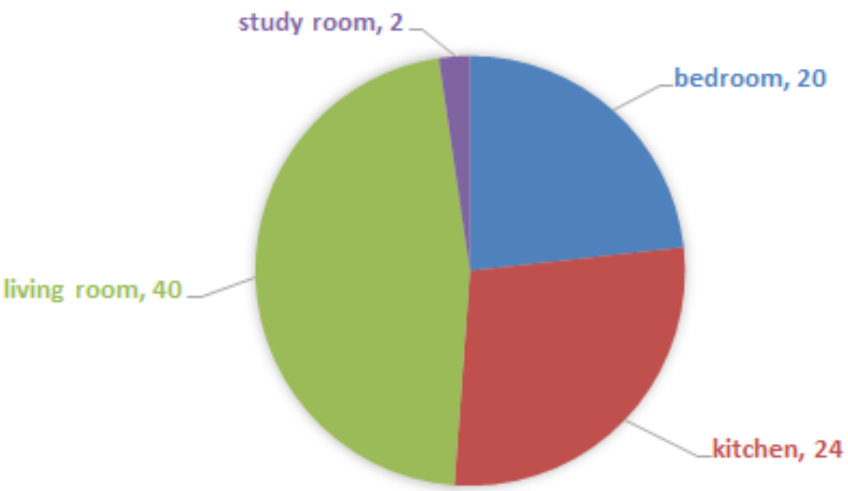

Figure 3 Overview of the 86 monitored rooms.

3 The social housing context

Social housing provides houses for those who cannot afford to buy one in the UK. Social homes represent 17% of the total number of houses in UK (DCLG, 2015a). There are some peculiar characteristics about social houses which make them particularly vulnerable to overheating:

- They have the highest rate of overcrowding in the country (DCLG, 2015a).
- Their tenants have the highest unemployment rate and the lowest average income (DCLG, 2015b).
- Their tenants belong to the highest age bands.
- Windows of new build social housing are forced to only open to an angle of no more than 10 degrees for security reasons (RoSPA, 2008); this limits the possibility of ventilation through the windows.

4 CIBSE TM52 adaptive thermal comfort benchmark

The adaptive overheating criteria of CIBSE TM52 are based on the European Standard EN15251 adaptive model of thermal comfort. According to it, the maximum allowable temperature T_{max} for free running buildings is not a fixed threshold but it depends on the outdoor temperature (Nicol and Humphreys, 2010). There are two maximum temperature limits which depend on the degree of vulnerability of the occupants:

$$T_{max} = 0.33 * T_{rm} + 20.8 \text{ for Category I}$$

$$T_{max} = 0.33 * T_{rm} + 21.8 \text{ for Category II}$$

where T_{rm} is the exponentially weighted running mean of the daily mean outdoor air temperature (Figure 7). Category I includes particularly fragile and vulnerable occupants while Category II is for normal expectation occupants (Figure 7).

According to the adaptive overheating criteria of CIBSE TM52, a room is overheated if two of the three following criteria fail:

- *Frequency of overheating: Hours of Exceedance Criterion.* The number of hours during which DeltaT (i.e. the difference between Operative and Maximum Temperature, $T_0 - T_{max}$) is above 1°C (Hours of Exceedance, H_e) should not exceed 3% of the occupied hours during the summer season (May to September). $H_e < 3\%$.
- *Severity of overheating within any day: Daily Weighted Exceedance Criterion.* The Daily Weighted Exceedance (W_e) shall be less than or equal to 6 in any day during the summer season (May to September). $\sum(W_e > 6) < 0\%$:

  $W_e = (h_{e_0} * 0) + (h_{e_1} * 1) + (h_{e_2} * 2) + (h_{e_3} * 3)$ where h_{e_γ} is the time in hours when T_0 is above T_{max} by γ°C.

- *Upper limit temperature criterion.* δT (i.e. $T_0 - T_{max}$) should never exceed 4°C. $\sum(\delta T > 4) < 0\%$.

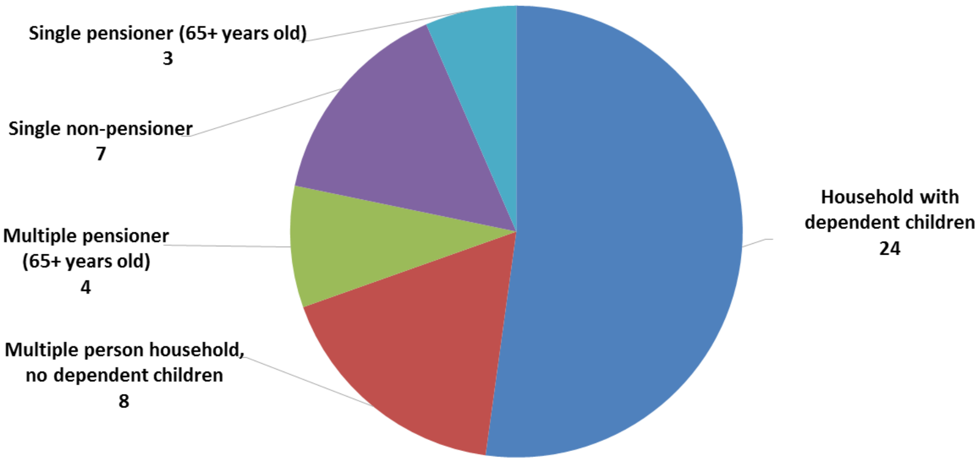

Figure 4 Overview of the demographic of the households

5 Study methodology

A monitoring campaign was conducted in living rooms, kitchens and bedrooms of more than 60 social housing dwellings in Exeter for over 2 years. Environmental and motion wireless sensors were installed in every monitored room and reported data every 5 minutes to a university-hosted database. Additionally, during the summer of 2015, CO_2 levels were monitored in living rooms. The accuracy of the used sensors is reported in Table 2. This paper reports the results of the indoor temperatures monitored during the first summer (from 1st of May to 31st of September 2014). Results from only 46 houses are reported since the rest of the houses had too many data missing or the quality of the data was not sufficient to perform the analysis. Only those sensors reporting more than 75% of the time during the hottest months of June, July and August were selected for the analysis. Occupancy patterns were derived for each monitored room using the data from the infrared motion sensor, humidity and temperature sensors.

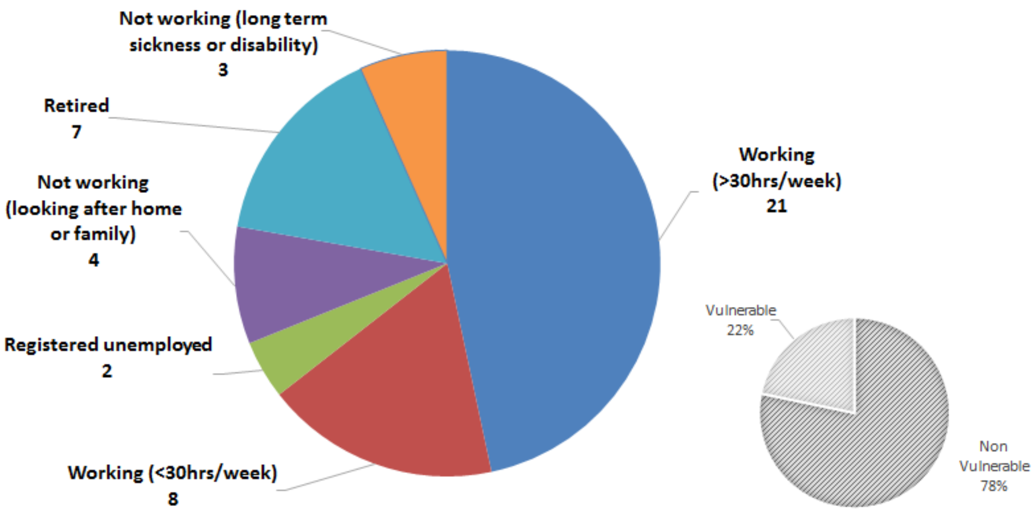

Figure 5 Economic status of households

The questionnaire administered at the end of summer 2014 included one question about the perceived subjective temperature in summer (This summer, when the weather was warm, how did you find the temperature in your home?) with 7 possible levels of comfort to choose from (1 = Much too cool, 2 = Too cool, 3 = Comfortably cool, 4 = Neither warm nor cool, 5 = Comfortably warm, 6 = Too warm, 7 = Much too warm). The questionnaire also included two questions assessing ventilation and cross ventilation habits. The first question was about window opening behaviours and can be seen in Table 1. The second question concerned cross-ventilation habits (At the moment, how often do you (or someone else in your household) open windows on opposite sides of the building to get a draught flowing through your home?) with five different level of frequency to choose from (1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Often, 5 = Every day).

Table 1 Question about window opening habits

When you open the windows in your home, how often is it for the following reasons?	
To cool your home down	1, 2, 3, 4, 5
To get rid of smells or smoke	1, 2, 3, 4, 5
To get rid of moisture	1, 2, 3, 4, 5
When a room is too stuffy	1, 2, 3, 4, 5
Because you are drying clothes	1, 2, 3, 4, 5

1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Often, 5 = Always

The dwellings monitored during the summer of 2014 consisted on 18 flats, 17 between semi-detached houses and bungalows, 2 detached houses, 6 between mid-terrace houses and bungalows and 3 end-terrace houses (Figure 2). A total of 17 dwelling were built in the period between 1930-1939, 9 between 1940 and 1959 and 20 between 1960 and 1989. Out of 46 dwellings 44 were built with cavity walls. All the residences were newly refurbished with double-glazed windows and, when possible, with loft and cavity wall insulation. None of the houses were air-conditioned and in none of them window shadings were present (neither fixed external shading devices nor external shutters). All the residences were meant to be naturally-ventilated and all the rooms in which data was gathered for the study were equipped with openable windows. Out of 86 monitored rooms 35 were ground floor rooms, 17 were mid floor rooms and 34 were roof-exposed rooms. The floor area of the dwellings ranged between 35 and 110 m^2 with an average value of 82 m^2. Cross ventilation was theoretically possible in all the dwellings.

For the analysis, we have divided the households into 2 categories according to their vulnerability. The group of vulnerable households include retired occupants older than 65 years old and disable or long term sick occupants. They represent 22% of the households (Figure 5).

6 Climatic characteristics of summer 2014

The outdoor temperature (T_{out}) was obtained performing a mean of the hourly temperatures monitored at different local weather stations. Daily mean, maximum and minimum outdoor temperatures recorded during the period May to September 2014 are shown in Figure 6. It is worth noticing that minimum outdoor temperatures fall always below 18°C. This suggests that night ventilation has a great potential for preventing overheating during the monitored summer and that, if any overheating is occurring, it should primarily be related to poor indoor ventilation.

The exponentially weighted running mean of T_{out} (T_{rm}) and the maximum allowable temperature (T_{max}) for Category I and II are shown in Figure 7.

Table 2 Instrumentation details

Parameter	Range	Accuracy
DS18B20 temperature sensor (used for both air and radiator surface temperature measurements)	-10 – +85°C	±0.5°C
RHT03 humidity sensor	0 – 100%	±2%
K30 Senseair CO_2 sensor	0 – 5000 ppm	±30ppm
HC-SR501 PIR Infrared Motion Sensor	120°, 0 - 7m	n.a.

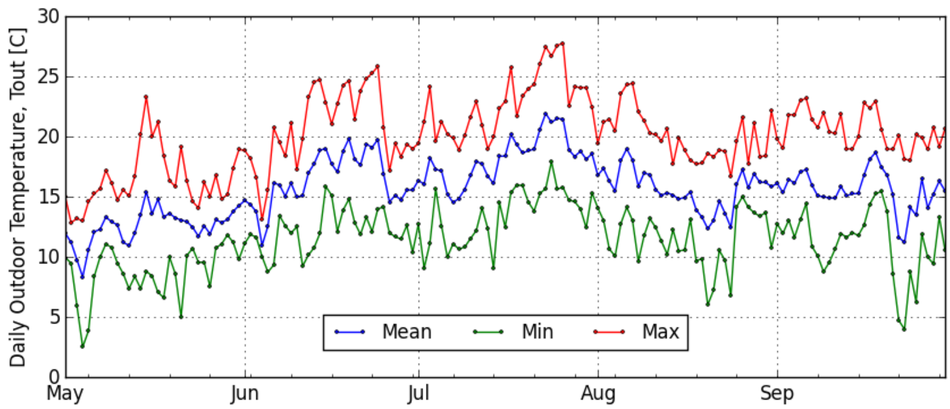

Figure 6 Daily mean, maximum and minimum outdoor temperature (T_{out}) during the period May-September 2014.

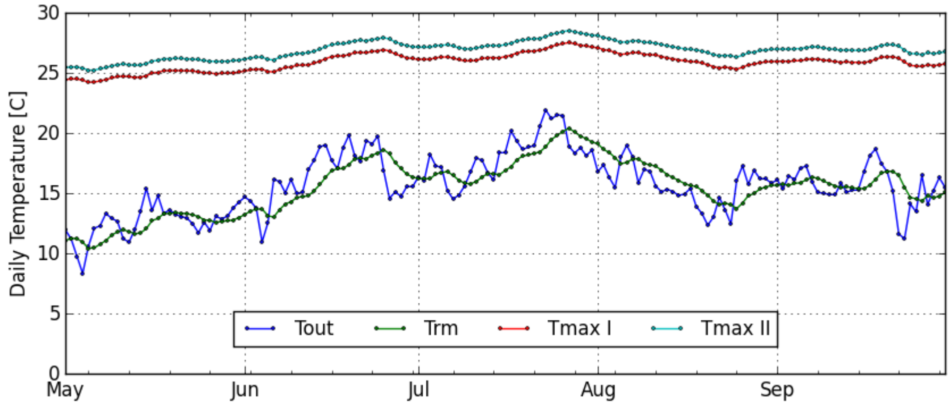

Figure 7 Daily mean outdoor temperature (T_{out}), exponentially weighted running mean of Tout (T_{rm}), maximum allowable temperature (T_{max}) for Category I and II during the period May-September 2014.

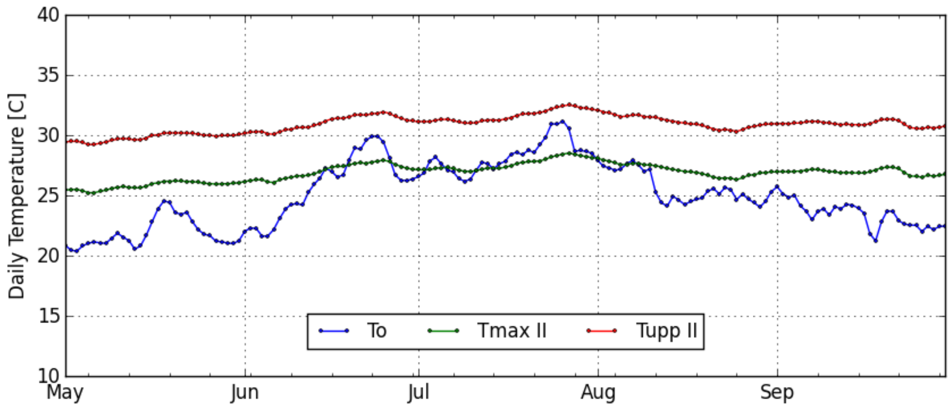

Figure 8 Daily mean indoor temperature (T_0) for the living room of home no. 33, maximum allowable temperature (T_{max}) and upper temperature (T_{upp}) for Category II during the period May-September 2014.

7 Results

Descriptive statistics of the meta-analysis of the mean indoor temperatures monitored during the months of June, July and August and filtered based on occupancy are reported in Table 3. The higher mean temperature is recorded in south-facing roof-exposed kitchens (25.1 ± 1.4°C), while the lowest in north-facing lower-floor living rooms (22.6 ± 1.2°C). Random Unbalanced Design Four-Way ANOVA was performed across the mean temperatures monitored in the different rooms and it took into account four factors: roof exposure, window façade orientation, occupants' vulnerability and type of room. Roof-exposed (RE) rooms were found to have statistically significant higher mean daily temperatures than lower-floor (LF) rooms (p-value < 0.05). South-facing rooms (i.e. rooms with at least 1 window façade facing south, between 90 and 270°C) were not found to have statistically significant different mean daily temperatures than north-facing rooms.

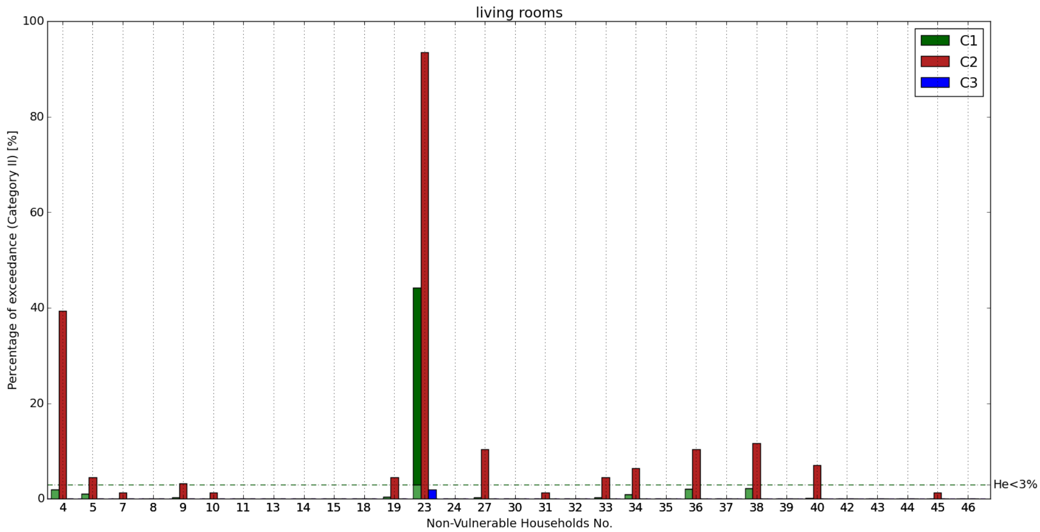

Figure 9 Percentage of exceedance for the 3 criteria (C1, C2 and C3) based on the number of occupied hours for Category II (Non-Vulnerable Households) in the monitored living rooms.

From the overheating assessment using the CIBSE TM52 adaptive benchmark, we found that 12% of the kitchens (3 kitchens, homes no. 2, 12 and 30 in

Figure 10), 27% of the bedrooms (6 bedrooms, houses no. 1, 3, 9, 25, 27 and 30 in Figure 11) and 2% of the living rooms (1 living room, house no. 23 in Figure 9) suffered overheating during summer 2014. Kitchens and bedrooms were more exposed to the risk of overheating than living rooms. The higher temperatures in kitchens could be due to the high internal heat gains associated with the cooking activities, while the higher temperatures of bedrooms can be explained with the fact that they are mostly located under the roof (68% of the monitored bedrooms are roof-exposed), being kitchens and living rooms usually downstairs in majority of the English houses. High temperatures in bedrooms are particularly dangerous since there is no way of avoiding spending time in those spaces and since they cause poor sleep quality.

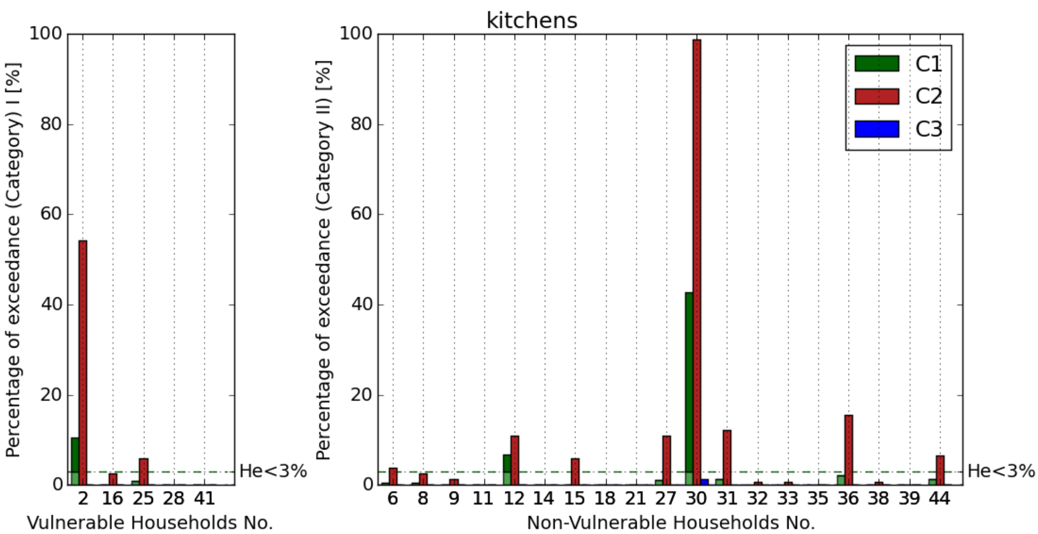

Figure 10 Percentage of exceedance for the 3 criteria (C1, C2 and C3) based on the number of occupied hours for both Category I (Vulnerable Households) and Category II (Non-Vulnerable Households) in the monitored kitchens.

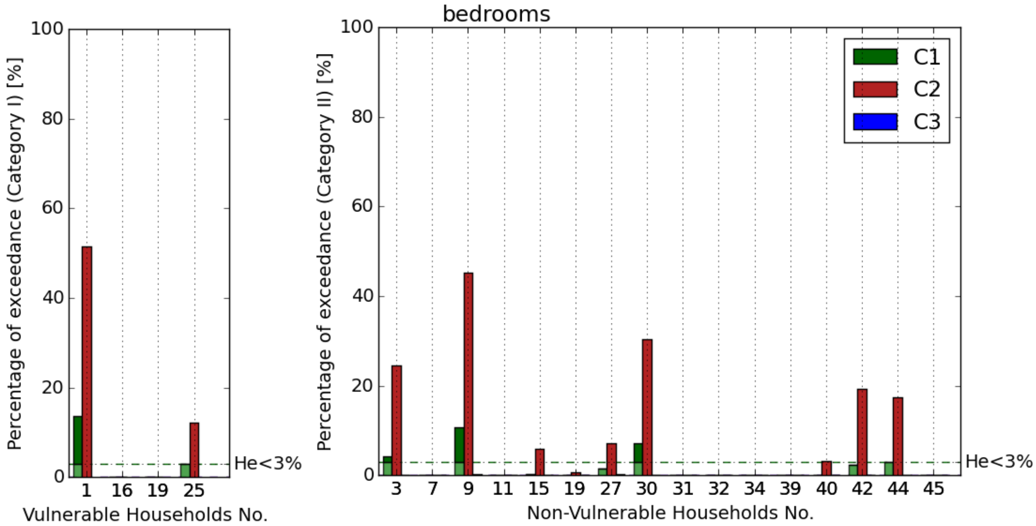

Figure 11 Percentage of exceedance for the 3 criteria (C1, C2 and C3) based on the number of occupied hours for both Category I (Vulnerable Households) and Category II (Non-Vulnerable Households) in the monitored bedrooms.

Vulnerable households were also found to have mean living rooms temperatures higher (about 0.7°C) than non-vulnerable homes but the difference is not statistically different due to the reduced sample of vulnerable living rooms compared to non-vulnerable ones. The higher temperatures recorded in vulnerable living rooms are probably due to high internal gains (high occupancy profiles) linked with poor ventilation which prevents the internal heat to be released outside.

Table 3 Descriptive statistics for mean daily indoor temperatures

Group1 vs. Group2	Room	No. Rooms Group1	No. Rooms Group2	Mean±Std Group1 (°C)	Mean±Std Group2 (°C)
S vs. N	Lr	28	12	23.4±1.9	22.7±1.2
S vs. N	Br	7	15	22.8±0.7	24±1.9
S vs. N	K	12	12	24.2±2.1	24±1.3
S-RE vs. S-LF	Lr	10	18	23.9±1.3	23.1±2.2
S-RE vs. S-LF	Br	4	3	22.9±0.8	22.7±0.7
S-RE vs. S-LF	K	2	10	25.1±1.4	24±2.2
N-RE vs. N-LF	Lr	0	12	-	22.6±1.2
N-RE vs. N-LF	Br	11	4	24.5±1.7	22.8±2.2
N-RE vs. N-LF	K	6	6	24.1±0.8	23.8±1.7
RE vs. LF	Lr	10	30	23.9±1.3	22.9±1.8
RE vs. LF	Br	15	7	24.07±1.6	22.8±1.6
RE vs. LF	K	8	16	24.4±1	24±2

S: Rooms with at least 1 window façade facing south, between 90° and 270°, N: The remaining rooms facing North. RE: Roof exposed rooms, LF: The remaining rooms in the lower floors. Lr: Living rooms, Br: Bedrooms or study rooms, K: Kitchens.

In fact, from the statistical analysis of the survey about ventilation we have found a statistically significant difference between the average vote of vulnerable and non-vulnerable households (Figure 12 and Table 4). This indicates that old, sick and disable people have a tendency to open less the windows. This poor ventilation habit can be attributed to different reasons (e.g. reduced physical mobility and security concerns) which need to be further investigated as mechanical ventilation could be the solution to both these concerns, what implies a big argument for future design of resilient buildings.

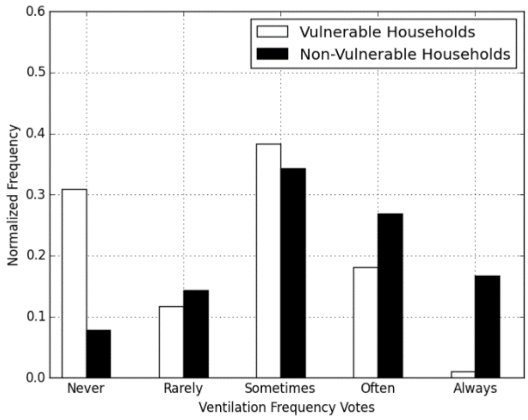

Figure 12 Ventilation frequency votes for vulnerable and non-vulnerable households.

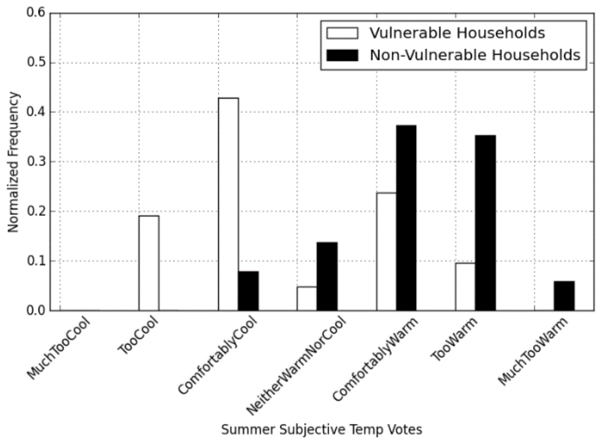

Figure 13 Summer subjective temperature votes for vulnerable and non-vulnerable households.

Table 4 Results of statistical tests for ventilation and thermal comfort votes

Groups	Items	Mean±Std Group 1 (°C)	Mean±Std Group 2 (°C)	Significance of difference	Statistical Test	P Value
V vs. nV	Ventilation votes	2.47±1.1	3.3±1.1	Strong	Mann-Whitney test	1.4E-08
V vs. nV	Cross ventilation votes	2.71±0.9	3.27±1.1	Weak	Mann-Whitney test	0.03
V vs. nV	Summer thermal comfort votes	3.62±1.3	5.18±1	Strong	Mann-Whitney test	1.2E-05

V; Vulnerable Houselholds, nV: Non-Vulnerable Households.

Furthermore, the analysis of the thermal comfort responses indicates that vulnerable people underestimated their heat perception when compared to non-vulnerable occupants. This could potentially make them less ready to undertake behavioural actions for heat protection. This could also indicate that it is convenient to assign lower floor dwellings to vulnerable people where they are less exposed to the risk of overheating.

8 Conclusions

This paper reports the results of the indoor temperatures monitored in 86 rooms of 46 homes during the period May to September 2014. Different housing design characteristics (roof exposure and façade orientation) and occupant variables (vulnerability and occupant ventilation patterns) were used to conduct the meta-analysis of the monitored rooms.

Firstly, it was found that roof exposed rooms are in general the ones recording the highest temperatures. Concerning room use, kitchens and bedrooms are in general warmer than living rooms. We also found that living rooms occupied by vulnerable occupants fall at higher risk of overheating due to behaviour of those. In fact, elderly and people with compromised health have restricted possibility of movement and could be socially isolated; this affects the time they spend indoor and their ability to behaviourally adapt to prolonged exposure to high indoor temperatures making their homes more at risk of overheating.

This suggests that occupants' characteristics play an important role in defining indoor conditions in newly insulated dwellings and that occupants' behaviour can powerfully alter indoor temperatures through the way occupants control ventilation in their homes. This is especially true when considering the fact that the minimum outdoor temperatures recorded during the summer 2014 are never higher than 18°C and that, therefore, night ventilation has a great potential for preventing overheating.

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WINDSOR CONFERENCE 2016

MAKING COMFORT RELEVANT

WORKSHOP 3.3

Understanding Comfort, Attitudes and Behaviours

Invited Chairs: Da Yan and Atze Boerstra

WS3.3: Understanding Comfort, Attitudes and Behaviours.
Chairs: Da Yan and Atze Boerstra

Occupant behaviour is now widely recognized as a major contributing uncertainty factor in building performance. Due to the complexity and unpredictability of an individual occupants responses, it is difficult to simulate occupant's behaviour influenced as they are by physical, physiological, psychological and other factors. There still are many gaps in our knowledge of the field and limitations to current methodologies applied by researchers and practitioners to integrate occupant behaviours at the design, operation, and retrofit of buildings stages. This workshop focuses on understanding of, and also the modelling and simulation of occupant behaviour in buildings. The IEA Annex 66: Definition and Simulation of Occupant Behaviour in Buildings, will also be introduced. Attendees will discuss the progress of occupant behaviour research in buildings, which including robustness experiment design, advanced modelling development, rigorous model evaluation, etc., with a view to stimulating in-depth discussions on methodologies of occupant behaviour modelling and simulation.

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Field Study of Air Conditioning and Thermal Comfort in Residential Buildings

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Abstract
The aim of this study is to better understand the external and internal drivers that affect residential air-conditioning (A/C) use decisions and occupant comfort. Field observations were carried out using instrumental measurements and smartphone questionnaires, recording householder's A/C usage patterns, indoor/outdoor climatic factors, perception of thermal comfort and adaptive behaviours. Throughout the 2-year monitoring period, a total of 4,867 A/C use events and 2,105 online comfort questionnaires were collected from 42 homes in Australia. The householders' neutral temperature was estimated to be 2 degrees lower than that predicted by the ASHRAE 55's adaptive model. Despite the lower-than-expected neutrality, comfort zone widths for 80% acceptability were found to be 9K in residential settings, which is 2K wider than that expected by the adaptive model. Our findings indicated that people in their homes are more adaptive to, and tolerant of significantly wider temperature variations than expected (in particular cooler temperature conditions). Based on the analysis of the results, an adaptive model that can be used for the assessment of residential thermal comfort is proposed in this paper. This study also revealed the householders' thermal adaptation behaviours as a function of temperature variations, which can be utilised in building energy modelling softwares.

Keywords: Thermal comfort, Air conditioning, Residential building, Adaptive model, Comfort zone

1 Introduction

The current international standards on human thermal comfort, such as ASHRAE Standard 55 (ASHRAE, 2013) and ISO 7730 (ISO, 2005), are regarded as universally applicable to all types of indoor spaces. These standards were originally intended to provide guidelines for centrally controlled HVAC systems, based on human heat-balance model exclusively derived from climate chamber experiments. The broad applicability of heat-balance model to real-world settings has been challenged by a number of field studies based on the theory of occupant thermal adaptation in which perception of comfort is affected by contextual factors such as outdoor climate, thermal history and expectations (e.g. Auliciems, 1981; Humphreys, 1978; Humphreys and Nicol, 2002). The adaptive comfort model, derived from empirical evidences quantifying the dependence of comfort zone on outdoor weather (de Dear and Brager, 2002), has been incorporated in the current ASHRAE Standard 55-2013 for naturally-ventilated spaces as an alternative to the heat-balance model. In adaptive hypothesis, occupants interact with the surrounding environment with a certain degree of control to achieve comfort, rather than just being passive recipients of the given thermal environment (Brager and de Dear, 1998). Therefore 'adaptive approach' is expected to adequately reflect human comfort in residential settings where occupants play an active role, by adjusting their behaviours or even modifying the surrounding environment to make themselves more comfortable. Nevertheless, whether the comfort zone defined by the ASHRAE 55's adaptive comfort standard can be directly applied to the residential context is somewhat questionable as the empirical data (i.e. ASHRAE RP-884 database) that formed the basis of the adaptive model was mainly from office buildings (de Dear, 1998), where occupants' activities and their control over the environment are relatively restricted, compared to their homes, mostly likely due to the shared use of space and organisational culture. On the other hand, in homes occupants are engaged in much more diverse activates, and have greater degree of adaptive opportunities and a higher level of perceived control (Hwang et al., 2009; Karjalainen, 2009). Given that the perceived degree of control is known to be one of the strongest predictor of thermal comfort (Leaman and Bordass, 1999; Paciuk 1990), home residents' comfort zone should be wider than that of office workers due to greater degree of adaptive opportunities as previously conceptualised by Baker and Standeven (1996).

Previous comfort studies conducted in residential settings have shown systematic discrepancies between the actual comfort level reported by occupants and the predicted by the comfort standards: such as neutralities lower than predicted by the PMV model (Feriadi and Wong, 2004; Hwang et al., 2009; Oseland, 1995), the PMV model's overestimation of the percentage of dissatisfied (Becker and Paciuk 2009; Han et al. 2007), and residents showing greater adaptability or tolerance than suggested by the adaptive model (Wang, 2006; Ye et al., 2006). The most compelling explanations for these discrepancies are contextual factors influencing occupant thermal perceptual processes in homes: including greater adaptive opportunities, greater control over the environment, more flexible clothing patterns, more diverse activities, or energy price affecting consumer patterns.

Despite air-conditioning (A/C) having become one of the fastest growing end-uses of electricity in Australian homes, there has never been a rigorous investigation into the occupant A/C use patterns, adaptive behaviours and perception of thermal comfort in residential contexts. Over a century of thermal comfort research activities worldwide, studies focused on residential environments are rare (e.g. Daniel et al., 2014; Lomas and Kane, 2013; Rijal et al., 2013) while overwhelming majority of them were based on office settings. The most likely reason for residential comfort being understudied is the difficulties in logistics. While researchers can collect objective and subjective comfort evaluations from a concentrated sample of occupants in office buildings, peoples' homes are geographically dispersed and there are potential issues with long-term installation of equipment and concerns of householder privacy.

This paper presents the results of a longitudinal field studies carried out in Australian homes for over a period of two years, with a focus on better understanding the external and internal drivers that affect householders' A/C use decisions, adaptive behaviours and thermal comfort. To test our hypothesis that greater adaptive opportunities in homes can result in a wider range of comfort zone, statistical analysis is performed to develop an adaptive model defining the comfort zone of householders. Our empirical finding is then compared with the ASHRAE 55's adaptive comfort standard and implications are discussed.

2 Methods

A total of 42 homes were recruited in Sydney (27 homes) and Wollongong (15 homes) for questionnaire surveys and instrumental monitoring. Only those homes equipped with at least one A/C unit were included in our field study. Field observations were made for two years (March 2012 ~ March 2014), focusing on; (1) each household's air-conditioning usage, (2) external climatic drivers of usage patterns, (3) internal factors influencing perceptions of thermal comfort, and (4) actual householders' perceptions of thermal comfort and related behaviours.

During the first site-visit researchers administered a background survey of household demographics, housing characteristics and air-conditioning appliances characteristics. Indoor air temperature and humidity monitoring devices, *iButtons*, were also installed in various locations in the occupied zone of the participants' homes (such as living room, bedroom, dining room, kitchen, study, etc.), recording indoor air temperature and humidity every 15 minutes. An *iButton* was also placed directly into the supply air path of the air conditioner or fan-coil unit, which enabled researchers to investigate when and where A/C units were used.

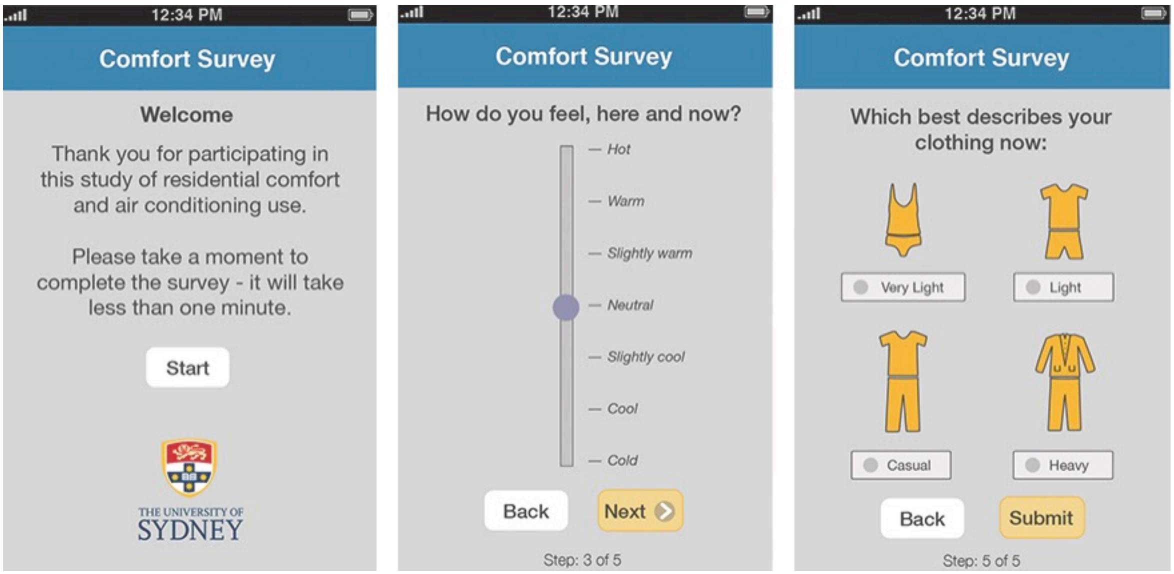


Fig. 1 Screenshots of the smartphone comfort questionnaire

An Excel macro was developed to detect sudden changes in the A/C supply air temperature and then compare it to the temperature in the occupied zone to determine the A/C operation mode being used. First, if the difference between two contiguous supply air temperature measurements was greater than 3.5°C then the A/C was considered to be switched on within that 15-minute period. The temperature in the occupied zone when the A/C was operational and two subsequent measurements (three total) were then analysed; the decision to use three measurements was made in consideration of temperature cycling. If the difference between the *maximum* of the three temperatures in the occupied zone and the supply air temperature was greater than the threshold specified for that house (nominally 3°C but changed to suit individual cases) then heating was being used. If not, the same logic was applied to the *minimum* of the three measurements to test if cooling was being used. This logic was continued until neither case was true and then the A/C was labelled as off. Extensive testing of the macro was done to ensure it was a robust approach to automating this process, but some intervention was required to remove false positives.

Throughout the 2-year monitoring period, researchers periodically sent SMS messages directly to the householders' smart phones, directing the participants to an online comfort questionnaire (screenshots shown in Fig. 1). More detailed technical information on this online questionnaire platform, aka '*Comfort Chimp*', can be found in the study done by Parkinson et al. (2013). This very brief questionnaire was designed to be completed in less than one minute, addressing simple questions; (1) identifying whether or not a participant is at home, (2) location inside home, (3) thermal sensation, (4) thermal adaptation strategies in use, and (5) simple classification of clothing type being worn. Table 1 summarises the structure of the questionnaire used for our smartphone surveys. Questionnaires were administered approximately once a week throughout the monitoring period, but during certain weather conditions (e.g. heat waves) it was sent out to the householders more frequently. Participants were allowed to respond to the questionnaire later at a more convenient time, if it arrived at an inconvenient time, as the responses were time-stamped at the point when the questionnaire was completed. The questionnaire was terminated if the participant was not home.

Table 1 Summary of the smartphone questionnaire structure, scales and coding

Questionnaire item	**Measuring scale (coding)**
"*Are you currently at home?*"	- Yes - No (questionnaire terminates)
Location at home: "*Where are you right now?*"	- Living room - Bedroom - Dining - Kitchen - Bathroom - Laundry - Study
Thermal sensation: "*How do you feel, right here, right now?*"	- Cold (-3) - Cool (-2) - Slightly cool (-1) - Neutral (0) - Slightly warm (+1) - Warm (+2) - Hot (+3)
Adaptive strategy: "*In this room here and now, do you have (you may select more than one)?*"	- Open windows / doors - Ceiling / desk fans operating - A/C on (cooling) - A/C on (heating) - Other heating appliances on - None
Clothing insulation (clo): "*Which best describes your clothing now?*"	- Very light (0.2) - Light (0.4) - Casual (0.6) - Heavy (1.0)

Throughout the 2-year monitoring period, a total of 4,867 A/C use events and 2,105 online comfort questionnaires were logged. The individual A/C use events and survey responses were matched *post hoc* with corresponding indoor (measured by *iButtons*) and outdoor (obtained from the closest *Bureau of Meteorology* station) climate observations for subsequent analyses. The prevailing mean outdoor air temperature ($T_{pma(out)}$) was also calculated (using the weighted 7-day running mean in ASHRAE Standard 55) for the day on which each comfort questionnaire was completed.

3 Results & Discussion

3.1 Characteristics of local climate and participating households

Sydney and Wollongong both belong to temperate climate regions in Australia. In general both cities have characteristics of coastal climate. However the climate of western parts of Sydney becomes more continental as the city spans toward inland due to its greater size. Monthly maximum/minimum outdoor temperatures of Sydney and Wollongong during the 2-year monitoring period, acquired from *Australian Bureau of Meteorology*, are illustrated in Fig. 2. The mean maximum temperature in Sydney during the monitoring period was 24.2°C, which was 2.7°C higher than that in Wollongong (21.5°C). The mean minimum temperature in Sydney was 12.2°C, which was 2.7°C lower than that reported in Wollongong (14.9°C) for the same period of time. On average, the temperature difference between the coldest and warmest months was relatively greater in Sydney, compared to Wollongong.

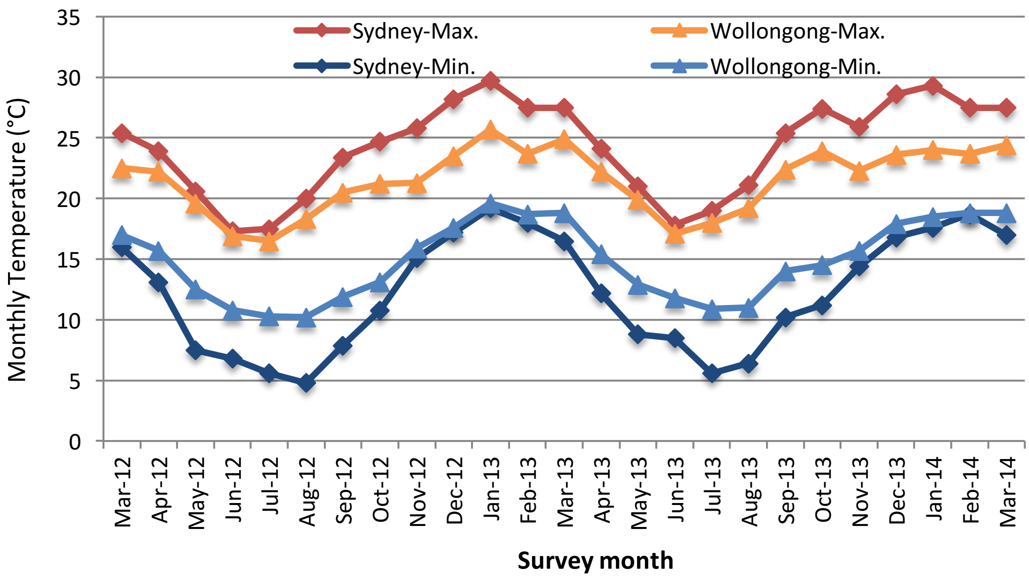


Fig. 2 Outdoor maximum/minimum temperature (monthly average) of Sydney and Wollongong during the monitoring period (data from *Australian Bureau of Meteorology*)

The participating householders' characteristics such as gender, the number of people living in the house, the level of education and the gross household income are described in Table 2. The number of female participants was higher (65%) than male participants (35%). The households were mostly comprised of 2 to 4 members (87%).

Table 2 Characteristics of the participating households

Description	Category	Percentage
Gender	Male	64.6%
	Female	35.4%
Household size (persons)	1	4.3%
	2	40.4%
	3	19.1%
	4	27.7%
	More than 4	8.6%
Education level	High school	2.4%
	TAFE (short-cycle tertiary)	9.5%
	University degree	19.0%
	Postgraduate coursework	35.7%
	PhD or research masters	33.3%
Household income (AUS$)	Up to $10,000	0%
	$10,001~30,000	2.2%
	$30,001~50,000	6.5%
	$50,001~70,000	13.0%
	$70,001~90,000	10.9%
	$90,001~110,000	13.0%
	More than $110,000	54.3%

3.2 Air-conditioning use patterns

Fig. 3 and Table 3 both summarise air-conditioning usage patterns of the households during the monitoring period. 98% of the A/C cooling events was recorded between late spring and early autumn (October ~ March), with the highest number of cases occurring in January (36%). As reported in Table 3, the room air temperature of 27.9°C was found to be the most common trigger temperature for space cooling among the participating householders. When air conditioning was operating on cooling mode, the average duration of usage was 2.5 hours cooling the room by 2.8°C. Late autumn and winter months (May ~ August) accounted for 89% of the A/C heating events. The A/C was used for space heating for an average of 2 hours, increasing the room temperature by 2.9°C, from 18.2 to 21.2°C.

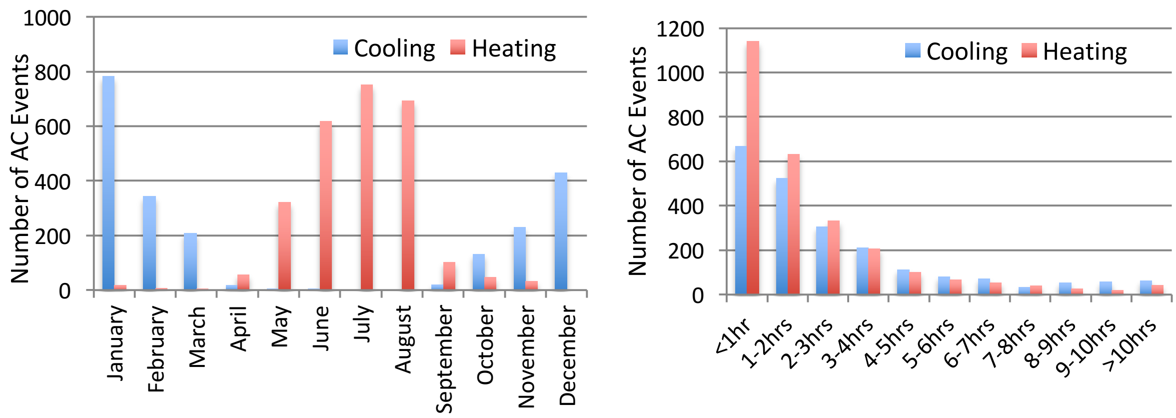


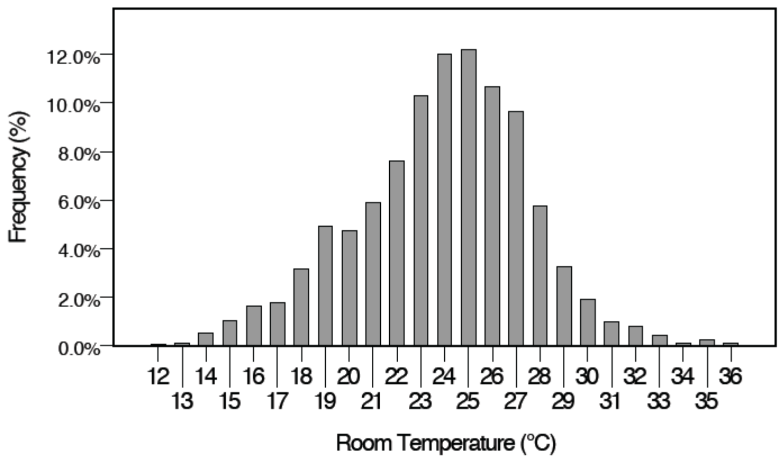
Fig. 3 Residential A/C events by month (left) and A/C usage duration (right)

Table 3 Summary of A/C use pattern

A/C mode	Description	Household average (S.D.)
Cooling	Total A/C (cooling) use per household	155.2 hrs (248.1)
	Average A/C (cooling) use duration per household	2.5 hrs (1.1)
	Cooling trigger temperature (temp when A/C was effectively switched on)	27.9°C (2.0)
	Cooling stop temperature (temp when A/C was effectively switched off)	25.2°C (1.8)
	Cooling ΔT (stop temp – trigger temp)	-2.8K (1.6)
Heating	Total A/C (heating) use per household	159.8 hrs (208.9)
	Average A/C (heating) use duration per household	2.0 hrs (1.3)
	Heating trigger temperature (temp when A/C was effectively switched on)	18.2 (3.4)
	Heating stop temperature (temp when A/C was effectively switched off)	21.2 (3.6)
	Heating ΔT (stop temp – trigger temp)	+2.9K

3.3 Subjective evaluation of the indoor thermal environment

The distribution of room air temperature (T_{rm}) recorded at the time of smartphone surveys (therefore the space can be regarded to be occupied) is illustrated in Fig. 4. The majority of survey responses were collected from living room (58%), followed by kitchen (14%), bedroom (11%), study (8%) and dining room (7%). Each bar in Fig. 4 represents the percentage of survey samples falling within each temperature bin. Over 90% of observed room temperature ranged between 18 ~ 29°C. The minimum and maximum temperature observations at survey times were 12.1°C and 36.1°C respectively. In Fig. 4, the distribution of the survey participants' thermal sensation is also attached. Almost half (47%) of the subjects expressed their thermal sensation as *neutral* in their homes. Assuming that people voting in the central three categories of the 7-point thermal sensation scale (i.e. *slightly cool*, *neutral*, or *slightly warm*) are satisfied with, therefore accepting their thermal environment, overall 83.4% of the participants were satisfied with the thermal conditions in their homes.



TSV	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Percentage	0.4%	1.8%	11.6%	46.9%	24.9%	11.7%	2.8%

Fig. 4 Distribution of room air temperature (T_{rm}) logged at the time of questionnaire responses, and thermal sensation votes (TSVs)

3.4 Householders’ adaptive behaviours

Clothing insulation is an important variable to investigate occupant behavioural adaptation in residential settings, as individuals would have much more flexibility to adjust their clothing in homes compared to workplaces where a certain dress code is most likely required. The mean value and 95% confidence intervals for the samples’ *clo*, categorised by indoor room air temperature (T_{rm}) binned at 1K intervals, are shown in Fig. 5. This figure describes how residents’ clothing insulation changes depending on indoor temperature variations. A wide range of mean *clo*-value (0.33~1.0) was observed during the survey period. According to Fig. 5, the subjects’ clothing adaptation was more noticeable when T_{rm} was between about 19 and 26°C. Between 19 and 26°C, the mean clothing insulation decreased by 0.1 *clo* (from 0.8 to 0.4) for every 1.8°C increase in T_{rm}. On the other hand, when T_{rm} was below 19°C or above 26°C, there was no clear tendency of occupants’ clothing adjustments. This implies that thermal adaptation through change in clothing may not be so effective beyond the indoor temperature range of 19~26°C in residential buildings. In other words, thermal adaptability by adjusting *clo* value in this Australian residential context seems bounded between 0.4 and 0.8 *clo*.

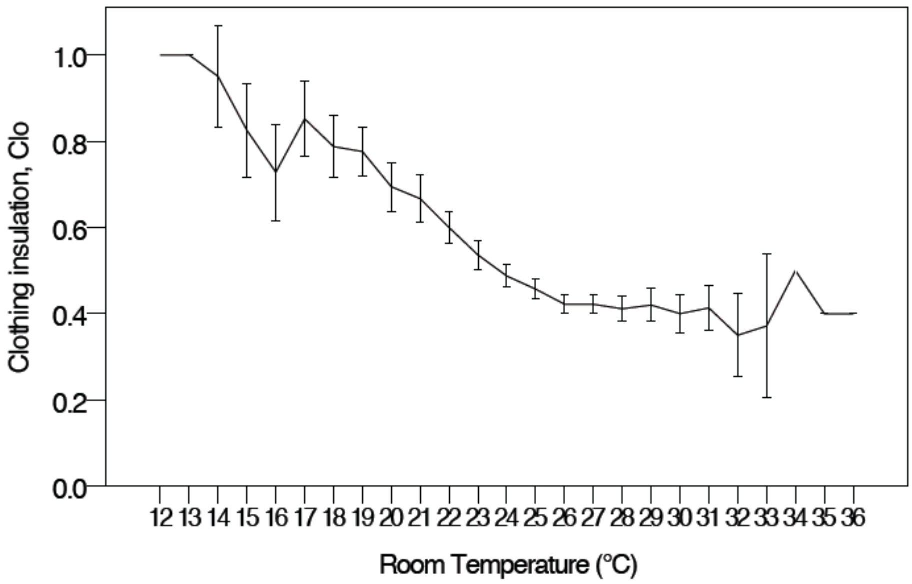


Fig. 5 Clothing insulation (*clo*) worn by householders in relation to air temperature (T_{rm}) of the room in which they were answering the comfort questionnaire. Error bars represent 95% confidence intervals.

Apart from clothing insulation, our online survey asked householders to identify their means of thermal adaptation at the time when the questionnaire was completed. To understand the participants’ behavioural adaptations in relation to temperature variations, a set of logistic regression analyses were performed with each of the adaptation strategies listed in Table 1 (i.e. *Open windows/doors, Ceiling/desk fans on, A/C-cooling on, Heating on*) as the dependent variables, and the outdoor air temperature ($T_{a(out)}$) as the independent variable. Thus the logistic regression models predict the probability of people using a particular adaptive strategy to achieve comfort, as a function of outdoor air temperature (Fig. 6).

Based on the results of logistic analyses, the predicted percentage of different adaptive strategies can be estimated as follows:

$$P\,(\textit{AC-cooling on}) = \frac{100}{1+\exp^{-(0.24T-8.20)}} \quad (1)$$

$$P\,(\textit{Heating on}) = \frac{100}{1+\exp^{-(-0.23T+3.58)}} \quad (2)$$

$$P\,(\textit{Fan on}) = \frac{100}{1+\exp^{-(0.11T-4.79)}} \quad (3)$$

$$P\,(\textit{Open windows/doors}) = 100 - \left(\frac{100}{1+\exp^{(0.33T-6.58)}} + \frac{100}{1+\exp^{(-0.17T+5.13)}}\right) \quad (4)$$

where T = the outdoor air temperature

According to Fig. 6, $T_{a(out)}$ of 22 and 28°C were found to be the thresholds that kept the percentage of people relying on mechanical heating and cooling respectively below 20% (note: '*Heating on*' in Fig. 6 is inclusive of survey votes on both '*A/C-heating on*' or '*Other heating appliance on*' given in Table 1). At $T_{a(out)}$ of about 25°C, '*A/C-cooling on*' and '*Heating on*' curves intersected each other, and the frequency of opening windows/doors was peaked. Therefore it seems reasonable to assume that the outdoor temperature of about 25°C is the most favourable temperature condition that can maximise the use of natural ventilation and minimise the householders' tendency of relying on the mechanical assistance in residential settings. Our findings of the occupant adaptive behaviour schedules as a function of temperature variations given in Fig. 6 can be utilised in energy modelling and simulation software in the Australian residential context. Although more detailed analysis should be followed (e.g. temperature-behaviour relationship by different rooms of the house and by different times throughout the day/night cycle), the result of the analysis can enable household energy efficiency rating tools such as *AccuRate* to perform more realistic, and therefore more precise energy assessments.

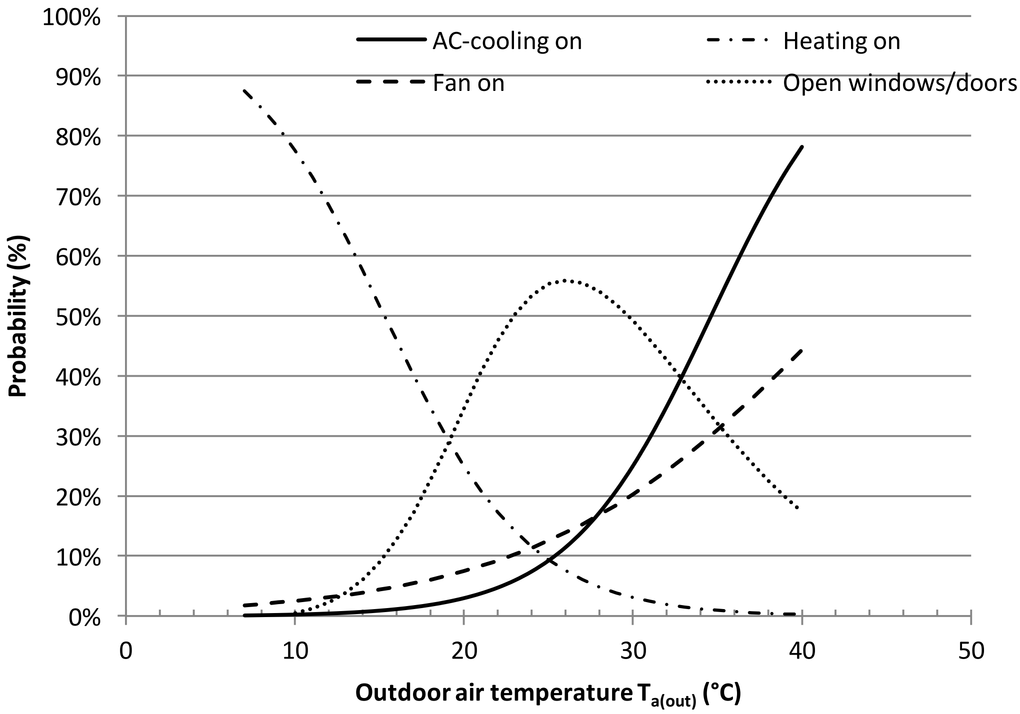


Fig. 6 The predicted percentage of adaptive strategies in use as a function of outdoor air temperature

3.5 Thermal sensation, acceptability, and the predicted percentage of dissatisfied

The relationship between thermal sensation votes (TSVs) and concurrent indoor temperature was investigated by fitting a linear regression between the two variables (Fig. 7). In comfort studies, the gradient of the regression model is typically interpreted as being inversely related to occupants' thermal adaptability. In other words, the steeper the regression line is, the more sensitive (or the less tolerant) the occupants are to temperature variations. In our analysis, the temperature difference (T_{diff}) between room air temperature (T_{rm}) and neutral temperature (T_n, calculated according to the ASHRAE 55's adaptive model: i.e. $T_n=0.31T_{pma(out)}+17.8$) was computed for each of the survey samples (i.e. $T_{diff} = T_{rm} - T_n$). Positive values of T_{diff} signify that room temperature is above the neutral temperature estimated by the ASHRAE 55's adaptive model, while negative values indicate that room is cooler than the neutrality. Then, TSVs were regressed on this relative temperature scale (binned into 0.5K intervals of T_{diff}), so the regression model was weighted by the number of TSVs falling in each of the T_{diff} bin (Fig. 7).

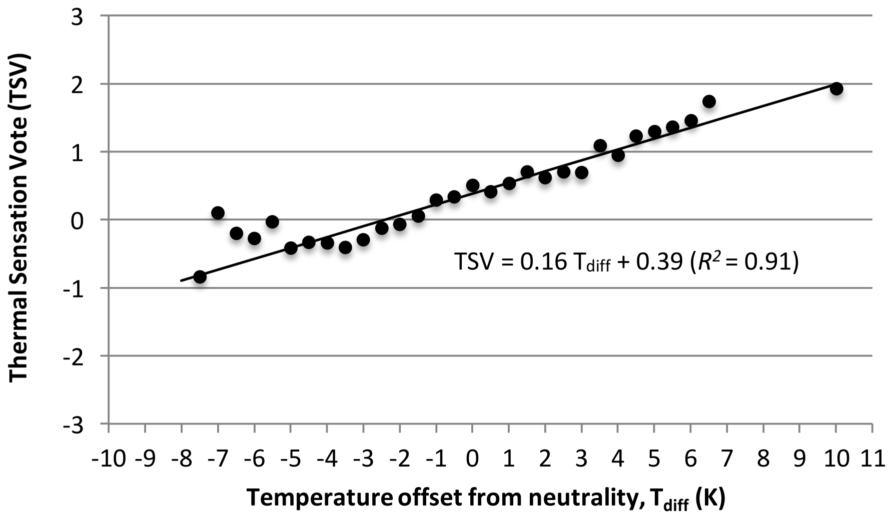


Fig. 7 Thermal sensation votes (TSVs) regressed on the relative temperature scale (i.e. room air temperature minus neutral temperature predicted by ASHRAE 55 adaptive model, $T_{diff} = T_{rm} – T_n$). Regression line is weighted by the number of TSVs falling in each of the half-degree temperature bins.

The logic behind using *temperature offset from neutrality* (i.e. T_{diff}) as the independent variable of the regression model rather than simply using room temperature, rests with the fundamental concept of adaptive comfort, which suggests that perception of thermal comfort can be influenced by contextual factors such as outdoor climate, seasons, past and current thermal experience (Brager and de Dear, 1998). For example, according to the adaptive theory, the same indoor temperature can be felt differently between those who have different thermal history. In our study, TSVs were collected from 42 different locations for the duration of 2 years encompassing two full cycles of seasonal changes. As a result, there was no basis to assume that each of the collected TSVs carried the equivalent thermal experiences prior to the survey. T_{diff} in this analysis was used in order to adjust the differences in individuals' thermal history across two years of the monitoring period, which might have influenced their TSVs.

The final regression model (R^2=0.91, significance level of coefficient and constant p<0.001) derived from the entire sample is:

$$TSV = 0.16 \times T_{diff} + 0.39 \quad (5)$$

According to the regression model, 6.3K of temperature change accounts for one unit change of thermal sensation on the 7-point scale (one over the regression coefficient of 0.16 in Equation 5). Interpreting the gradient of the regression equation as the group's thermal sensitivity, occupants of residential buildings were 70% more tolerant to indoor temperature variations, compared to occupants of naturally ventilated office buildings (comparing with the mean regression model gradient of 0.27 reported by de Dear and Brager (1998), whose study has been adopted as the ASHRAE 55's adaptive comfort standard). With more than 6K required to increase/decrease one thermal sensation unit, this group of householders was successfully adapting to the changes in indoor temperature conditions.

The estimated neutral temperature, by solving the equation for TSV of zero, was -2.4K. This means that the neutrality for this sample group in residential settings was 2.4K cooler than that predicted by the ASHRAE 55's adaptive model. This finding is in lines with studies reporting house residents' *cooler-than-expected* neutral (or preferred) temperatures (Oseland 1995; Pimbert and Fishman 1981).

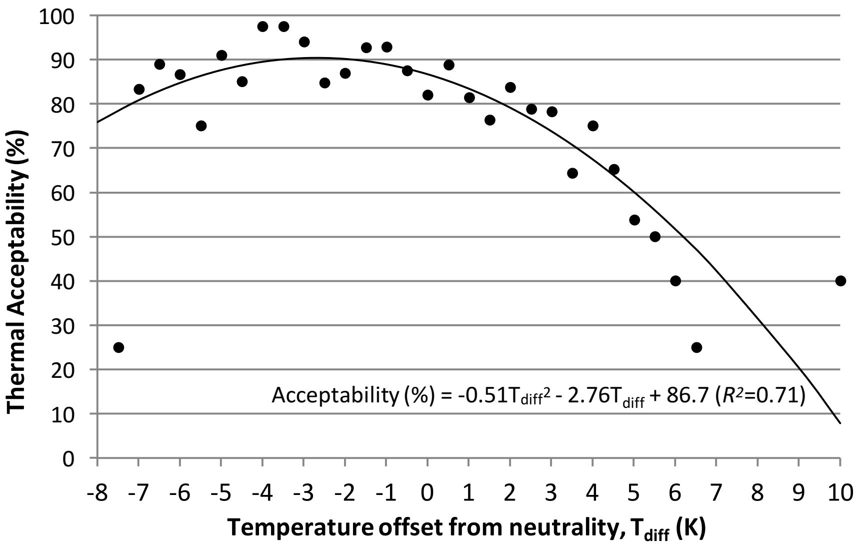


Fig. 8 Thermal acceptability (i.e. -1.5<TSV<+1.5) as a function of temperature offset from the ASHRAE 55 adaptive model's neutrality. Each data point represents the proportion of subjects voting in the central three categories (i.e. *slightly cool*, *neutral* or *slightly warm*) of the 7-point thermal sensation scale. The fit line is weighted by the total number of samples in each of the half-degree temperature bins.

In this study thermal acceptability was defined as the percentage of TSVs falling within the middle three categories of the 7-point (continuous) thermal sensation scale (i.e. -1.5<TSV<+1.5). The proportion of '*acceptable*' votes was calculated for each half-degree bin of T_{diff} and is illustrated in Fig. 8. Then a fit-curve was produced, weighted by the number of samples falling within each of the bins. The fit-curve was skewed toward the left side of the T_{diff} scale, reporting higher percentage of acceptability on '*cooler-than-neutral*' temperatures. While the householders' thermal acceptability generally maintained higher than 80% in *cooler-than-neutral* conditions, it started dropping below 80% at which indoor temperature was 2K warmer than the neutrality. Then again significant decrease in acceptability was observed as indoor temperature exceeded more than about 3 degrees higher than the neutral temperature. The present analysis indicates that residents required cooler temperature conditions than predicted by the standard in order to meet the 80%

acceptability target. Additional work seems essential to explore the potential drivers that make householders more tolerant in *cooler-than-neutral* conditions. However, householder's behavioural/psychological adjustments to cooler temperature conditions that couldn't be captured in our study might have played a role: such as using blankets, moving closer to warm radiant source (e.g. sunlight through window), exercising, cooking, and concerns on energy bills.

Further elaborating the analytical approach just used to calculate thermal acceptability in Fig. 8, a predictive model that is capable of estimating the percentage of people dissatisfied due to *warm-* or *cool discomfort* can be derived. The logic behind this analysis is directly comparable to that used by Fanger (1972) when he derived the PPD (Predicted Percentage of Dissatisfied) index from the PMV (Predicted Mean Vote) estimation. '*Warm discomfort*' votes (TSV>+1.5, i.e. *warm* or *hot*) and '*cool discomfort*' votes (TSV<-1.5, i.e. *cool* or *cold*) were binned into 0.5K intervals of T_{diff} and became the basis of probit regression models predicting what percentage of people is expected to be *cool-* or *warm dissatisfied* (probit models' significance level for coefficient and intercept: $p<0.001$). Then they were added into one curve representing the total percentage of dissatisfied as a function of temperature offset from the neutrality (Fig. 9). The predictive curve has a minimum value of 9% (PPD) when indoor temperature was 3K cooler than expected by the ASHRAE 55 adaptive model. This is in line with the result of an earlier filed study conducted in hot-humid climate (Hwang et al. 2009) in which the minimum value of PPD was estimated to be 9% and the PPD curve shifted towards the cool side of the scale. An increase of the minimum PPD to 9% from 5% suggested by Fanger (1972) is not surprising, as the PPD from climate chamber experiments has been found to be substantially underestimating the dissatisfaction rate observed in actual buildings (Arens et al., 2010). Considering the fact that ASHRAE Standard 55 presumes another 10% dissatisfied resulting from local discomfort in addition to the PPD value, minimum 9% of total dissatisfied rate seems more realistic as local discomfort issues are already factored into the current adaptive approach.

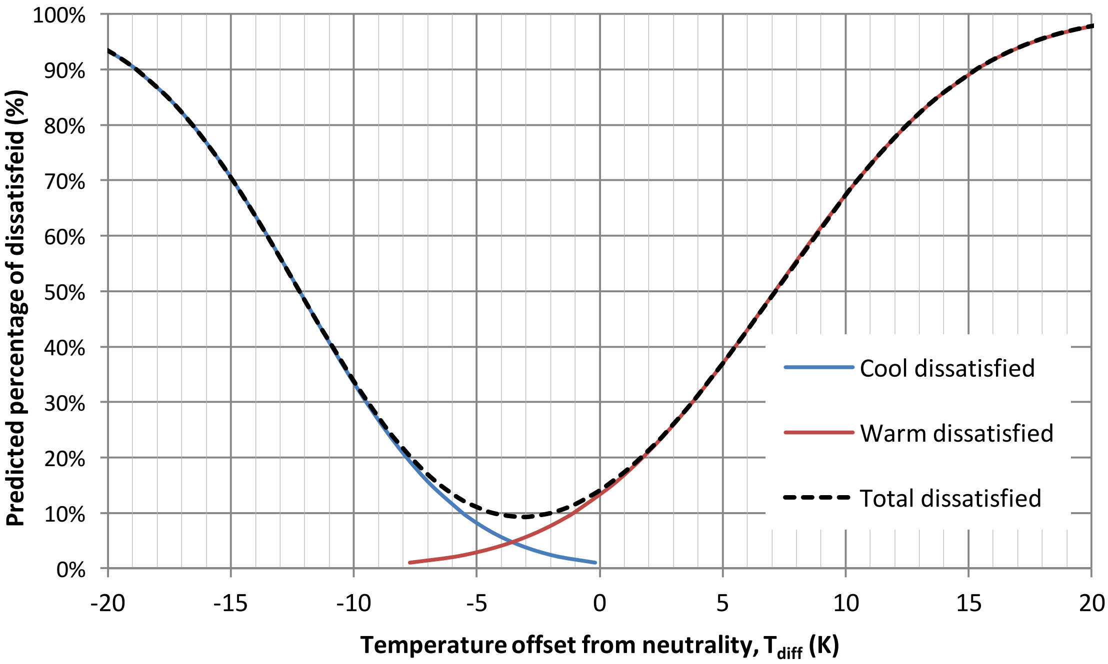


Fig. 9 Predicted proportion of thermally dissatisfied individuals in their homes, as a function of temperature offset from the ASHRAE 55's adaptive model neutrality There are no numbers on the Y axis Jungso?

Now the point of intersections between the predictive curve and 20% dissatisfied can be used to define the boundaries of 80% comfort zone. According to Fig 9, the range of temperatures at which more than 80% of the subject felt comfortable (i.e. PPD < 20%) was estimated to be 9K. The span of acceptable indoor temperatures for the current resident samples came to 9K, which is 2K wider than the width of ASHRAE's 80% acceptability (ASHRAE, 2013). Therefore our hypothesis that occupants in houses will have a wider range of comfort zone due to greater adaptive opportunities was supported by the empirical findings.

Our analyses so far have shown that occupants' reaction towards the thermal environments in their homes appeared to be considerably different to what suggested by previous adaptive comfort studies that were based on office building contexts. As seen in Fig. 7 and Fig. 8, the householders' group mean neutral temperature and optimal temperature drifted 2~3K towards cooler side of the relative temperature scale, compared to that estimated by the ASHRAE 55's adaptive model. Interpreting regression slope in Fig. 7 as an index of thermal adaptability, people seemed to be more adaptable in their homes than in workplaces. Residents' greater adaptability was also confirmed in Fig. 9 in which the comfort range for 80% acceptability was estimated to be 2K wider than the ASHRAE 55 adaptive standard. Given the noticeably different empirical findings between home and workplace settings, it seems to be meaningful with no doubt to revisit the adaptive comfort model in the context of residential settings, in order to better understand occupants comfort and adaptive behaviours in their homes.

3.6 Adaptive model for residential comfort

To investigate the fundamental concept of adaptive comfort that the indoor neutral temperature depends on the prevailing mean outdoor temperature (Humphreys, 1978; Nicol and Humphreys, 2002), the following analytical steps were taken:

1. The entire survey samples were divided according to the month and the city, obtaining 24 sub-groups (i.e. 12 months × 2 cities).
2. A weighted linear regression model was fitted separately to each of the 24 sample groups, to quantify the relationship between the group mean thermal sensation and indoor room temperature (TSV = $b \times T_{rm} + c$). Excluding regression models failed to achieve 95% significance, a total of 14 regression models retained for further analysis; mean model gradient b = 0.17, mean model constant c = -3.67, mean sample size n = 76, and mean R^2 = 0.51.
3. The neutrality temperature was calculated from each of the 14 regression equations, then matched with the concurrent prevailing mean outdoor temperature ($T_{pma(out)}$).

The association between our residential sample's monthly neutral temperature ($T_{n(resi)}$) and prevailing outdoor temperature ($T_{pma(out)}$) is graphed in Fig. 10. Indoor neutrality tended to increase as outdoor temperature became warmer, validating the hypothesis of adaptive comfort model in the residential context. The regression equation defining the relationship between $T_{n(resi)}$ and $T_{pma(out)}$ achieved statistical significance (p<0.05) and is as follows:

$$T_{n(resi)}\ (°C) = 0.26 \times T_{pma(out)} + 16.75\ (R^2 = 0.37) \qquad (6)$$

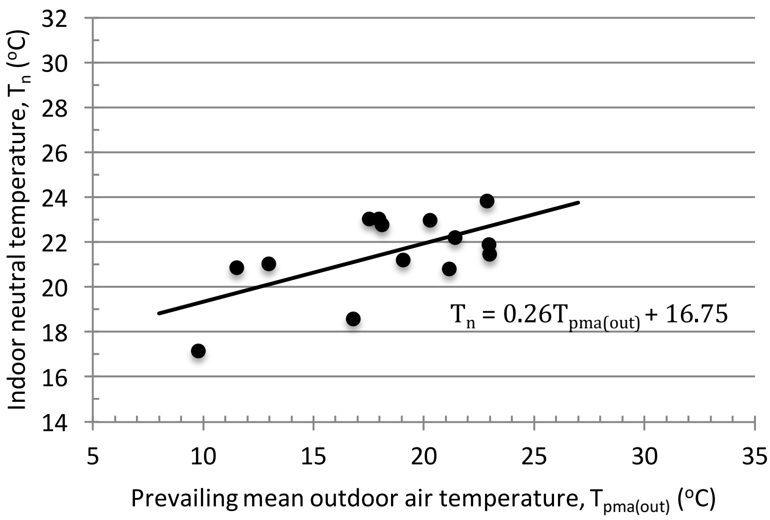


Fig. 10 Relationship between householders' monthly neutral indoor temperature ($T_{n(resi)}$) and prevailing outdoor temperature ($T_{pma(out)}$). The regression model's $R^2 = 0.37$ ($p<0.05$).

The next step was to define acceptable temperature limits from Equation 6. In the ASHRAE 55's adaptive comfort standard, a regression equation fitted between group mean TSV and indoor temperature was used to define the acceptability boundaries. That is, 80% acceptability limits in the ASHRAE 55 adaptive model was determined by solving the regression equation for TSV of ±0.85 (de Dear and Brager, 1998). The logic behind this definition was directly derived from Fanger's PMV-PPD relationship in which PPD reaches 20% when the group mean thermal sensation (PMV) equals ±0.85 (Fanger, 1972). However, in the present study the predictive curve showing the relationship between the proportion of thermal dissatisfaction and temperature variations (Fig. 9) has already produced 80% acceptability zone without having to borrow Fanger's PMV-PPD curve. Plus, there is no empirical basis to assume that the PMV-PPD relationship derived from climate chamber experiments is directly applicable to real world setting, in particular residential buildings where people are given with nearly all kinds of adaptive opportunities. As already shown in Fig. 10, the comfort range for 80% thermal acceptability was 9K. The 9K for 80% acceptability band, centred on the neutral temperature in Equation 6, determined upper- and lower 80% acceptability limit as follows:

$$\text{Upper 80\% acceptability limit (°C)} = 0.26 \times T_{pma(out)} + 21.25 \qquad (7)$$

$$\text{Lower 80\% acceptability limit (°C)} = 0.26 \times T_{pma(out)} + 12.25 \qquad (8)$$

The 80% acceptability range derived from our analysis on residential samples, compared against that of the ASHRAE 55 adaptive standard, is depicted in Fig. 11. It should be noted that the comfort zone of residents proposed in this study is only defined within the prevailing mean outdoor temperature of approximately 8 ~ 27 °C, due to the lack of data samples with $T_{pma(out)}$ values falling beyond this range. The width of 80% acceptable temperature range in the present study was about 30% wider (2K) than that prescribed in the ASHRAE 55's adaptive comfort standard. Despite of the wider comfort range, householders' comfort zone shifted down toward lower indoor temperatures due to their approximately 2K-cooler neutrality than that of the ASHRAE 55 adaptive model. Fig. 11 suggests that occupants of houses are more tolerant of, or more adaptable to cooler temperature variations than occupants of office buildings.

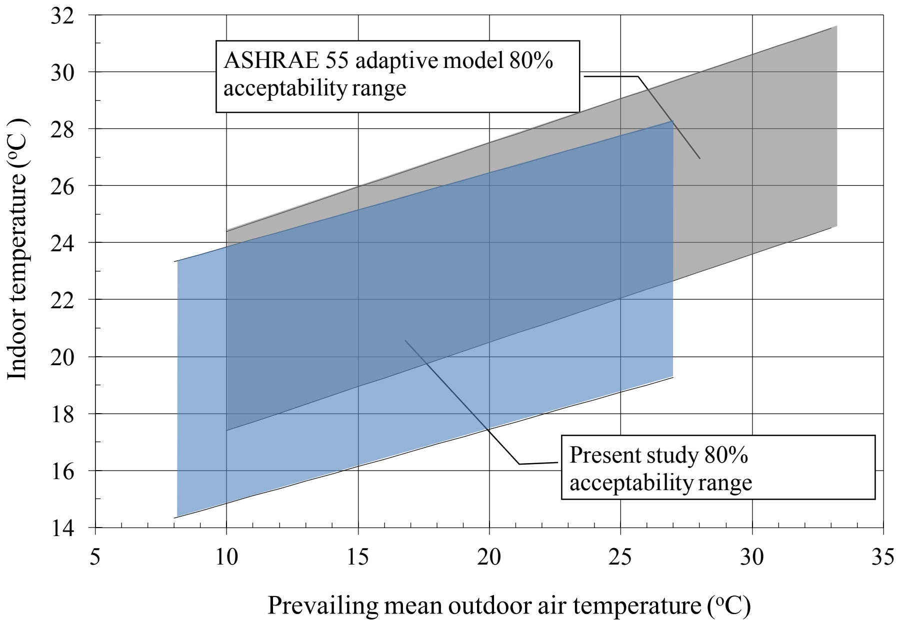
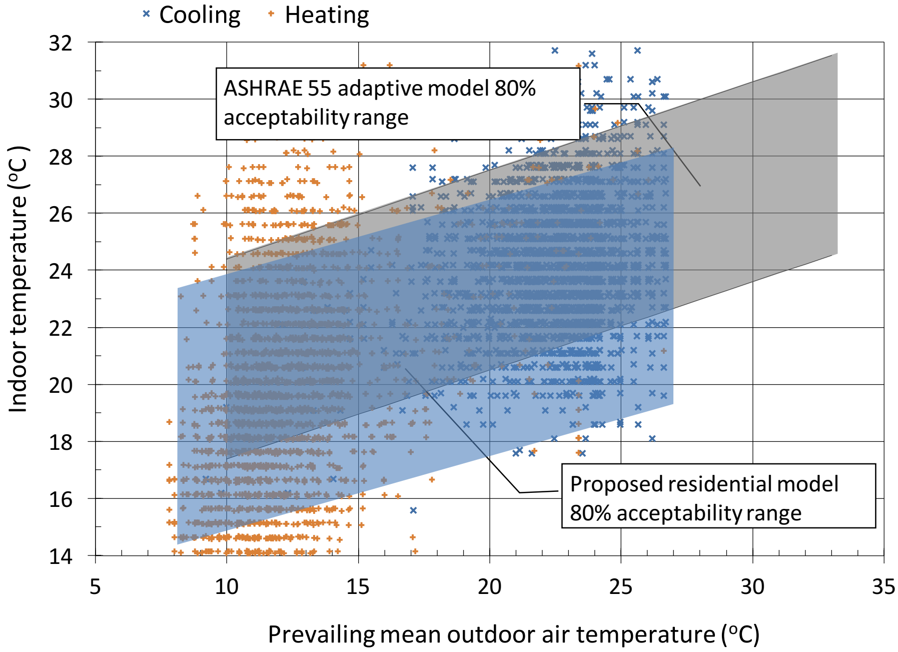


Fig. 11 Comparison of the 80% acceptable temperature ranges between the ASHRAE 55's adaptive comfort model and the proposed residential adaptive model in the present study

To test and validate the residential comfort zone just proposed in Fig. 11, the entire A/C events data samples (n=4,867) recorded during our monitoring period was utilised. Indoor room temperature readings when A/C was effectively switched off were assumed as the residents' comfort temperatures. These AC '*stop*' temperatures may not be the perfect index of comfort/preferred temperature inside the room in which AC was used, as there could be cases that A/C was switched off simply because the room in question was not occupied, regardless of occupant comfort. Nevertheless, it seemed rational, for most of the cases, to regard the AC '*stop*' temperature as a good approximation of the residents' comfort temperature. Then, supposedly, more than 80% of those temperature readings should fall within the 80% acceptability range of the adaptive comfort model. Fig. 12 illustrates indoor temperatures when A/C was switched off as a function of prevailing mean outdoor temperature, plotted against the 80% acceptable zone prescribed by ASHRAE 55's adaptive comfort standard and the current study. The percentage of data points falling within or beyond the acceptable temperature ranges is also summarised in Fig 12. Out of total 4,867 A/C '*stop*' temperature observations, 70.4% fell within the ASHRAE 55's adaptive 80% acceptability range, indicating about 10% of discrepancy between the predicted and the observed (for the dots falling outside of the vertical boundaries of the 80% acceptability zone, i.e. $T_{pma(out)}$<10°C, it was assumed that the upper- and lower- boundaries will continue on the same gradient). A considerable number (24.5%) of the AC '*stop*' temperature observations fell below the lower 80% limit of the ASHRAE 55 adaptive model, implying that the model is overestimating the comfort temperature of occupants in homes and underestimating home occupants' adaptability to lower temperature conditions. On the other hand, comparing the same A/C events data against the residential adaptive model, 80.4% of data samples fell within the 80% acceptability limits. And the percentage of samples falling over the upper 80% limit and under the lower 80% limit was almost identical at 10.1% and 9.5% respectively. Therefore it seems reasonable to assume that the proposed 80% acceptable temperature range in this study provides usable predictability of home residents' comfort temperatures.



	ASHRAE 55 adaptive model	Proposed residential adaptive model
Within range	70.4%	80.4%
Above 80%	5.1%	10.1%
Below 80%	24.5%	9.5%

Fig. 12 Indoor A/C (cooling or heating) 'stop' temperatures (*n*=4,840) plotted against the 80% acceptability range defined by the ASHRAE 55 adaptive model and the present study (top). Percentage breakdown of the data points shown in the table (bottom).

Although Fig. 12 suggests that the proposed residential adaptive model is valid in predicting comfort of home occupants, more research work is necessary to strengthen the predictability and the applicability of the model. While the ASHRAE 55's adaptive comfort standard was based on the data from different locations covering a broad spectrum of climate zones (de Dear, 1998), the sample used in the current study came exclusively from temperate climate regions. As a result, the comfort zone when a prevailing mean outdoor temperature falls beyond the range of 8 ~ 27 °C couldn't be defined (Fig. 11). Data collected from more extreme climate regions is required to strengthen the predictability of the proposed model and to widen its boundaries.

4 Conclusions

This paper presented results from an extensive field study on thermal comfort and adaptive behaviours carried out in Australian homes. The participating householders' thermal sensations and adaptive strategies collected through a smartphone comfort questionnaire were compared with the corresponding indoor and outdoor climatic data. The statistical analysis performed on the entire samples provided sufficient empirical evidences to enquire ‘classic’ research questions in thermal comfort research including neutrality, sensitivity, acceptability, adaptive behaviours and comfort zone. An outdoor temperature of 25°C was found to be the most favourable condition in terms of maximising the use of operable windows/doors and minimising occupant reliance on mechanical air-conditioning (Fig. 6). Both linear and probit models fitted between thermal sensation votes and temperature variations (Fig. 7 and Fig. 9) estimated that the neutrality of home occupants fell about 2~3K cooler than the ASHRAE 55 adaptive comfort standard’s prediction. Occupants in homes were more tolerant particularly in cooler temperature conditions than expected by the comfort standards. Despite the cooler-than-expected neutrality, occupants of residential buildings showed a greater degree of thermal adaptability compared to that expected for office occupants, taking 6.3K of temperature change to shift one unit on the 7-point thermal sensation scale (Equation 5). According to our predictive model (Fig. 9), the span of indoor temperatures for 80% acceptability came to 9K, which is 2K wider than the width of the ASHRAE 55 adaptive model’s 80% acceptability. Based on our findings, an adaptive model for residential building was proposed to estimate comfort temperatures in relation to outdoor temperature variations (Equation 6 and Fig. 11).

Acknowledgements

This research was supported under Australian Research Council’s Discovery Projects (project number DP11010559). The authors thank Sustainable Buildings Research Centre at University of Wollongong, Dr Max Deuble, Tatiana Schukkert, Paola Cerda, Greg Zheng, Marina Rodrigues, and all households participated in this study.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
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A field study on occupants' ventilation behaviour through balcony doors in university students' apartments during transitional seasons in Beijing

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Abstract

Occupant behaviour has an important role in both the environmental performance and energy performance of buildings, which has been thoroughly demonstrated in the past several decades. Based on a review work, some research gaps have been identified in the area of occupants' ventilation behaviour and to answer those gaps a field study was carried out in a student dormitory building in Beijing, China, over the period of one transitional season in 2015. The study monitored students' ventilation behaviour dynamically with concurrent measurement of relevant influential factors that have been identified in existing studies carried out in conventional buildings.

The analysis carried out in the study aimed to demonstrate the influence of those previously-identified factors in the case study building. The factors examined in the study included outdoor air temperature, indoor air temperature, occupant presence, and certain aspects relating to personal preferences. From the analysis, it was found that all these factors can influence students' ventilation behaviour in dormitories. However, the influence of occupant presence seems to be different from the findings in conventional buildings which focused mainly on the use of external windows, and not balcony doors, which are included in this study.

Keywords: Environmental Performance, Residential buildings, Ventilation behaviour, China.

1 Introduction

In the past several decades, occupants' adaptive behaviour, for example, opening/closing windows and adjusting thermostatic settings(Brager and de Dear 1998) has been critically demonstrated to have significant impact on the energy performance of buildings, using both real measured data (Haas, Auer et al. 1998, Steemers and Yun 2009, Gill, Tierney et al. 2010) and building performance simulation (de Meester, Marique et al. 2013, Fabi, Andersen et al. 2013, Wei 2014). Additionally, providing occupants with more adaptive opportunities may also help them respond better to their local thermal environment (de Dear and Brager 2002, Luo, Cao et al. 2014), hence reduce building energy demands. When performing energy retrofitting for existing buildings, a good understanding of occupant behaviour and its influence on the retrofitting measures is also essential for selecting the most suitable measure(s) (Ben and Steemers 2014, Wei, Hassan et al. 2016).

Occupant behaviour is complicated. It is influenced by a number of factors (Fabi, Andersen et al. 2012, O'Brien and Gunay 2014, Wei, Jones et al. 2014) and may also performs in various modes, i.e. time-related, environment-related and random (Peng, Yan et al. 2012). In dynamic building performance simulation, occupant behaviour has been acknowledged as one of the most important factors that cause the performance gap: that is, the difference between the simulated performance of buildings and the actually measured one (de Wilde 2014). In order to achieve energy efficient buildings, the so-called 'golden rule' for occupant behaviour is '*If you don't need it, don't use it*' (Masoso and Grobler 2010). Thus, many studies have been carried out with an aim of making occupants use their building more energy-efficiently (Staats, van Leeuwen et al. 2000, Abrahamse, Steg et al. 2005, Jian, Li et al. 2015, Wei, Goodhew et al. 2015).

Ventilation behaviour, usually referring to window opening behaviour, has a key influence on the buildings' indoor thermal environment (Yun, Tuohy et al. 2009, Porritt, Cropper et al. 2012), the air quality (Offermann 2009, Bekö, Lund et al. 2010) and energy consumption (Wei, Wang et al. 2014, Wang and Greenberg 2015). In order to obtain a good understanding of occupants' ventilation behaviour in buildings, field studies have been carried out in both domestic and commercial buildings, and Wei (2014) and Fabi et al. (2012) have both carried out a thorough review of related studies and collected influential factors of ventilation behaviour that have been identified in existing studies. Combining the results introduced in these two publications, a number of factors have been listed in Table 1. Additionally, Wei et al. (2013) have pointed out the influence of 'personal preference' on the various behavioural patterns among occupants and have demonstrated its importance for achieving a more accurate modelling of occupant ventilation behaviour (Wei, Buswell et al. 2014).

Table 1: Influential factors of ventilation behaviour in buildings

Building level factors	Sub-group level factors	Personal level factors
Outdoor climate (dominated by outdoor air temperature) Indoor climate (dominated by indoor air temperature) Season Time of day Previous window state Presence	Window type Window orientation Floor level Shared offices/rooms Building type Room type Heating system type Occupant age Occupant gender Property ownership Smoking	Personal preference

The above classification method has been introduced in detail in a PhD thesis by one of the author's (Wei 2014).

Based on a review of more than 30 relevant studies, the following research gaps have been identified:

1. Existing studies focused mainly on conventional residential buildings (i.e. houses and apartments) and student dormitories were usually ignored. However, student dormitories often have a much higher energy demand than conventional residential buildings as in most case the energy bills are included in the rent. Therefore, a good understanding of students' energy behaviour is also essential. Schweiker et al. (2011) have made some initial exploration on students ventilation behaviour in dormitories in Japan, but their study did not considered the second research gap;
2. Many apartment/dormitory buildings have balconies for the rooms and occupants' ventilation behaviour for this special condition (i.e. the ventilation of the living space is dependent on the state of both external windows and the balcony door) has not been investigated;
3. Most studies in this area were carried out in European countries, such as the UK, Denmark and Germany, and high resolution data on occupants' ventilation behaviour in China are still needed.

To answer the above gaps, this paper introduces a case study carried out in a student dormitory in Beijing, China, during a transitional season in 2015, when no mechanical cooling and heating are available. In the study, students' ventilation behaviour (mainly their use of the balcony door in each room) was monitored dynamically, with concurrent measurement of the relevant influential factors listed in Table 1. This study provided evidence about the similarity of ventilation behaviour in student dormitories with balconies and conventional buildings, with respect to factors influencing their ventilation behaviour.

2 Research Method

2.1 Case study building

The case study building is located in the southeast of Beijing, China, with a climatic condition of hot & wet summer and cold & dry winter. It is a dormitory building of a university. The building has 17 floors, with a total number of students around 1200 (see Figure 1, left). Six dormitories were selected for the study. A small number of samples is a weakness of many field studies with respect to occupant behaviour in buildings, mainly because of the cost intensive nature of using electronic devices to achieve dynamic monitoring (as described following). To tackle this issue, the researchers in the current study tried to diminish the uncertainties caused by some factors through a careful selection of monitored rooms: all selected dormitories (Figure 1 right: 3m X 6m) were all occupied by male students, located on the 10th floor (with no shading effect from their surroundings) and on the east facade of the building. Therefore, the influence of occupant gender, floor level and window orientation can be ignored in the analysis. Each room may be occupied by a maximum number of four students, all between 18-23 years, and this selection eliminated the influence of occupant age.

Figure 1: The case study building (left) and a monitored dormitory (right)

Each room has a balcony with some external windows and the balcony is linked to the living space through a sliding door, as shown in Figure 1 (right). During the transitional seasons in Beijing (i.e. from the middle of March to the end of April and from the beginning of October to the middle of November) (Wei, Xu et al. 2015), all windows would typically be always left open in order to increase the ventilation of the building. Therefore, additional ventilation for the indoor thermal environment was mainly dependent on the opening of the balcony door. Because of this, the later analysis will be mainly based on occupants' behaviour with respect to the use of the balcony door.

(a) Indoor air temperature

(b) Occupancy

(c) Window state

(d) Outdoor air temperature

Figure 2. Monitoring devices

2.2 Data collection

The case study was carried out during the first transitional season in 2015, which was between 16th March and the 30th April. During this period, no mechanical cooling and heating was available and the whole building was naturally ventilated through opening the balcony door and external windows. Figure 2 shows some electronic devices that were used in the study to capture indoor air temperature (Figure 2a: Accuracy: ±0.35°C; Monitoring interval: 10min), room occupancy (Figure 2b: Detection range: 5m; Monitoring interval: 1min), window state (Figure 2c: Monitoring interval: 0.5s) and outdoor air temperature (Figure 2d: Accuracy: ±0.5°C; Monitoring interval: 10min). All indoor measurement devices were placed on a book shelf situated away from local heat gains (such as human bodies and computers) and solar gains. The exception was the window state sensor which was placed on the frame of the balcony door. The outdoor air temperature sensor was placed within the main campus of the university, which was about 800m away from the case study site. Before the tests, all indoor temperature sensors were calibrated against a Testo 650 thermometer.

3 Data analysis

Using the field data collected in this study, the influence of outdoor air temperature, indoor air temperature, the time of day, occupant presence and personal preference on the state of the balcony door was analysed using a systematic approach used by Wei et al. (2013).

3.1 Influence from outdoor air temperature

The influence of outdoor air temperature on the state of dormitory balcony doors is presented by the correlation between the proportion of opening time and the 'binned' outdoor air temperature (the following proportions were calculated based on data within each 3°C range). Figure 3 shows the results based on data collected during the occupied time. It reflects that the opening of balcony doors was generally proportional to the outdoor air temperature, i.e. with the increase of outdoor air temperature, the opening of doors increased.

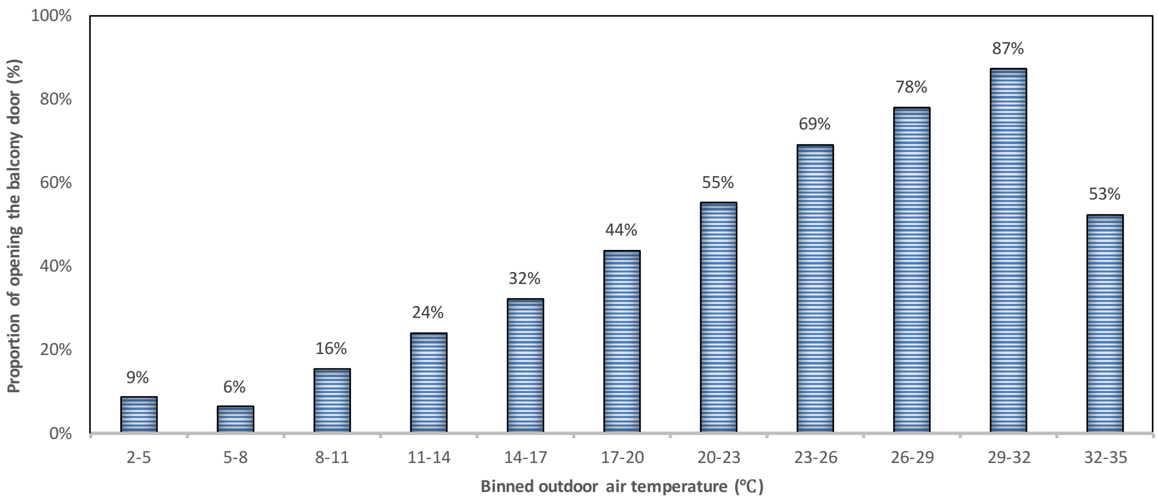

Figure 3: Relationship between the proportion of opening balcony doors and outdoor air temperature

This phenomenon has been identified in existing studies (Herkel, Knapp et al. 2008, Haldi and Robinson 2009, Zhang and Barrett 2012, Wei, Buswell et al. 2013). There was, however, a significant drop when outdoor air temperature exceeded 32°C. This may be caused by two reasons. Firstly, occupants prefer to shut off the ventilation at high outdoor temperature conditions in order to stop hot air outdoors coming into the living space; and this has been observed by other researchers (Haldi and Robinson 2008). Secondly, this analysis method was based on the proportion so the number of samples used in each bin may also influence the results (Haldi and Robinson 2009, Wei, Buswell et al. 2013). Therefore, more data are required in future studies to examine the validity of the first reason. However, for other temperature bins, a clear proportional relationship has been observed from this study.

3.2 Influence from indoor air temperature

Figure 4 shows the relationship between the proportion of opening balcony doors and indoor air temperature, also based on data collected during occupied time. Due to the smaller changing range of indoor air temperature, 2°C was used to bin the data. From Figure 4, a general proportional relationship between the proportion of door opening and the indoor air temperature can be observed, although not as good as for outdoor air temperature.

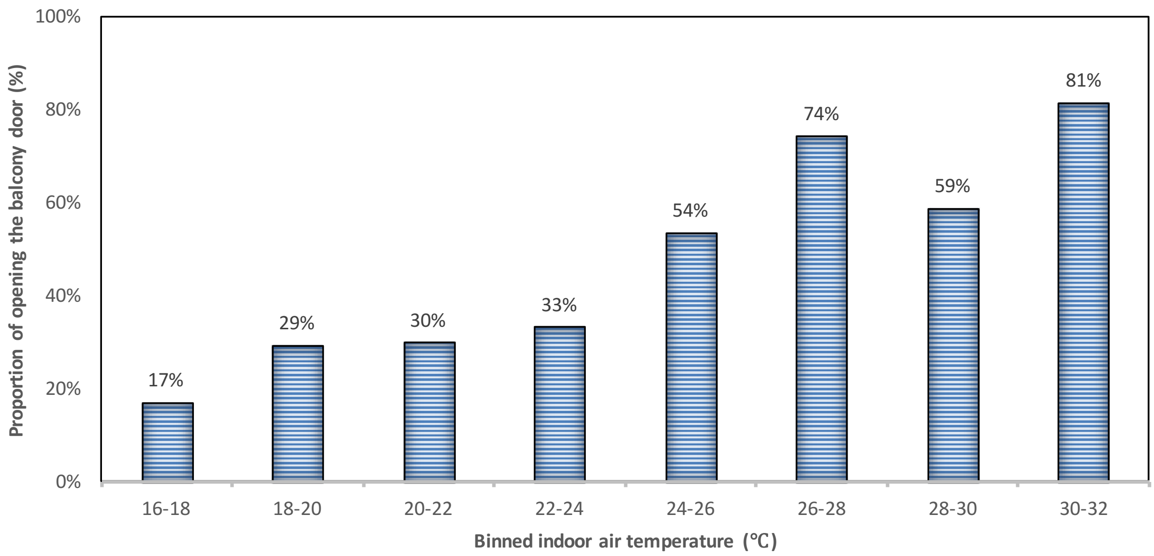

Figure 4: Relationship between the proportion of opening balcony doors and indoor air temperature

3.3 Influence from occupant presence

Figure 5 reflects that occupants' door opening/closing actions mostly happened during the occupied period (78%), rather than entering (15%) or leaving the room (6%). This finding is not consistent with what has been observed in office buildings (Herkel, Knapp et al. 2008, Haldi and Robinson 2009, Pan, Xu et al. 2015), where more ventilation-related actions happened when arriving at the office or leaving it. This may be because the various situations between office buildings and residential buildings. For example, in residential buildings, occupants generally have more adaptive opportunities to adjust the indoor thermal environment and their thermal sensation than in office buildings. Another reason may because doors have one more function than windows which is linking the balcony and the living space. Therefore, occupants may need to use them to enter the balcony or come back to the room, which may also trigger the change of the door state. Further studies are still needed to confirm this finding.

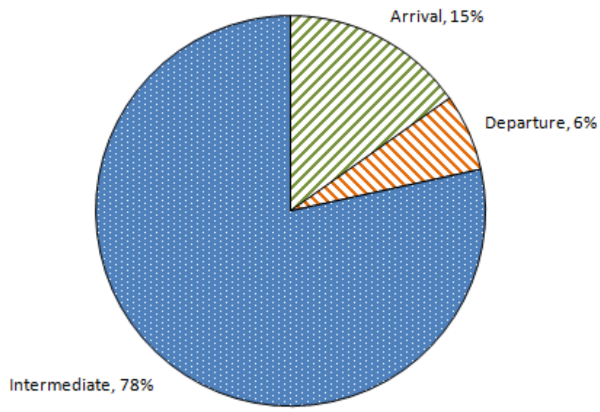

Figure 5: Relationship between the occupant presence and the percentage of open-balcony-door actions

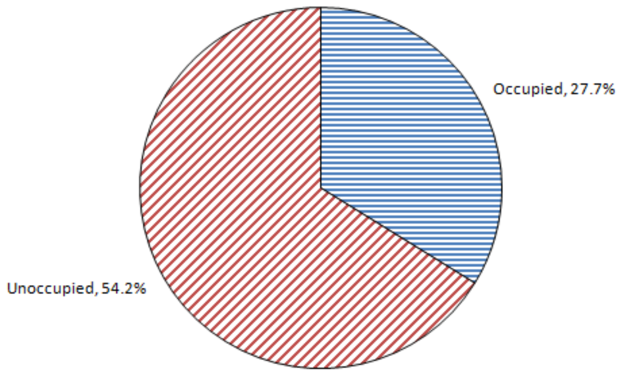

Figure 6: Relationship between the occupant presence and the percentage of opening the balcony door

Figure 5 illustrates occupants' ventilation actions, i.e. opening/closing the balcony door. Figure 6 compares the proportion of keeping balcony doors open for occupied time and unoccupied time, so it is based on the state of the balcony door. The data used here do not include those taken when subjects arrived or left the room. The comparison reflects the fact that students preferred to leave the balcony door open when not in the room and close them when staying in the room. This also contradicts what has been suggested for window use in office buildings. This may be because the monitored rooms are located on the 10th floor so security issues can be ignored. Further studies are still needed to further demonstrate this conclusion.

3.4 Influence from personal preference

Many studies have suggested that occupants' ventilation behaviour differs significantly between individuals; some used windows actively whereas other used passively (McCartney and Fergus Nicol 2002, Haldi and Robinson 2009, Yun, Tuohy et al. 2009). Wei et al. (2013) have defined this as 'personal preference'. To investigate the influence of this factor on the observed dormitories, each room's door-use pattern during occupied time was drawn and compared in Figure 7, based on outdoor air temperature (this parameter performed better than indoor air temperature in the previous analysis). The comparison reflects that occupants in various rooms used the balcony differently but with a similar correlation to the outdoor air temperature.

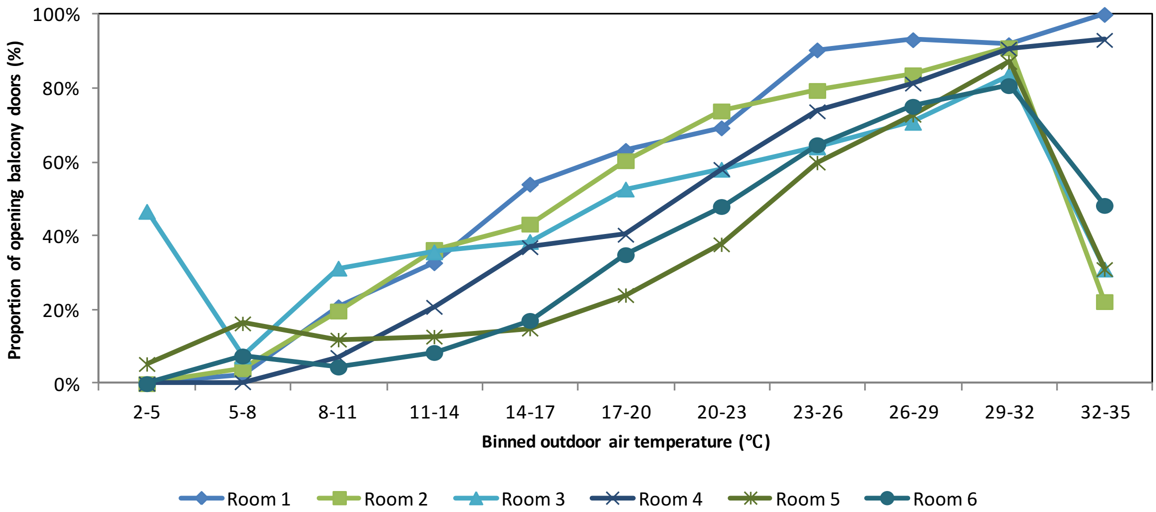

Figure 7: Influence of personal preference on occupants' opening of the balcony door with respect to outdoor air temperature

4 Conclusions

Occupant behaviour has a significant influence on both the environmental performance and energy performance of buildings, especially their ventilation behaviour. This paper used field data collected from a student dormitory building in Beijing, China, and analysed the influence of previously acknowledged factors on the use of ventilation in six monitored dormitories, mainly focused on students' use of balcony doors. These factors include outdoor air temperature, indoor air temperature, occupant presence and personal preference. The results reflect that all these factors can significantly influence students' ventilation behaviour in Beijing, China and can be used to further analyse when those students use natural ventilation, i.e. through statistical modelling of occupant ventilation behaviour (Herkel, Knapp et al. 2008, Yun and Steemers 2008, Haldi and Robinson 2009, Yun and Steemers 2010, Andersen, Fabi et al. 2013). Additionally, an inconsistent finding was found for the influence from occupant presence between student dormitories and conventional buildings, as more ventilation behaviour happened when occupants are using the room, not when they arriving at or leaving the room. Additionally, students preferred to use more natural ventilation when they were not in the room which also contradicts the findings from conventional buildings. This may be because the difference between the use of windows and balcony doors, and further studies are still needed to confirm this conclusion.

Due to the small number of samples, the monitored rooms were carefully selected so the influence of other factors (shown in Table 1) cannot be examined in this study. Future studies also need to expand the samples and test the influence of the remaining factors.

Acknowledgement

The work reported in this paper is funded by the National Science Foundation of China (NSFC), no. 51578011 and the Engineering and Physics Sciences Research Council (EPSRC, UK) under the 'Transforming Energy Demand in Building through Digital Innovation' (TEDDI) eViz project (grant reference EP/K002465/1).

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Barriers and opportunities in the design and delivery of social housing *Passivhaus* for adaptive comfort

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Abstract

This research resides *Passivhaus* concept under the framework of adaptive comfort, reviews two case studies of social housing *Passivhaus* communities in Scotland, and explores the occupants' lived experience and their perception of comfort in *Passivhaus*. The study focuses on the concept of comfort from a socio-technical point of view in order to explore more effective adaptive opportunities that can be integrated at the design stage. Through in-depth interviews with the occupants, site visits and architectural analysis, the research highlights comfort issues in those two social housing *Passivhaus* projects, and identifies barriers and opportunities for behavioural and psychological adaptations specifically for designing social housing *Passivhaus*. The findings suggest that the *Passivhaus* concept has potential opportunities for promoting behavioral and psychological adaptations and sustainable living. However, in order to ensure the energy performance, the design and delivery of *Passivhaus* system in some cases tends to limit the role of occupants and their adaptive opportunities. The research argues that through careful consideration of architectural and mechanical design, and through effective communication of technology and supportive role of community to establish sustainable social norms, the social housing *Passivhaus* can provide the opportunity for the occupants to 'co-evolve' with the house itself, and to achieve a transformation to sustainable living.

Keywords: *Passivhaus* design, adaptive comfort, behavioural and psychological adaptations, social housing, sustainable living

1 Introduction

Passivhaus concept was established in 1990s and has been gradually developed into a rigorous building quality standard over the past twenty years. Regarded as a design methodology that provides comfort with energy efficiency, the standard is widely adopted in Germany and Scandinavian countries. The number of Projects built to *Passivhaus* standard in the UK has also grown rapidly in the past decade. The *Passivhaus* concept sets out performance goals that require the buildings to be designed with a 'fabric first' approach and a hybrid service system, where mechanical ventilation and heat recovery system (MVHR) is often complimented by natural ventilation (Mead et al, 2010). As noted by Nicol (2011), in hybrid buildings, the adaptiveness of indoor comfort depends on the control of hybrid systems. Post occupancy research conducted by Stevenson (2013) suggested that as a new type of hybrid building, *Passivhaus* has employed resilient building envelopes and advanced control systems, which has subsequently raised challenges and barriers for the occupants to adaptive comfort, and maintenance of an established way of living. On the other hand, the *Passivhaus* concept as an environmental statement also embodies the potential to support more sustainable behavioural and psychological adaptations. Distinct from the definition of

Passivhaus concept, the realized *Passivhaus* buildings represent a diverse range of architectural characteristics, and vary in terms of site, construction method and material quality. Since the concept of *Passivhaus* only sets out the performance standard without providing detailed design regulation, the flexibility in approaching the concept enables each project to have its own take in terms of architectural properties such as size, structure system, insulation type, material, orientation, layout, interior fittings, and additional technical devices such as PV panels, wood burner, thermal tank, etc. Construction quality, also varies from project to project. Hence the adaptive opportunities provided by such systems vary between each individual project. Therefore to understand *Passivhaus* concept and design in relation to adaptive comfort, and to study *Passivhaus* buildings on a case by case basis is crucial.

Meanwhile, although much attention has been given to thermal comfort in *Passivhaus* research, other aspects of comfort in relation to the built environment are less explored. This paper argues that the social side of comfort, such as personalized space, ease of housework, etc. is as important for the occupants as physical comfort, especially for social tenants of *Passivhaus*. Those aspects of comfort can affect the occupants' overall comfort evaluation and adaptations, and can also be affected by the adaptive opportunities provided by the built environment. The research presents two case studies of social housing *Passivhaus* projects in Scotland, draws qualitative evidences from occupants interview and architectural analysis, examines the barriers and opportunities for adaptive comfort in the built environment built with *Passivhaus* methodology, in order to improve ways to design *Passivhaus* buildings which use adaptive behaviour to achieve comfort, energy efficiency and sustainable living at the same time.

2 Research context

2.1 Comfort paradigm and adaptation process

The past two decades in the field of thermal comfort research witnesses a paradigm shift from Fanger's seminal (1970) Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD) to the adaptive comfort model developed by Humphrey and Nicol (1998). This change has been accompanied and supported by research from sociology and socio-technical study that puts human behaviour at the centre of the attention in thermal comfort, suggesting that users of built environments are active participants rather than passive recipients of comfort, and that comfort is an 'achievement' that needs to be practiced, rather than an 'attribute' (Shove, 2003). The adaptive comfort model recognizes the deviations of what is regarded as 'comfortable indoor environment' in terms of geographical, cultural, socio-economic differences, and emphasizes the relation between inhabitants' comfort temperature and outdoor temperature (Nicol, 2011). It has also been suggested that the indoor comfort can be achieved by three adaptive processes which building occupants undergo in order to 'improve the 'fit' of the indoor climate to their personal or collective requirements' (de Dear et al, 1998). The three adaptive processes are Behavioural adaptation, Physiological adaptation, and Psychological adaptation, among which behavioural and psychological adaptation are the most influential factors for actively acquiring comfort (de Dear et al, 1998).

Behavioural adaptation includes: a) personal adjustment (adjusting clothing, drinking hot beverages); b) technological/environmental adjustment (controlling windows and mechanical equipment); and c) cultural adjustment (changing dress code, rescheduling activities). Psychological adaptation entails the shift of one's expectations regarding indoor climate, which relates more to habituation and experience (de Dear et al, 1998). The evidences of adaptation strategies can be found in a rich selection of literature in thermal comfort research in general, and research on *Passivhaus* in particular. Paciuk (1990) has identified the correlation between 'perceived control', which measures the expectation and perception of control opportunity and comfort satisfaction. Rijal et al (2015) surveyed 120 homes for thermal comfort votes where behavioural adaptation such as the opening of windows and fan use were reported by the occupants to improve thermal comfort. Mlecnik (2013) published a report on *Passivhaus* occupants' satisfaction of comfort which revealed several issues with construction and service/control that have been proven to be common comfort failures in *Passivhaus* construction. Mlecnik's report also showed occupants' adaptation of original settings as response to the problems. Rohdin (2014) also gave a detailed evaluation of how everyday lives were changed by living in *Passivhaus*. For instance, due to large windows on the south side of *Passivhaus*es, behaviour change occurred where occupant either staying away from the windows or used curtains; ventilation habits changed from manually operating windows to using programmable controls (Brunsgaard et al., 2012).

Besides thermal comfort research, Rybczynski (1987) has suggested that from a socio-historical point of view that comfort is highly dependent on social, cultural and historical context. This point of view argued that 'home comfort' is not a static and quantitative figure determined solely by temperature and humidity. The values of the different aspects of comfort appear to differ between individual households, although, also derived and constructed in a collective socio-historical, socio-technical framework (Rybczynski, 1987; Zhao, 2015). Rybczynski (1987) has further painted a picture of how comfort relates to the user of the space. This explains why different appearance and arrangement of rooms (in terms of layout, style, furnishing, services, etc.) made sense during different periods of history, as they contrived 'a setting for a particular type of behaviour'. Another example has been suggested by Canter (1977) that the open fire and hearth have always remained as a focal point in British domestic spaces, and the arrangement of other furniture and activities have been designed around it.

2.2 Delivery of social housing *Passivhaus* system

As noted in an English housing survey (2013), social housing makes up to 17% of all UK homes, and over 10% of the households suffered from fuel poverty. It is particularly relevant to examine social housing that built to *Passivhaus* standard if we wish to improve the energy efficiency and environmental benefits. The first social housing *Passivhaus* in Scotland was completed in 2010. The post occupancy report showed that the appreciation from the occupants regarding the low energy bill and warm indoor environment in the winter, and confirmed the feasibility and benefits of adopting *Passivhaus* system in the social housing sector. More recent research into social housing *Passivhaus* revealed a concern regarding overheating. With the escalation of global warming and the increase of extreme weather such as heatwaves in the near future (Murphy et al, 2010), more and more overheating problems have been noted either by *Passivhaus* occupants or by monitored data in *Passivhaus* research (Masoud et al, 2015; Mlecnik et al, 2012; Ridley et al, 2013).

Social housing *Passivhaus* is especially difficult to design due to the unpredictability of the future tenants. Research conducted by Brown et al. (2015) recommended that designers employ resilient design strategies that allow for varied preferences (e.g., for passive ventilation) to be exercised by inhabitants without undermining suite- or building-level performance. Chui et al (2014) demonstrated the importance of adaptability of social housing by 10 case studies of retrofit project in the UK, and proposed that the relationship between buildings and people can be designed as ‘mutually constitutive’ and ‘co-evolving’ through a process of ‘interactive adaptation’. Likewise, the social housing *Passivhaus* should fully integrate the adaptive opportunities in post occupancy early on in design stage in order to achieve a state of ‘co-evolvement’.

3 Methodology

The variation of the actual delivery of each *Passivhaus* project, as stated before, formed the rationale to study each project on a case by case basis. The case study in this paper includes two sets of data: a) semi-structured interviews, and b) drawings and images of architectural properties and mechanical services. It has been proven to be beneficial to analyse and cross-reference the two sets of data in order to discover comfort and comfort practice in relation to the built environment, and to determine if the design serves as a supportive role for adaptive comfort and provides adaptive opportunities. The analysis of the interview data adopts an inductive process, the open-ended questions are directed by the conversation between the interviewer and the participant, thus the questions asked vary between each household. The questions are organized under three sections. The first section examines the tenants’ perception of home comfort, the second section asks about their knowledge and opinions on technology of the house, and the last section explores their lifestyle and behaviour change.

As noted by Goins (2011), textual data often requires a ‘reframing of top-down perspectives’, for the researcher’s assumptions in designing the interview ‘may not be shared by the survey respondent’ (Goins et al, 2011). The analysis of the interview used text search to pick out keywords of comfort, behavioural and psychological adaptation particularly in relation to architectural properties and mechanical systems in order to examine adaptive comfort from *Passivhaus* design perspective. The analysis focused particularly on discomfort and issues the occupants had when they moved into the new house and how these problems were solved/ adapted to through the lived experience. The architectural properties and mechanical service system are cross-referenced to the interview text to find out what features embedded in *Passivhaus* concept are potential barriers or opportunities for adaptive comfort, and how to successfully overcome the barriers and realize the potentials in designing and delivering the *Passivhaus* system.

4 Two case studies of social housing *Passivhaus* projects in Scotland

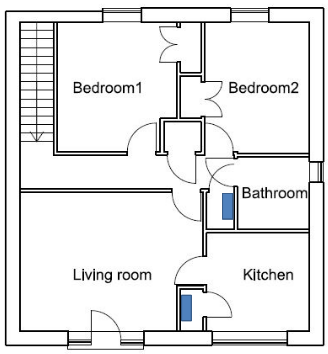
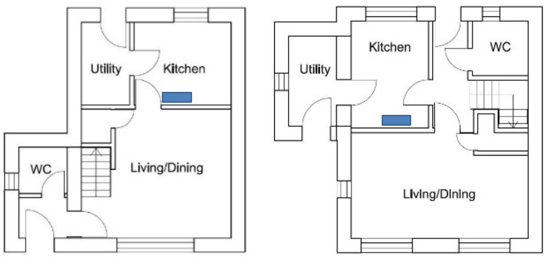
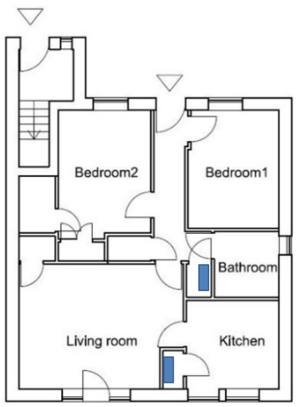
The two studied cases both belong to social housing sector, developed respectively by a private landlord (DO project) and a housing association (SL project). Case DO includes 8 semi-detached houses, four of the households participated in this research (two no. 2 bedroom and two no. 3 bedroom). SL project includes four flats in two semi-detached houses, of which two households took part in this research. The general information can be observed from the following table (Table 1). The two projects have many similarities in terms of floor area, bioclimatic region, construction, household size and service systems, the major difference being the length of occupation – residents in DO project have at least two years of lived experience whereas SL occupants only moved in for less than three months till the date of interview.

Table 1. General information on DO and SL case studies.

	DO project				SL project	
						
Household code	DO1	DO2	DO3	DO4	SL1	SL2
Bioclimatic region	Scotland East					
Construction type	Timber					
Floor area (sq.m)	103	103	88	88	74	80
Household size	3	5	2	2	2	2
Occupants age group	18-60	18-60	18-60	60+	60+	18-60
Occupation date	07/2011				07/2015	
Interview date	05/2014				10/2015	

The DO project is located in the south of Scotland. The two rows of 8 semi-detached timber frame houses are all directly south facing, with limited natural shading on the site. The SL project on the other hand, is facing south-west, and is heavily shaded on the south side of the building. The mechanical system of DO *Passivhaus* features Paul Novus mechanical ventilation and heat recovery (MVHR) unit to provide air circulation, the backup heating is provided by a post heater installed in the MVHR system and a wood burning stove in the living room. The wood burning stove also provides domestic hot water to the household whenever the solar thermal system falls short. All control panels are located in the kitchen or hallway with easy access. The SL project features a similar system, although it is less complex. The MVHR system is more integrated in that it has a built-in thermostat. The domestic hot water is heated by electricity generated from PV panels and stored in a thermal tank. The control panels are located inside cupboards with limited access. The architectural and mechanical properties can be observed in the following table (table 2):

Table 2. Architectural and mechanical properties of DO and SL case studies.

Ventilation strategy	Paul Novus MVHR, opening windows	Genvex MVHR, opening windows
Heating strategy	Post heater on MVHR, wood burner in living room	Post heater on MVHR, electric fire in living room
Water strategy	Solar thermal system and wood burner backed up by immersion heater	PV Panel backed up by immersion heater
Shading strategy	N/A	Natural shading
U Value	Wall: 0.1 W/m^{2}K, Roof: 0.1W/ m^{2}K, Floor: 0.1W/ m^{2}K,	Wall: 0.1 W/m^{2}K Roof: 0.1 W/m^{2}K Floor: 0.1 W/m^{2}K
User interface	 MVHR, thermostat and solar thermal control panel	 MVHR and thermal tank control panel
First floor plan (square indicates MVHR and thermostat control panel location)		
Ground floor plan (square indicates MVHR and thermostat control panel location)		

The demographic information of the interviewees also makes an interesting comparison. The tenants of DO project were initially selected through social housing sector and had no previous knowledge about *Passivhaus*, nor did they move in to the *Passivhaus* specifically for its energy performance feature. Although in the interview there are indications that tenants have increased their knowledge of *Passivhaus*, and showed active change of behaviour through an up to 9 months learning curve. On the other hand, the study on SL project reveals two very distinctive households in terms of their knowledge and confidence in *Passivhaus* system. SL1 occupants knew nothing about *Passivhaus* before moved in and still know nothing about it after three months of occupancy, whereas SL2 occupants, being professionals in home automation technology themselves, had very good knowledge about *Passivhaus* both before and after the occupancy. Yet none of the occupants felt confident in operating the *Passivhaus* or experienced noticeable behavioural or psychological adaptation. The following sections will demonstrate in detail the occupants' opinions on comfort and strategies in adaptations, and will explain their relations to the design of their *Passivhaus*.

4.1 Case DO – 'get into a routine of knowing'

4.1.1 Comfort and built environment

In the interview, all four occupants showed satisfaction when asked about the comfort value of their houses. The DO2 occupant mentioned that the biggest indication of comfort is the change of indoor clothing, specifically in the context of 'having friends' around, so the new house seems to provide a more 'sociable environment' for the tenant as a consequence of thermal comfort. In speaking specifically about thermal comfort, the occupants suggested the house is better at providing shelter from cold weather than at 'getting rid of the heat'. All occupants mentioned the house gets 'a bit too warm' in the summer, especially for DO1 occupant who suggested that mechanical ventilation alone was not sufficient for cooling.

> *DO1: It's comfortable, in the summer it can get warm, really warm, if you don't have your doors and windows open, you can use the ventilation system, MVHR unit, you use that, you know, to cool the house, the ventilation, I don't think that's enough[…]*

In terms of air quality, DO3 occupant suggested the air was a bit dry for her preference, she found it a downside to her health, and opened windows regularly for ventilation. Whereas DO2 occupant considered dry atmosphere as an upside for drying clothes efficiently. The comparison suggested social comfort of convenience outweighs air quality in some cases.

Because of the change in thermal environment and service system, the *Passivhaus* in this project has created issues that need to be adapted to by the occupants. The adaptations are the result of their learning curve, including adjustments to the interior, changes in the occupants' daily activities and habits, and unconscious shift of their concept of comfort and ideology of sustainability.

4.1.2 Behavioural and psychological adaptation

As noted in the previous section, for DO1 occupant, the house gets a bit overheated in the summer, although the thermal environment in winter was quite pleasant. By adjusting the flooring and blinds, the comfort has been tuned to a personal thermal sensation.

> *DO1: Yea, it's really warm [in summer]. My friend J lives across, she got big mats, she's older, she's got curtains, […] Cos I got blinds, everybody else's got curtains, I got blinds. I think it's a lot cooler and airier…*

More interestingly, with a higher indoor temperature and better thermal capacity, the traditional perception and use of a stove as a 'focal point' in the living room has changed. The 'focal point' has slightly shifted away from the stove.

> *DO1: Particularly I think the fire, so before I would put the fire on and it was a nice thing to sit around and I still trying to use the fire like that just to have a nice thing in the room, then I realized it's just completely pointless, cos you just sit there and take off all your clothes and open all the windows […]*

Learning to control the fire is the biggest adaptation for all tenants. Unlike a traditional stove which serves as a heating source, the wood burner in this project performs a different function, as 90% of its heat goes to boil the water. If the stove is to be lit the same way, the tank of water boils very quickly and the system automatically flushes in cold water to prevent overheating. Having tried to resolve the problem for several months in the first winter, the tenants learned then to burn the stove slowly and only light it if necessary. The manager of the estate also installed a simple lighting system by the stove to indicate if it is necessary to light the fire. The occupants showed active changes of behaviour, such as to controlling the stove to specific needs of hot water, and increased awareness of the weather. They have also showed a shift in expectations of indoor environment, and become more patient in waiting for the slow response of temperature change, and achieving internal gains through their lived experience.

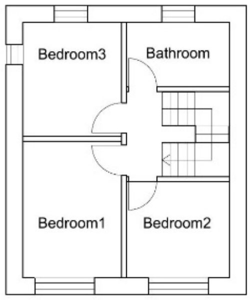
The encouragement given by the housing association has allowed for 'trial and error' to take place, and the technical support has helped the tenants to go through a learning curve. The energy use of each household has been monitored and made available to the tenants, from which the consequences of not using the *Passivhaus* system properly was added to the knowledge base of the community.

> *DO1:[…] the woman who lives down the road who just moved out, she never used the fire, and she never used the solar panels, think she used immersion for hot water, and bills must have been a lot higher, a lot higher.*

When examining those comfort issues and adaptation processes with architectural drawings and photos taken on site, connections can be made between the three. The problems and discomfort experienced by the occupants, the adaptations they made and related architectural and mechanical features of the project are summarized in the table below:

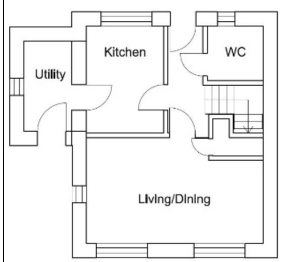
Table 3. Summary of comfort issues, adaptive process in relation to the built environment in DO project

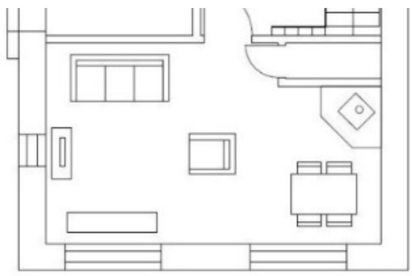
<table>
<tr><th>Discomfort /problems</th><th>Adaptive process</th><th>Built environment</th></tr>
<tr><td>Overheating (in summer)</td><td>1. Fitting in curtains/blinds on south-facing windows, and timber floor in living room (House DO1, 3, 4)

2. Open windows to cool the house (House DO2, 3, 4)</td><td>

The overheating issue is especially severe in upstairs bedroom2 where the glazing area is relatively large comparing with the room size.

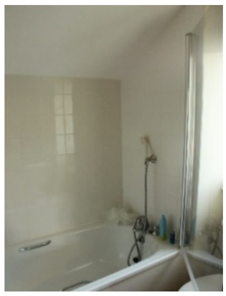
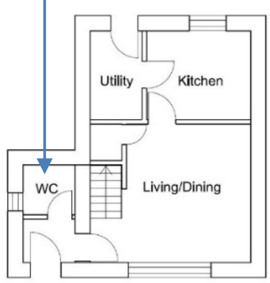
The tenants have liberty to arrange interior fittings, the windows are all openable for natural ventilation.</td></tr>
<tr><td>Overheating (from wood burner)</td><td>1. Shifting the focal point of living room away from the stove (House DO1, 2)

2. Burn the wood slowly to achieve mild and steady heat (House1, 2, 3, 4)</td><td>

The open plan living/dining space enabled the shift of focal point.
</td></tr>
<tr><td>Slow response when trying to increase internal temperature</td><td>1. Being patient to wait for the temperature to slowly go up (House DO1)

2. Cook, light up candles or do exercise to use internal gain to increase temperature (House DO1, 2, 4)

3. Thermostat control and thermometer are installed and</td><td>
The thermometer installed in every house is indicative.</td></tr>
</table>

	accessible to simplify temperature control and visualize actual temperature. (House DO1, 2, 3, 4)	 All control panels are with easy access
Operating wood burner to get DHW	1. Adapting to new ways of operating the wood burner (House DO1, 2, 3, 4) 2. Fitting in a lighting system as indicator to control the stove more efficiently (DO1, 2, 3, 4) 3. Developing the habit of checking the weather frequently (House DO1, 3, 4) 4. Very careful not to use immersion heater (House DO1, 2, 3, 4)	  Immersion heater switch has been tucked away behind shelves intentionally by DO4 occupant so not to use it often.
Shower head too low (reported only by DO4)	The occupant changed the downstairs WC into a shower room.	Flexible layout compensated the design problem and made it possible for the WC to be changed into a shower room.  

4.2 Case SL – 'if we understood this place better we'd be a lot happier'

4.2.1 Comfort and built environment

For both households in SL project, although they did find the flat can 'get a bit hot' during the night, the summer that just passed was quite pleasant, the general opinion on thermal environment is very positive. For SL2 occupants especially, the *Passivhaus* is a big step up in terms of thermal comfort. Other aspects of comfort were also mentioned in the conversation. Privacy is the most praised aspect of comfort. The SL project features a 'reversed plan', where the living room is tucked away from the main road, facing the south-side with a garden view and full bloom of trees, whereas the bedrooms are facing North onto the driveway and car park. From design point of view, it's well suited for *Passivhaus* where the most likely overheated room is naturally sheltered from summer sun, and the bedroom benefits from a slightly colder temperature overall. Although for SL1 occupant, they find the house 'darker' for this very reason, and shared scepticism about the reversed layout. On the other hand, this reversed plan together with the feature of triple glazed windows have been highly praised by SL2 occupants for the privacy the house enables.

> *SL2: This is very good actually, for privacy, if you see back there, trees and hens, you wouldn't need blinds here cuz nobody can see inside, I don't see the neighbours, […] the triple glazing is quite effective. Children next door downstairs, haven't heard a word,[…] I think it's excellent in that sense […]*

Other issues they have encountered in SL1 household includes difficulties to 'keep the house clean', as the doorway connecting living room to the garden doesn't have any steps to stop leaves and insects coming in.

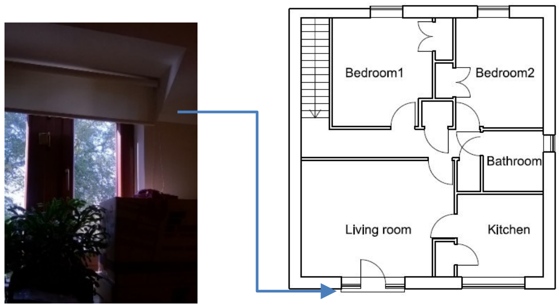
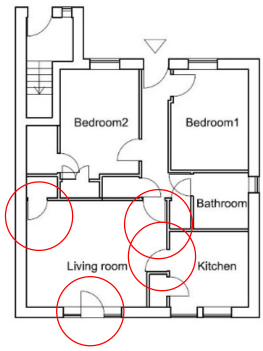
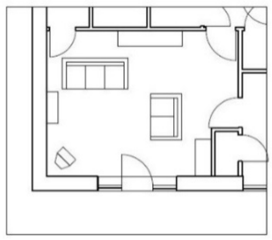
4.2.2 Behavioural and psychological adaptation

Since the SL project has only been completed and occupied in May 2015, the interview captured the first stage of *Passivhaus* living. The first observation was how different the two flats look. According to the occupants, very strict rules applied for alteration and fittings in order not to compromise *Passivhaus* performance. For example, special screws are required, each wall fittings need to be checked so not to penetrate the thermal envelope. As a result, SL2 occupants never had the chance to do any fittings.

Meanwhile, more severe and interesting problem was to do with the technology in their houses. Despite the demographic differences between the two households, they expressed similar opinions and experienced similar changes in their lives. These changes have mainly been adapting to a rural environment, their behaviour and habits in controlling the *Passivhaus* system have yet to be established as a 'routine of knowing'. For both households, the available information regarding the control of the house is far from adequate. There are many mysteries unsolved in controlling the service system. For instance, how to control the temperature, how to get hot water in the winter if the PV panel is covered by snow, what usage does the smart metre actually show, how the PV panel is connected, or what does 'the switch in the cupboard' do? Even though the system has been explored extensively by the SL2 occupants, there are still quite a few uncertainties. Regarding such issues, the conversation with the occupants revealed that the main problem is not what and how much information was given, but the way the information was communicated. A demonstration session was hosted with all tenants just before they first moved in, both occupants suggested they didn't 'take it in'. The tenants were also given a very big user manual afterwards. Both occupants mentioned this 'big booklet' that contains everything they need to know to operate the house, but none of them felt the information was effective. SL2 occupant suggested that the manual was translated directly from German with quite a bit of the instructions lost in translation. Besides communication issue, the interview also revealed that the users were restricted by the housing association from changing the controls on MVHR or thermotank. Once the system was set up and commissioned, the users were told not to change any setting, or to open windows to ventilate. On the other hand, it has also been suggested that the neighbours in this community share knowledge and help each other in adapting to the new environment, although community knowledge sharing was said to be ineffective, the ineffectiveness was due to a collective unknown and a lack of means for collective learning to take place.

Table 3. Summary of comfort issues, adaptive process in relation to the built environment in SL project

Discomfort /problems	Adaptive process	Built environment
Overheating and stuffy (in summer)	Open windows at night to cool the house (House SL1, 2)	The houses are heavily shaded on the south side, which prevents the rooms from overheating. The houses all have openable windows, although the occupants were not recommended to open windows.
SL1 living room too dark	No adaptation observed	Because of the shadings, the occupants felt the living room is very dark. 
Not able to control temperature (default setting not suitable for lifestyle)	Putting a cardigan on, or turn on electric fire when feel cold (House SL1)	The MVHR system in this case has a built-in thermostat in the control panel, but none of the residents knew or understood how to control it. The control panels are located in a dark cupboard that decreased its accessibility 
Not knowing the DHW and PV system	No adaptation observed, occupants are worried about hot water supply in winter when PV system is ineffective	
Not knowing how to use smart metre	No adaptation observed, occupants don't know their energy consumption	The smart metre has been installed in both households, SL1 occupants do not know what it means, SL2 

		occupants are not clear what it measures.
Having trouble to Personalize interior space	For SL2, no major furnishing has been done. The upstairs living room is partially under a tilted ceiling as a result of pitched roof, the door opens inwards, from which the juliete balcony can be accessed. For a lack of means to fit in curtains, blinds have been fitted instead.	
	SL1 occupants furnished the interior despite the housing association suggested otherwise, the living room has four doors opening towards the space which limited the furniture arrangement	 
Bath water not hot enough	Using electric shower instead (House SL1, 2)	
No height difference between living room and back yard, hard to clean (House SL1)	No adaptation observed	

5 Discussion: barriers and opportunities in *Passivhaus* design for adaptive comfort

In order to operate the *Passivhaus* to its design intention, adaptations are essential for the occupants. Comparing the two case studies, evidently, the novel technical system of *Passivhaus* has in both cases formed the biggest and most unavoidable barrier in the adaptation process. The temperature, humidity and ventilation control require a new set of knowledge and a certain period of learning process to adapt to. In this process, being able to gain effective information and sufficient support and maintenance from professionals is crucial for adaptation.

Meanwhile, the architectural and mechanical design of the *Passivhaus* also affect how comfort is experienced and achieved through daily lives. In both cases, overheating in summer has been reported as a comfort issue, and the occupants felt the need to open windows to cool the house. The *Passivhaus* standard sets out energy performance goals without specifying any design regulation. This flexibility has been appreciated in DO project where the occupants became an important part of *Passivhaus* system to make adaptations, and to help achieving energy performance, home comfort, as well as sustainable living. Whereas in SL project, the interaction between users and the buildings has been limited to a minimum to ensure a designed performance, as a result the experience of comfort and the opportunity to practise comfort has also been restricted. This has led to dissatisfaction and inactive adaptation. Being able to personalize interior space, to open windows when needed, to perform housework efficiently, and to fully control the indoor thermal environment are important for the occupants to practice comfort and perform active adaptation, in order to achieve an all-encompassing spectrum of comfort.

Furthermore, the potential benefit and opportunity for pro-environmental behaviour in the design of *Passivhaus* community needs to be addressed, particularly in social housing *Passivhaus* where the community plays an important part in promoting sustainable social norms and lifestyle. The DO project has demonstrated how the occupants and their community have evolved together with the *Passivhaus* as they learned to adapt to the house at the same time modified and improved the system. The design of social housing *Passivhaus* has the potential to encourage behavioural and psychological adaptation at a community level to achieve a better-than-best-performance *Passivhaus*-style sustainable living.

6 Conclusion

The *Passivhaus* concept as a quality standard has put a considerable amount of emphasis on energy performance. In order to reach the performance standard, the delivery of *Passivhaus* system adopts resilient design to minimize performance gap. However, the environmental value embodied in *Passivhaus* and other low energy house concepts should be further explored where occupants are the centre of the design for sustainable housing. The design and delivery of such sustainable housing need to focus on the flexibility and personalization of the built environment, and to ensure a good communication and support throughout post occupancy, as well as to establish a collective learning hub for the occupants to fully appreciate sustainable dwellings and its ideology. Rather than seeing occupants as negative factors that compromise the energy performance of *Passivhaus*, the occupant factor should be positively incorporated into design. Occupancy will do much to push the *Passivhaus* idea to a wider domain and realize its full potential for sustainable housing.

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The Extraction of Typical Occupant Behaviour Patterns for Building Performance Simulation

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Abstract

The interaction between the occupant and the building contributes to the building energy performance significantly. In building simulation, occupants are represented as several different patterns, which may lead to a large discrepancy of building energy consumption. The categorization of occupants in the sense of energy use may also provide references for energy policy makers, as well as the building designers. As a significant contributor to building energy, typical occupant behaviour patterns are required by the application associated with building performance simulation. This study explores the approach to conclude several occupant behaviour patterns by combining the detailed behaviour modelling with the large-scale questionnaire survey. The survey is used to get the drivers for energy-related behaviours. The diversity of drivers is input to the building energy simulation program to discriminate the energy consumption under different patterns. The typical behaviour patterns are finally concluded from the simulation, and the patterns are verified through the comparison between the large-scale questionnaire survey result and the simulated one.

Keywords: Occupant behaviour, Building simulation, Questionnaire survey, Typical behaviour

1 Introduction

Occupant behaviour draws much attention in building simulation as it is a non-negligible factor to building energy consumption. It influences energy use in multiple ways, such as occupancy-based casual gain, operations on appliances, set points of air-conditioning, etc. To present occupant behaviour in buildings in a quantitative way, various models have been developed. For example, Nicol and Humphreys (2004) studied the use of windows, lighting, heating, etc. with surveys to see how the use of each control varies with outdoor temperature. Andersen, Fabi et al. (2013) measured occupants' window opening behaviour, as well as indoor and outdoor environmental conditions, based on which a logit model is developed, describing the probability of an opening/closing event takes place. Ren, Yan et al. (2014) conducted surveys and continuous measurements of AC usage in residential buildings, and developed models with both environments triggered and event triggered to present the probability of an occupant to turn on or off the AC. These models are developed from intensive field surveys or measurements, and correlate behaviour with some extrinsic factors like temperature or daily events.

Current research in occupant behaviour focuses on the quantitative modelling, which still has a margin from industrial application of occupant behaviour in simulation, since they are limited to the cases from which they are developed. Occupants behave in various ways, so it may not be practical to describe each occupant using these models in building simulation scenario analysis, instead the diversity and representativeness of occupants are to be considered. Yu, Fung et al. (2011) applied the mathematical technique, cluster analysis, in attempt to classify occupants into several categories in terms of their behaviour. Similar studies fail to classify occupants from the perspective of energy use, which is our goal in developing occupant behaviour models.

It is meaningful to conclude several typical behaviour patterns in terms of energy consumption to be used in energy simulation and technology evaluation. This study tries to narrow the gap between modelling and application of occupant behaviour by classifying occupants' heating behaviour in the hot summer cold winter zone in China into several typical patterns, which could be used to analyse the energy differences among different patterns. As a validation to the result of the typical patterns, the distribution of building energy consumption in both the simulation and the survey are compared.

2 Approach

It should be noted that the purpose for us to conclude the air-conditioning behaviour patterns is to differentiate energy usage levels regarding to different behaviours. Starting with this, we use energy consumption as an index to tell apart behaviour patterns. The extraction of typical occupant behaviour requires a large amount of data, which could be obtained by the questionnaire survey which collects information of the driving factors for behaviour. The driving factors are represented in the occupant behaviour model as the independent variables, and the probability for occupants to take action as the dependent variable. The models are then input into the simulation program DeST (Designer's Simulation Tool), in which a novel occupant behaviour module has been developed, to simulate the energy consumption with each mode. The typical patterns are extracted from the simulated energy consumption by differentiating several levels. Furthermore, the typical patterns could be validated by comparing the distribution of energy consumption with the surveyed results.

Figure 1 shows the technical approach of this study.

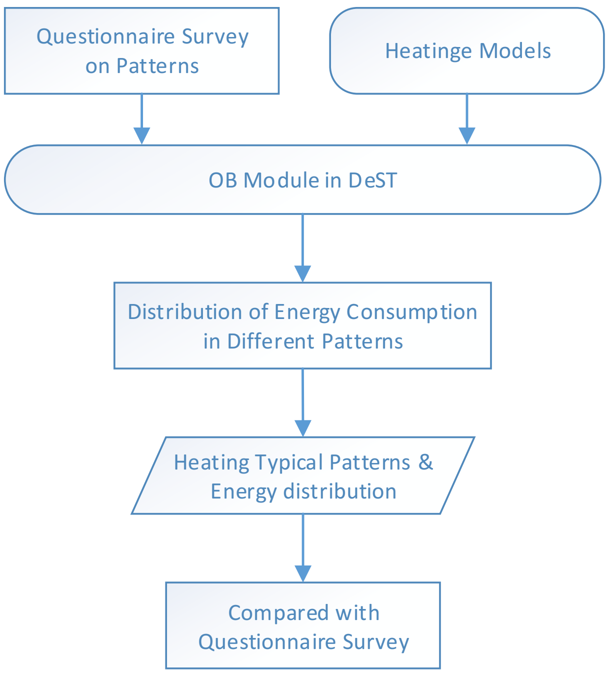

Figure 1. Technical approach of this study

2.1 Questionnaire survey

A questionnaire survey to learn occupants' heating behaviour was conducted in Shanghai, China in winter, 2015. The questionnaire contains demographic investigation such as number of residents, education level, and basic information of the building, as well as a list of options describing under what occasion they would open or close heating devices and windows in their living-rooms and bedrooms. Is should be noted that the centralized heating system is not available in Shanghai, therefore the heating system commonly used is the split air-conditioner.

Table 1 and Table 2 show the options for heating modes in the living-room and bedroom listed in the questionnaire, respectively.

Table 1. Options in the questionnaire for heating modes in the living-room

Opening Modes	Closing Modes
[a] Never on	[a] Never off
[b] Always on	[b] Always off
[c] On as long as entering the living-room	[c] Off when leaving the living-room
[d] On when feeling cold	[d] Off when leaving home
[e] On if there is a guest	[e] Off before sleeping
	[f] Off when feeling hot

Table 2. Options in the questionnaire for heating modes in the bedroom

Opening Modes	Closing Modes
[a] Never on	[a] Never off
[b] Always on	[b] Always off
[c] On as long as entering the living-room	[c] Off when leaving the bedroom
[d] On when feeling cold	[d] Off before sleeping
[e] On when sleeping	[e] Off when getting up
	[f] Off when feeling hot

Table 3 and Table 4 show the options for heating modes in the living-room and bedroom listed in the questionnaire, respectively.

Table 3. Options in the questionnaire for window modes in the living-room

Opening Modes	Closing Modes
[a] Never on	[a] Never off
[b] Always on	[b] Always off
[c] On as long as entering the living-room	[c] Off when leaving home
[d] On when getting up	[d] Off when sleeping
[e] On when leaving home	[e] Off when entering the living-room
[f] On when feeling stuffy	[f] Off when feeling cold
[g] On when warm outdoor	[g] Off when it is raining/windy/noisy
[h] On when feeling hot	

Table 4. Options in the questionnaire for window modes in the bedroom

Opening Modes	Closing Modes
[a] Never on	**[a] Never off**
[b] Always on	**[b] Always off**
[c] On as long as entering the bedroom	**[c] Off when leaving home**
[d] On when getting up	**[d] Off when sleeping**
[e] On when leaving home	**[e] Off when entering the bedroom**
[f] On when feeling stuffy	**[f] Off when feeling cold**
[g] On when warm outdoor	**[g] Off when it is raining/windy/noisy**
[h] On when feeling hot	

Multiple choices were allowed in our survey, e.g. occupants may choose "[c] On as long as entering the living-room" and "[d] On when feeling cold" at the same time. The total amount of the survey distributed in Shanghai is 1031, among which 814 respondents answered the question regarding the heating operation in the living-room, and 999 respondents answered the question regarding the heating operation in the bedroom. 852 respondents answered the question regarding the window operation in the living-room, and 988 answered the question regarding the window operation in the bedroom.

2.2 Heating behaviour model

The modelling of heating behaviour is presented in Wang (2014). Factors influencing occupants' turning on/off heating are divided into environmental triggered and event triggered. Whether the control of air-conditioning takes place is presented as a probability correlated with indoor temperature or daily events, varying with the patterns.

For example, the pattern "turn on when feeling cold" is described as

$$P_{on} = \begin{cases} 1 - e^{-\left(\frac{t-u}{l}\right)^k \Delta\tau}, \ t \geq u, \ when\ occupied \\ 0, \ t < u \end{cases}$$

Where t is the indoor temperature, u, l, k are constant parameters that could be decided by data fitting, and $\Delta\tau$ is the time step we use in simulation, typically 5 or 10 minutes. This model correlates each pattern with specific influencing factors, not only temperatures but also some daily events.

2.3 Occupant behaviour simulation module in DeST

Occupant behaviour models are implemented in DeST at present. The structure of the occupant behaviour simulation module is shown in Figure 2.

Models regarding occupancy, operations on lighting, air-conditioning/heating and windows are implemented. Building models are built in traditional DeST environment, with an additional dialog to input patterns and parameters describing occupants' movement and actions. Attributes of the building is stored in a database, from which the room layout is known. In the occupancy and lighting module, the output would be schedules representing specific occupants in rooms, lighting energy consumption, and casual gain of occupants and lighting. The calculation is not coupled with thermal simulation of the building, so they are simulated prior to thermal simulation, providing core program of DeST with a SQLite database storing the schedules of occupant number and lighting.

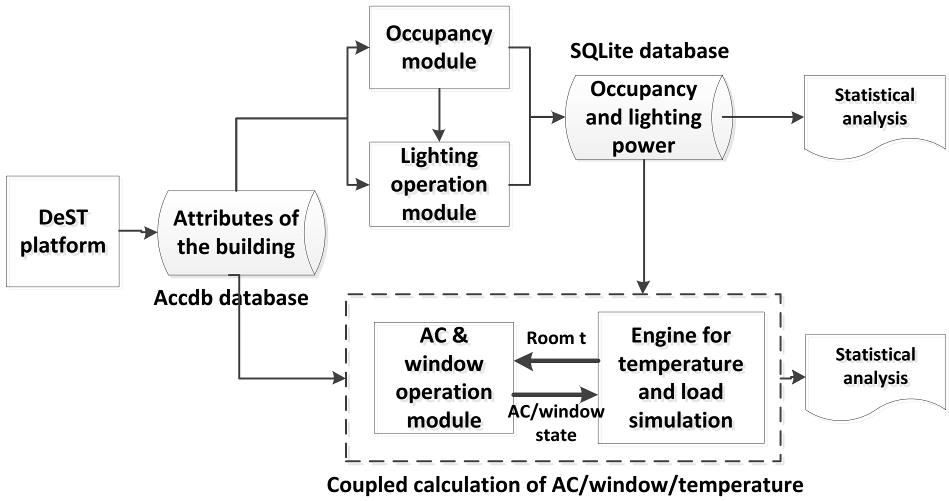

Figure 2. Occupant behaviour simulation module in DeST

Cooling/heating and window operation are more complicated than occupancy and lighting, as they are strongly coupled with thermal condition in rooms. They are discretized into 5 or 10 minutes as a time step. In each time step, the operations on cooling/heating and windows are dependent on their previous state, the previous environmental conditions and the events that have just taken place. This module outputs the current on/off states of cooling/heating and windows, which are used as inputs for calculation in the next time step. Finally, occupant behaviour module outputs the schedules of the states of devices and also the cooling/heating energy consumption.

2.4 Data

The data collected from the survey provides an overview on the heating behaviour patterns in Shanghai, China. Figure 3 and Figure 4 show the operation modes of the heating system in the living-room and bedroom. The variety of the heating operation could be seen.

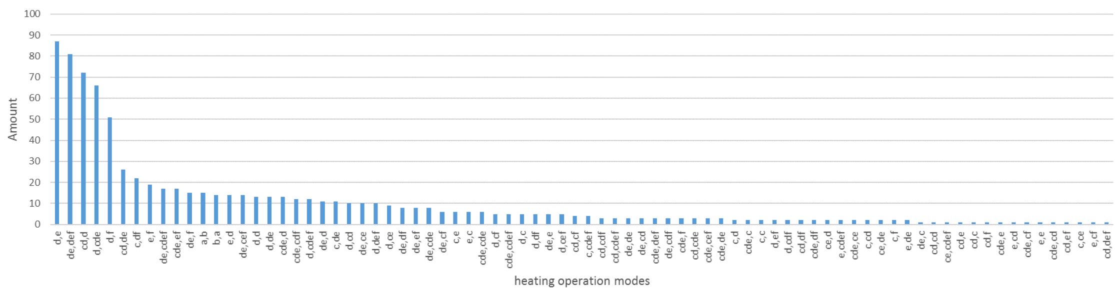

Figure 3. Amount of each heating operation modes in the living-room

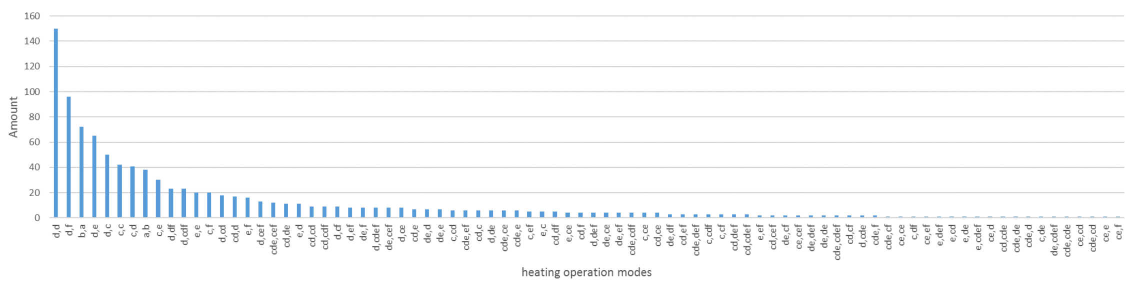

Figure 4. Amount of each heating operation modes in the bedroom

There are even more operation modes for the window operation than those for the heating operation modes. Figure 5 and Figure 6 illustrates the majority (consisting of approximately 60%) of the window operation modes in the survey (not all of them).

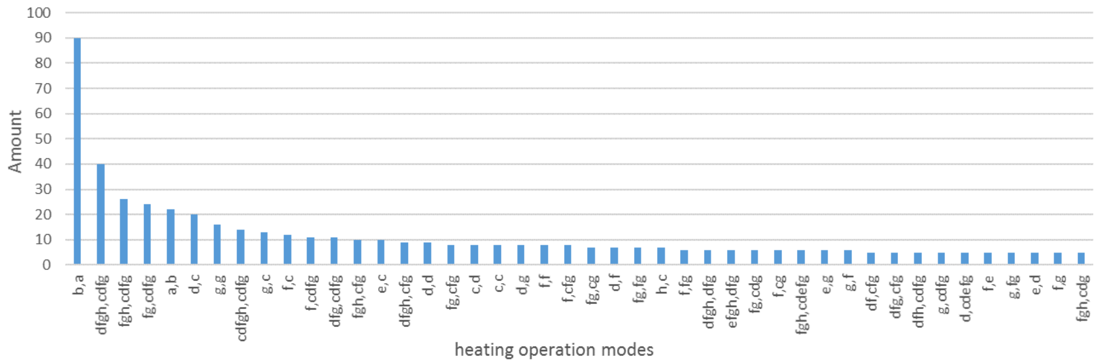

Figure 5. Amount of each window operation modes in the living-room (majority)

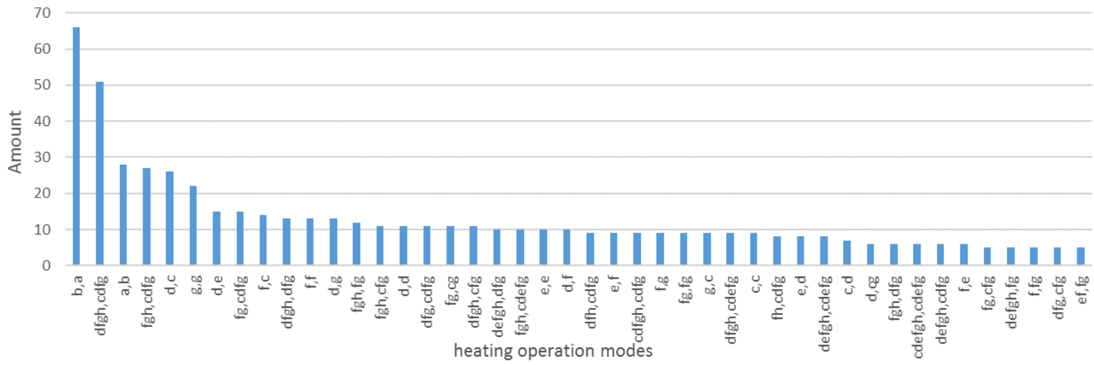

Figure 6. Amount of each window operation modes in the bedroom (majority)

2.5 Simulation

A simple 3-floor residential building model located in Shanghai, China is built in DeST. Figure 7 shows the layout of the 2nd floor, consisting of two households. Floor 1 and 3 are simplified to a large room respectively.

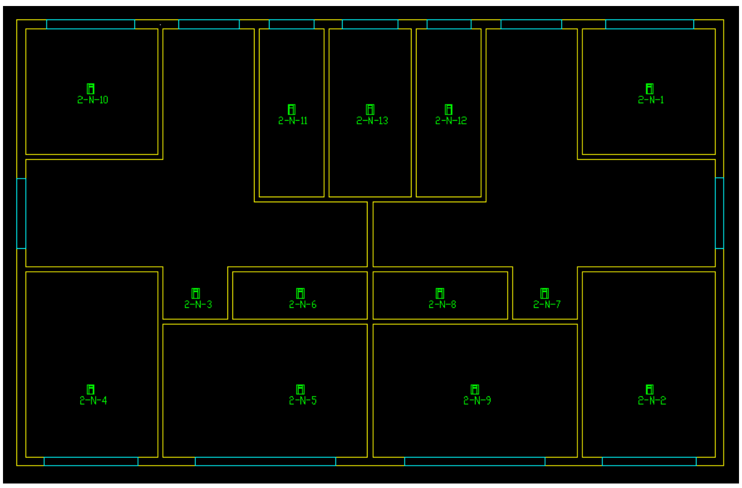

Figure 7. Layout of 2nd floor of the building model in Shanghai

The envelope is designed to comply with JGJ134-2001 (2006), the Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Cold Winter Zone.

To see the effect of occupants' control on air-conditioning clearly, only one occupant is assumed to be in the household in our simulation. The movement of the occupant is generated following the model developed by Wang, Yan et al. (2011). The occupant is set to frequently stay in his bedroom and the living-room, with long-run proportions of 0.4 and 0.45 respectively. Since lighting is not so intense in households, lighting behaviour of the occupant is neglected in simulation. window operation is another strong factor influencing indoor thermal condition, which needs further efforts in detailed modelling. In the current study, we assume two extreme occasions for the window operation: 1. The window is always closed; 2. The window is always open except when the heating is on.

We limit our analysis to the living-room and the bedroom. The set-point of the air-conditioning is 18ºC, the median set point in the survey, which means that once the heating is on, the room temperature is set to be 18ºC if current temperature is lower than 18ºC.

As we have discussed the building context, the occupant and his behaviour patterns, we set up scenarios with both models and parameters therein to be simulated, which is shown in the following tables.

Table 5. Models of opening heating in the living-room

Opening Modes	Model
[a] Never on	$p_{on} = 0$
[b] Always on	$p_{on} = 1$
[c] On as long as entering the living-room	$p_{on} = 0.9$
[d] On when feeling cold	$p_{on} = 1 - e^{-\left(\frac{24-t}{25}\right)^3 \Delta\tau}$
[e] On if there is a guest	$p_{on} = 0.01$

Table 6. Models of closing heating in the living-room

Closing Modes	Model
[a] Never off	$p_{off} = 0$
[b] Always off	$p_{off} = 1$
[c] Off when leaving the living-room	$p_{off} = 0.9$
[d] Off when leaving home	$p_{off} = 0.9$
[e] Off before sleeping	$p_{off} = 0.9$
[f] Off when feeling hot	$p_{on} = 1 - e^{-\left(\frac{t-20}{18}\right)^3 \Delta\tau}$

Table 7. Models of opening heating in the bedroom

Opening Modes	Model
[a] Never on	$p_{on} = 0$
[b] Always on	$p_{on} = 1$
[c] On as long as entering the living-room	$p_{on} = 0.9$
[d] On when feeling cold	$p_{on} = 1 - e^{-\left(\frac{24-t}{25}\right)^3 \Delta\tau}$
[e] On when sleeping	$p_{on} = 0.9$

Table 8. Models of closing heating in the bedroom

Closing Modes	Model
[a] Never off	$p_{off} = 0$
[b] Always off	$p_{off} = 1$
[c] Off when leaving the bedroom	$p_{off} = 0.9$
[d] Off before sleeping	$p_{off} = 0.9$
[e] Off when getting up	$p_{off} = 0.9$
[f] Off when feeling hot	$p_{on} = 1 - e^{-\left(\frac{t-20}{18}\right)^3 \Delta\tau}$

Each mode is assumed to be independent, therefore the union of events is calculated by summing up the modes in terms of probability. If event A has a probability of p_A to take place, event B, independent with event A, has a probability of p_B to take place, the sum of A and B in terms of probability is defined as

$$p_{A+B} = p_A + p_B - p_A \cdot p_B$$

With the boundary conditions we have set up, a series of different patterns derived from the questionnaire survey are simulated to determine the energy consumption. The simulation period is set to be from Dec. 1st to Mar. 1st.

3 Analysis

The simulation could output the schedules of occupant presence, heating states, room temperature, heating energy consumption, etc., which is stored in a .csv file. The simulated results for the mode "[c] On as long as entering the living-room, [c] Off when leaving the living-room" in the living-room are shown in Figure 8.

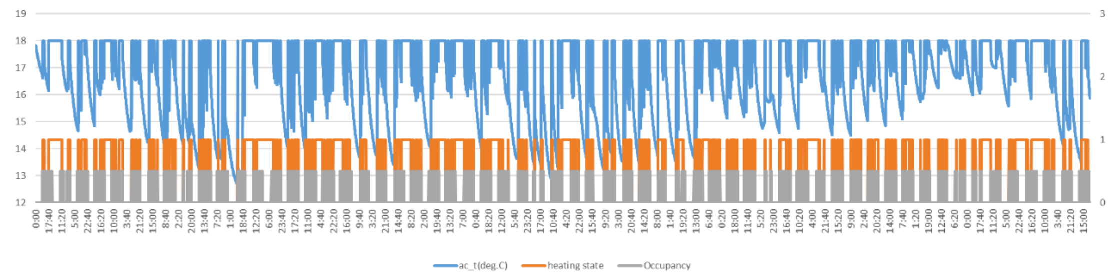

Figure 8. Simulation results of the heating operation in the living-room with mode c,c

In this mode, the heating state is strongly correlated with the occupancy state in the living-room, as the occupant would turn on the heating as long as he/she enters the room, while turn it off as long as he/she leaves the room.

The energy consumption of each mode is simulated following this framework. The influence of window on the heating energy consumption is simplified to two extreme cases as mentioned before. With the window closed all the time, the distribution of energy consumption with different heating operation modes in the living-room is shown in Figure 9, and the one in the bedroom is shown in Figure 10.

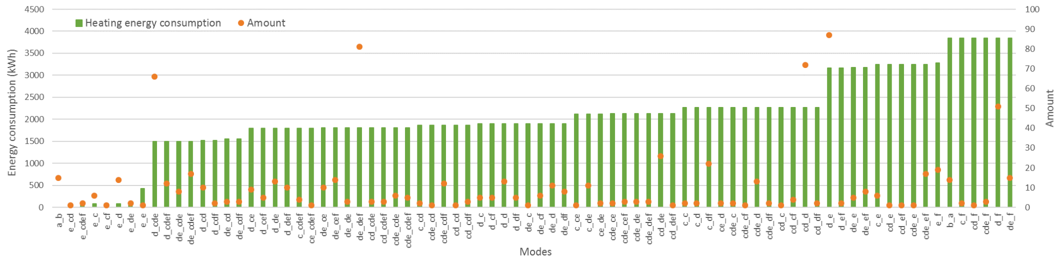

Figure 9. Energy consumption with each heating behaviour mode in living-room with window closed

Figure 10. Energy consumption with each heating behaviour mode in bedroom with window closed

To decide the influence of window on/off state on the energy consumption, another extreme case where the window would be open all the time except when the heating is on is simulated. The results are shown in Figure 11 (living-room) and Figure 12 (bedroom) respectively.

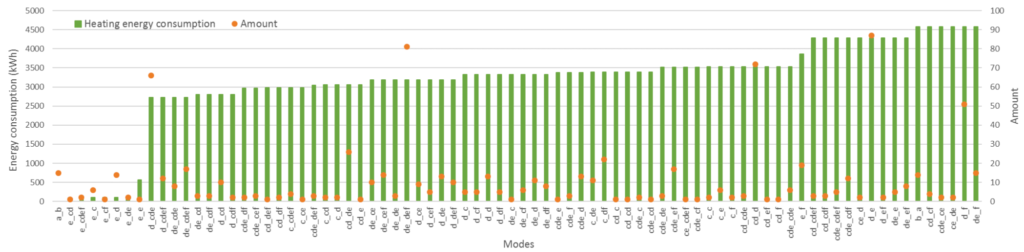

Figure 11. Energy consumption with each heating behaviour mode in living-room with window open

Figure 12. Energy consumption with each heating behaviour mode in bedroom with window open

It could be seen that the window states have influence on the heating energy consumption, while the influence with different modes is approximately consistent, meaning that the window states have little influence on the relative energy consumption with different heating operation modes.

In the following, the average of the two extreme cases is used as the index for the classification of behaviour patterns. Cluster analysis is introduced to divide the behaviour patterns into different categories and the typical patterns could be selected based on the amount. The clusters are illustrated in Figure 13 for the living-room.

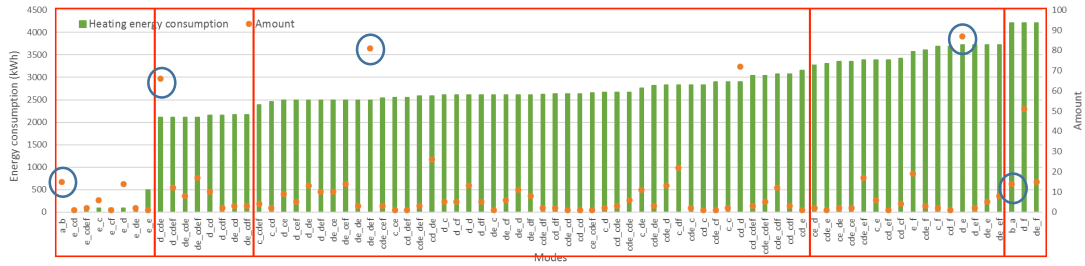

Figure 13. Classification of energy consumption in living-room

For each level of heating energy consumption, a representative could be selected based on the majority of the modes in that cluster. The selected 5 patterns are shown in Table 9.

Table 9. Five typical patterns in the heating operation in the living-room

No.	Typical pattern	Proportion
1	**Never on, Always off**	**0.06**
2	**On when feeling cold, Off when leaving or before sleeping**	**0.16**
3	**On when feeling cold or there is a guest, Off when leaving or before sleeping or feeling hot**	**0.55**
4	**On when feeling cold, Off before sleeping**	**0.22**
5	**Always on, Never off**	**0.02**

It should be noted that the last category contains two modes consuming more energy than the extreme case where the heating is always on. The program should be further checked. At present, these two modes were excluded from the analysis.

Based on the 5 typical patterns, the heating energy distribution could be illustrated and compared with the results of electricity charging in the survey. The survey has investigated the electricity consumption in spring/autumn, and the electricity consumption in winter. The difference between them is considered to be contributed by the heating. Figure 14 illustrates the electricity charging for heating in the survey, the distribution of the electricity charging is nearly normally distributed.

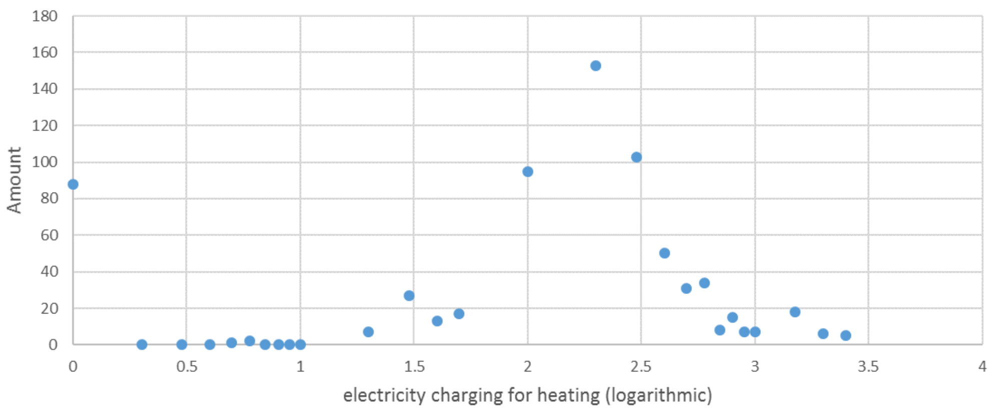

Figure 14. Electricity charging for heating in the survey

Meanwhile, the energy consumption with different typical patterns could be seen from . A similar normal distribution could be found in Figure 15.

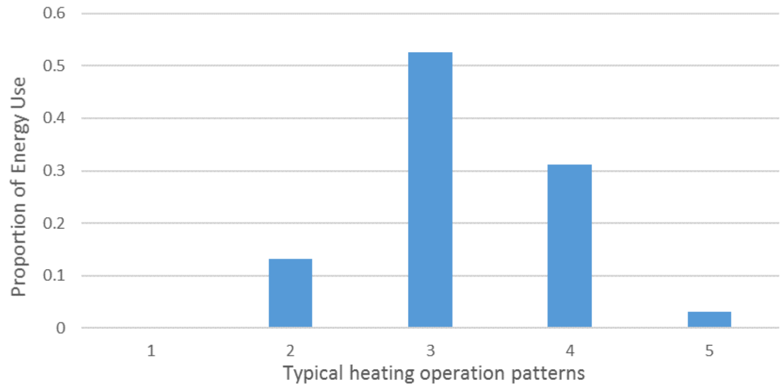

Figure 15. Proportion of energy consumption with the typical heating operation patterns

The comparison gives a preliminary confidence for the simulation results and the extraction of the typical patterns. Nevertheless, to further validate the simulation and the typical behaviour patterns, rigorous behaviour models should be built and the parameters should be obtained from field measurement, which is unavailable at present. Furthermore, the electricity charging is fulfilled by the occupants with no supervision, which has introduced inaccuracy into the data. This study has introduced a novel approach to the extraction of typical behaviour patterns, with more validation work to do.

4 Conclusion

A questionnaire survey investigating occupants' heating behaviour patterns has been conducted in 2015 in Shanghai, China. Based on the questionnaire survey, we set up a simulation scenario to study the difference of energy consumption caused by the variation in occupants' heating behaviour patterns, aiming at conclude several typical behaviour patterns to represent both variety and individuality of occupants in terms of energy consumption.

We analysed the simulation results, and finally grouped the occupants' heating operation behaviour in the living-room into 5 groups. The distribution of the energy consumption with the typical patterns is compared with the surveyed electricity charging of the respondents.

Further efforts lie in the field measurement, the data regarding the actual electricity consumption in a large community, the validation of the simulation results and the typical patterns.

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Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Influence of overheating criteria in the appraisal of building fabric performance

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Abstract

In response to the threat of anthropogenic climate change, heating dominated countries have focused on reducing the space conditioning demand by increasing insulation and airtightness. However, given climate projections and lifespan of buildings, concerns have arisen on whether these strategies deliver resilient solutions. As overheating can be evaluated through different criteria, this paper investigates if building fabric performance is subject to bias from the assessment method chosen and account for discrepancies between previous studies.

To answer this, we modelled dwellings compliant with 1995 and 2006 UK building regulations and the FEES and Passivhaus standards in a consistent and realistic manner. The parametric study included different weathers, thermal mass, glazing ratios, shading strategies, occupancy profiles, infiltration levels, purge ventilation strategies and orientations, resulting in 16128 simulation models. To provide confidence in the output, the base model was first validated against data collected from a real well-insulated dwelling.

Results show that the benchmark choice is influential in the evaluation of building fabric performance as it is able to inverse overheating trends. Criteria based on adaptive comfort best represented expected behaviour, where improved building fabric is a resilient measure that reduces overheating as long as occupants are able to open windows for ventilation.

Keywords: comfort, overheating, resilience, insulation, building simulation

1 Introduction

Over the last decades, an increasing body of evidence has associated human activities as the drivers of current climate change due to the release of an unsustainable amount of greenhouse gases (GHG) (IPCC 2015). Among these, the building sector accounts for a notorious fraction, especially in the UK, where it represents 45% (Pout and MacKenzie 2012). Thus, numerous initiatives have been adopted to lower and optimise the energy consumption in buildings, particularly since it has been steadily increasing (European Commission 2014). As heating is responsible for 47% of buildings' GHG —16% of UK's total—, there has been a special interest in improving the building fabric, mainly through higher thermal resistance and lower air leakage.

Aligning with the interests for reduced energy consumption that arose after the oil crises, building regulations started to become increasingly strict. New dwellings are now required to achieve transmittances three times smaller than in 1970 (Office of the Deputy Prime Minister 2013a), whereas airtightness is expected to deliver between half to a quarter of the air leakage at that time (Office of the Deputy Prime Minister 2013b; CIBSE 2000). Additionally, several standards have lowered these targets further in the UK, where the Fabric Energy Efficiency Standard (FEES) aims to reduce heat losses by half of what regulations require. Furthermore, the Passivhaus standard (PH) seeks a consumption of 15kWh·m^{-2}·year, what is about 60% less than FEES.

Another point of concern is that the climate keeps changing (IPCC 2015). Besides global warming, it is considered *virtually certain* that future climate will feature more extreme weather events, specially more severe and longer heat waves (IPCC 2012). These can increase morbidity and mortality as seen in the European heat wave of 2003, where over 14000 persons died inside buildings in France (Vandentorren et al. 2006). Numerous studies have been looking at such experiences to understand and prevent these rates, where they recognised the fundamental role buildings have to alter the final indoor temperature and thus, promoting higher or lower risks. Two fundamental questions arise. Which are the limits of indoor thermal conditions? How building features affect its overheating performance?

Regarding the limits of indoor thermal conditions, a number of criteria have been proposed. These allow researchers and practitioners to quantify overheating, which, in turn, can translate into an evaluation and classification of the performance of existing buildings (Mavrogianni et al. 2012), design strategies (Porritt et al. 2012; McLeod et al. 2013) or potential impact of climate change (de Wilde and Tian 2010). Despite their usefulness, current criteria are not equally developed (Zero Carbon Hub 2015a), they do not identify the same amounts of overheating (Lomas and Kane 2013) and their adoption is voluntary, despite certain clauses in some building regulations (Office of the Deputy Prime Minister 2013a).

At the same time, there has been an increasing amount of research devoted to see if improved building fabric exacerbates temperatures during summertime in heating dominated countries. During the mentioned heat wave, it was found that higher internal temperatures were recorded in rooms without insulation. However, Orme et al. (cited by Dengel and Swainson 2012) linked higher overheating risk with increases of insulation when assessing an update to UK's Building Regulations. The projections of the UKCIP02 allowed, at about the same time, insights of future performance, in which CIBSE (2005) concluded that the performance of increased insulation and reduced air leakage shifts depending on the hourly balance of the building. Subsequent studies have kept proving one possibility or the other, but the particular research questions, scopes, overheating standards, methods and parameters under study do not allow for comparison.

As a result, further research has been requested to clarify the role of improved building fabric together with the overheating criteria currently available (Mylona and Davies 2015; Gupta and Kapsali 2015; Zero Carbon Hub 2015c). The aim of this paper is to review current benchmarks and to perform a holistic assessment of overheating related to building fabric. The hypotheses that will be tested on this study are:

1. 'Different overheating criteria show inconsistent risk trends when evaluating the same buildings'. This will test the robustness of current prediction methods and will detect whether conclusions about building fabric performance can be expressed as their function.
2. 'Dwellings built to meet low targets of heating energy demand develop lower overheating risk but are less robust'. This will characterise the performance according to current knowledge of the drivers of overheating and occupant behaviour.

The study is organised as follows. Firstly, overheating criteria background and development is reviewed. Next, the methods to test the hypotheses are described. Further, overheating criteria are applied to appraise the building fabric performance and discussed. Lastly, key findings are summarised and recommendations for future work are given.

2 Background

There is not yet a widely accepted definition for overheating. Intuitively, it can be said that 'overheating is the raise of a certain temperature over a certain threshold for a certain period of time', where further specification is subject to discussion. In addition, overheating is better expressed as a risk because temperatures depend on the energy exchange in constantly varying circumstances and is subject to occupant psychological evaluation and physiological reactions. According to what is assessed, it relates to health risks, comfort and productivity, of which only the first two are relevant for dwellings (Zero Carbon Hub 2015a).

The knowledge about overheating and health risks is twofold. On the one hand, the relationship on healthy adults is defined in regulations. Here, an implementation of the Wet Bulb Globe Temperature defines the threshold for the 'heat stress index', a metric that integrates all parameters involved. The standard ISO-7243:1989 (British Standards Institution 1994) establishes the reference method, which maintains its approach in the upcoming revision, recently opened for consultation (British Standards Institution 2015). On the other hand, the relationships for vulnerable groups —namely children, elderly and sick people— are not that developed. Despite early warnings of the IPCC (1990), it has not been until more recent experiences of heat waves (e.g. that of France in 2003) and extreme weather events projections that an increasing amount of efforts have focused on this area (Dengel and Swainson 2012). Nonetheless, there is not a framework that clarifies and quantifies these risks in relation to indoor air temperature (Zero Carbon Hub 2015b).

Unlike with health risks, thermal comfort features numerous schemes to assess overheating. Here, it can be reworded as 'an unacceptable level of dissatisfaction due to excessive heat' according to the two main theories of understanding thermal comfort: Fanger's Predicted Mean Vote – Predicted Percentage of Dissatisfied (PMV–PPD) and Adaptive Comfort Models (ACMs). Thus, they can entail explicit temperature thresholds, although it is still a risk. However, the limits of this expectation, duration and severity, do not translate directly from the PMV-PPD or the ACMs, having being proposed a number of overheating criteria based on them. The following sections focus exclusively on the thermal comfort perspective, since known health risk thresholds (i.e. healthy adults) cannot be reached in these circumstances.

2.1 Comfort criteria based on PMV-PPD

Two main standards implement the PMV-PPD model, the ANSI/ASHRAE-55 (2013) and the EN-7730 (British Standards Institution 2005). The only noteworthy difference is that the American regards as acceptable a PPD up to 10%, whereas the European proposes categories based on degrees of satisfaction up to a PPD of 15%. Knowing the typical situations in dwellings, an operative temperature and its dispersion can be worked out. From this, studies have consecutively supported the raising of temperatures to set limits to discomfort, where the main references are CIBSE, Passivhaus and the EN-15251.

CIBSE's TM-36 provides an illustrative fixed threshold for free-running buildings based on PMV-PPD. They argued that an assessment using ACMs —ASHRAE's model was included in the 55-2004 Standard a year ago— "results can be difficult to interpret" (CIBSE 2005 p.9). The criteria rely in setting 'warm' and 'hot' limits —PMV +2 and +3, respectively— by adapting clothing and PPD. A building is said to overheat it 'hot' conditions are met for more than 1% of the occupied time (reasons why 1% not given and the cited 5% for 'warm' is deprecated). Severity is overlooked. The limits for dwellings are derived from research and experiences in offices and schools, as usual. Although precise values for clothing and metabolic activities are not specified, the operative temperature limit in living areas is established to 25°C (‘warm’, PPD<10%) and 28°C (‘hot’, PPD<20%). Thresholds for bedrooms are adapted to 21°C and 25°C, respectively, according to what they considered occupant's expectations. However, Humphreys’ findings support these values (CIBSE 2006), but the PMV-PPD application would result in 26–27°C due to the lower metabolic activity, provided suitable bedding (0.9met, 0.5–0.7clo). For predictions, the 1% criterion implies the use of Design Summer Years (DSYs) (i.e. third Apr–Sep hottest year on average in 1983–2002) rather than Test Reference Years (TRYs) (i.e. typical year with 1976–1990 average months) so the risk is explicitly taken into account by maximizing it within ‘reasonable’ limits.

Built on the same grounds, Passivhaus sets the default limit to 25°C (customizable) for a duration up to 10% (compulsory) of the occupied time, implementing findings from Kolmetz (1996) (Passivhaus Institute 2014). Hence, it is stricter for the temperature but more relaxed for the deviation. Here, severity is also overlooked.

The standard EN-15251 (British Standards Institution 2007) proposes a procedure to characterise comfort performance and establishes a time limit for discomfort, applicable to both PMV-PPD and the European ACM. The length of deviation is set, as an example, to 3% or 5%, and it has to be met simultaneously for the occupied periods at year, month, week and day levels. Then, it offers three alternatives to compute occupied hours in discomfort. The first one is a count of the time when comfort is exceeded, as seen before. The second is a degree-hours approach like in HDD-CDD according to the temperature difference ΔT_o over the limit. The third one is a PPD-weighted metric, similar to the previous but using the ΔPPD over the limit as the weighting, more suitable as this parameter does assess comfort. They point out that PPD-weightings yield greater hours, not explaining the causes. Here, they are attributed to the exponential expression of PPD(ΔT_o), common to every thermal comfort model. In fact, it can be seen that each of these methods gives higher results than the previous, potentially discouraging the use of the last two. The category of the building is the highest one that is satisfied in 95% of its spaces. However, this can be misleading as the period and counting method are voluntary, as seen by Nicol and Wilson (2011).

2.2 Comfort criteria based on adaptive models

Likewise, the standards ANSI-ASHRAE 55 (2013) and EN-15251 implement ACMs. The different databases from which they were derived —RP-884 ‘worldwide’ (de Dear et al. 1997) and SCATs ‘Europe’ (McCartney and Fergus Nicol 2002), respectively—, the methods and the assumptions involved do not allow for a direct comparison (Nicol and Humphreys 2010; de Dear et al. 2013). As explained by de Dear et al. (1997), adaptations under PMV-PPD only accounted for about 50% of the comfort experienced under ACMs, making adaptive models more appropriate for free-running buildings. The ANSI-ASHRAE 55 offers two limits for comfort that result in 80% and 90% acceptability (general and higher comfort, respectively). The EN-15251 gives three qualitative levels —I/II/III— of which the first two coincide in their intended use with the previous standard —80% for II and 90% for I—. Only the EN-15251 suggests how to quantify the performance of the building regarding discomfort, as explained previously. Interestingly, the concept of ACDD for energy demand was not defined nor validated until later on by McGilligan et al. (2011).

CIBSE’s TM-52 (2013) followed research suggestions and recommends the European ACM to appraise overheating in free-running buildings. The background summarises the state-of-the-art of this adaptive model and establishes a limit to overheating inspired in the EN-15251. It is based on three criterions and a building is said to overheat if any two are exceeded. The first one establishes a limit of 3% on the May-September occupied hours for $\Delta T_o \geq 1K$. The second uses the hour-degree method limited to six in any one day. The reasons given for this particular value is that it "is an initial assessment of what constitutes an acceptable limit of overheating" (CIBSE 2013 p.14). The third one is novel and sets 4K limit to severity, which maintains the PPD under approximately 35%. This way, TM-52 catches up with previous critics (e.g. Nicol et al. (2012)). Additionally, it mentions that ACMs should be suitable for dwellings as adaptability premises are truer, despite being derived from offices. Moreover, it reminds that EN-15251 Category I could be used if tighter control is deemed necessary. ACMs' suitability for bedrooms is not discussed, where it might not be applicable as they were devised for a range of 1–1.3met (offices) and sleeping is 0.9. The Guide A (CIBSE 2015) does mention them, setting comfort up to 24°C and an absolute limit of 26°C.

3 Methodology

The appraisal of overheating and building fabric is complex due to two main aspects. Firstly, true limits of discomfort —duration, severity and their relationship— are not yet known, especially in dwellings. Secondly, the need to cover several parameters requires pairwise models to ease the analysis, unlikely to be found in reality. However, these simulations aim to predict *temperatures*, requiring a careful approach (Nicol et al. 2012). Because of this and the need of knowing occupants' perception, thermal comfort research tends to focus on field studies (de Dear et al. 2013).

As a result, the methods for this study are designed to provide a balanced solution. Parametric building simulations implementing different overheating criteria better approach the hypotheses established, while concerns for such techniques are reduced by validating modelling procedures. Thus, a monitored well-insulated dwelling was chosen as the case study and confidence in the parametric simulations is provided based on the reproduction of its performance (sec. 3.3).

3.1 Overheating assessment

The overheating criteria considered are PH, TM-36 and TM-52 to cover limits based on PMV-PPD and ACM theories and given their widespread adoption in both research and construction industry. They establish well-defined thresholds (table 1) for which the following parameters are calculated:

1. **Hours of discomfort:** Count of occupied hours as defined in the criteria.
2. **Weighted hours of discomfort:** Sum of the occupied hours in overheating multiplied by the temperature deviation from the threshold.
3. **Failure rate of rooms:** This set will provide Pass/Fail summary. Additionally, it will indicate whether different criteria yield different trends among them or not.

Table 1: Overview of selected standard overheating criteria

Passivhaus		25°C (customizable)	for	10%	of the occupied time
TM-36	Bedrooms:	25°C	for	1%	of the occupied time
	Living areas:	28°C	for	1%	of the occupied time
TM-52*	Criterion 1:	$\Delta T_{cm,max} \geq 1K$	for	3%	of the occupied time May–Sep
	Criterion 2:	$\Delta T_{cm,max} \cdot time \leq 6$	in		any one day
	Criterion 3:	$\Delta T_{cm,max} \leq 4K$	for		anytime

*Under this benchmark, a building is said to overheat if any two criterions are exceeded.

3.2 Dynamic Simulation Modelling

The base model is a mid-terrace located next to Southampton (UK) built in the late 2000s to meet the Code for Sustainable Homes Level 4 (fig. 1). The election of a terrace is based on that it is the most common dwelling type prone to overheating, being ranked second to flats in overall risk (Palmer and Cooper 2013; Zero Carbon Hub 2015c). In this regard, studies highlight that the key difference between terraces and flats lies in the options for natural ventilation, aspect that is considered as a parameter. Within terraces, research has shown that mid ones are at higher risk for the same reason (Porritt et al. 2012; Gupta and Gregg 2013). The parametric study is done through EnergyPlus (v8.4), a robust tool extensively validated and used in research.

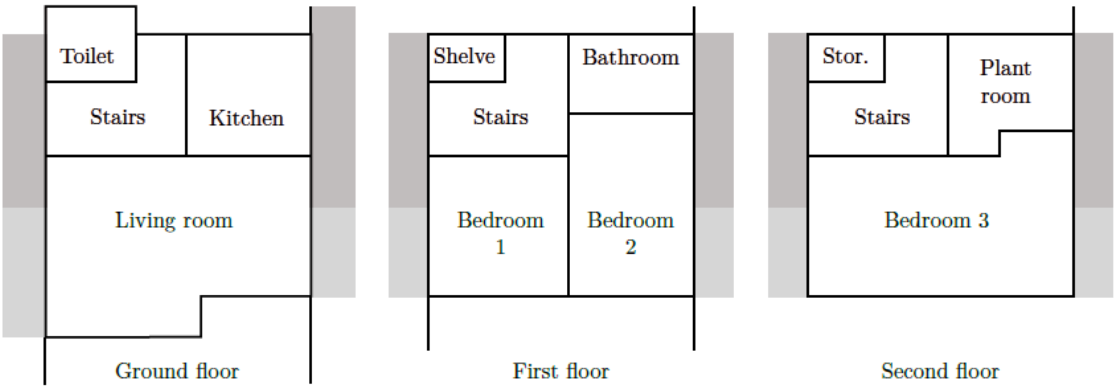


Figure 1: Geometry of the mid-terrace

3.2.1 Base model

The house is modelled to the external side of the thermal envelope following Passivhaus conventions. Each room constitutes a zone to obtain individual temperature readings and to have better control over the definition of heat gains (e.g. the solar distribution model assigns the solar gain to the floor or the room (Ernest Orlando Lawrence Berkeley National Laboratory 2015)). Heating is provided through an ideal loads system to control the energy demand without modelling particular building services, generalizing the results.

The conditions for the elements defining each zone are:

- **Ground floor:** Outdoors, exposed to wind. According to construction details, the house features a suspended floor with a vented cavity.
- **Façades:** Outdoors, exposed to wind and sun.
- **Party walls:** Adiabatic. This simplifies the analysis and is congruent with the study of high insulation levels. Nevertheless, the thermal mass of these walls is still taken into account.
- **Internal walls and floors**: Energy exchanges through these elements are modelled to capture the effect of higher gains in certain rooms (i.e. kitchen and plant room).

3.2.2 Insulation

Studies have associated changes in overheating performance with high insulation levels while they are responsible for substantial space heating energy savings. In order to capture a wide range of building fabric, the modelled cases were dwellings compliant with 1995–2006 regulations and the FEES and Passivhaus standards (table 2). Because they set the context of other parameters (e.g. ventilation systems), this had to be explicitly taken into account in the way the parametric study was carried out (sec. 3.2.11).

Table 2: Definition of the building fabric: U-values and glazing properties

	1995	2006	FEES	PH	Unit
U-value$_{Wall}$	0.45	0.35	0.18	0.10	$Wm^{-2}K^{-1}$
U-value$_{Roof}$	0.25	0.25	0.13	0.10	$Wm^{-2}K^{-1}$
U-value$_{Ground}$	0.45	0.25	0.18	0.10	$Wm^{-2}K^{-1}$
U-value$_{Door}$	3.30	2.20	1.40	0.85	$Wm^{-2}K^{-1}$
U-value$_{Window,limit}$	3.30	2.20	1.40	0.85	$Wm^{-2}K^{-1}$
U-value$_{Window,real}$ (ISO-10292/EN-673)	3.30	2.20	1.30	0.76	$Wm^{-2}K^{-1}$
g-value	0.74	0.70	0.60	0.59	—
Light transmission	0.80	0.76	0.76	0.69	—
Windows layers	4+6+4	4+8+4	4+16+4	5+12+4+12+5	—

3.2.3 Thermal mass

Thermal mass has been identified as a key parameter to assess the influence of insulation and airtightness on overheating. For instance, the Standard Assessment Procedure overheating check depicts a 4K difference between low and high Thermal Mass Parameter (TMP) values (The Concrete Centre 2015). Consequently, three cases were established based on TMP as it takes into account the thermally-active depth of constructions. Lightweight ones are defined as $38KJm^{-2}K^{-1}$ and the medium and heavyweight to 281 and 520, respectively (figures as per ISO-13790 method). To account for dynamic effects, the time step of the simulation was set to 10min as a balance between accuracy and runtime.

Constructions were serialized in three groups, one per thermal mass. Lightweight constructions rely on internal insulation whereas mid and heavyweight rely on internal blocks of different properties and external insulation. Cavities are avoided to simplify the model. The insulation thickness is adapted to the year or standard of construction, according to the remaining thermal resistance. Internal areas and volumes for each of the twelve combinations were worked out and used to override automatic calculations. Thus, energy exchanges are invested in the real enclosed air. Lastly, wall thickness affects the solar heat gain model through reveals of windows, which were designed to keep recesses at 5cm.

3.2.4 Glazing

The original window-to-floor ratio was taken as the base case because the original house was reported to have an adequate winter–summer balance. Variations of ±5% around the baseline were explored by modifying the geometry while keeping shading conditions (fig. 2). Frames and dividers have been considered consistently with the way EnergyPlus takes them into account to keep solar gains constant between building fabrics, while acknowledging changes in U-values (5cm frames in 1995–2006 and 10cm in FEES–PH).

3.2.5 Shading

The knowledge of occupant behaviour (e.g. shading operation) is among the challenges of defining a model because it is still unknown (Mavrogianni et al. 2014). Thus, the original shading based on fixed elements is maintained because it was assessed to provide adequate performance *by default*. Northern devices were updated to meet the same shading angles as the southern ones. However, the bedroom in the loft was modelled with a shading device with optimal operation based on the indoor temperature to approximate good shading conditions because it is completely exposed to the sun. This way shading strategies remain useful regardless the orientation. This ‘fully shaded’ condition constitutes the best-case scenario whereas the worst one is established with no shading but that of the urban landscape where the same terrace was replicated 15m apart.

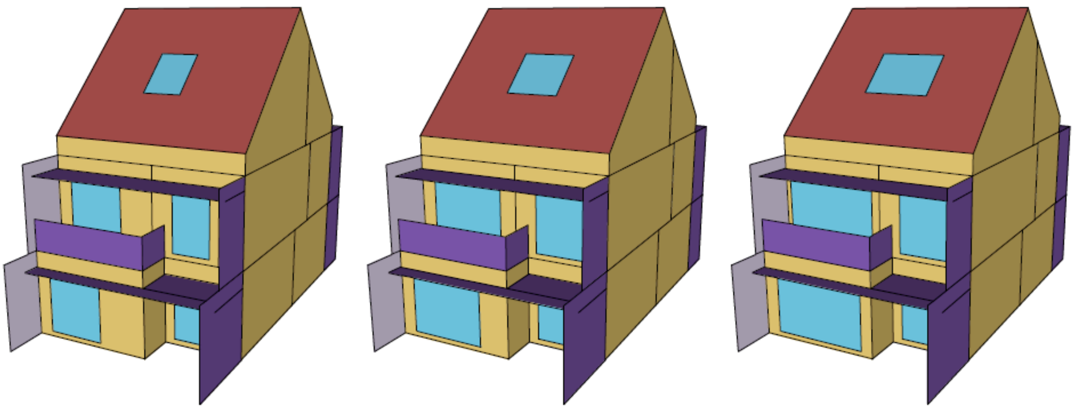


Figure 2: Glazing definition (wall-to-floor glazing ratio)

3.2.6 Internal gains

Likewise shading, two cases have been considered following knowledge limitations. The first is a working family of five members where occupants are away from 9:00 to 17:00. The second is three occupants home all-day-long ('high' and 'low' scenario, respectively).

Occupancy was modelled as discrete individuals in specific rooms. Lighting and other gains such as appliances were based on a customized version of the Passivhaus methodology, informed by UK-specific data and models (Richardson et al. 2010; McLeod et al. 2013; Palmer and Cooper 2013). These established a 'budget' spent accordingly to occupancy, considering residual loads and specific appliances in the kitchen and service rooms. Resulting average gains are 3.83Wm^{-2} and 3.03Wm^{-2} for the high and low scenarios, respectively, considering their respective contributions to the thermal load.

3.2.7 Infiltration

Infiltration has been estimated according to studies, regulations or their specific targets (table 3). To account for wind speed and stack effects, reference infiltrations were translated as permeability in the Walker and Wilson's model, which also considers dwelling geometry, features and suburban exposure. Additionally, flow coefficients were prorated per room according to their external envelope area. To account for the dispersion in airtightness values, high and low scenarios were taken around expected mean values.

Table 3: Infiltration definition of cases (*Data adapted from its original definition)

Construction	Case	q50 [m^{-3}h^{-1}m^{-2}]	n [ach]	Data source for reference values
1995	High	30	2.264*	CIBSE (2000)
	Low	10	0.755*	
2006	High	10	0.768*	ODPM (2006b; 2006a)
	Low	5	0.384*	
FEES	High	4	0.337*	ZCH (2009) and ODPM (2013a)
	Low	2	0.169*	
PH	High	0.5*	0.042*	Cotterell and Dadeby (2012)
	Low	0.25*	0.021*	

3.2.8 Ventilation: purge ventilation availability and occupant behaviour

The different years of construction entail particular ventilation systems and modes of operation. These were adapted from regulations and standards to the simulation engine capabilities (table 4). For the considered airtightness in 1995 and 2006, background ventilators are advised, whereas mechanical ventilation (MV) is for FEES and PH, with the latter including a Heat Recovery (HR) section that is by-passed during summertime.

Table 4: Ventilation systems summary

<table>
<tr><th>Case</th><th>CO_2-oriented</th><th>Extract</th><th>Purge</th></tr>
<tr><td>1995</td><td>Background ventilators.
Model: Weather-driven shallow openings.
Operation: Constant.</td><td>Specific Fan.
Model: Extraction fan.
Operation: On-demand, according to internal activity.</td><td rowspan="4">Windows, 20% openable area.
Model: Weather-driven model for wind and stack effect.
Operation: three different behaviours (‘low’, ‘medium’ and ‘high’)</td></tr>
<tr><td>2006</td><td>Background ventilators.
Model: Weather-driven shallow openings.
Operation: Constant.</td><td>Specific Fan.
Model: Extraction fan.
Operation: On-demand, according to internal activity.</td></tr>
<tr><td>FEES</td><td>MV unit.
Model: Ideal system.
Operation: According to 2013 Building Regulations for mechanical systems.</td><td>Extraction to MV unit.
Model: ideal system.
Operation: According to supply. Airflow increased when extraction is greater due to activity.</td></tr>
<tr><td>PH</td><td>MVHR unit.
Model: Ideal system, with HR (by-pass allowed)
Operation: According to Passivhaus standard.</td><td>Extraction to MV(HR) unit.
Model: ideal system.
Operation: According to supply. Airflow increased when extraction is greater due to activity.</td></tr>
</table>

Real window opening behaviour is not yet well-known for building simulation purposes. As each of the overheating criteria suggests limits of discomfort, it has often been modelled to satisfy their requirements, assuming that occupants would take actions to prevent excessive overheating. Although this premise is exclusive of adaptive comfort, it has been taken into account for PH and TM-36 criteria as a traditional assumption in previous studies. Therefore, windows are opened if the following conditions are met simultaneously:

1. A trigger temperature is surpassed.
2. The external temperature is lower than the internal.
3. There are occupants in the house.

Because in adaptive comfort the first condition depends on the external running mean, the temperature trigger was implemented through hourly schedules calculated for each case. To study the impact of purge ventilation, three availability scenarios were studied:

1. **Low:** Purge ventilation is never available. This constitutes a worst-case scenario for control purposes.
2. **Medium:** Purge ventilation is available during daytime if there are occupants in the dwelling. The trigger temperature is established according to each overheating criteria as the threshold for overheating.
3. **High:** Purge ventilation is always available as long as there are occupants. This constitutes a best-case scenario where occupants optimize window opening behaviour. Here, occupants aim to maintain the neutrality temperature. Because in PMV-PPD this tem-

perature would be the same, PH was modelled to 23°C and TM-36 to 25°C during the day and 21°C during the night.

3.2.9 Orientations

Four cases, one per cardinal point, were modelled to approach results in any orientation.

3.2.10 Location and future projection

London was taken as the reference location. Due to the known problems with DSYs weather files, TRYs were used to carry out the simulations (Jentsch et al. 2014). To explore performance under higher external temperatures and approach the resilience of different building fabrics, the climate change projection given by Eames et al. (2011) for 2080 (high emissions scenario, 90% percentile) was considered.

3.2.11 Conditional assemblies

The appraisal of a wide range of building fabrics entails different conditions and systems for each building model. Following the capabilities of EnergyPlus, components were defined in separate files and only relevant combinations were assembled for the simulation. For instance, ventilation featured conditions based on regulations and standards (system type and capacity), occupancy (availability) and purge strategy (parameter and overheating criteria). Altogether, these generate 16128 computational models.

3.3 Validation

The adequacy of modelling techniques is appraised through internal temperatures on free-running mode and the space heating energy demand. The first is aimed specifically to overheating performance and it is based on the original house specifications (table 5), real occupancy derived from sensors and simulation with the real external conditions. The latter were recreated from official weather stations given the limitations of on-site external measurements (Met Office 2015; World Meteorological Organization 2015).

Table 5: Base case general properties

Building Fabric	Opaque transmittances	0.11–0.15 $Wm^{-2}K^{-1}$
	Windows transmittances	0.78–1.24 $Wm^{-2}K^{-1}$
	Thermal Mass Parameter	250 $KJm^{-2}K^{-1}$
	Window-to-floor ratio	21%
	Airtightness	1.25ach@50Pa
MVHR unit	Airflow capacity	0.50ach
	Consumption	13.2kW $m^{-2}y^{-1}$
	Heat Recovery	77%

Norms were taken to appraise the goodness of fit between the real and the simulated time series (fig. 3). The 2-norm was used as the indicator of the average dissimilitude between signals, which, divided by that of the real one, resulted in deviations of 2.4% (≈0.6K). Similarly, the ∞-norm was taken as the indicator of the peak dissimilitude, being 6.1% (≈1.6K). Given the number of uncertainties, simplifications and assumptions in the process, these have been interpreted as a reasonable guarantee of the validity of the simulation. However, they are high enough to prevent accurate absolute values for a study in overheating and the results of the study will necessarily depend on the ranking of figures.

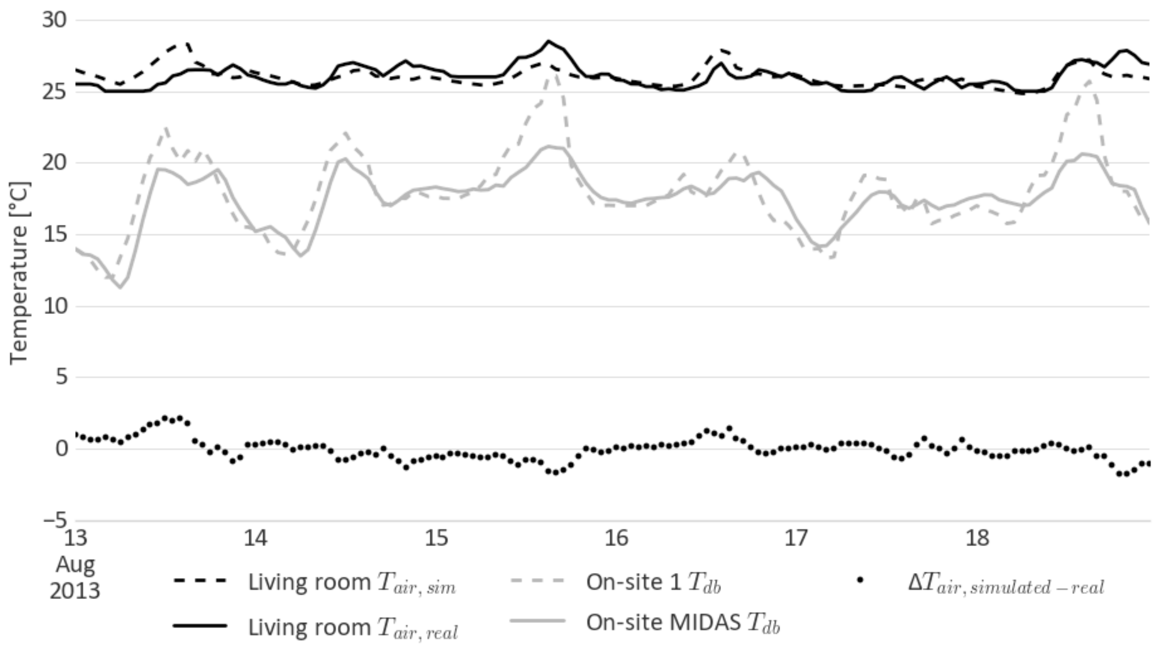


Figure 3: Validation of the overheating model: typical summer week

The validation of space heating demand ensures that simulations under the current weather are within reasonable limits (fig. 4). This is done comparing the space heating demand intensity of the simulations with the heating energy consumption of the UK stock or FEES and PH goals. The heating energy consumption takes into account domestic hot water (DHW) and the efficiency of the equipment. Considering that DHW is about 30% of the demand and a boiler efficiency of 85%, values would be 1.5 times greater, in the range of known values (Palmer and Cooper 2013; BRE 2005). On the contrary, FEES and PH directly specify their heating energy demand, being the average of the locations close to the goals of 39kWh·m^{-2}·y^{-1} and 15kWh·m^{-2}·y^{-1}, respectively. It must be considered that FEES and PH achieve their goals by an iterative design process, meaning that the dispersion in the demand is due to the propagation of cases that have not been optimized to satisfy them.

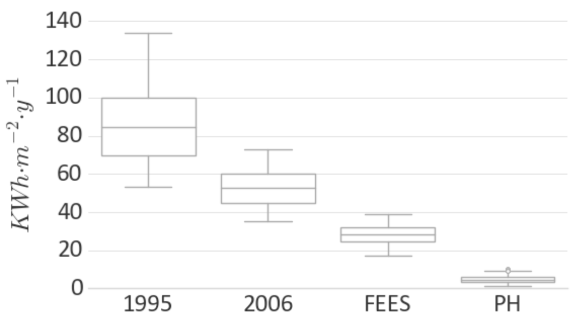


Figure 4: Space heating energy demand intensity

4 Results and discussion

Overheating criteria appraise performance based on annual indicators, which have been computed coherently with the simulations. The exception is when purge ventilation is not available as there is no occupant behaviour involved. Here, each benchmark was applied directly to the results. Data has been stratified in equally sized samples according to the parameters of interest for each indicator, namely purge strategy, overheating criteria (linked to the opening behaviour modelled), weather, and building fabric.

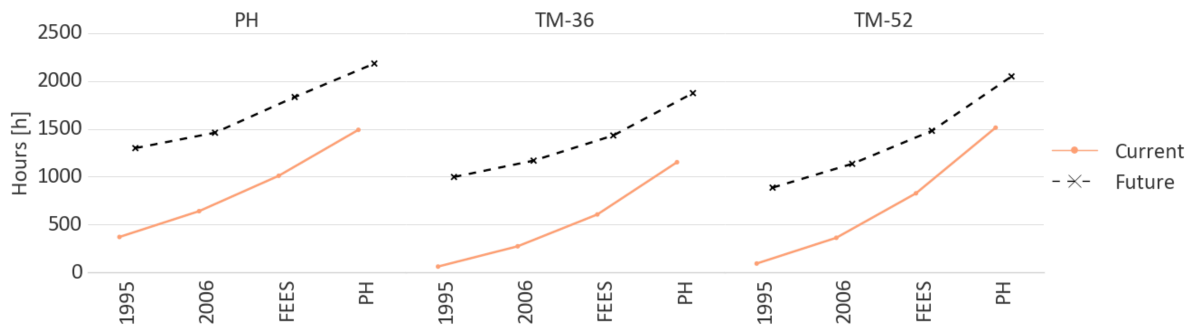
The analysis relies on pairwise comparisons given the hypotheses, the way simulations were generated and the outcome of the validation. Hence, results are presented through the average of each subset (over 5000 observations). Because rooms with very different occupancies are summarized together in this assessment, absolute figures cannot be translated directly to specific cases. Finally, each group is analysed through the Kruskal-Wallis test to appraise whether the changes observed are statistically significant or not. These are followed by the Nemenyi post-hoc tests to see which construction pairs within the same group are significantly different, if any.

4.1 Hours in discomfort

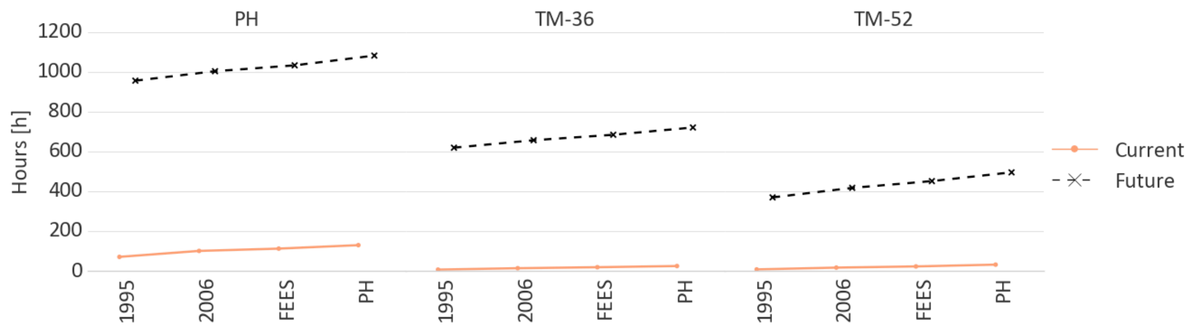
The results show the variation of overheating hours for different purge ventilation strategies and weathers (fig. 5, table 6). When windows cannot be opened ('low' scenario) the risk is significantly higher, reaching maximums over 2000h (≈23% of the year). The values for each overheating benchmark differ quantitatively, as known, but with an unusual ranking. PH yields more hours than TM-36 as it could be expected from the temperature thresholds, but for TM-36 and TM-52, the latter tends to report higher values for the current weather. This is due to the definition of the thresholds and the TRY weather file. The TM-36 defines an absolute limit of 28°C whereas the TM-52 focuses on the ΔT over the running mean. Thus, the TM-36 would result in fewer hours under circumstances prone to overheating as this one in a mild weather. For 1995, infiltration levels at 0.75–2.24ach provide a major cooling mechanism because it is the only option available. Contrarily, the mechanical ventilation and infiltration in a PH gives about 0.40 and 0.02–0.04ach, respectively. The result is that criteria show that improved building fabric develops higher overheating in every case. Nevertheless, overall figures suggest that this situation would be unbearable for occupants with the exception of 1995 dwellings under current weather.

The case where windows can be opened during daytime aimed to represent a 'medium' scenario where occupants, assuming a behavioural model inferred from the benchmarks, take action to keep rooms just below the thresholds. Here, absolute values are several times lower, ranging 8-180h and 400–1100h for current and future weather, respectively. Criteria now follow the ranking reported by previous studies, highlighting the advantages of adaptation for the climate change scenario. Improved building fabric also results in more hours above the threshold although the slope of the curve has diminished remarkably.

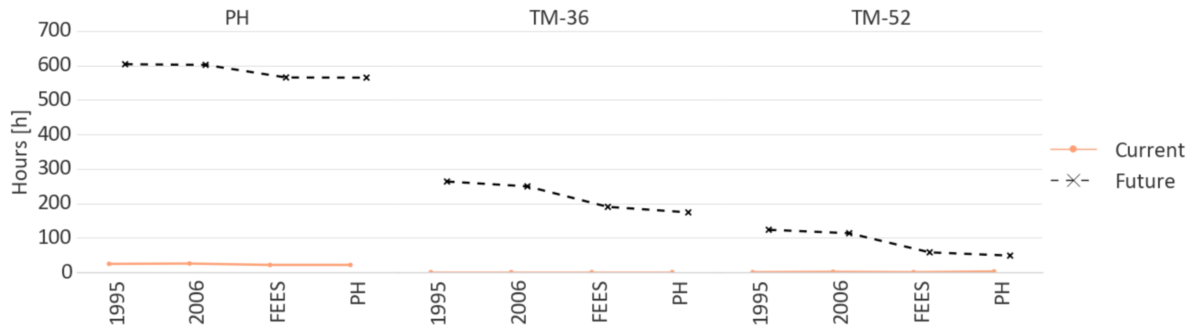
In contrast, when occupants are expected to restore neutrality, the risk diminishes over 50% and every benchmark reports benefits from higher levels of insulation and airtightness. The temperature trigger for opening windows is lower than the threshold and indoor conditions are kept as neutral as comfort and occupancy allow. The TM-52 evaluation reports values fewer than 150h (≈1.7% of the year) for the future weather. Combined with the previous result, this indicates that there is still great potential for comfort in occupant adaptation and the external temperature daily swing. Now, improved envelopes are always beneficial although not necessarily significant between 1995 and 2006 or FEES and PH.



a) Purge ventilation ‘Low’



b) Purge ventilation ‘Medium’



c) Purge ventilation ‘High’

Figure 5: Mean overheating hours (Y-axis adapted per strategy)

4.2 Weighted hours in discomfort

Weighted hours are only considered in the TM-52, although they have been widely used to account for severity with a single value. The outcome provides a different perspective on what the hour count seemed to suggest (fig. 6). The ranking of the criteria is consistent with other studies and stresses the harmful effects of sealing up dwellings when windows are kept shut. However, results for TM-52 show values several times lower even though indoor temperatures are above the threshold as often as in the other cases. Therefore, this overheating is due to lower ΔT, being about one for 1995 and two for PH.

Weighted hours show different trends than before for the ‘medium’ purge strategy. The PH threshold of 25°C in the current weather shows increasing overheating, from 85h in 1995 to 116h in PH. It decreases in the future from 3572h to 3437h, respectively, although only the reductions experienced by FEES are statistically significant (table 7). TM-36 experiences the same results as PH whereas in the TM-52 trends keep growing but at a slower rate than before. Overall, the response is not the same when the maximum comfort temperature allowed varies. The comparison with the values obtained in the hour count shows that houses with a PH-based window opening algorithm had an average ΔT of 3, TM-36 of 2 and TM-52 lower than 1. Hence, FEES and PH achieve lower overheating for high external temperatures since 1995 and 2006 reported higher weighted hours despite being less time over the thresholds, situation that does not take place in TM-52 due to its ΔT.

Previous considerations towards the maximum comfort temperature also arise in the 'high' purge ventilation strategy. Aiming for neutrality improves the behaviour of better building fabric but the specific temperatures generate similar ΔT. Altogether, these results indicate that FEES and PH stabilise temperatures in a smaller range than the others. They report less overheating for large deviation from their limits, but not for the small ones. Additionally, they improve results if they are given margin as in the 'high' case. 1995 and 2006 benefit from higher infiltration and conduction when the weather is colder than their thresholds, but they are no longer beneficial given the temperature increment in 2080.

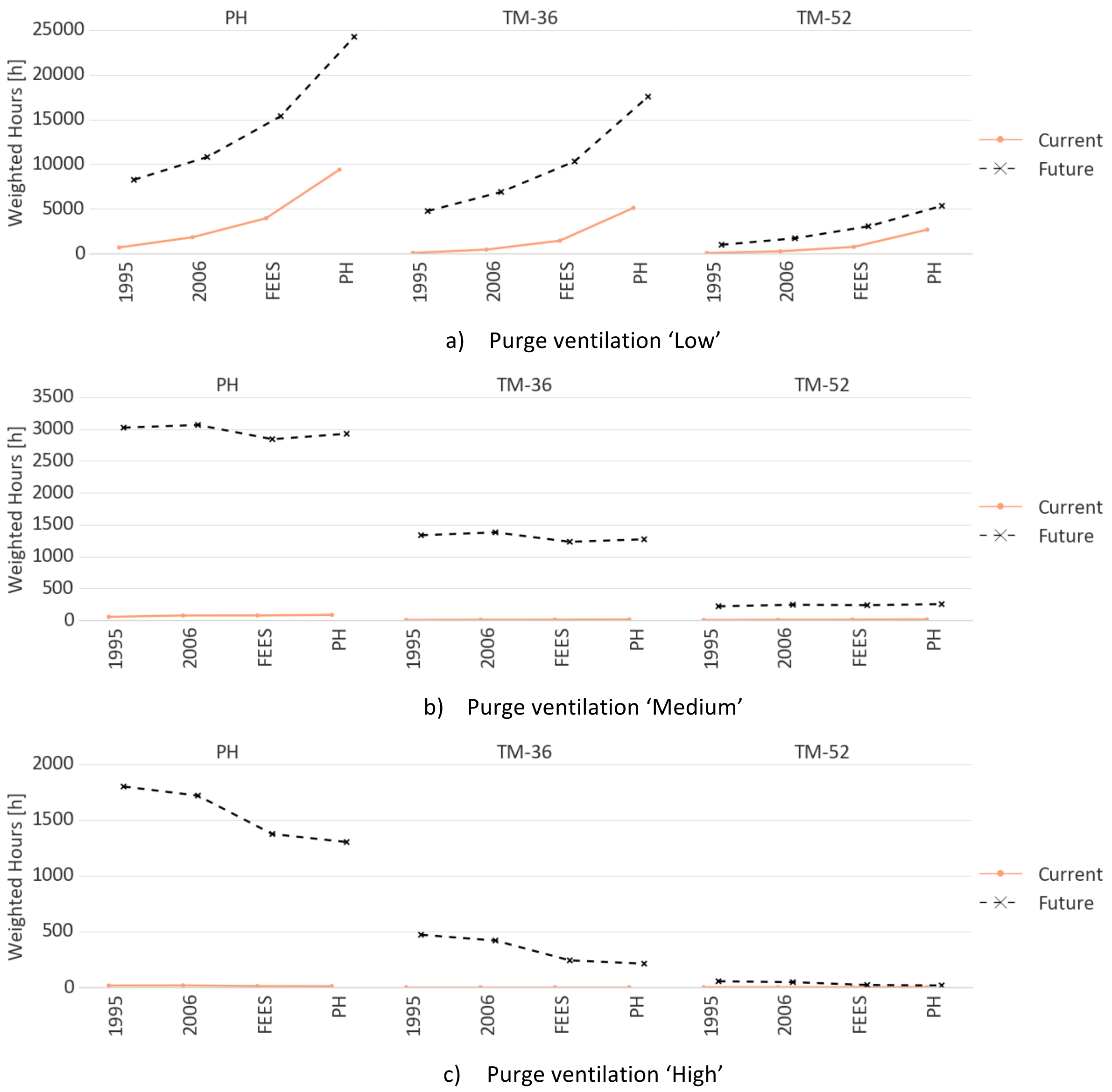


Figure 6: Mean overheating weighted hours (Y-axis adapted per strategy)

4.3 Overheating criteria

Figure 7 shows the overall results of the benchmarks. It has to be considered that the approach through extreme cases —low-high parameter values— make large proportions of the simulations prone to overheating. The lack of purge ventilation shows a steep evolution towards 100% for current weather as building fabric changes and a complete failure for the future scenario. The only noteworthy difference is that TM-52 depicts lower values than TM-36 despite figures obtained in the hour count. The reasons are that TM-52 implements three criterions of which two need to be failed to report overheating. Moreover, the hour count is done for ΔT≥1 and the other two allow for restrained deviations, even though the maximum comfort threshold is met before 28°C.

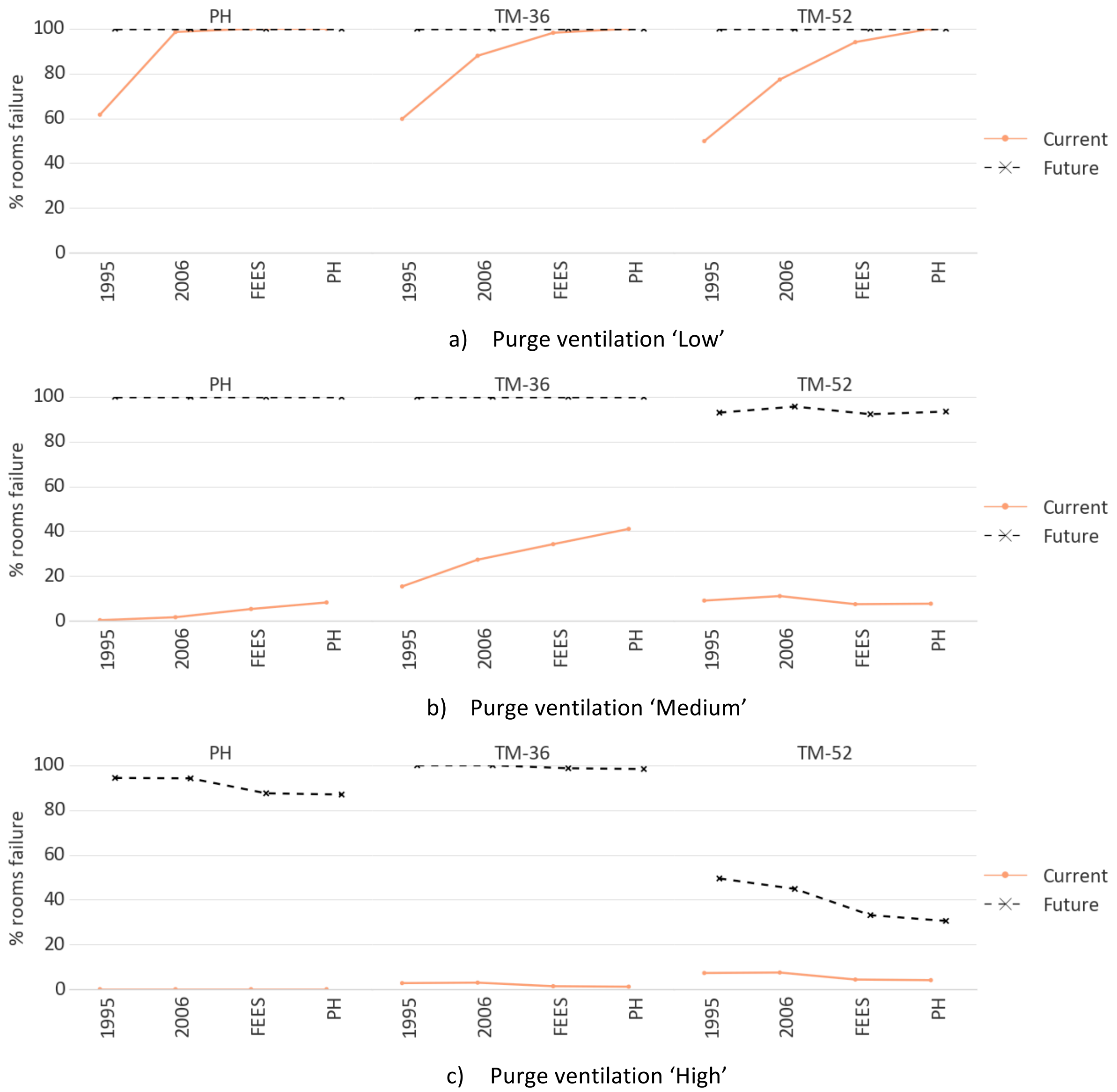


Figure 7: Percentage of room per group failing their overheating criteria

Inconsistencies and limitations between criteria are evident in subfigure 7-b. PH and TM-36 report trends as in the hour breakdown, but now TM-36 has a higher failure rate under current weather. This is because the relationship between the temperature limit and the amount of time is unfavourable (28°C–1% of the occupied time against 25°C–10%). Remarkably, and unlike the previous, TM-52 captures reductions in the risk with improved building fabric under current climate. Nevertheless, only those by FEES are statistically significant in the future scenario (table 8). These results contrast with the indicator breakdown shown earlier because small overheating is neglected in TM-52. This further reinforces that FEES and PH tend to maintain better indoor temperatures for ΔT≥1 whereas they are more sensitive to smaller ones. Lastly, 'high' purge ventilation results also support these conclusions. The temperature offset from the maximum threshold not only lowers the risk substantially but also inverses trends in PH and TM-36 while demonstrating the effectiveness of better building envelopes.

5 Conclusions

Given past experiences of heat waves and the projections of climate change, researchers and practitioners need to be able to quantify their impact in the thermal environment. However, there is a lack of agreement in the methods to use. At the same time, the role of building fabric in overheating risk has been subject of numerous studies that have arrived at apparently contradictory conclusions. This paper has examined the criteria provided by Passivhaus and CIBSE to appraise the performance of four building envelopes and tested their coherence and suitability in the quantification of overheating.

The results demonstrate that available criteria can identify different overheating trends, depending on the considered occupant window opening behaviour and constructions. The TM-52 is deemed the most appropriate among the benchmarks considered because it was specifically derived from comfort evaluations in free running buildings and recommends sensible limits to duration and severity of discomfort. Nonetheless, none of them seem advisable as the only metric to appraise performance and further efforts are deemed necessary to improve the evaluation and communication of overheating risk. Moreover, it remains essential a better understanding of the properties of discomfort and health risks as assessment procedures relies heavily on them.

Results regarding overheating and building fabric are twofold. The combination of insulation, airtightness and ventilation for 1995 translates in lower overheating risk when purge ventilation is not available since the external temperatures are below the maximum comfort threshold most of the time. However, better building fabric arises as the best option against severe overheating or when windows are operated to reach the neutrality temperature in both current and future climates. Although further studies should extend these findings to other dwelling types, they suggest that the goals of lowering carbon emissions and the delivery of resilient and comfortable dwellings can align through improved building fabric.

Acknowledgements

The authors gratefully acknowledge the Engineering and Physical Science Research Council (EPSRC) for their financial support of "The creation of localized current and future weather for the built environment" (COLBE) project (Grant EP/021890/1) and Rachel Mitchel for providing the experimental data for the validation. Daniel Fosas de Pando expresses his gratitude for the financial support of the 'laCaixa' Foundation.

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Appendix

Table 6: Significance of statistical tests for hour count in figure 5

Purge	Standard	Weather	Kruskal-Wallis	2006-1995	FEES-1995	PH-1995	FEES-2006	PH-2006	PH-FEES
Low	PH	Current	***	***	***	***	***	***	***
Low	PH	Future	***	***	***	***	***	***	***
Low	TM-36	Current	***	***	***	***	***	***	***
Low	TM-36	Future	***	***	***	***	***	***	***
Low	TM-52	Current	***	***	***	***	***	***	***
Low	TM-52	Future	***	***	***	***	***	***	***
Medium	PH	Current	***	***	***	***	***	***	***
Medium	PH	Future	***	**	***	***	*	***	*
Medium	TM-36	Current	***	***	***	***	***	***	***
Medium	TM-36	Future	***	***	***	***	**	***	**
Medium	TM-52	Current	***	***	***	***	**	***	***
Medium	TM-52	Future	***	***	***	***	***	***	***
High	PH	Current	***			.	*	**	
High	PH	Future	***		***	***	***	***	
High	TM-36	Current	***		***	***	***	***	
High	TM-36	Future	***		***	***	***	***	
High	TM-52	Current	***			***		***	***
High	TM-52	Future	***		***	***	***	***	

p-values: 0 < *** ≤ 0.001 < ** ≤ 0.01 < * ≤ 0.05 ≤ . < 0.1

Table 7: Significance of statistical tests for weighted hours in figure 6

Purge	Standard	Weather	Kruskal-Wallis	2006-1995	FEES-1995	PH-1995	FEES-2006	PH-2006	PH-FEES
Low	PH	Current	***	***	***	***	***	***	***
Low	PH	Future	***	***	***	***	***	***	***
Low	TM-36	Current	***	***	***	***	***	***	***
Low	TM-36	Future	***	***	***	***	***	***	***
Low	TM-52	Current	***	***	***	***	***	***	***
Low	TM-52	Future	***	***	***	***	***	***	***
Medium	PH	Current	***	***	***	***		**	**
Medium	PH	Future	***		**		***	**	
Medium	TM-36	Current	***	***	***	***	.	***	***
Medium	TM-36	Future	***	.	*		***	*	
Medium	TM-52	Current	***	***	***	***	*	***	***
Medium	TM-52	Future	***	***	***	***		*	**
High	PH	Current	***		**	***	***	***	
High	PH	Future	***		***	***	***	***	
High	TM-36	Current	***		***	***	***	***	
High	TM-36	Future	***	.	***	***	***	***	
High	TM-52	Current	***			***		**	***
High	TM-52	Future	***		***	***	***	***	

p-values: 0 < *** ≤ 0.001 < ** ≤ 0.01 < * ≤ 0.05 ≤ . < 0.1

Table 8: Significance of statistical tests for percentage of rooms failing in figure 7

Purge	Standard	Weather	Kruskal-Wallis	2006-1995	FEES-1995	PH-1995	FEES-2006	PH-2006	PH-FEES
Low	PH	Current	***	***	***	***			
Low	PH	Future	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Low	TM-36	Current	***	***	***	***	***	***	
Low	TM-36	Future	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Low	TM-52	Current	***	***	***	***	***	***	**
Low	TM-52	Future	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Medium	PH	Current	***		***	***	***	***	***
Medium	PH	Future	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Medium	TM-36	Current	***	***	***	***	***	***	**
Medium	TM-36	Future	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Medium	TM-52	Current	**				**	*	
Medium	TM-52	Future	**	*			**		
High	PH	Current	n/a	n/a	n/a	n/a	n/a	n/a	n/a
High	PH	Future	***		***	***	***	***	
High	TM-36	Current	***		.	*	*	**	
High	TM-36	Future	***		***	***	***	***	
High	TM-52	Current	***		*	**	**	**	
High	TM-52	Future	***	.	***	***	***	***	

p-values: 0 < *** ≤ 0.001 < ** ≤ 0.01 < * ≤ 0.05 ≤ . < 0.1

SESSION 7

Future Facing Hot Topics

Invited Chairs: Susan Roaf and Fergus Nicol

Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

A new method to develop the adaptive thermal comfort model

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Abstract
The existing thermal comfort standard in natural ventilation buildings only rely on the outdoor temperature to calculate the neutral temperature, and the coupling effect of other climatic parameters on human thermal adaptation and the body's self-regulation and the ability to adapt in response to different climate and building type were ignored. To explore the influence of the long-term outdoor climatic parameters on the neutral temperature, based on the existing thermal comfort researches and our survey, by means of multivariate regression statistical analysis, the relationship between human neutral temperature and long-term outdoor temperature, humidity, wind speed, and solar radiation ware analyzed. The results showed that, apart from outdoor temperature, water vapour pressure and solar radiation were the other important environment parameter influence to the neutral temperature of the southern and the northern people. Then the multivariate nonlinear regression models between the neutral temperature and long-term outdoor temperature and water vapour pressure were developed. Test results showed that the new model was more accurate than the single factor regression model. The above result further improve the calculation accuracy of the adaptive thermal comfort model, and provide a new method and angle to develop the adaptive thermal comfort model in different climatic zones.

Keywords: neutral temperature, long-term meteorological parameter, thermal adaptive model

1 Introduction

Thermal comfort is one of the most important factors to evaluate the indoor thermal environment of the buildings. It is widely accepted that PMV model based on the climate chamber can perform well in the AC buildings but often deviate widely in defining comfort conditions in naturally ventilated buildings. The reasons for the discrepancy between them were that thermal comfort of the subjects in the NV buildings greatly affected by climate, building, culture, and society, etc (Nicol, 2004; Nicol, 2002). Humphreys lay behind the first exploration of the quantitative relation between comfort and climate by a meta-analysis of more than 200,000 observations from some 30 field-surveys of thermal comfort conducted between 1930 and 1975 (Nicol, 2002). This correlation between indoor comfort temperature and outdoor monthly mean temperature were also confirmed in the other in thermal comfort surveys. The adaptive thermal comfort model was developed and became the part of the standards of ASHRAE 55 and EN 15251 based on these above researches.

Problems appear when the adaptive model suggests the same neutral temperature for ambiences with the same indoor temperature but different relative humidity (Humphreys, 1976). Farghal and Wagner (2010) (Farghal, A., et al., 2010) classify naturally ventilated buildings into seven climatic zones among which significant differences were noted in thermal neutralities. They conducted field surveys in Cairo and proposed a steeper adaptive comfort equation for hot-dry climate than those of existing adaptive standards (ASHRAE, 2010; BSI, 2008). Doris Hooi Chyee Toe et al. (Doris H., et al., 2013) sorted ASHRAE RP-884 database into three climate groups including hot-humid, hot-dry, and moderate, they revealed that the regression coefficients of the adaptive equation in the different climate different from the existing adaptive standards. The field studies in different climatic zones of North-East India conducted by Singh, M.K. showed that the adaptive coefficient values are varying for different seasons and also for different climatic zones. This reflected the various levels of adaptation in different seasons in a particular climatic zone. Moreover, Singh, M.K. et Al. (Singh, M.K., et al., 2015) developed the comfort models based on the relationship between the neutral temperatures and indoor and outdoor temperature, relative humidity and clothing insulation. This study also concluded that it was not possible to obtain a generalized thermal comfort model for all climatic zone because adaptation process, expectation and perception of people were region specific and governed by local socio-cultural requirement. But in recently years it has been argued that using just the outdoor temperature to calculate comfort temperatures ignores a whole lot of other factors such as the humidity and air movement (Nicol, 2002).

Some attempts have already been done to evaluate the effect of humidity on adaptive thermal sensation, as in (Nicol, F., et al., 2002). Nicol suggested that occupants may require comfort temperatures approximately $1^{\circ}C$ lower than that specified by the overall data when the outdoor relative humidity is greater than 75% (Nicol, 2004). Neglecting humidity can bring to overestimating the adapt-ability of occupants. Rajib Rana et al. show that humidex is a good predictor of indoor thermal comfort at high humidity (Fountain M E., et al., 1999).

Based on the above results, the neutral temperature of different climatic zone affected mainly by the outdoor temperature, we suppose, it may be influenced by other meteorological factors, such as humidity or radiation. Therefore, the objective of the paper is to explore the relationship between the neutral temperature and the multi-parameters of outdoor climate, time scale for month, season, a year, years to hundreds of years. The average climate of 30 years reflects long-term climatic characteristic of cold, warm, dry, wet of a certain region. For the residents who long live in a certain region, they adapted the local climatic characteristics physiologically and psychologically. Therefore, the influence factors of the neutral temperature involved not only in the short-term outdoor climatic parameters people experienced, but also in the long-term mean climatic character. Based on the thermal comfort data of China, the neutral temperature is regarded as the dependent variable, and the long-term mean values of outdoor climatic parameters such as temperature, humidity, air speed, and solar radiation, which have an effect on the human thermal comfort, are regarded as the independent variable. The regression relationship of dependent variable and independent variable is analyzed by SPSS software.

2 Methodology

2.1 Thermal comfort data

To explore the relationship between the neutral temperature and long-term climatic parameters, the database of the neutral temperature and climate should be developed firstly. By reviewing the literature, the total number of papers on thermal comfort field study conducted in China reached 34 from 1993 (not including Hang Kong and Taiwan). The sample size of the field study of thermal comfort conducted by our team from 2006 is 6751. Other data came from the reports in publication. We developed the field study of thermal comfort database in China. The total sample size was 26107 (see appendix 1), which covered all typical climate of China (Figure 1(a)).

Qinling Mountain - Huaihe River is the regional and climatic divide line of the south and the north of China (Figure 1(b)). The climate of the north of this line is cold and dry, and the climate of the south is warm and humid. Thus, there is a significant difference between the climate of the north and south. The indoor and outdoor environmental stimulus intensity and duration vary with the south and the north of climate, which result in the different adaptation. The results of thermal comfort surveys are analyzed statistically to estimate the temperature at which the average survey participant will be comfortable, usually called "comfort temperature" or"neutral temperature", alternatively, the temperature at which the largest number of participants will be comfortable. The neutral temperatures of the south and north people are the reflection of their adaptation level.

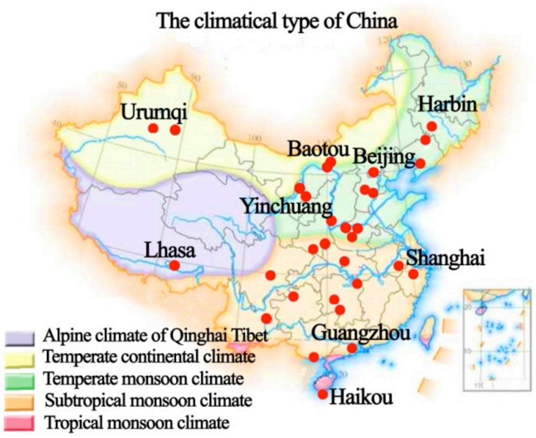

Figure 1(a). The thermal comfort field studies in China.

Figure 1(b). The division line of the north and south of China.

The neutral temperature of the database was the neutral temperature of the occupants of every season or every month in each survey. The effective sample size of the neutral temperature in our database is 85. The sample size of the neutral temperature in winter is 33, the sample size of the neutral temperature in winter is 38, and the sample size of the transition season is 14.

2.2 The longer-term outdoor climatic parameters (30 years)

The World Meteorological Organization prescribed that the shortest statistical period to determine the climatic characteristic of a region by means of the climatic parameters was 30 years. The 30 years climatic parameters (including outdoor temperature, water vapour pressure, air speed, total solar radiation) from January 1st, 1997 to December 30th, 2000 were selected, which provided by the national meteorological information centre of China(Rajib Rana, et al., 2013). The long-term meteorological parameter referred to the mean value of the outdoor meteorological parameters in 30 years during the survey period (winter, summer, or the transient season).

3 Results

3.1 The relationship between the neutral temperature and the long-term outdoor temperature

The strong linear relationship between the neutral temperature and outdoor prevailing temperature is the most important productions in field study of thermal comfort, which is confirmed in the following surveys of thermal comfort. The relationships between the neutral temperature of the south and north people and the corresponding long-term outdoor mean temperature in winter or in summer were regressed. The scatter point and the regression line are as shown in Figure 2.

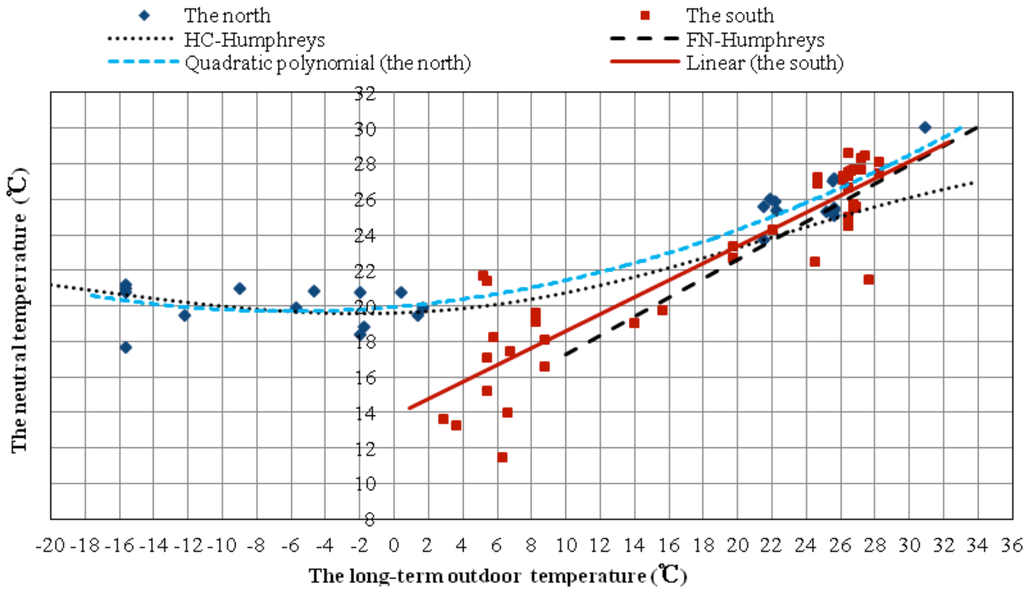

Figure 2. The relationship between the neutral temperature of the north and south people and the long-term outdoor temperature.

In the south region, there is a strong linear relationship between the neutral temperature and the long-term outdoor temperature, but in the north region, there is a second degree polynomial relationship between them. The regression equations of different regions are shown in Eq. (1) and Eq. (2).

The south: $T_n=0.477T_{a,out\_30}+13.8129$ R=0.9041 P<0.001 （1）

The north: $T_n=0.007T_{a,out\_30}^2+0.083T_{a,out\_30}+19.94$ R=0.9524 P<0.001（2）

Where, T_n is the neutral temperature (°C), T_{a,out_30} is the long-term outdoor temperature (°C).

This was due to the different climate conditions and building operation mode between the south and the north of China. The north of China has a cold winter; the northern buildings are provided the heat by the district heating or other heating methods in order to satisfy the essential thermal comfort requirement. Therefore, the neutral temperatures of the north people in winter are higher than those of the south of people, and which are weaker relationship with the outdoor temperature. Either the winter or the summer in the south of China, in most of time, the buildings are the free-running mode. Thus, the neutral temperatures of the south of China have a strong linear relationship with the outdoor temperature.

Fig. 2 also shows that, the season temperature difference between the summer and the winter in the north region is higher than that of the south region, but the difference of the neutral temperature between the summer and the winter in the north region is lower than that of the south region. In winter, the neutral temperatures of the north region are higher than those of the south region, but the neutral temperatures of the north region in summer are close to those of the south region. The regression coefficient of the adaptive thermal comfort model of free-running buildings developed by Humphreys in 1975 was 0.534/K, and the regression coefficients of the adaptive thermal comfort models based on ASHRAE and SCATs database were 0.31/K and 0.33/K, respectively. Compared with the above results, the sensitivity of neutral temperature to the outdoor temperature (0.477/K) is lower than that of Humphreys model, but higher than that of ASHRAE model and SCATs model.

3.2 The relationship of the neutral temperature and long-term outdoor climatic parameters

3.2.1 (1) The northern region

The neutral temperatures of the occupants in summer and winter of the north region were taken as the dependent variable, and the responding month mean values of long-term outdoor climatic parameters were taken as the independent variable. The relationship between the dependent variable and independent variable was estimated by four functions: linear function, quadratic function, power function and exponential function. The summary of the model and the estimation value of parameters are as shown in Table 1 and Figure 3.

Table 1 shows that the relationship between the neutral temperature of the northern people and the long-term outdoor temperature, water vapour pressure, and solar radiation all reach statistical significance in the five function relationship ($P<0.001$). Among the five functions, the linear and quadratic curve equation fitted better. Thus, it was selected to describe the relationship between the neutral temperature and long-term outdoor meteorological factors (temperature (T), water vapour pressure (V) and solar radiation (R)). However, there was no statistical significance between the neutral temperature of northern people and long-term outdoor air speed ($P>0.05$).

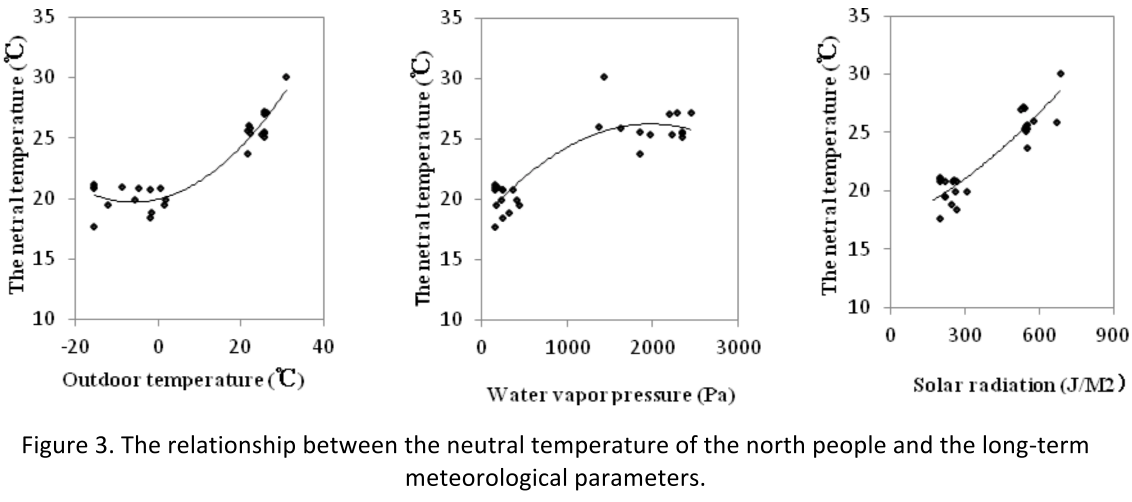

Figure 3. The relationship between the neutral temperature of the north people and the long-term meteorological parameters.

Table 1. The model summary and estimation value of the parameters between the neutral temperature and each of outdoor meteorological parameters.

Outdoor climatic parameters	function	Model summary					Estimation		
		R^2	F	df1	df2	P	Constant	b1	b2
Air temperature	Linear	0.8008	100.5	1	25	<0.001	21.4474	0.1791	
	Quadratic	0.9077	117.9	2	24	<0.001	19.9433	0.0826	0.0067
	Power[a]	—	—	—	—	—	0.0000	0.0000	
	Exponential	0.7977	98.5	1	25	<0.001	21.2784	0.0078	
Water vapor pressure	Linear	0.7453	73.1	1	25	<0.001	19.5426	0.0308	
	Quadratic	0.8015	48.4	2	24	<0.001	18.3242	0.0799	-0.0002
	Power	0.7633	80.6	1	25	<0.001	14.3109	0.1108	
	Exponential	0.7566	77.7	1	25	<0.001	19.5611	0.0014	
Air speed	Linear	0.0533	1.4	1	25	0.2467	25.6793	-1.1344	
	Quadratic	0.1259	1.7	2	24	0.1988	19.6732	4.9502	-1.3816
	Power	0.0130	0.3	1	25	0.5713	23.5208	-0.0432	
	Exponential	0.0486	1.2	1	25	0.2692	25.4411	-0.0471	
Solar radiation	Linear	0.8539	146.1	1	25	<0.001	15.7859	0.1802	
	Quadratic	0.8563	71.4	2	24	<0.001	17.2134	0.0961	0.0010
	Power	0.8275	119.9	1	25	<0.001	8.0141	0.2906	
	Exponential	0.8490	140.5	1	25	<0.001	16.6441	0.0078	

Note: a. the independent variable (the monthly mean air temperature in winter) contains non-positive values, so the log and power function can't be calculated. The significant level P=0.05.

3.2.2 (2) The southern region

The same data proceeding method was used to analyze the relationship between the neutral temperature and each of long-term outdoor meteorological parameters in the southern region. The analysis results were summarized in Table 2 and Figure 4. The relationships between the neutral temperature of the southern people and each of the outdoor temperature, water vapour pressure, and solar radiation were statistical significance (P<0.001). Among the five functions, the linear and the quadratic curve equation fitted better. There was no statistical significance between the neutral temperature of the southern people and the long-term outdoor air speed (P>0.05).

The single factor analysis revealed that the long-term outdoor temperature, water vapour pressure and solar radiation affected the neutral temperature. Moreover, the linear and quadratic curve equation fitted better.

Table 2. The model summary and estimation value of the parameters between the neutral temperature and each of outdoor meteorological parameters.

Outdoor parameters	Function relation	Model summary					The estimate parameters		
		R^2	F	df1	df2	P	constant	b1	b2
Air temperature	Linear	0.8174	174.5	1	39	<0.001	13.8129	0.4772	
	Quadratic	0.8180	85.4	2	38	<0.001	14.3643	0.3727	0.0032
	Power a	0.7753	134.6	1	39	<0.001	9.6617	0.3035	
	Exponential	0.7847	142.1	1	39	<0.001	14.3695	0.0231	
Water vapour pressure	Linear	0.8099	166.1	1	39	<0.001	13.5779	0.0473	
	Quadratic	0.8175	85.1	2	38	<0.001	11.2949	0.0834	-0.0001
	Power a	0.7838	141.4	1	39	<0.001	3.6997	0.3505	
	Exponential	0.7649	126.9	1	39	<0.001	14.2580	0.0023	
Air speed	Linear	0.0243	1.0	1	39	0.3300	20.2331	1.1919	
	Quadratic	0.0245	0.5	2	38	0.6241	19.6433	1.8306	-0.1555
	Power a	0.0230	0.9	1	39	0.3440	20.5435	0.1072	
	Exponential	0.0173	0.7	1	39	0.4118	19.9210	0.0496	
Solar radiation	Linear	0.6416	69.8	1	39	<0.001	11.5470	0.2901	
	Quadratic	0.6486	35.1	2	38	<0.001	14.9702	0.0451	0.0036
	Power a	0.5702	51.7	1	39	<0.001	5.1000	0.4113	
	Exponential	0.6190	63.4	1	39	<0.001	12.8620	0.0141	

Note： The significant level P=0.05.

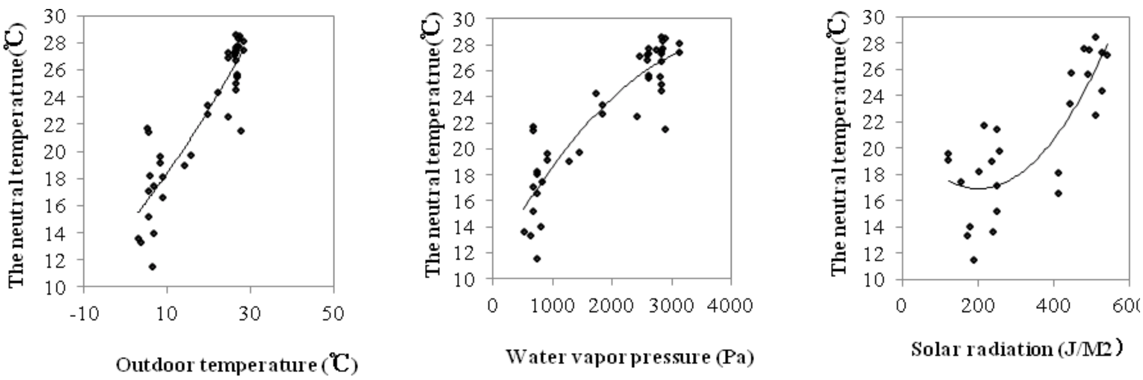

Figure 4. The relationship between the neutral temperature of the south people and the long-term meteorological parameters.

3.3 Screening of outdoor meteorological factors affecting the neutral temperature

Due to the correlation between the dependent and multiple independent variables, it is possible to carry out the multivariate analysis between them. Statistical test revealed that the correlations between the independent variables (outdoor meteorological factors) were significant at the 0.01 level (2-tailed), which resulted in the inaccuracy of estimation model. The multiplicity stepwise linear regression method can be used to screen the most influential variable on the dependent variable and exclude the less influential variable, when there is multicollinearity between the independent variable. So, the multiplicity stepwise linear regression method was selected to carry out the multivariate analysis between the neutral temperatures and outdoor meteorological factors.

The multiplicity stepwise linear regression method required a linear relationship between the dependent and independent variable. However, the quadratic curve function between the neutral temperature and the outdoor meteorological factors (T, V, R) fitted better than the linear regression. So, the quadratic curve function should be converted into linear function.

$$Y = A + BX + CX^2$$

Make $X_1 = X$, $X_2 = X^2$, the unary quadratic model can be converted into the binary linear model:

$$Y = A + BX_1 + CX_2$$

Thus, the quadratic function between the neutral temperature and the three independent variables (T, V, R) converted into the linear function between the neutral temperature and the six independent variable (T, V, R, T^2, V^2, R^2).

The multiplicity stepwise linear regression method was used to determine the importance order of the six independent variables influenced on the neutral temperature. The results were as shown in Table 3. The order of importance of long-term outdoor meteorological factors affected the neutral temperature of the northern people were temperature square (T^2), solar radiation (R), solar radiation square (R^2) and temperature (R). The order of importance of long-term outdoor meteorological factors affected the neutral temperature of the southern people were temperature (T), water vapour pressure (P), temperature square (T^2) and water vapour pressure square (P^2). The above results suggested that, the most important influence factor on the neutral temperature was outdoor temperature. From the view point of long-term average climate, apart from outdoor temperature, the main influence factor affected the neutral temperature of the northern people was solar radiation, and the main influence factor affected the neutral temperature of the southern people was water vapour pressure. This is due to the different climatic features of the north and south of China. The north of China is arid and rainless, and intense solar radiation, and the south of China is high temperature and humid. So outdoor temperature and solar radiation were chose as the independent variables influence on the neutral temperature of the northern people, and outdoor temperature and water vapour pressure were chose as the independent variables influence on the neutral temperature of the southern people.

Table 3. the screening the importance rank of long-term outdoor meteorological factors influential on the neutral temperature.

Different regions	The independent variable	Regression method	Screening independent variable
North	T, P, R, T^2, P^2, R^2	Multiple of linear stepwise	T^2、R
	T, P, P^2, R^2		R^2
	T, P, P^2		T
South	T, P, R, T^2, P^2, R^2		T
	P, R, T^2, P^2, R^2		P
	R, T^2, P^2, R^2		T^2
	R, P^2, R^2		P^2

3.4 The double factors adaptive model of the neutral temperature

To develop the double factors adaptive model between the neutral temperature and outdoor meteorological factors, a suitable model should be considered.

Nonlinear regression analysis is the statistical method of nonlinear correlation model to explore the dependent variable and a set of independent variables, the estimated parameters are obtained by a iterative approach, which can estimate model with the arbitrary relationship between the dependent and independent variable based on their own specific forms. Because there were significant binary curve relationships between the neutral temperatures and outdoor temperature, water vapour pressure, and the solar radiation, moreover, there was a cross influence between the independent variables (the outdoor temperature, water vapour pressure, and solar radiation). So we developed the nonlinear regression equation between the neutral temperature and outdoor meteorological factors. When the nonlinear regression analysis is developed, the first step is to determine the exact function relationship between the dependent and independent variable. From the analysis of section 3.2, there were significant relationships between the neutral temperature and outdoor temperature, water vapour pressure, and solar radiation. Moreover, there was the cross influence of independent variable impacted on the neutral temperature. Thus, we developed the nonlinear regression equations of the neutral temperature and outdoor meteorological parameters (Eq. 1 and Eq. 2)

The north： $T_n = a + bT_{30} + cR_{30} + dT_{30} \times R_{L30} + eT_{30}^2 + fR_{30}^2$ （1）

The south： $T_n = a + bT_{30} + cP_{30} + dT_{30} \times P_{30} + eT_{30}^2 + fP_{30}^2$ （2）

Where, T_n is the neutral temperature（°C），T_{30} is the corresponding long-term outdoor temperature of the winter or summer (the period: 1970~2000）（°C），R_{30} is the corresponding long-term outdoor solar radiation of the winter or summer (the period: 1970~2000）（0.01MJ/M^2），V_{30} is the corresponding long-term outdoor water vapour pressure of the winter or summer (the period: 1970~2000）（0.1hPa）.

The double factors models of the neutral temperature were estimated by nonlinear regression analysis with SPSS soft. The summary of estimated parameters and ANOVA are shown in Table 4 and the regression equations are equation (3) and (4).

Table 4. The estimated parameters and analysis of variance table of multivariate nonlinear regression model

region	The estimated parameters					ANOVA				
	parameters	estimation	Standard error	95% confidence interval			Sum of square	df	R	R^2
				Lower limit	Upper limit					
North	a	18.4276	6.90	4.08	32.78	regression	14464.8	6	2410.8	0.9159
	b	-0.1256	0.54	-1.26	1.01	residual	24.79	21	1.18	
	c	0.0905	0.45	-0.85	1.03	Uncorrected total	14489.6	27		
	d	0.0061	0.02	-0.03	0.04	Corrected total	294.85	26		
	e	0.0021	0.01	-0.02	0.02					
	f	-0.0013	0.01	-0.02	0.01					

South	a	12.6135	3.81	4.87	20.35	regression	21941.8	6	3656.9	0.8203
	b	0.2831	0.69	-1.11	1.67	residual	182.61	35	5.22	
	c	0.0354	0.10	-0.17	0.24	Uncorrected total	22124.4	41		
	d	-0.0059	0.02	-0.05	0.04	Corrected total	1016.16	40		
	e	0.0273	0.11	-0.19	0.24					
	f	0.0003	0.00	0.00	0.00					

The north：

T_n=18.4276－0.1256T_{L30}+0.0905R_{L30}+0.0061T_{L30}×R_{L30}+0.0021T_{L30}^2－0.0013R_{L30}^2（3）

The south：

T_n=12.6135+0.2831T_{L30}+0.0354P_{L30}－0.0059T_{L30}×P_{L30}+0.0273T_{L30}^2+0.0003P_{L30}^2 （4）

3.5 Comparison with the different models

The goodness of fit of the single factor model (outdoor temperature) and the double factors model of the neutral temperature (North: outdoor temperature and solar radiation; South: outdoor temperature and water vapour pressure) were compared with each other by the following evaluation index, for example, determination coefficient (R^2), adjusted determination coefficient R_{adj}^2, estimate of the standard residential error (see Table 5).

Table 5. Comparison with the goodness of fit of different estimated model.

Different regions	Evaluation index	Single factor model	Double factor model
The north	determination coefficient (R^2)	0.8008	0.9159
	Adjusted determination coefficient R_{adj}^2	0.7929	0.8949
	Estimate of the standard residential error	2.1815	1.0865
The south	determination coefficient (R^2)	0.8174	0.8203
	Adjusted determination coefficient R_{adj}^2	0.8145	0.7946
	Estimate of the standard residential error	2.1815	2.2842

In the north region, the determined coefficient (R^2) and adjusted determination coefficient (R_{adj}^2) of the double factors model are greater than those of the single factor model, the estimate of the standard residential error of the double factors model is less than that of the single factor model. The above three evaluation indexes show that the goodness of fit of the double factor model is better than that of the single factor model. But in the south region, the determine coefficient of the double factor model is greater than that of the single factor model, and the other evaluation indexes can’t explain that the goodness of fit of the double factors model is better than that of the single double factor model. It shows that the predicted results of the two models are similar to.

4 Conclusions

1) There were significant relationships between the neutral temperature of Chinese and long-term (30 years) outdoor temperature, water vapour pressure, and the solar radiation.

2) In terms of the linear conversion and multiple stepwise linear regression analysis, the two importance influence variables impacted on the neutral temperature were screened. They were the outdoor temperature and solar radiation in the north region, but outdoor temperature and water vapour pressure in the south region.

3) The estimated model between the neutral temperature and the two outdoor meteorological factors were developed by mean of the multiple nonlinear regression method. The estimated results of the double factor models were more accurate than that of the single factor model.

Acknowledgements

The work is supported by the National Natural Science Foundation of China (Project No. 51408198, 51408479, 51325803), the Project of Science and Technology Department in Henan Province (162102310421), and the China Postdoctoral Science Foundation (2015M570818). The authors are grateful to the occupants for their kindness and generosity in allowing the field survey to be conducted in their living quarters. The authors would also thank their students for their help with the data gathering and analysis.

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The database of national meteorological information center of China, http://cdc.cma.gov.cn.

Appendix 1

Source of original thermal comfort database in China

Serial number	Researcher	Survey area	Building type	Season	Heating mode	Location	No. of sample
1	Yan H.(2013)	Baotou	Residences	Winter	District heating	North	377
2	Yan H.(2013)	Yinchuan	Residences	Winter	District heating	North	519
3	Yan H.(2013)	Jiaozuo	Residences	Winter	District heating	North	702
4	Yan H.(2013)	Xi'an	Residences	Winter	District heating	North	153
5	Mao Y. (2007)	Harbin, Changchun, Shenyang	Residences	Winter	District heating	North	30
6	Mao Y. (2007)	Beijing, Zhengzhou, Xi'an	Residences	Winter	District heating	North	30
7	LI J.(2007)	Nanyang	Residences	Winter	District heating	South	Total276
8	Wang Z.(2003)	Harbin	Residences	Winter	District heating	North	120
9	Tan F.(1993)	Harbin	Offices	Winter	Intermittent district heating	North	141
10	He H.(2007)	Harbin	Classrooms	Winter	District heating	North	643
11	Su Q.(2009)	Urumchi	Offices	Winter	District heating	North	60
12	Cao B.(2011)	Beijing	Classrooms and offices in the campus	Winter	District heating and/Fan coil system	North	124
13	Lv F.(2000)	Tianjin	Residences and offices	Winter	District heating	North	74
14	Yang S.(2007)	Harbin	Classrooms in campus	Winter	District heating	North	396
15	Yan H.(2013)	Jiaozuo	Residences	Winter	Coal furnace \Electric heater\Air conditioner	North	189
16	Yan H.(2013)	Lhasa	Residences	Winter	Coal furnace\Electric heater\Air conditioner	North	357
17	Yan H.(2013)	Kunming	Residences	Winter	No heating measures	South	422
18	Li J.(2007)	Nanyang	Residences	Winter	Coal furnace\Electric heater\Air conditioner	South	Total276
19	Mao Y. (2007)	Nanjing, Chongqing, Shanghai	Residences	Winter	Coal furnace\Electric heater\Air conditioner	South	30
20	Mao Y. (2007)	Nanning, Guangzhou, Haikou	Residences	Winter	No heating measures	South	30

21	Su Q.(2009)	Changsha	Classrooms in campus	Winter	No heating measures	South	Total 301
22	Ye X.(2009)	Wuhan	Classrooms in campus	Winter	No heating measures	South	1725
23	Han J.(2007)	Changsha	Residence，Classrooms in campus	Winter	Coal furnace\Electric heater\Air conditioner	South	53
24	Liu H.(2009)	Chongqing	Residences and offices	Winter	Coal furnace\Electric heater\Air conditioner	South	220
25	Liu J.(2007)	Chongqing	Classrooms in campus	Winter	No heating measures	South	Total 3621
26	Li B.(2007)	Chongqing	Classrooms in campus	Winter	No heating measures	South	-
27-29	Ye X.(2005)	Shanghai	Residences, classrooms in campus	Winter	Coal furnace\Electric heater\Air conditioner	City	Total 1768
30	Zheng L.(2011)	Nanning	Offices	Winter	Air conditioner heating	South	239
31	Mao H.(2010)	Chengdu	Residences	Winter	Natural ventilation	South	Total 1737
32	Wang W.(2010)	Kunming	Residences	Winter	Natural ventilation	South	200
33－35	Liu J.(2007)	Chongqing	Classrooms in campus	Winter	No heating measures	South	Total 3621
36	Yan H.(2013)	Hanzhong	Rural house	Winter	Coal furnace\Electric heater	South	258
37	Yan H.(2013)	Weinan	Rural house	Winter	Electric heater\Coal furnace\	North	198
38	Han J.(2007)	Yueyang	Rural house	Winter	Natural ventilation	South	50
39	Jian Y.(2010)	Beijing	Rural house	Winter	No heating measures	North	-
40	Jian Y.(2010)	Beijing	Rural house	Winter	Kang /Coal furnace	North	-
41	Yan H.(2013)	Turpan	Rural house with Kang	Winter	Kang	North	199
42	Huang L.(2010)	Beijing	Rural house	Winter	Coal furnace	North	227
43	Cao G.(2011)	Shenyang	Rural house with Kang	Winter	Kang	North	-
44	Yan H.(2013)	Baotou	Residences	Summer	Natural ventilation	North	357
45	Yan H.(2013)	Yinchuan	Residences	Summer	Natural ventilation	North	462

46	Yan H.(2013)	Lhasa	Residences	Summer	Natural ventilation	North	193
47	Yan H.(2013)	Kunming	Residences	Summer	Natural ventilation	South	533
48	Mao Y.(2007)	Harbin, Changchun, Shenyang	Residences	Summer	Natural ventilation	North	30
49	Mao Y.(2007)	Beijing, Zhengzhou, Xi'an	Residences	Summer	Natural ventilation	North	30
50-52	Liu J.(2007)	Chongqing	Classrooms in campus	Summer	Natural ventilation	South	Total 3621
53	Ji X.(2004)	Jiangsu and Zhejiang	Public buildings	Summer	No-Air conditioner environment	South	1814
54	Lv F.(2000)	Tianjin	Residences and offices	Summer	Natural ventilation	North	Total 210
55	Xia Y.(1999)	Beijing	Residences	Summer	Natural ventilation	North	88
56	Han J.(2007)	Changsha	Residences	Summer	Natural ventilation	South	48
57	Zhang Y.(2010)	Guangzhou	Classrooms\dormitory in campus	Summer	Natural ventilation	South	501
58	Yang W.(2007)	Changsha\Wuhan\Jiujiang\Nanjing\Shanghai	Residences	Summer	Natural ventilation	South	129
59-60	Ye X.(2009)	Shanghai	Residences	Summer	Natural ventilation	South	Total1768
61	Guo X.(2011)	Harbin	Classrooms in campus	Summer	Natural ventilation	North	135
62	Luo M.(2005)	Chongqing	Classrooms in campus	Summer	Natural ventilation	South	-
63－66	Wu J.(2005)	Chongqing	Classrooms in campus	Summer	Natural ventilation	South	555
67	Su Q.(2009)	Changsha	Classrooms in campus	Summer	Natural ventilation	South	Total301
68	Mao H.(2010)	Chengtu	Residences	Summer	Natural ventilation	South	Total1737
69	Wei W.(2010)	Kunming	Residences	Summer	Natural ventilation	South	200
70	Yan H.(2013)	Hanzhong	Rural house	Summer	Natural ventilation	South	287
71	Yan H.(2013)	Weinan	Rural house	Summer	Natural ventilation	North	103
72	Yan H.(2013)	Turpan	Rural house	Summer	Semi outdoor space	North	273
73	Han J.(2007)	Yueyang	Rural house	Summer	Natural	South	81

					ventilation		
74	Wang Y.(2009)	Chengdu	Rural house	Summer	Natural ventilation	South	42
75—78	Ye X.(2009)	Shanghai	Residences	Summer	Natural ventilation	South	Total1768
79	Mao Y.(2007)	Nanjing, Chongqing, Shanghai	Residences	Summer	Air conditioner， Natural ventilation	South	30
80	Mao Y.(2007)	Nanning, Guangzhou, Haikou	Residences	Summer	Air conditioner， Natural ventilation	South	30
81	Yan H.(2013)	Xi'an	Residences	Summer	Air conditioner, natural ventilation	North	80
82	Li J.(2007)	Nanyang	Residences	Summer	Air conditioner and natural ventilation	South	1320
83	Liu H.(2009)	Chongqing	Residences and offices	Summer	Air conditioner \Natural ventilation	South	210
84	Yan H.(2013)	Jiaozuo	Residences	Summer	Air conditioner \Natural ventilation	North	1089
85	Lv F.(2000)	Tianjin	Residences and offices	Summer	Air conditioner and Natural ventilation	North	Total 210
86	Lv F.(2000)	Tianjin	Residences and offices	Summer	Air conditioner and Natural ventilation	North	Total 210
87	Yang W.(2007)	Changsha\Wuhan\Jiujiang\Nanjing\Shanghai	Residences	Summer	Air conditioner	South	100
88—89	Su Q.(2009)	Changsha	Classrooms in campus	Transitional season	Natural ventilation	South	Total 301
90	Yang W.(2007)	Changsha	Classrooms and dormitory in campus	Transitional season	Natural ventilation	South	-
91	Zhang L.(2010)	Harbin	Classrooms in campus	Yearly		North	1285
92—97	Liu J.(2007)	Chongqing	Classrooms in campus	Transitional season	Natural ventilation	South	Total 3621
98—108	Ye X.(2009)	Shanghai	Residences	Transitional season	Natural ventilation	South	Total 1768
108							25684

Note: "Total……" , represent the sum total of the sample sizes of winter and summer, or the sum total of all year sample sizes.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Cooling Effect of a Mist Fan for Large Indoor Spaces

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Abstract

Large indoor workspaces such as factories can become dangerously hot during summer. Japan's safety standard for work in hot environments (based on ISO 7243) requires long work breaks, reducing productivity. The large air volume makes standard air conditioning too costly. Water mist for local evaporative cooling of workspaces can be used in the large space with little worry of saturation. Mist nozzles mated with an oscillating fan spreads and aids the cooling effect.

An oscillating mist fan system, spraying 86L/h was tested in summer in a 40,000m^2 factory space in Japan. The temperature decrease and humidity increase ranged at about 0.2–1.9K and +5-10% respectively inside the misted area. A heated skin analogue with heat flux sensors measured the cooling effect of the mist and fan throughout the cooled area. The cooling effect with mist is compared to the fan alone. When oscillating, the mist and fan yielded an average of 17-26W/m^2 more cooling than the fan alone. This data is used to develop a mist cooling comfort model, adapting the "cooling effect" due to air speed in ASHRAE 55-2013 to include the mist effect.

Keywords: Evaporation, Mist, Fan, Cooling, Standards

1 Background

Air conditioning of factories, warehouses and large spaces can be expensive. On summer days, many factors such as lack of insulation, a metal roof and walls being heated by sunlight, or waste heat from machinery can lead to the indoor work environments that cause thermal stress hazardous to health. Doorways for workers and vehicles may be left open during the day, making standard air conditioning impractical. For safety, workers may be required to wear long-sleeved work clothes, helmets, and the like, increasing their thermal load. The occurrence of heat stroke increases exponentially at high temperatures. (Miyatake et al. 2013) Standards applicable to worker safety such as ISO 7243 and 7933 characterize the heat stress and require increasingly longer rest breaks or cessation of work entirely at increasing levels of thermal stress, which reduces productivity.

Water mists can be used to provide outdoor cooling on hot summer days at a low energy cost even in relatively humid climates such as Japan. In single-fluid (hydraulic) mist spray systems, water is pressurized and sprayed through nozzles to create fine droplets. Each nozzle commonly sprays on the order of liters per hour. Fine droplets with diameters on the order of microns or tens of microns tend to not "break" on contact with a surface, but rather rebound, thus reducing wetting.

Even in sub-tropical climates, such as much of Japan, the droplets evaporate quickly enough that it is easy to position the nozzles such that surfaces in the cooled space will not be wetted.

The latent heat of evaporation of the droplets, which causes the cooling effect, is well over 100 times the electricity consumption of the pump used here. The major drawback is that evaporation also increases humidity. Further, the lower limit of the temperature reduction is to the wet bulb temperature. In outdoor and semi-enclosed spaces such as shopping arcades and stadiums, the natural ventilation of fresh air can help prevent the misted space from becoming saturated with water vapor. However, if a hydraulic mist nozzle is used indoors, a small space could quickly reach 100% humidity if even a single spray nozzle is used constantly, unless the air exchange rate was high enough to compensate.

In this research, mist nozzles that spray droplets with a Sauter mean diameter of 25 microns are combined with a large oscillating fan used as localized cooling for workspace areas in a factory warehouse with floor space of about 40,000m^2, air volume of over 500,000m^3 and no internal walls dividing the space. The large volume and many open doors make the factory similar to an outdoor or semi-enclosed space. The oscillation of the fan aids circulation of the air, preventing a local buildup of humid air in the targeted space. Even if the warehouse has no ventilation, it is expected that the humidification effect of the mist averaged across the building will not approach saturation even after several hours of continuous use.

The system used here is optimized such that a single high-pressure water pump can supply 6 such mist fans. In Table 1, the system specifications and running costs are based on a 6-fan, 1-pump system. Using fewer nozzles than the pump capacity can supply would reduce the overall efficiency of the system.

The experimental goal was to measure the local cooling and humidification effect of the mist fan over the targeted space. Calculating the rate at which indoor humidity increases as a function of air exchanges and mist spray rate allows selection of a mist fan of appropriate spray capacity as well as permissible duration of spraying to avoid exceeding a chosen humidity level.

Table 1 Specifications of the mist fan system

Spray rate (6 fans, 192 nozzles)	0.51m^3/h
Fan air output (per fan)	320m^3/min
Fan diameter	0.60m
Average droplet diameter (Sauter)	25µm
Water pump pressure	6MPa
Water pump electric consumption	1.5kW
Fan electric consumption (6fans)	11.4kW
Fan oscillating angle, period	60°, 50s
Automated-stop control option	Stop at RH>70%
Floor area to be cooled (6 fans)	Approx. 4000m^2
Electricity cost (Tokyo, weekday peak, corporation rate)	Approx. 20yen/kWh
Water cost (Tokyo, tap water, over 1000m^3/month)	Approx. 400yen/m^3
1-day running cost (8 hours, water + electric)	Approx. 3660yen (US$30)

1.1 Mist evaporation

Water mist droplets in non-saturated air evaporate, exchanging latent heat for sensible heat from the air. The droplet surface reaches a surface temperature within +/-0.5˚C of the wet bulb temperature within about 1 microsecond in typical atmospheric conditions (Pruppacher and Klett, 1997). Further, their small mass allows the entire droplet temperature to reach the wet bulb temperature while the effect of air resistance decelerates the droplets to near-zero velocity relative to surrounding air within tens of microseconds. These nearly-instantaneous temperature and speed effects can be calculated iteratively as outlined in the work of Chaker et al. (2002) and Holterman (2003). Thus mist droplets can be assumed as being at near wet bulb temperature and relative air velocity of zero.

The speed of evaporation of a droplet in still air is calculated by assuming that water vapor is an ideal gas, which evaporates at a rate proportional to the difference in its density between the droplet surface and the environment air. The droplet surface is a saturated state at the wet bulb temperature of the environment, such that the change in droplet radius, r over time can be expressed as,

$$r\frac{dr}{dt} = \frac{\Delta T_{\mathrm{wb}} k}{L\rho_{\mathrm{w}}} \tag{1}$$

where ΔT_{wb} is the wet bulb depression, k is the thermal conductivity of moist air, L is the latent heat of evaporation of water, and ρ_{w} is the density of water. This can be integrated over time to find the approximate time to complete evaporation, t_{ev} for a single droplet.

$$t_{ev} = \frac{L\rho_{\mathrm{w}}}{\Delta T_{\mathrm{wb}} k} r^2 \tag{2}$$

Taking approximate values for properties of air and water at 25°C, L=2450kJ/kg, ρ_{w}=1000kg/m^3, k=0.025J/m s K and expressing drop size as diameter d^* in units of microns rather than meters, the approximate time for evaporation is,

$$t_{ev} = \frac{\left(d^*\right)^2}{80\Delta T_{\mathrm{wb}}} \tag{3}$$

with wet bulb depression in units of Kelvin. Thus, a 20 micron diameter droplet on a hot relatively dry day (35˚C, 45%RH, ΔT_{wb}=10K) the time to complete evaporation is about 0.5s, a 40 micron droplet would be about 2 seconds. However, this calculation assumes a single droplet in unchanging air conditions, as a mist cloud evaporates, ΔT_{wb} becomes smaller, reducing evaporation speed in inverse proportion to the change. Thus, even if the mist yields a relatively strong cooling to eventually reduce an air stream temperature halfway to the wet bulb temperature, the mist droplet evaporation time would be in a range between single droplet evaporation period and double that period. The 40 micron droplet maximum evaporation time would extend from 2s to something less than 4s. If the mist is carried by air currents or forced ventilation for a few seconds before reaching any wall or ground surface, there should be little of no wetting or pooling of water.

The cooling effect of mist is the transfer of the latent heat with sensible heat of air. There may also be a small effect from the sensible heat in the supply water itself as it changes to the wet bulb temperature. As the latent heat of evaporation of water at 25˚C is about 2450 kJ/kg, while the specific heat is about 4.2 kJ/kg K, then even a supply water temperature 30K above the wet bulb temperature would only cancel out about 5% of the evaporative cooling effect, and is thus ignored here. If the mist completely evaporates, the cooling effect to the air is thus approximately a balance between the temperature change of the air and the spray rate of the mist spray,

$$L m_{\mathrm{m}} = m_{\mathrm{a}} C_{\mathrm{P}} \left(T_{\mathrm{i}} - T_{\mathrm{c}}\right) \tag{4}$$

where m_m is the mist mass, m_a is the air mass with which the mist interacts, C_P is the specific heat of air, T_i is the initial temperature of the air and T_c is the final temperature of the cooled air. For this mist fan system, if the blown air were confined to a duct such that no other air were entrained into the flow, the evaporative effect would cool the air by about 9.0K, assuming the wet bulb depression is initially above 9.0K and complete evaporation occurs. In practice, the blown air and mist entrain other air into the flow, the effect diffuses, reducing the temperature drop, but also helping prevent saturation. Thus, entrainment can allow complete evaporation even if the wet bulb depression is not as large (in this case lower than 9.0K).

1.2 Evaporative cooling in a ventilated building

As nearly all mist droplets completely evaporate within a few seconds, when examining ventilation of the space on the time scale of hours, mist spray is assumed as an instantaneous source of water vapor with the same mass flow, F, as the nozzle spray rate. The transient mass flow balance of a ventilated room, assuming that the air density is constant and the water vapor is uniformly mixed through the air, is

$$M \frac{dY}{dt} = F + qY_{\mathrm{o}} - qY \tag{5}$$

where q is the constant ventilation mass flow rate into a room containing an unchanging mass of air M, where the mass fraction of water vapor of inside air is Y, and for outside air is Y_o.

In the case of misting with no ventilation, the mass fraction of water vapor increases linearly with time.

$$Y = Y_{\mathrm{i}} + \frac{F}{M} t \tag{6}$$

where Y_i is the initial mass fraction of water vapor before spraying.

In the case of constant-rate ventilation, the mass fraction of water vapor in the room for a steady-state at Y_s with continuous misting would be,

$$Y_{\mathrm{s}} = \frac{F}{EM} + Y_{\mathrm{o}} \tag{7}$$

where E is the room air exchange rate, $E = q/M$ (in terms of mass flow rather than volume flow). This assumes that q is sufficient to prevent Y_s from reaching the saturated state, which would prevent mist evaporation.

The water vapor mass fraction at any time for constant-rate ventilation and mist spraying from an initial condition with water vapor fraction Y_i, assuming the uniform mixing and no change in air density is,

$$Y = \frac{F}{EM} + Y_o - \left[\frac{F}{EM} + \left(Y_o - Y_i \right) \right] e^{-Et} \quad (8)$$

where t is elapsed time in hours. Thus the inverse of the air exchange rate is the time constant, τ of the system with the asymptotic limit as Eq.(7). The equation also yields Y for ventilation after misting stops by resetting Y_i and setting F to zero. Some deviation from the equations is expected from application because the mist spray changes the temperature and density of the indoor air, the water vapor is not perfectly mixed throughout the indoor space, and the ventilation rate itself and mass of moist air in the room is neither constant nor perfectly balanced, among other factors.

As an example, substitute the values for the full mist system here (all 6 mist fans) applied to the building in which the experiment was done, with an air temperature of 35˚C, humidity of 40% and natural ventilation at 0.3 air changes per hour, the total rise in water vapour mass fraction after 8 hours of continuous spray would be about 2.6g/kg moist air, yielding a new relative humidity of about 47%, assuming the air temperature remains stable.

1.3 Standards regarding heat stress and relation to mist

Various indices of thermal comfort and thermal load are not well-suited to evaluate mist cooling. They are not designed to handle the effect of added wetness to the skin or clothing from the mist droplets. Further, the fact that the enthalpy of air does not change in evaporative cooling can yield counter-intuitive results from models.

When the measured or theoretical air conditions resulting from mist cooling are input as parameters into thermal comfort models such as simple steady-state and two-node versions of PMV (Predicted Mean Vote) and ET* (New Effective Temperature), they yield relatively small changes. The wet bulb globe temperature (WBGT), which is the basis of the ISO (International Standards Organization) 7243 (1989) and the related JIS (Japan Industrial Standard) Z8504 standards governing work in hot environments (JISC, 1999), shows almost no change at all. The constant-enthalpy process of evaporation cooling is nearly the same as a constant-wet bulb temperature process on the psychrometric chart.

However, much research (Uchiyama et al. 2008, Kodama et al.,2006, Narita et al.,2013) shows people respond in great majorities that mist cooling in hot summer conditions yields increased thermal comfort. The models contradict the survey results.

The thermal comfort model as per ASHRAE 55(2013), which is based on a 2-node Pierce model, includes an evaluation in terms of a “cooling effect” which quantifies the effect of local air speed control. The heat balance and Pierce SET* temperature is evaluated for the air temperature, mean radiant temperature, increased air speed, humidity, metabolic rate and clothing level. Then the same condition is evaluated as if there were minimal air speed, setting air speed to 0.15 m/s, and a new resulting SET* temperature is calculated. Then the air temperature and mean radiant temperature are changed by the same amount until the resulting SET* is equal to that at the increased air speed. This amount is the “cooling effect”. If the change in the body heat balance due to use of a mist fan causing an increased heat flux beyond that of the fan alone is known, then it could be similarly incorporated into the “cooling effect” model as an additional heat flux term “E” in the heat balance, to yield the “cooling effect of mist” as in the diagram, Figure 1. If confirmed with human subjects, this could be a basis for application to a new standard that can handle the mist cooling effect where standards such as the WBGT index does not.

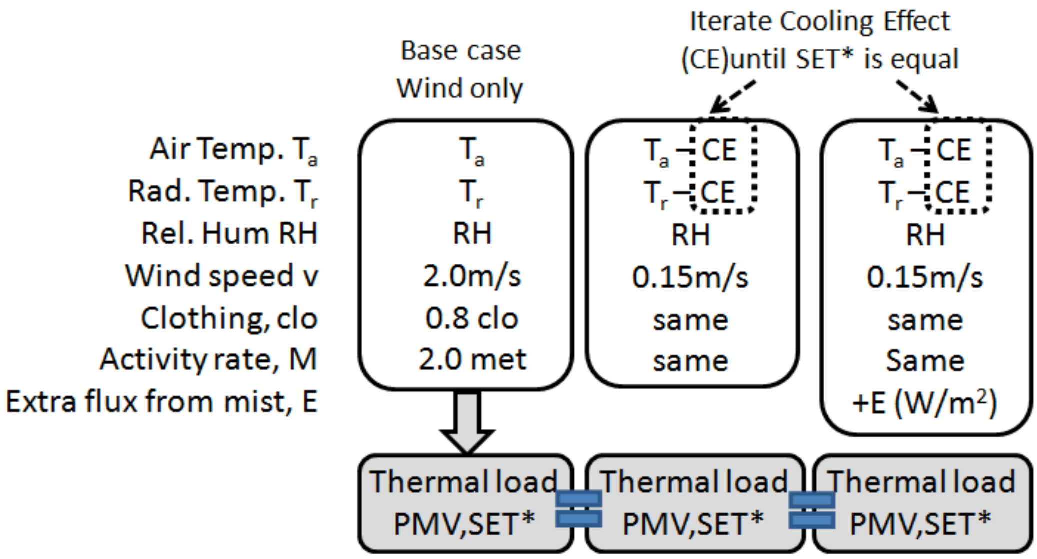


Figure 1. Diagram of the "Cooling effect" concept for air speed effect, then modified for mist

2 Experiment apparatus

In this experiment, the cooling and humidification effect of a single large mist fan was measured. The fan is mounted on a platform with the fan axis centered at 2.5m height. A circular header with 32 spray nozzles is mounted on the circumference of the fan outlet as shown in Figure 2. The air speed profile of the fan was measured along the centerline (see Figure 3) at 1.2m height at 5m intervals. The fan was fixed, and air speed measurements taken with a hot-wire anemometer. The values shown in Figure 3 are the max/min values. The fan can oscillate over a 60 degree span with a 50 second period. The fan can be tilted up and down. In these experiments, the fan was either set level with horizontal as 0˚, or with a slight downward tilt at -4˚.

Temperature and humidity sensors were set at 10 locations, 8 within the sprayed area, and 2 outside the sprayed area (one near the fan inlet and one at 15m distance perpendicular to the fan airflow) as a check on any changes in the indoor environment beyond the sprayed area, as shown in Figure 3. These were thermistors with capacitive film humidity sensors with built-in data loggers. Response time (90%) in still air is 7 minutes, though can be expected to respond faster due to the forced convection from the fan. These were set to log at 20-second intervals and referred to from here on as the "slow-response sensors".

T-type thermocouples made from 0.4mm single-core wire with solder beads averaging 1.1mm diameter were also mounted at each location, connected to an electronic data logger set to record at 1-second intervals. From here on these are referred to as the "fast-response sensors". In order to allow the mist to quickly affect them, they were not shielded as is typically recommended to prevent influence of radiant temperature. An additional T-type thermocouple was mounted inside a standard matte-black 15cm copper sphere to measure the globe temperature. It was placed at 1.2m height perpendicular to the air flow at a distance of 5m from the fan, outside the misted area.

To directly measure the cooling effect on a surface, a heated skin analogue was built. Four sheets of 0.4mm silicone rubber were stretched over the surface of a 1-liter water tank, including a rubber strip heater with temperature control. Two 5cm-square heat flux sensors were inserted between the sheets as shown in Figure 4. The water tank heater was set to 37˚C, which yielded a skin surface temperature of about 34-35˚C, similar to the human body.

Figure 2. Photo of mist fan while spraying (Note: fan diameter is 60cm)

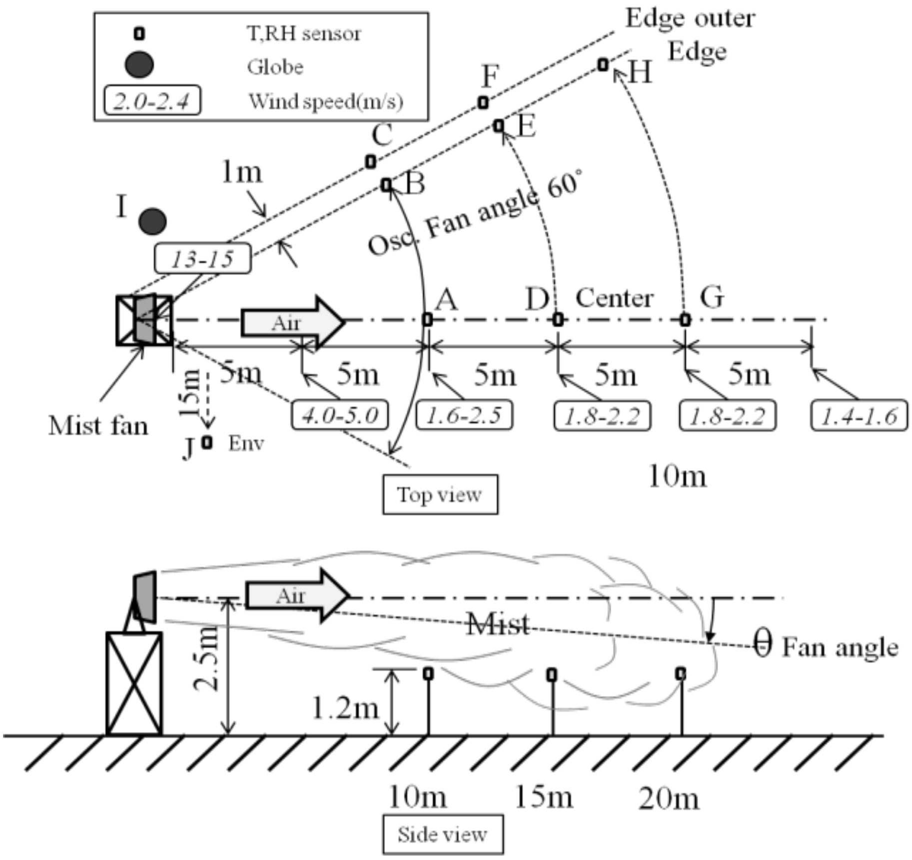
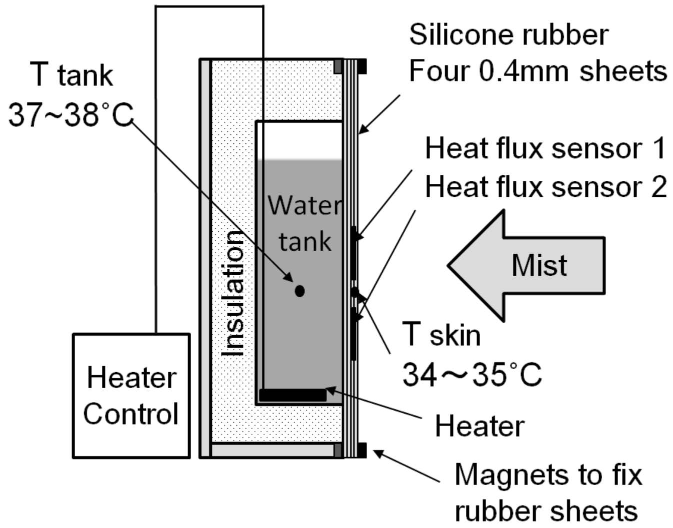


Figure 3. Experiment layout, measurement points and wind speed



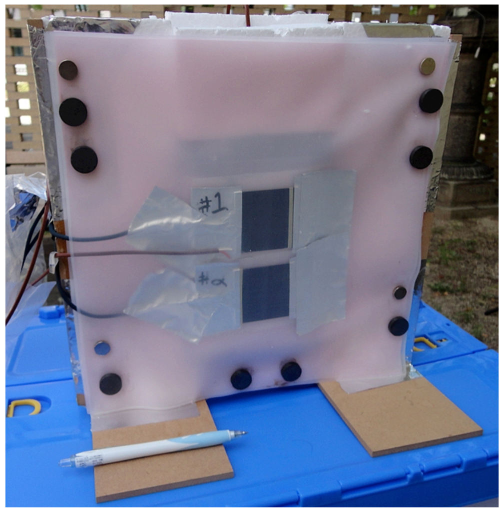


Figure 4. Cross-section diagram of heated skin analogue (L) Photo with pen in foreground for scale (R)

3 Experiment procedure

On-site trials were done at a factory warehouse and assembly area for prefabricated housing sections with dimensions of approximately 250m X 150m X 14m. Floors are concrete slab, covered with paint that had largely worn away. Walls and roof were non-insulated corrugated steel. Much of the space is storage for wood and steel parts, with some workstations with hand tools or small machine tools. Forklifts are used regularly, and large cargo vehicles regularly enter the space.

The system was already being used during work shifts, but experiments and measurement were not allowed during normal work hours. The trials were done on the weekend of Sept. 21-22, 2014 between the hours of 10:00AM and 4:00PM. There was no work activity within the test area, and minimal activity in the entire warehouse. Several large vehicle doors can accommodate trailer trucks, and are usually left open during working hours and were open during the trials. Windows near ceiling level were closed during the trials. The initial air temperature in the factory ranged over 26-29˚C and humidity from 30-45% during the test periods.

A 30-minute testing cycle as shown in Figure 5 was repeated for 16 trials. During the short break between each 30-minute trial, the skin analogue rig was moved to a different position. The short spans of misting allowed the rig to recover to a steady state. The short spans were intended to test the “recovery time” of the room air after stopping the mist, and to avoid the risk of saturating the indoor air and requiring the entire experiment be aborted to wait for the air conditions to recover. Further, the changes in outdoor air (and thus indoor environment) temperature and humidity over the span of the day from morning to afternoon could easily become a confounding factor when determining the effect of the mist on air conditions. (i.e. If a mist spray trial were run continuously from 10:00AM to 1:00PM, while the outdoor and indoor temperature slowly rose by 3K, given that the mists used here typically yield a temperature decrease on the order of 1-2K, it would be difficult to determine the mist cooling effect over the entire period.)

The effect of the fan only and fan with mist were measured in each trial, with the expectation that fan only periods would serve as a control case, yielding no significant change in temperature or humidity. The fan was set to oscillate for 12 trials, and fixed for 4 trials. The fan was set at a 0˚ tilt for 12 trials and at a -4˚ (downward) tilt for 4 trials.

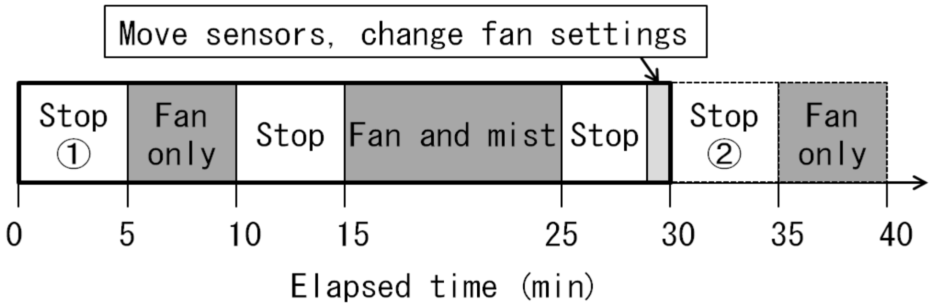


Figure 5. Experiment procedure schedule

4 Results

The mist caused measurable temperature drops and humidity increases. As expected, humidity and temperature did not significantly change during the fan-only periods. An example of this is in the sensor data in Figure 6, which shows the measurements along the fan centerline (points A,D,F). Temperature drops by up to about 1.5K while humidity rises by about 5%. However, the slow response of the sensors may be a factor. The quick-response sensors only measure temperature. They clearly show the temperature dropping and recovering to nearly the initial temperature as the fan oscillates, as in the example data in Figure 7. This fast-response data was used to calculate an average temperature drop ΔT_{avg} over each misting period and the average maximum temperature drop ΔT_{max} of the peaks as the mist cloud passes over each sensor. These results are in Table 2. The example data also illustrates the calculation method of interpolating between the temperature before and after misting as what the temperature would have been without mist. The average cooling is the difference between that interpolated value and the average measured temperatures. When oscillating, the period when there is no mist is included in ΔT_{avg}, yielding a small change over the misting period. The larger ΔT_{max} better shows the change when the mist effect is reaching the sensors. The maximum temperature drop in each 50 second oscillation (or 25 seconds when measured along the centerline) is taken, and all these maxima are averaged to yield the average of the "peak" temperature drops. The effect on comfort of repeated large temperature drops with recovery to original ambient may be more pleasant than a fairly small drop averaged over time, the concept of alleisthesia. When the fan is fixed, there is almost no change outside the centerline.

The average temperature drops during oscillation range only from 0.2K – 0.5K, due to the relatively large portion of time in which the mist is not passing over the sensor. Peak drops range from 1 – 3K during oscillation. When fixed, the temperature drops along the centreline range from 1.2K – 1.9K with the exception of Position A, 10m from the fan, with the tilt angle at -4°, in which the geometry results in the fan directly aimed at the sensor. The mist cloud was visibly observed to completely evaporate around the 10m – 15m distance, thus there was likely some wetting of this sensor. No dripping was observed. It is likely the fan air flow promoted evaporation.

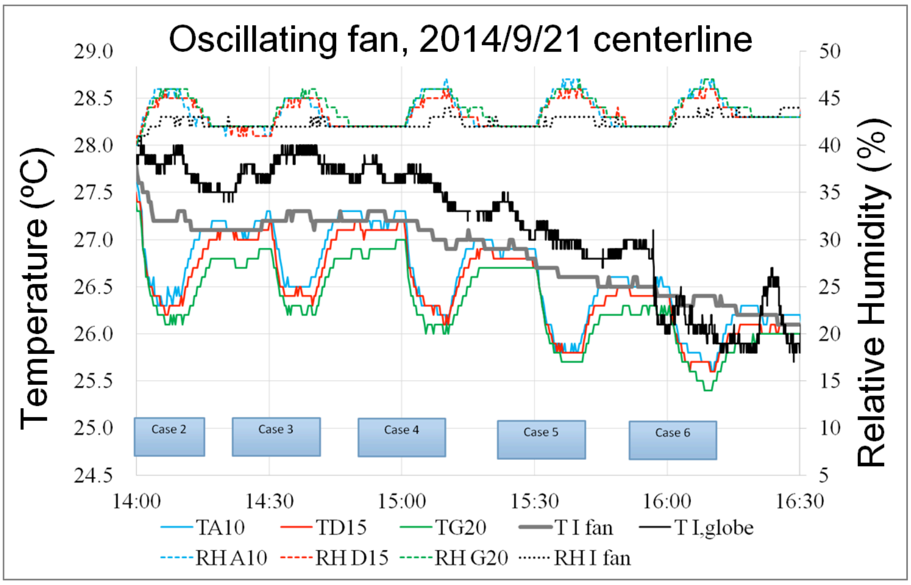


Figure 6. Example of temperature and humidity data from slow-response sensors

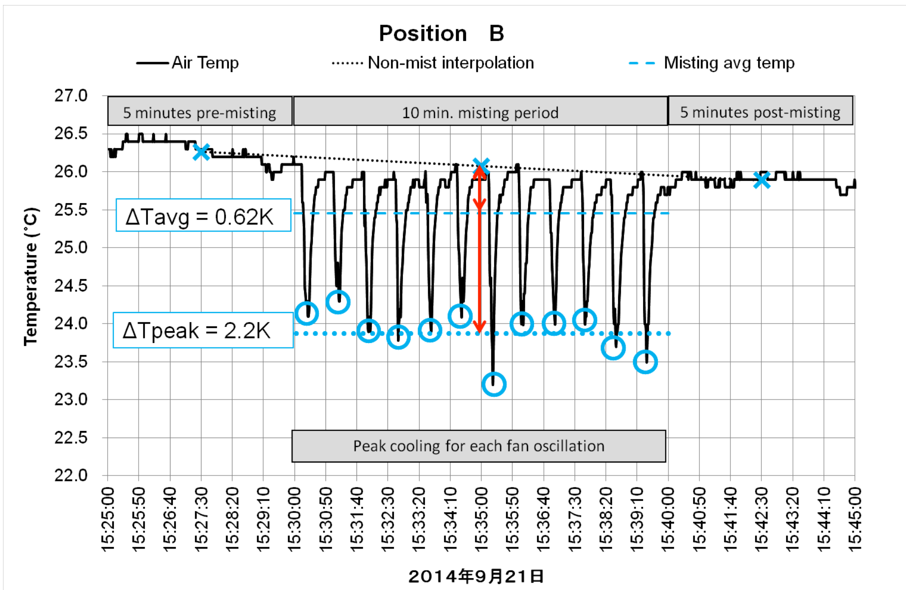


Figure 7. Example of method to average and average peak temperature drop in the misted area

Table 2 Average and average peak temperature drops at all positions according to fast-response sensors

Test runs			1 through 6		7 and 8		9 and 10		11 through 16	
Conditions			Osc. Tilt = 0˚		Fixed, Tilt = 0˚		Fixed, Tilt = -4˚		Osc. Tilt = -4˚	
Sensor location	Dist (m)	Align	ΔT_{avg} (K)	ΔT_{peak} (K)	ΔT_{avg} (K)	ΔT_{peak} (K)	ΔT_{avg} (K)	ΔT_{peak} (K)	ΔT_{avg} (K)	ΔT_{peak} (K)
A	10	Ctr	0.5	1.9	1.7	3.1	3.7	4.8	0.5	3.0
B	10	Edge	0.5	2.6	-0.1	0.6	0.0	0.6	0.5	2.5
C	10	Outer	0.0	1.0	-0.3	0.3	-0.5	-0.1	0.2	1.8
D	15	Ctr	0.3	1.2	1.3	1.8	1.6	2.1	0.2	1.6
E	15	Edge	0.5	1.7	-0.6	0.4	-0.7	0.0	0.3	1.8
F	15	Outer	0.3	1.3	-0.1	0.9	0.0	0.8	0.2	1.6
G	20	Ctr	0.4	1.1	1.2	1.9	1.3	1.8	0.2	1.2
H	20	Edge	0.5	1.5	0.0	0.6	-0.2	0.3	0.4	1.5

Heat flux results were evaluated similarly to the temperature drops, with results of all trials in Table 3. The simple time average during each fan or fan and mist period, and the average of the peaks within each oscillation cycle (see example data in Figure 8) were calculated. On average heat flux of the mist and fan is about 17W/m^2 higher than the fan alone on time-averaged basis, while peaks are about 26W/m^2 higher.

Table 3 Heat flux results for all trials, fan only and fan and mist

Conditions				Fan only			Fan and Mist			Fan effect		Fan and Mist effect	
Dist (m)	Align	Tilt (˚)	Osc/ Fixed	Heat flux (W/m^2) Before	Avg	Peak	Heat flux (W/m^2) Before	Avg	Peak	(W/m^2) Avg	Peak	(W/m^2) Avg	Peak
10	Ctr	0	Osc	67	93	112	80	109	134	+ 26	+ 45	+ 29	+ 54
10	Edge	0	Osc	75	99	135	76	110	166	+ 24	+ 60	+ 34	+ 90
15	Ctr	0	Osc	73	98	114	72	105	126	+ 25	+ 41	+ 33	+ 53
15	Edge	0	Osc	67	90	120	66	100	144	+ 23	+ 53	+ 33	+ 77
20	Ctr	0	Osc	73	96	106	77	108	127	+ 23	+ 33	+ 31	+ 49
20	Edge	0	Osc	73	97	117	75	105	138	+ 23	+ 44	+ 30	+ 63
15	Ctr	0	Fixed	89	161	176	87	179	189	+ 72	+ 87	+ 92	+ 102
20	Ctr	0	Fixed	80	131	143	75	144	155	+ 51	+ 64	+ 68	+ 80
15	Ctr	-4	Fixed	73	144	153	77	179	190	+ 70	+ 80	+ 102	+ 113
10	Ctr	-4	Fixed	74	155	174	73	237	262	+ 81	+ 100	+ 164	+ 189
10	Ctr	-4	Osc	73	104	152	65	108	171	+ 31	+ 78	+ 43	+ 107
10	Edge	-4	Osc	59	92	144	60	108	191	+ 33	+ 85	+ 48	+ 131
15	Ctr	-4	Osc	65	95	120	70	107	137	+ 30	+ 55	+ 37	+ 67
15	Edge	-4	Osc	66	95	135	68	109	169	+ 29	+ 69	+ 41	+ 101
20	Ctr	-4	Osc	75	105	118	76	114	133	+ 30	+ 43	+ 39	+ 57
20	Edge	-4	Osc	81	105	133	82	119	158	+ 24	+ 52	+ 37	+ 76
Avg.				73	110	134	74	128	162	**+ 37**	**+ 62**	**+ 54**	**+ 88**

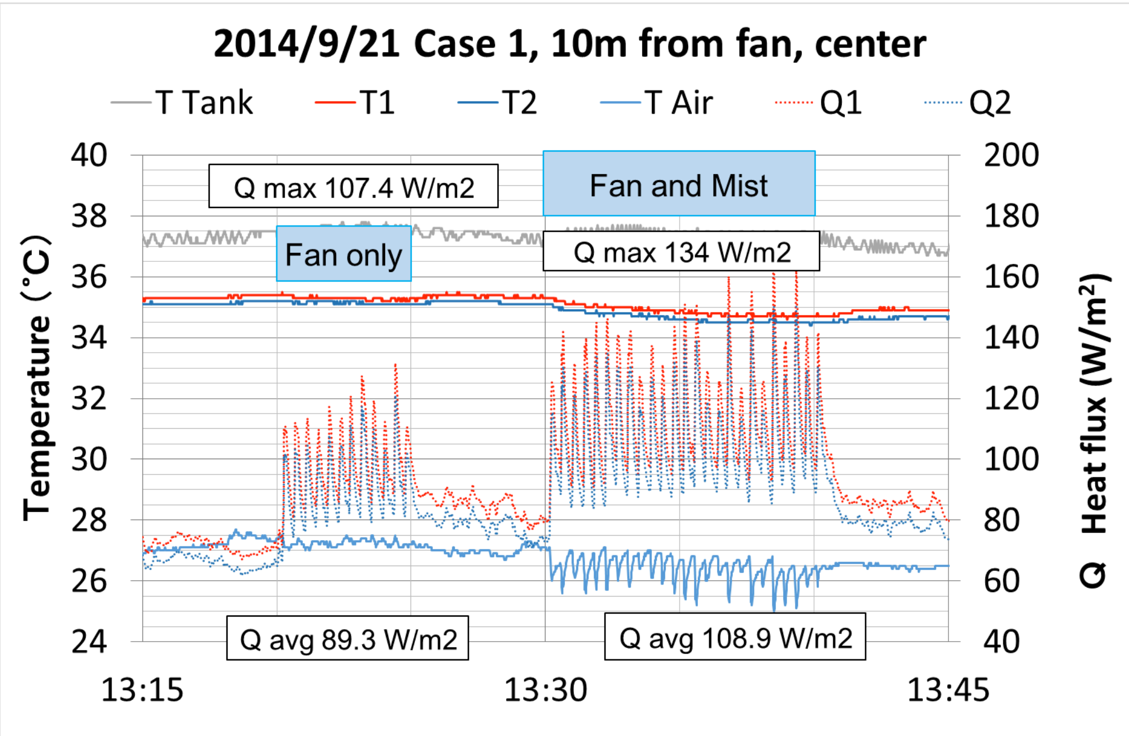


Figure 8. Example of skin analogue heat flux measurement for cooling oscillating fan and fan with mist

5 Discussion

The cooling effect of the mist and fan exceeds that of the fan alone in the measurements of heat flux on a skin analogue. The simple average of all cases is about $17W/m^2$ increased cooling and of all peaks is about $26W/m^2$. The temperature measurements show that the air is cooled by the mist. However, there is also a likelihood that some surface cooling is caused by micron scale droplets reaching sensors and surfaces, but evaporating quickly, rather than pooling and dripping. This would be due to their small size, the forced convection from the fan, and the dry periods when mist is not present in the oscillation cycle. The amount of droplets hitting and then instantly evaporating from a surface could not be measured with the available instruments, though this surface evaporation effect is included in the heat flux measurement.

One approach to making a heat balance model for mist would quantify the heat flux change due to the several components of mist fan cooling; forced convection of the fan, the reduction in air temperature, the slight increase in humidity, and the evaporation of droplets adhering to the surface. This compares to a fan only case, which only has the forced convection component. Thus for the heated skin analogue, the heat flux in excess of the fan only case is the sum of all other components. This can then be entered as a new cooling term into the heat balance equation in any model of heat exchange, which is set to the non-mist initial conditions and the air speed due to the fan as a base.

As an example, we modify the ASHRAE 55 “cooling effect” model with this extra term in the heat balance and calculate the cooling effect over a range of air temperatures. The radiant temperature is set as 2K higher than air temperature in all cases. The humidity is initially 50%, but in some cases is increased by the amount that should result from an adiabatic cooling of 2K (thus about a 5-10%RH increase) to test the accumulated negative effect of humidification. The air speed is set at 0.1m/s or 2m/s (the speed at 10 – 20m from the fan used here). The clo is set at 0.8 for heavy factory uniform and met set at 2 for fairly active work. The air temperature is not changed for the mist calculation, only an extra heat flux, E_{mist} of $10W/m^2$ or $20W/m^2$ is added into the balance. The results are shown in Figure 9.

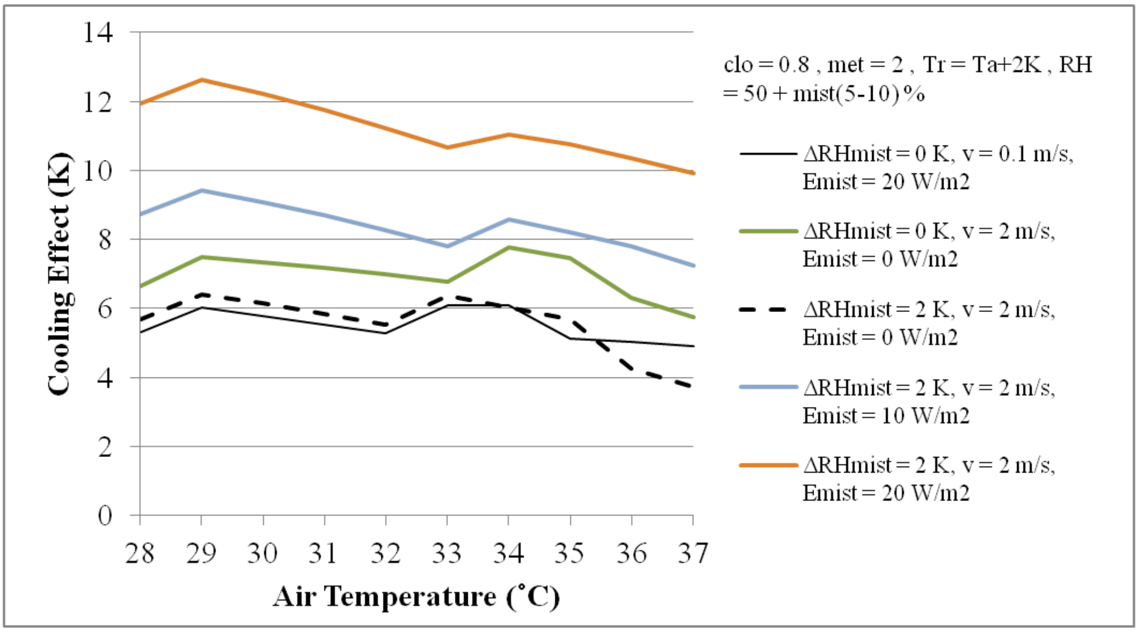


Figure 9. Calculated values of “Cooling effect” for various air speed and mist heat flux conditions

A 2m/s air speed combined with a 20W/m^2 added cooling from mist yields about double the cooling effect of a base case of air speed 2m/s with no mist. A mist and fan combination on a 31°C day might feel as a 19°C environment with still air. A case of negligible air speed (0.1m/s) with a 20W/m^2 added heat flux due to mist (termed E_{mist}) yields about the same cooling effect as a 2m/s air peed with no mist. The cases of E_{mist} as zero show that the humidification expected from a mist that cools 2K does not significantly change the result.

A major concern with this skin analogue measurement is that the rubber skin is both dry and has no clothing covering it. The fan only case will yield stronger cooling on wet skin than dry. The interaction of mist droplets with skin and sweat is unknown. Do impacting mist droplets add moisture to the film of sweat on the skin or clothing? Do they become trapped in body hair of clothing fibers and evaporate separately? Previous research with mist fans showed that mists may cause in increased sensation of wettedness, but that this wettedness is felt as pleasant by the great majority on a hot summer day. (Farnham et al., 2015) Further research on the interaction of the mist with wet skin and with clothing is needed. Experiments to measure the skin and body temperature of human subjects are currently underway at our laboratory.

6 Conclusions

Mist evaporation is a cost-effective cooling method has already been shown to yield increased thermal comfort in outdoor spaces on hot summer days even in the subtropical climate of Japan. The humidification effect makes it seem an unlikely candidate for indoor use for fear of saturating the air. In this experiment, oscillating mist fans are used in a factory space that is large enough that they can be used for spot cooling, while only increasing average humidity on the order of 5-10% over an 8 hour period. The mist yielded temperature drops of 0.2-0.5K on a time-averaged basis, with peak drops of 1 -3K while the mist passes by. The heat flux of the mist on a dry heated surface was about 18-27W/m^2 higher than the fan alone.

Although the ISO 7243 index based on WBGT would indicate that mist has almost no effect, a modification of the ASHRAE 55 model to include the added cooling of the mist could be quantify the mist effect in a similar manner as the cooling effect of increased local air speed. If the mist effect causes a 20W/m^2 increase in heat flux, the cooling effect could be about double that of the fan alone.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
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Thermal pleasure and alliesthesia in the built environment

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Abstract
Most of the thermal comfort literature and international standards either explicitly preclude or at least penalise nonsteady-state and asymmetric thermal environmental conditions. This prioritising of isothermal environments has driven a one-size-fits-all, neutral-as-optimum approach to the engineering of occupant thermal comfort. But despite the ability of modern HVAC systems to more-or-less deliver on the promise of thermal constancy, comfort surveys conducted in contemporary office buildings rarely report overall thermal satisfaction ratings above the 80% threshold.

This paper applies the physiological concept of alliesthesia as a framework for understanding thermal perception in dynamic conditions. Empirical evidence supporting the alliesthesia hypothesis is presented as a summary of findings from a series of human-subject laboratory experiments. The principal conclusion is that strong subjective discomfort is not a necessary precondition to experience thermal pleasure. Indeed, alliesthesia continues to operate in the thermoneutral zone, and pleasure may be elicited through moderate local skin temperature changes that are contrapuntal to the whole-body thermal state. Our results indicate that successful implementation of alliesthesial design in built environments depends heavily on some form of individual control. Alliesthesia provides a sound conceptual basis to drive the understanding of thermal comfort beyond steady-state notions based on heat-balance models to something more closely aligned with the neurophysiological mechanisms of human thermosensation.

Keywords: alliesthesia; nonsteady-state environments; personal control; thermal pleasure; thermophysiology

1 Introduction
People in the developed world now spend more than 90% of their time inside the built environment, most often in conditioned spaces where temperature is tightly regulated to remove any temporal or spatial variations. The heating, ventilation, and air-conditioning (HVAC) systems designed to deliver and maintain thermal constancy are now the single largest source of base building energy consumption in the commercial sector (Sinclair Knight Merz, 2006). Such taxing energy demand is unsurprising when a universal temperature deadband has been programmed into building management systems around the world, irrespective of prevailing weather, climatic context, or cultural specificities. There are very clear environmental impacts of such profligate energy use required for the provision of isothermal environments, namely the prodigious greenhouse gas emissions that contribute to the ongoing challenge of climate change (Nazaroff, 2008).

International comfort standards such as ASHRAE 55-2013 (ASHRAE, 2013) and EN ISO 7730:2005 (ISO, 2005) explicitly document guidelines designed to minimise or eradicate the thermal textures of buildings. Yet indoor environments are rarely isothermal. Not only are asymmetries common in conditioned environments (e.g. solar ingress or local sources of heating or cooling), but occupants also experience a series of exposures as they move within the built environment. The attention of engineers and architects over recent decades has been to relegate the thermal realm to one that is largely ignored or imperceptible (Pallasmaa, 2013). This has shaped the one-size-fits-all, neutral-as-optimum strategy that aims to eliminate occupant discomfort as the dominant paradigm. But despite the ability of modern HVAC systems to more-or-less deliver on the promise of thermal constancy, surveys conducted in real-world settings very rarely report overall thermal satisfaction ratings above the 80% threshold set as the target nearly 50 years ago (Arens et al, 2010).

There is a need for a fundamental shift in our understanding of the perceptual processes defining why particular thermal environments are comfortable for some but distinctly uncomfortable for others. Littered throughout thermal comfort discourse are references to the potential co-benefit of nonsteady-state environments to increase thermal satisfaction of occupants (see Zhang et al, 2015) whilst reducing the energy costs of conditioning indoor spaces by widening setpoint ranges (Hoyt et al, 2015). Research interest in personal environmental control systems (e.g. Melikov, 2004; Zhang et al, 2010; Zhang et al, 2015) is a clear example of that paradigm shift away from resource-intensive space conditioning towards bespoke microclimates. Yet there is no overarching conceptual framework that provides a cohesive interpretation of these disparate findings. Steady-state models such as PMV/PPD that have overseen the important contributions towards our understanding of thermal comfort were never intended for use in dynamic conditions.

The authors have conducted a series of human-subject laboratory experiments aimed at uncovering empirical evidence in support of the alliesthesia hypothesis. The ultimate aim of the series of published works (Parkinson & de Dear, 2015a; Parkinson et al, 2016; Parkinson & de Dear, 2016a,b) was to present alliesthesia as an overarching theoretical framework that reconciles previously contradictory strands of thermal comfort research in nonsteady-state environments, and provides a more unified understanding of the many facets of thermal perception in the built environment. The principal outcomes of these investigations will be summarised in the present paper to argue that alliesthesia provides a sound conceptual basis to drive the understanding of thermal comfort beyond steady-state notions based on heat-balance models to something that more closely aligns with the neurophysiological mechanisms actually responsible for human thermosensation.

2 Thermal Alliesthesia

It seems appropriate to offer a brief review of the alliesthesia concept before introducing the empirical evidence supporting the hypothesis. This section is purposefully brief, but a more detailed and comprehensive review may be found in de Dear (2011) and Parkinson & de Dear (2015a).

The fundamental principle of thermal alliesthesia, as defined and elaborated through a series of works by Cabanac (1971, 1979, 1992), is simple: any peripheral (skin) thermal stimulus that offsets or counters a thermoregulatory load-error will be pleasantly perceived. For example, elevated air movement with the prospect of increasing net heat loss from skin tissue during exercise is likely to be pleasant. This is referred to as positive alliesthesia because the stimulus has the effect of removing excess body heat accumulated from physical activity. Whether a stimulus is deemed positive (pleasant) or negative (unpleasant) is known as hedonic valence, and is determined by the effect of environmental stimuli on thermoregulation in relation to the current thermophysiological state. Cold stimuli will be perceived as pleasant if the core temperature is elevated above normal temperatures, and warm stimuli will be experienced as pleasant if core temperature is below normal settings. Conversely, warm peripheral stimulation when the subject's whole body thermal state is warmer-than-neutral or cool peripheral stimulation when cooler-than-neutral will lead to negative alliesthesia - unpleasant.

2.1 Thermophysiology of alliesthesia

The human thermoregulatory system is often depicted as having a single controller located in the hypothalamus that is responsible for integrating signals from different temperature sensors distributed throughout the body, and then comparing them against a reference or setpoint to produce a load-error output to which thermo-effectors respond. The regulated variable – assumed to be hypothalamic temperature – defends the body against environmental or metabolic heat load perturbation. Yet thermophysiological research in recent decades has generated compelling empirical evidence that fundamentally challenges this control theory orthodoxy. The contemporary view is that our thermoregulatory system comprises multiple controllers that achieve proportional control through separate thermoeffector loops (Romanovsky, 2007; Werner et al, 2008; Kanosue et al, 2010). Each controller is responsible for the activity of a particular thermoeffector but are selectively initiated or deactivated in a coordinated response as body temperature changes.

In the earlier publications on the alliesthesial concept (Cabanac, 1971) it was presumed that the load-error signal originated entirely from the body core. However significant research attention aimed at defining the relative contributions of skin and core temperatures to autonomic responses (Cheng et al, 1995; Cotter & Taylor, 2005; Nadel et al, 1970; Saltin et al, 1970) suggests that the thermoafferents inputs change with body temperature. It seems likely that individual controllers generate their load-error signals based on feedback from sensors distributed throughout the entire body (Boulant, 2000; Nakamura & Morrison, 2008). Under this model, peripheral inputs would dominate while body temperatures fall within the thresholds of the thermoneutral range (see Figure 1).

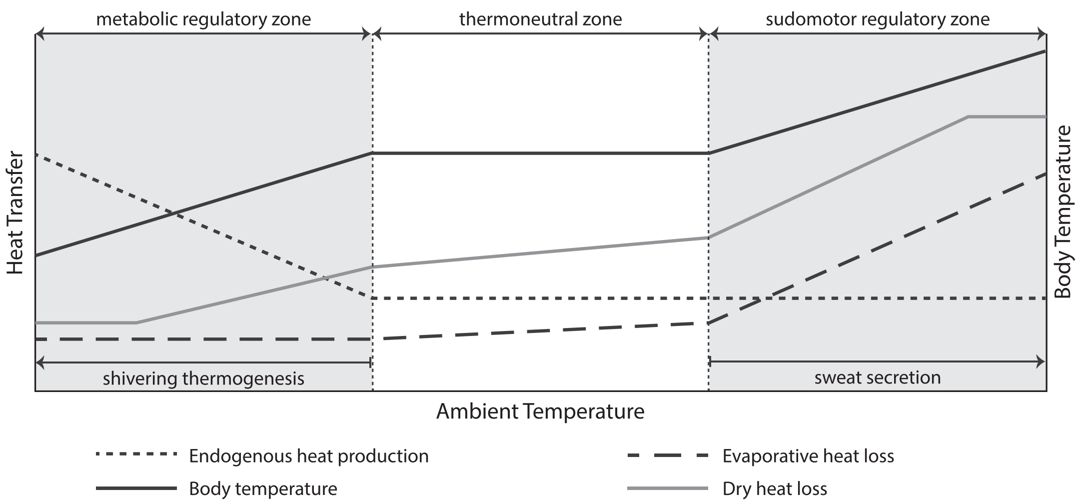

Figure 1. A theoretical model of thermoregulatory actions across different ambient temperatures. Idealised vectors of heat generation and transfer within the physiological system are shown. The vertical dashed lines mark thermoeffector thresholds and shaded areas mark the zones either side of thermoneutral (modified after Werner et al., 2008).

The misconceptions that there is a single controller and that thermoregulatory load-error must be derived from deviations in core temperature deviations may explain why the built-environment research community has largely ignored alliesthesia. But if the thermoeffector response during innocuous indoor exposures is scaled on the basis of peripheral, not core signals, then the obvious 'displeasure before pleasure' logic is no longer relevant. Moderate thermal sensations resulting from minor fluctuations in skin temperature could potentially generate a sufficient load-error for alliesthesia. We have coined the term spatial alliesthesia to describe the hedonic response driven predominantly by cutaneous signals, different from the more conventional, whole-body model of alliesthesia driven from load errors of central origin.

2.2 Neurophysiology of spatial alliesthesia

We commonly derive simple thermal pleasures from subtle experiences which occur routinely as we move around the built environment without ever disturbing core temperature; wrapping cool hands around a warm mug, or the contrast of a chilled metal balustrade under the palm of our hand as we ascend a staircase. These seemingly derive from rapid changes in local skin temperature that counter the 'global' or whole-body skin temperature trend. Information on peripheral temperature is transduced by thermo-sensitive structures known as cutaneous thermoreceptors, which are unevenly distributed across the body surface. Neural firing rates by cutaneous thermoreceptors demonstrate both static and dynamic components, the latter being highly sensitive to changes in local skin temperature (Hensel, 1981; de Dear et al, 1993). Thermal perception is strongly related to the rate of change of skin temperature when in the thermoneutral zone (Marks & Gonzalez, 1974; Rohles, 1981). Stronger thermal sensations are consistently reported at the immediate onset of ambient temperature step-change stimuli (de Dear et al, 1993) and also ambient temperature cycles (Kingma et al, 2012), suggesting that the dynamic response of cutaneous thermoreceptors is the key drivers for the perception of sudden change in the thermal environment.

The underlying principle of the spatial alliesthesia hypothesis is that pleasure is derived from the contrast between a regional skin temperature and the mean or whole-body skin temperature. This is based on the understanding that both thermosensitivity and skin temperature varies across and between body segments. Both the rate of change of local skin temperature and the spatial difference between local and whole-body skin temperature are likely to be driving mechanisms for spatial alliesthesia. The first (temporal change) determines the intensity and magnitude of the change brought about by the stimulus, and the second (local whole-body contrast) determines the direction, and therefore the 'usefulness' of the change. Both of these contribute towards the 'corrective potential', or the ability of a stimulus to reverse or reduce an incurred thermophysiological load-error.

2.3 Thermal pleasure

Extant research has generally focused on the descriptive (thermal sensation) or evaluative (thermal comfort) assessment of thermal perception, but very little attention has been given to the *affective* dimension. The use of psychometric indices for hedonic valence is largely unexplored in the context of the built environment, and has been confined mostly to earlier investigations of alliesthesia (e.g. Attia & Engel, 1982; Cabanac, 1971, Mower, 1976; Winslow et al, 1937). In this series of experiments on thermal alliesthesia we have used thermal pleasure as the psychometric to explore the hedonic tones attached to thermal transients and stimuli.

The phenomenological differences between sensation, comfort and pleasure are important to the stated aims of this research project. A simple defence of the decision to use thermal pleasure in-place of thermal comfort is because Cabanac believed pleasure to be the ‘currency’ of alliesthesia (Cabanac, 1992). But beyond just the idea of maintaining consistency with the psychological foundations of the original concept, the authors believe that thermal pleasure is a better psychometric scale to use in investigations of perception in nonsteady-state exposures than thermal comfort. As per the ASHRAE definition, thermal comfort is a “condition of mind”. Whilst comfort is a recognized state of being, it cannot be localized as it has no known sense organ. Thus it is an evaluative process, and would therefore be likely to include consideration of many factors beyond the physical environment such as happiness and health. Pleasure, or pleasantness, is different in that it directly addresses the affective component of the stimuli. Within the realm of hedonic psychology, affect is considered basic because it is an irreducible component of all phenomena within the global affective domain (Ekkekakis, 2003). So comfort is a high-order evaluation that considers many factors, whilst pleasure is considered to be low-level or ‘primal’ because of its role in interpreting the ‘usefulness’ of a stimulus for regulation of all of our homeostatic systems. Using evaluations of pleasure instead of comfort is of teleological appeal because the interpretation of perceptual processes through an alliesthesial framework is better understood through the mechanisms of the thermosensory system rather than a condition of mind.

3 Empirical evidence for thermal alliesthesia

This research project was conceived as a multi-part investigation of thermal alliesthesia. The material is sequenced to gradually increase the focus on the operating characteristics of alliesthesia: the theoretical underpinnings of thermosensation in the context of the built environment (Parkinson & de Dear, 2015); presentation of empirical data describing whole-body alliesthesia during sequential temperature step-changes (Parkinson et al., 2016); and spatial alliesthesia from asymmetrical exposures on the lower (Parkinson & de Dear, 2016a) and upper fringe (Parkinson & de Dear, 2016b) of the comfort zone. An unpublished final paper will present an exercise in modelling thermoreceptor fibre during these nonsteady-state exposures. Figure 2 presents the conceptual foundation of the project and places each work within the context of the physiological and perceptual zones that were theoretically defined and empirically tested.

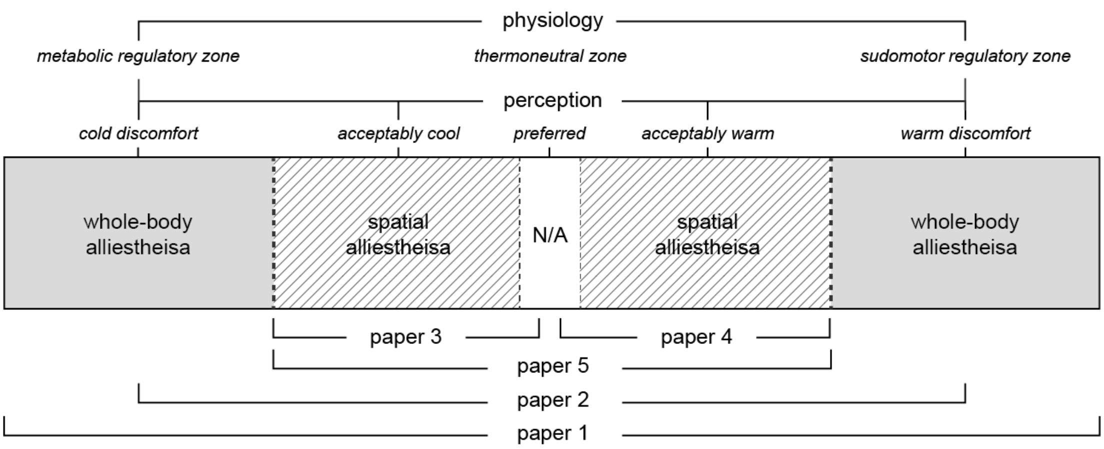

Figure 2. A conceptual representation of the proposed coupling between thermal perception and thermophysiology. The ‘alliesthesial type’ is superimposed within each zone, as per the findings of the papers listed within the figure.

Some overarching themes emerged from the series of human-subject laboratory experiments, and the remainder of the present paper will be dedicated to presenting these in the context of thermal perception during innocuous exposures in the built environment.

3.1 Alliesthesia in the thermoneutral zone

The assumption that an affective response to thermal stimuli is framed by a central load-error has prompted many in the thermal comfort research community to dismiss the entire concept of alliesthesia as irrelevant to them because one has to be distinctly uncomfortable in order to enjoy positive pleasure of a thermal environmental transient. But as discussed in the review of the physiological basis of alliesthesia earlier in this paper and in Parkinson & de Dear (2015), a heavier reliance on skin rather than core temperature affords the concept much greater relevance to thermal perception in quotidian environments.

The general hypothesis of the first human-subject experiment (Parkinson et al, 2016) was that positive alliesthesia is experienced in mild, innocuous thermal environments that do not necessitate displacements in core temperature. Thermal pleasure responses from thirteen (6 females; 7 males) participants were characterised in nonsteady-state conditions. Sequences were modelled on thermal exposures routinely experienced within the built environment, and designed to force three different physiological states - thermoneutral; the upper and lower fringes of the thermoneutral zone; and mild excursions into the sudomotor and metabolic regulatory zones.

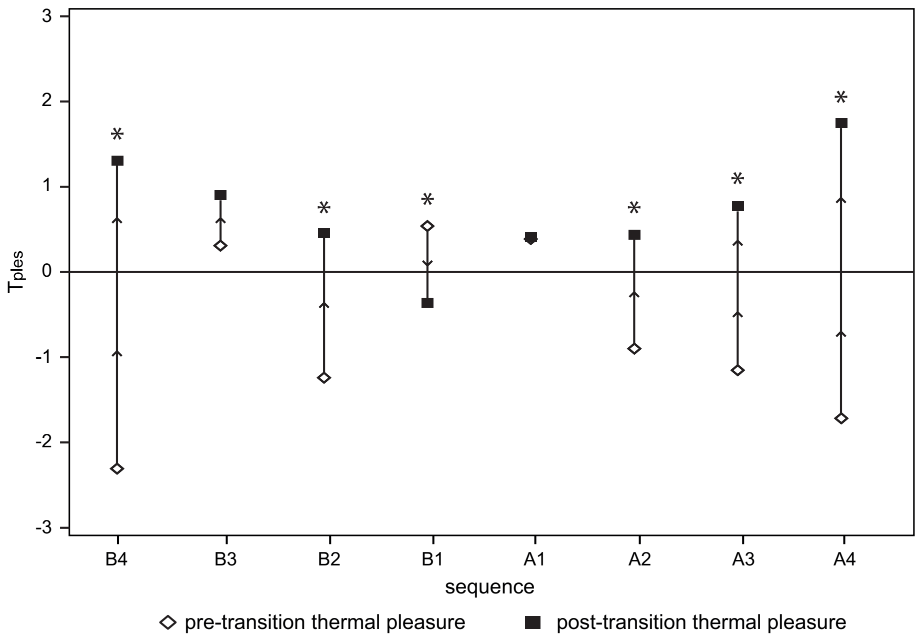

Figure 3. Group thermal pleasure votes cast pre- (1-minute before the transition) and post-transition (immediately following the transition). Warm (A) and cool (B) exposures were designed to increase magnitude of the incurred load-error (1 being the smallest, 4 being the largest). * marks the transitions with significant differences. From Parkinson et al (2016).

Subjects reported positive pleasure following corrective transitions (figure 3) during exposures designed to keep their physiological state within the thermoneutral zone (sequences 1-3). The corrective change delivered through peripheral stimulation forced the subjects' thermal state back towards neutrality, eliciting a positive pleasure response. Changes in skin temperature were observed but core temperature remained relatively table throughout the innocuous exposures. Clearly the psychophysiological foundations of thermal alliesthesia continue to operate within the thermoneutral zone, a state that is most likely to characterise the physiological status of occupants in moderate indoor environments.

The magnitude of the pleasure response is related to two important factors: the level of displeasure preceding the transition (i.e. the magnitude of the load-error), and the potential of the peripheral stimuli to correct the load-error. A more pronounced alliesthesial response is likely to emerge if there is greater preceding displeasure (e.g. sequence 4) and a stronger corrective change compared to more moderate scenarios (e.g. sequence 1 or 2). These results, albeit from a small sample of subjects, dismiss the notion that significant thermal discomfort is a necessary pre-condition for positive thermal alliesthesia.

3.2 Spatial alliesthesia

The spatial alliesthesia hypothesis posits that thermal pleasure arises from the differences in skin temperature between individual body segments when corrective stimuli are applied locally. This may be understood as the ‘flip-side’ to the conventional understanding of local discomfort. Localized peripheral stimulation tested in Parkinson et al. (2016) showed a positive alliesthesial change occurred when local skin temperatures were forced in an opposing direction to the mean skin temperature (figure 4). This indicates that thermal pleasure may occur during skin temperature divergence even though ambient temperatures may be displaced from the subject’s thermal preference.

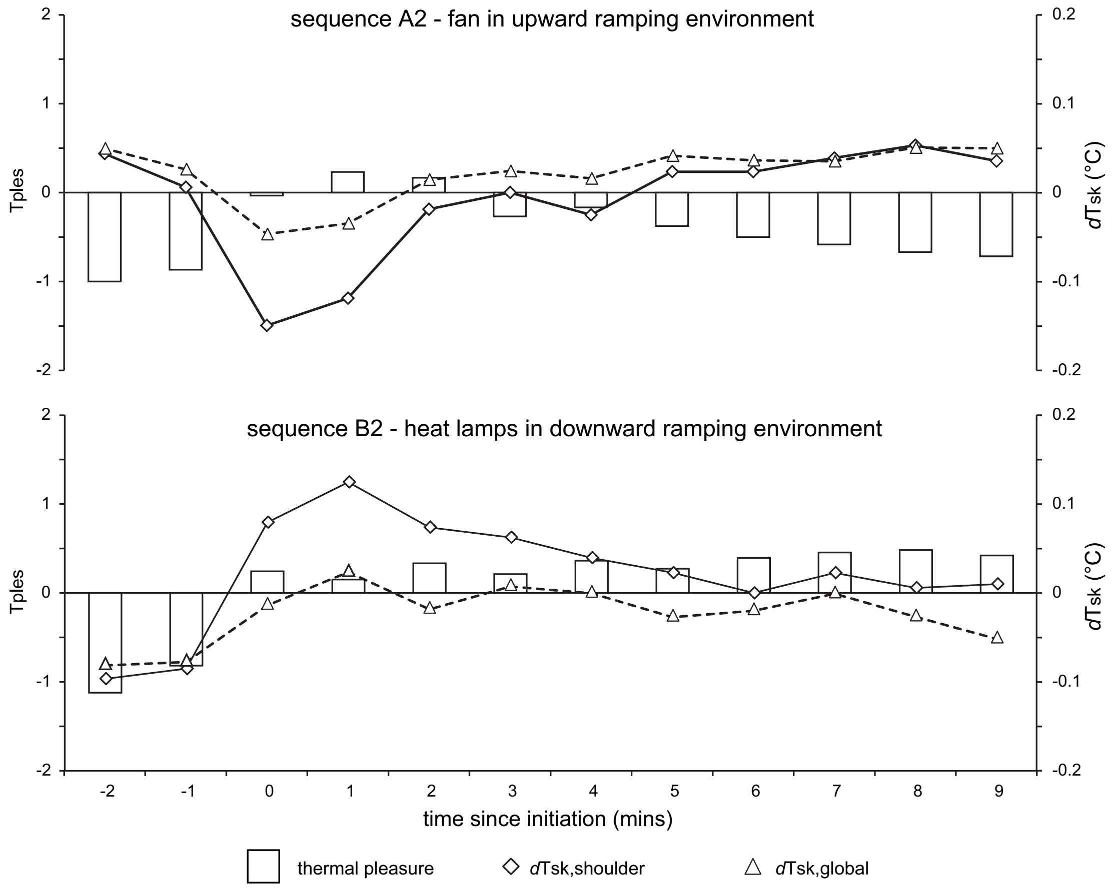

Figure 4. Evidence of spatial alliesthesia from the divergence in mean rate of change of skin temperature of the shoulder (dTsk,shoulder) and the calculated 12-point mean skin temperature (dTsk,global on secondary y-axis). Mean thermal pleasure votes are represented by the bars and are plotted on the primary y-axis. From Parkinson et al (2016).

The next two papers in the series examined reverse instances of local discomfort from warm contact stimuli applied to the hand and feet in cooler ambient temperatures (Parkinson & de Dear, 2016a) and dynamic air movement applied to the back of the neck in warmer ambient temperatures (Parkinson & de Dear, 2016b). Subjects in both experiments were exposed to conditions designed to be on the fringe of the thermal comfort zone in order to force their mean skin temperature. An opposing or contrasting thermal stimuli was then applied to a particular body site to test the hedonic response following changes in local skin temperature. The results support the underlying principle of the spatial alliesthesia hypothesis - that whole-body pleasure may be elicited from locally applied stimuli that contrast the whole-body state (characterised by the mean skin temperature in those experiments).

The change in local skin temperature experienced in these experiments was small, so the thermal pleasure attached to the thermal environmental stimuli was commensurately modest. This is likely due to the load-error being more modest when generated by spatial differences in skin temperature, and larger when there is a deviation in core temperature. However, not all subjects reported a positive hedonic shift in Parkinson & de Dear (2016a). The interindividual responses are likely to be the result of some predisposing psychophysiological conditions that will be discussed in the following sections.

3.3 Predictable psychophysiological pattern

A more detailed exploration of the psychophysical mechanisms driving spatial alliesthesia during rapid changes in local skin temperatures was undertaken in Parkinson & de Dear (2016a,b). Subjects were clustered based on their trend of thermal pleasure votes during the stimulation period. A MANOVA tested between-group differences of psychological and physiological parameters deemed to be relevant to the spatial alliesthesia hypothesis. In both experiments there were significant between-group differences discerned by MANOVA tests (figures 5 and 6) that could be interpreted within the framework of spatial alliesthesia.

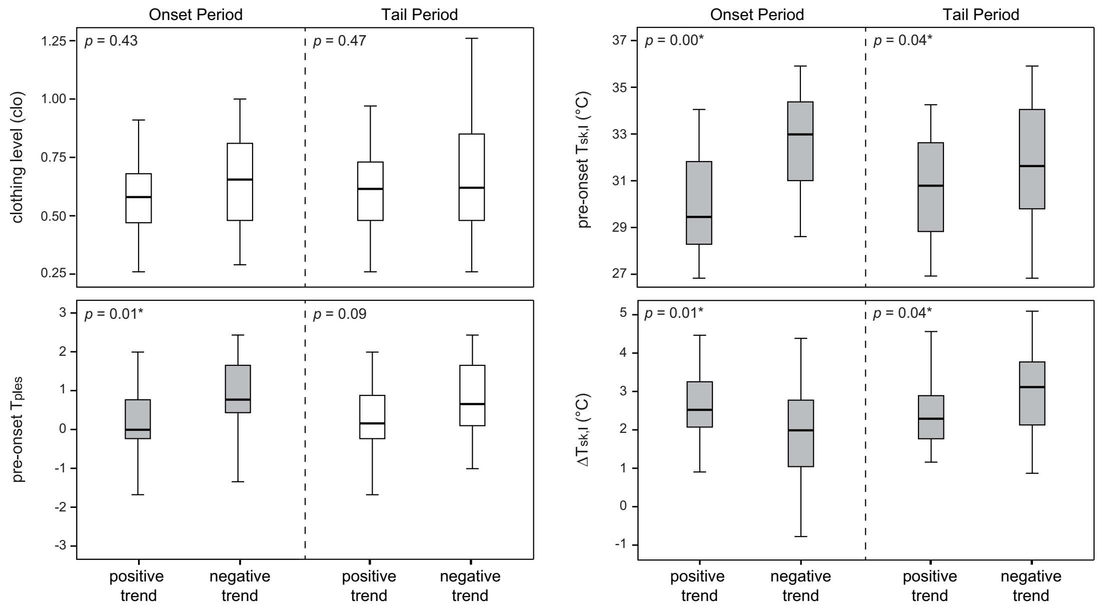

Figure 5. Boxplots of the tested parameters for the pooled hand and feet warming experiments. The onset (first 3 minutes) and tail periods (final 7 minutes) are included in the same plot and are separated by a dashed line. P-values from the MANOVA are inset and significant between-group differences are shaded. Note: $\Delta T_{sk,l}$ is 3-minutes for the onset period and 5-minutes for the tail period. From Parkinson & de Dear (2016a).

The most important variable distinguishing the tone and magnitude of thermal pleasure reported by subjects was the intensity of their displeasure in the preconditioning environment. In the experiment on local warming, the participants who were already experiencing slight pleasure on the fringes of the adaptive comfort zone responded negatively to local thermal stimuli, while those reporting slight pre-onset displeasure responded positively. This may be reframed to represent the size of the physiological load-error, which was shown in the first experiment (Parkinson et al. 2016) to largely influence the pleasure response. So those without the 'need' for corrective stimuli are likely to respond negatively to any forcing of their thermal state.

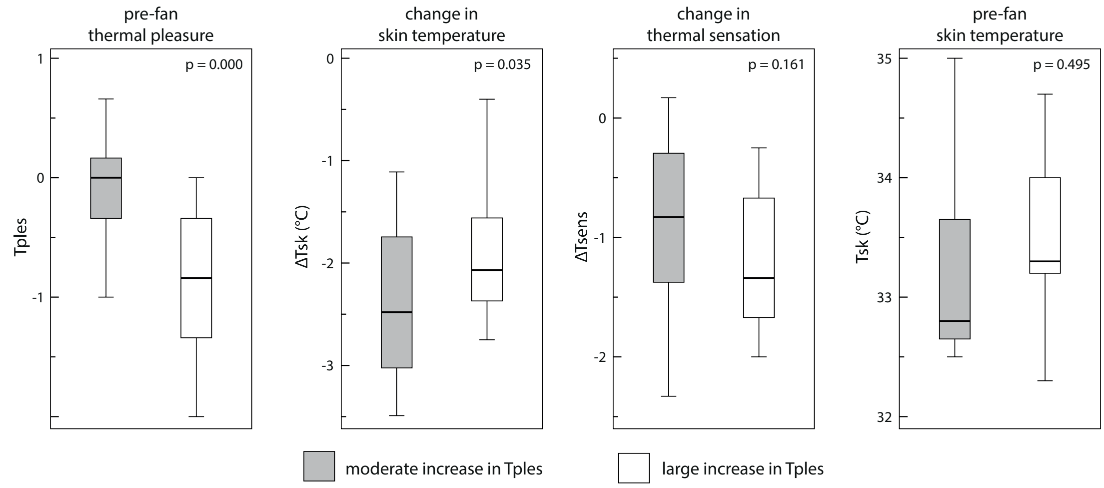

Figure 6. The results of the MANOVA testing the difference in psychophysiological variables between clusters. Subjects were clustered based on the magnitude of their pleasure response to elevated air movement. P-values from the MANOVA are inset. From Parkinson & de Dear (2016a).

A significant difference in alliesthesial response was also observed to depend on the change in local skin temperature from the application of local stimuli in both experiments. At the initial onset of warming, the subjects with a larger increase in local skin temperature had positively trending pleasure responses. However, high levels of local warming became unpleasant during the tail period of stimulation. This surprising result was also observed in the experiments on elevated air movement, where subjects reporting only a modest increase in thermal pleasure had experienced greater convective heat loss than those with a stronger positive response. It was concluded that the most important variable distinguishing the magnitude of thermal pleasure reported by subjects in both experiments was the intensity of their displeasure in the preconditioning environment. However, there is likely to be an ideal rate and magnitude of temperature change that will vary between subjects depending on physiological state and thermal preference.

The results of the MANOVA testing the differences in pleasure responses following local warming were used to fit a binomial logistic regression model to determine if spatial alliesthesia followed a consistent pattern. The binary dependent variable was a positive or negative trend in change in thermal pleasure votes, and the model was found to be highly significant at increasing the correct prediction of hedonic response following local warming beyond prior probability (the known probability of a response based on the collected data). Initial skin temperature and initial thermal pleasure status were shown to very good predictors of the hedonic response to localised warming, in some instances improving correct prediction close to 90% (figure 7). This strongly suggests that hedonic responses to local stimulation tend to follow a pattern consistent with the spatial alliesthesia hypothesis, and that it may be possible to predict the alliesthesial response with more extensive experimentation.

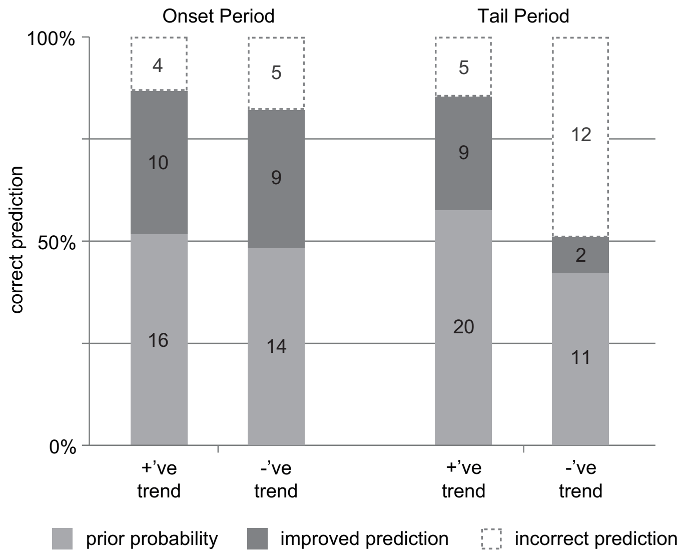

Figure 7. Model classification results based on the logistic regression for positively and negatively trending ΔTples. Different models were developed for the onset and tail periods. The sample size in each group is indicated within the bar. From Parkinson & de Dear (2016b).

3.4 Whole-body thermal pleasure from local stimulation

The significant increase in thermal pleasure reported by subjects in the two experiments on spatial alliesthesia indicate a responsiveness from distal thermal stimulation when changing the skin temperature of the targeted area in the opposing direction of the trend in mean skin temperature. The application of local stimuli also had a 'neutralising' effect on global thermal sensation. However, the change is relatively modest when compared to the earlier temporal alliesthesia experiments (see Parkinson et al, 2016, Mower, 1976, or Cabanac, 1971). The most likely explanation for this is because only a single stimulation site representing a small fraction of body surface and mass was stimulated, as opposed to whole-body transitions used in the earlier investigations.

It is clear that changes in local skin temperatures, even on distal sites like the hands and feet, are capable of influencing whole-body thermal perception. The thermoafferent signals generated at these small, distal cutaneous sites are capable of overriding whole-body perception in dynamic thermal environments, albeit briefly. This is particularly significant considering distal sites are known to be less sensitive to temperature variation than proximal sites such as the chest and back (Zhang et al. 2010a,b,c; Cotter & Taylor, 2005). Furthermore, the body sites that were tested represent skin area that is commonly exposed to the environment. Alliesthesia is therefore possible within the comfort zone and neither thermal stress nor discomforts are necessary preconditions. These findings offer an excellent basis for further research into the potential of alliesthesia to increase thermal comfort through the provision of personally controlled systems capable of forcing local skin temperatures against the dominant mean skin temperature trend.

3.5 Inter-individual differences and personal control

The empirical data on alliesthesia presented in the series of papers clearly shows that the hedonic tone attached to thermal stimuli, both local and whole-body, exhibits pronounced between-subject variability. This is clearly evident in the approximately normal distribution of hedon units around a neutral centre (figure 8) in Parkinson & de Dear (2016a). Unlike the objective evaluation of thermal sensation, stimuli may be perceived to be distinctly positive for one subject but negative for another. This underscores the fundamental semantic differences in these two rating scales. Quantitative descriptions of thermal stimuli (sensations) may vary in magnitude, but their tone is generally the same, irrespective of the subject's physiological state. In contrast, qualitative, affective appraisals of the same stimuli may vary in both magnitude estimates and hedonic valence, depending on the subject's thermophysiological status at the time. This polytonic response pattern necessitated the analytical approach of clustering subjects based on their psychometric responses that was employed in both papers on spatial alliesthesia.

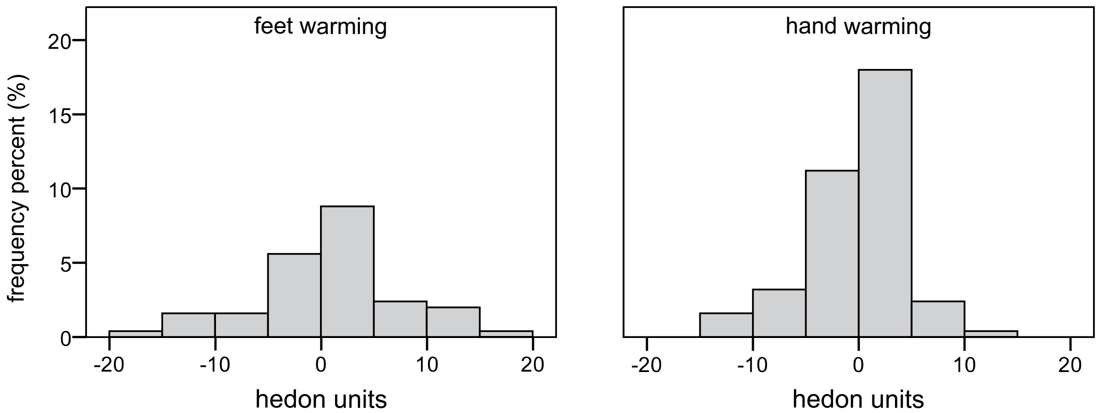

Figure 8. A histogram of frequency percentage distribution of hedon units (a non-dimensional index of thermal pleasure calculated by integrating pleasure votes cast by each subject for the total duration of the warming period). Feet stimulation (10 minutes) lasted longer than hand stimulation (5 minutes). Data is binned in 5-unit increments. From Parkinson & de Dear (2016a).

Pleasure ratings reported by subjects in response to the change in thermal environment – whole-body temperature step-changes in Parkinson et al. (2016), local warming in cool ambient temperatures (Parkinson & de Dear, 2016a), and targeted elevated air movement in warm ambient temperatures (Parkinson & de Dear, 2016b) – varied both in magnitude and valence. Notwithstanding this psychophysical diversity amongst occupants, there is ample opportunity for positive spatial alliesthesia to enhance occupant satisfaction with their thermal environment if appropriate engineering solutions are provided. Clearly not everyone experiences the same quality or intensity of thermal pleasure from the same thermal stimuli, but this simply adds further experimental support for the concept of Personal Environmental Control (PEC) systems, which will be discussed later.

4 Designing for alliesthesia in the built environment

In order to maximise the potential of these dynamic environments to create instances of thermal pleasure, efforts to integrate hedonics into the built environment need to be articulated. The most obvious application of the whole-body variant of alliesthesia is the characterization of thermal perception within a Lagrangian frame of reference, as the subject travels through an urban environment. Fluctuations in both external and internal heat load along this trajectory would significantly modify mean skin temperature and potentially displace core temperature, making alliesthesia the appropriate conceptual framework to interpret thermal perception in this context.

Conditioning the transitional space of an office building by lowering ambient temperature below the sedentary thermoneutrality, or rather a more energy efficient strategy such as increasing air movement, will elicit strong positive alliesthesia upon entry to the building. Accelerated peripheral cooling would help purge some of the excess body heat and provide relief pleasure without leading to significant cold discomfort providing the exposure within foyer is of short duration. In most cases there would be some carryover and the alliesthesial design concept suggests that workstation temperatures could be maintained in the upper regions of the adaptive comfort range while sustaining positive thermal pleasure. The HVAC energy penalty of over-chilling a relatively small transitional zone would be significantly outweighed by reduced cooling demand in the much larger, adaptively conditioned sedentary work area.

Temperature transients and thermal asymmetries found in the indoor environments of naturally ventilated or mixed mode ventilated buildings therefore afford ample opportunity for the elicitation of spatial alliesthesial pleasure. A pragmatic design solution to the provision of comfort in nonsteady-state conditions is Personal Environmental Control (PEC) systems. By embedding PEC systems in workstations, occupants can create bespoke micro-environments that are capable of eliciting positive hedonic tones through the spatial alliesthesia properties of their cutaneous thermal sense. The physiological load-error of the dissatisfied occupants provides latent pleasure that can be realised through the provision of corrective stimuli to distal skin sites. Displeasure would act as a sufficient motivator to initiate and regulate thermal stimuli if proper systems were provisioned, and dissatisfaction would transform into thermal pleasure. PEC permits this without the individual's thermal preferences impinging upon the environment of others. Earlier research by Zhang et al. (2010a, 2015) has demonstrated the potential for the PEC approach to improve percentages of thermal satisfaction above those typically associated with shared thermal environments. This could lead to significant energy savings by widening the central setpoint temperatures (Hoyt et al, 2015) and using low-energy personal environmental control (PEC) systems to deliver corrective stimuli directly to the occupant.

5 Conclusion

The concept of alliesthesia does not displace established knowledge of comfort in steady-state conditions, but rather compliments it by shedding some light on non-uniform and dynamic thermal environmental exposures. The substantial body of research literature on local thermal discomfort, as well as the international standards based on it may now be coherently interpreted within the theoretical framework of spatial alliesthesia. But because the flip-side of local thermal discomfort - positive spatial alliesthesia - is grossly under-researched, we have very little empirical understanding of overt design strategies for thermal delight in built environments.

It is the hope of the authors that this series on alliesthesia will prompt further research activity on the overlooked hedonic dimension of thermal perception. The results from this series of human-subject tests suggest that to successfully elicit alliesthesial pleasure control must be returned to occupants by embedding adaptive opportunities into the design or fit-out using PEC systems. Alliesthesia represents an exciting new paradigm in thermal comfort research that ties together several emerging trends in the literature (de Dear et al., 2013; Brager et al, 2015), including PEC systems, spatially heterogeneous thermal environments, local thermal discomfort, and transient thermal environments.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Real-time personal continuous monitoring of air temperature, relative humidity, carbon dioxide, and thermal and perceived air quality acceptability in Singapore

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Abstract
Occupants' determination of thermal acceptability (TA) and perceived air quality acceptability (PAQA) are typically analysed in climate chambers or cross-sectional field studies. Individual factors, such as expectations, environmental context, and thermal and air quality history, may contribute to the acceptability response. Fifteen Singaporean subjects participated in a 7-day longitudinal experiment in which they continuously carried a portable sensor that continuously recorded personal air temperature (T_a), relative humidity (*RH*) and carbon dioxide (CO_2) mixing ratio at 1-minute intervals. They answered several times a day an online survey about TA and PAQA, as well as providing their current location and air-conditioning status. The findings recorded acceptability ratios of over 80 % at home, in restaurants and at workplaces, but not in outdoor and vehicle environments. Sample clustering by locations contributes to recognizing the patterns between acceptability and objectively measured parameters. Operating air-conditioner was positively associated with TA and PAQA at home and in restaurants. Moreover, participants who slept in air-conditioned bedrooms tended to show lower acceptability values at workplaces with uncontrollable ventilation. This longitudinal study following the same group of participants has identified the importance of location in TA and PAQA analyses with respect to physical parameter change, air-conditioning status and individual habits for sleeping ventilation mode. The database could assist in the prediction of individual TA and PAQA preference in future research.

Keywords: Environment, Longitudinal Study, Perceived Air Quality Acceptability (PAQA), Thermal Acceptability (TA)

1 Introduction
An acceptable thermal and perceived air quality environment is one important goal of environmental design. Evidence in the literature indicates that thermal acceptability (TA) may affect occupant productivity or working efficiency (Wargocki and Seppänen, 2006), and perceived air quality acceptability (PAQA) was found to be associated with a number of sick building syndrome (SBS) symptoms (Cheong et al., 2006; Wargocki et al., 2000).

Prior TA and PAQA studies have usually been conducted in controlled environmental chambers or using cross-sectional field surveys focusing on specific environments, such as offices, residences and classrooms (Sun et al., 2012). Some studies have extended the measurement protocol to a longitudinal experiment, evaluating over longer periods the assessment of acceptability and monitoring a few environment parameters, such as air temperature T_a (°C), relative humidity RH (%) and carbon dioxide mixing ratio CO_2 (ppm) at a fixed location (e.g., Pei et al., 2015). In studies with a large sample size with different participants, variability of the acceptability responses has usually been attributed to personal factors. Beyond the physiological attributes, a person's assessment of environmental acceptability can also be psychologically affected by past experience, expectation, environmental context, the availability of environmental control, and the thermal and perceived air quality history of the subjects (Frontczak and Wargocki, 2011). Despite such indications about the importance to personal factors on TA and PAQA studies, existing survey methods have been limited in evaluating the influence of such differences.

To contribute acceptability assessments, we conducted a longitudinal experiment that combined assessments of thermal and perceived air quality acceptability with real-time personal continuous monitoring of T_a, RH and CO_2. Potential influencing factors might include, but are not limited to, short-term changes in the objective physical parameters, differences in location and associated expectations, current ventilation status and occupant's habits with regard to controllable parameters (such as window opening or air-conditioner operation). The advantages of longitudinal study that follows people include its ability to trace the history of individual exposure to physical parameters and the possibility to study the influence of personal expectations in various environments, which is a pioneering step to identify unknown confounding factors that driving occupant's thermal and perceived air quality acceptability responses.

The objective of this paper is to identify the variation of TA and PAQA for the same group of participants in different locations with respect to physical parameters change (T_a, RH and CO_2), air-conditioning status and occupant's habits regarding thermal control in their sleeping environment using the personal continuous monitoring method. The study is conducted in a tropical setting in which two modes of thermal environmental control in the sleeping environment are common and distinct: open windows and closed windows with the operation of split-unit air conditioning. The thermal environment for sleeping reflects a high degree of autonomous choice, which can reflect people's preferred status for ventilation and thermal environmental control.

2 Methods

Subject's backgrounds

Fifteen educated young adult subjects living in Singapore participated in this study. The participants' demographics and air-conditioner usage habits at home were collected, including age, gender, body height and weight, action priority when feeling hot (i.e. adjustment to clothing, window, cooling fan and air-conditioner), number of air-conditioner units at home and their sleeping ventilation status (i.e. sleeping in an air-conditioned bedroom (AC group) or in a bedroom with window open (AV group).) In an adventitiously ventilated (AV) environment, ventilation is incidental, and the ventilation system has not been taken into account and designed to achieve any particular code, standard or best practice (Schiavon, 2014).

Physical measurements

Each participant carried a portable sensor, which recording air temperature T_a (°C), relative humidity RH (%) and carbon dioxide mixing ratio CO_2 (ppm) at 1-minute intervals, continuously, for seven consecutive days. The subjects were instructed that the sensor should be carried or kept near the participant at all times during the measurement period. The real-time continuous measurement revealed information about environmental conditions in relation to the participant's activity patterns and their exposure to environment parameters. The chosen data logger was CM-0018 (CO2Meter Inc., Ormond Beach, FL, USA) with sensor accuracy of ±30 ppm ± 3% of the measured value for CO_2, ±0.4 °C for T_a and ±3% for *RH* (CO2Meter, 2014).

Subjective acceptability survey

An online survey was established to elicit and record each subject's instantaneous evaluation of thermal acceptability (TA) and perceived air quality acceptability (PAQA) (SinBerBEST, 2015). For acceptability, the subject marked their response on a continuous scale from clearly acceptable (+1) to just acceptable (+0.1) and from just unacceptable (-0.1) to clearly unacceptable (-1). In this scale, subjects must distinguish clearly between acceptable and unacceptable. A response was expected after each environment change (i.e. home > outdoor > transit > office) throughout a day, yet was constrained by the participant's availability.

Activity schedule record

Participants were also asked to record their daily activity schedule and the characteristics of each perceived environment during the measurement period, including the time of entry in each place, a description of the type of location (including home, workplace, outdoor, restaurant and vehicle, and places not in these categories were to be clearly defined in remarks), their activity (walking, sleeping, working, etc.), air-conditioning (AC) status (on / off) and window status (open / close). It is noted that the "AC group" classified under subject's backgrounds only refers to participants who slept in an air-conditioned bedroom; it does not necessarily imply that the AC group participants always operate their air-conditioner at home.

Data analysis

A local polynomial regression fitting method, 'loess' function in R programming, was applied to visualize the non-linear association between the evaluated acceptabilities (TA and PAQA) and potential predictor variables. The regression line was fitted locally by weighted least-squares with an approximation of the 95% interval bounds in grey shading. Furthermore, the Wilcoxon rank sum non-parametric test, also known as the Mann-Whitney test, was used to identify any difference of two distributions by a location shift. If the computed *p*-value is less than 0.05, the null hypothesis of 'observations come from the same population' was rejected.

3 Results and discussions

Table 1 shows the results of overall measured parameters (T_a (°C), *RH* (%) and CO_2 (ppm)) and surveyed acceptability (TA and PAQA) classified in five different environments. Measurement samples at a location outside of the five categories are not considered due to limited data. The cumulative data count suggested that participants spent most of their time at home, followed by the workplace, outdoors, in restaurants and in vehicles.

Owing to its geographical location in a tropical region, the outdoor environment recorded in Singapore was usually hot (10 percentile, median, 90 percentile = 26.4, 29.7, 31.8 °C) and humid (59, 70, 81% RH). About two-thirds of the samples acquired at home were without air-conditioning and the physical parameters were comparable to those outdoor (28.2, 30.6, 31.7 °C; 62, 69, 75%). In the air-conditioned home environment, the temperature and humidity were, on average, 2.6 °C and 8.6% lower. The carbon dioxide mixing ratio at home with AC on was higher (557, 1003, 2227 ppm) than in the cases without air-conditioning (410, 574, 1260 ppm). Similarly, the restaurant environment included both AC (N = 3623) and non-AC (N = 2472) samples. Sampled T_a, *RH* and CO_2 at AC restaurants were 23.1, 25.0, 29.9 °C; 52, 59, 70%; and 498, 713, 1432 ppm, while at the non-AC restaurants values were found on average to be 2.8 °C and 3.1% higher but 330 ppm lower. All measured samples in vehicle and workplace environments were with air-conditioning operating. Workplaces were equipped with centralized air conditioning with fresh air supply. The T_a was (24.1, 26.0, 27.7 °C) and the CO_2 mixing ratio was (409, 506, 868 ppm). In vehicles, the collected *RH* (43, 55, 71%) was found comparable with the workplace, but a higher T_a (26.0, 28.4, 30.9 °C) was recorded. Also, the CO_2 mixing ratio (447, 1327, 3053 ppm) in vehicles was found to be much higher than in all other environments, especially during rush hour with high occupant density in vehicle cabins such as buses and the rail mass rapid transit system (MRT). Table 1 also summarizes the surveyed subjects' assessment of acceptability. The TA and PAQA were evaluated as acceptable at levels above 80% at all locations, except outdoors (TA: 50%, PAQA: 76%) and in vehicles (TA: 55%, PAQA: 36%).

Table 1 Overview of measured and surveyed data in different environments

	Home (N = 90963)			Outdoor (N = 6610)			Restaurant (N = 6103)			Vehicle (N = 4938)			Workplace (N = 38384)		
Percentile	T_a	*RH*	CO_2	T_a	*RH*	CO_2	T_a	*RH*	CO_2	T_a	*RH*	CO_2	T_a	*RH*	CO_2
10%	26.2	56	428	26.4	59	406	24.4	53	407	26.0	43	447	24.1	47	409
25%	27.9	61	513	28.1	65	420	26.3	56	448	27.1	49	760	25.1	53	453
50%	29.7	65	717	29.7	70	466	27.5	60	590	28.4	55	1327	26.0	56	506
75%	30.9	70	1070	31.0	75	550	29.9	67	780	29.8	62	2152	26.8	60	602
90%	31.6	74	1520	31.8	81	740	31.4	71	1247	30.9	71	3053	27.7	90	868
	Number of surveyed acceptability														
Accept. TA	115			9			39			83			159		
Unaccept. TA	26			9			7			69			32		
Accept. PAQA	118			13			37			55			173		
Unaccept. PAQA	22			4			8			97			18		

N = Number of measured samples; sampling time resolution = 1 min.

Figure 1 presents a boxplot of TA and PAQA in the five different microenvironment categories. Higher thermal acceptability was found in restaurants, workplaces and at home, respectively, with median values of 0.40, 0.44 and 0.55. A lower median TA was observed in vehicles (0.11) and half of the outdoor TA votes were "unacceptable" with a median value of -0.12. For perceived air quality acceptability, high median PAQA value was observed at home (0.63), at the workplace (0.62), in restaurants (0.59) and outdoors (0.51), but a much lower median PAQA (-0.29) was reported in vehicles. The high CO_2 mixing ratio in vehicle cabins (2152 ppm at the 75^{th} percentile and 3053 ppm at the 90^{th} percentile) could be one contributor to unacceptable air quality, but this interpretation may not equivalently hold when applied to other places. No unacceptable PAQA was recorded at home when the AC was on. The criteria of people's assessment of acceptability might vary with location and with the subject's expectation, and changes in the physical parameters (i.e. T_a, *RH*, CO_2) may not be the only contributing factors.

Figure 2 illustrates the relationships between surveyed subject's acceptability assessments (TA, PAQA) and measured environmental parameters (Ta, RH, CO2). Clearly, for the tested conditions, there is not a relationship between acceptability (both TA and PAQA) and Ta and RH ( ). The weighted-regression lines suggest generally acceptable conditions within the sampled temperature and relative humidity ranges (22.5–32.5 °C and 40–80%). The highest TA (0.41) was observed when Ta was 26.5 °C. These diagrams show that participant's thermal or perceived air quality acceptability cannot be determined simply by using Ta and RH.

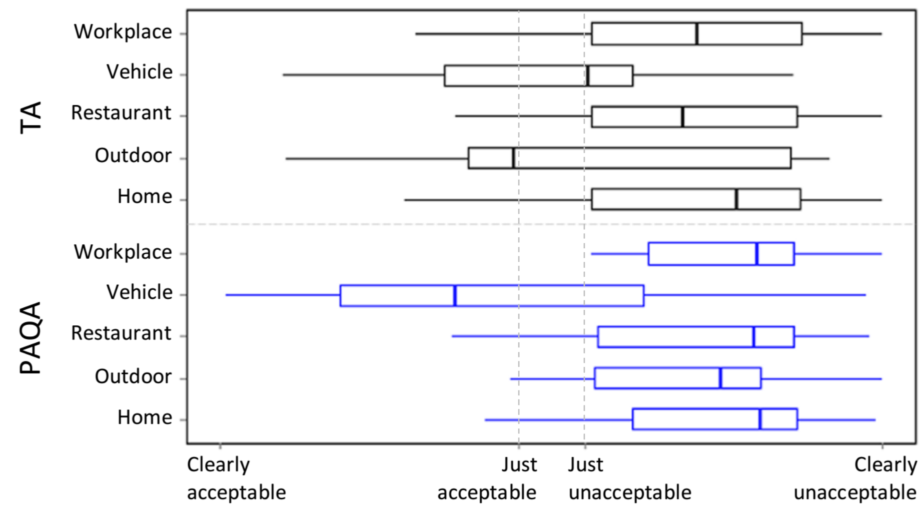

Figure 1 Overview of subject's assessments of thermal acceptability (TA) and perceived air quality acceptability (PAQA) in various places.

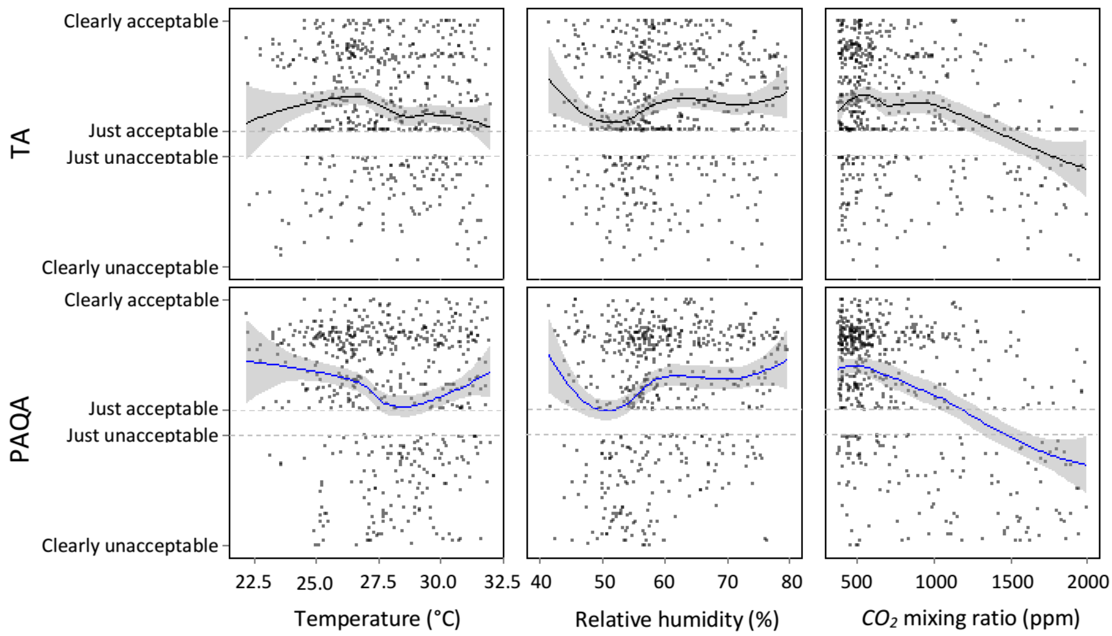

Figure 2 Overall relationships between assessed acceptabilities (TA/PAQA) and environmental parameters (T_a, RH, CO_2)

Figure 2 also shows an almost negative linear relationships are seen between acceptabilities and the CO_2 mixing ratio. The regression lines cross the "just unacceptable" region at a CO_2 mixing ratio of approximately 1500 ppm. The negative association between PAQA and CO_2 mixing ratio is reasonably attributed to insufficient ventilation, but the same trend in TA samples remains physically unexplained. Another analysis, not reported here, shows a generally positive relationship between TA and PAQA, which could be a confounding reason for the similar trend between assessed acceptabilities and CO_2 mixing ratio. This evidence suggests that apart from physical parameters some other factors might have to be considered for fully predicting thermal acceptability.

Figure 3 illustrates the relationships (a) between TA and T_a and RH and (b) between PAQA and CO_2 mixing ratio, when data are clustered by location. (The outdoor environment is excluded owing to insufficient data.) Thermal acceptability was found to decrease with higher air temperature and relative humidity at home and in restaurant environments. Less than 10% occurrence of thermal unacceptability was reported in air-conditioned homes and restaurants, but the proportion dissatisfied with the thermal environment increased to 41% and 57%, respectively, in non-air-conditioned homes and restaurants. On the other hand, all sampled workplaces and vehicle cabins were air-conditioned. Although a weak association was observed between thermal acceptability and environmental parameters, the data suggest that lowering the temperature in these air-conditioned places did not necessarily enhance the perceived thermal acceptability. Dissatisfaction regarding over-cooled working environments have been reported for Singapore offices (Sekhar, 2016). The percentage of thermal acceptance was found to be less than 80% when T_a was lower than 25 °C, according to a bin temperature of ±0.5 °C, in the workplace. It dropped below 50% in vehicles when T_a was below 25 °C or above 32 °C. No remarkable trend was found between TA and CO_2 mixing ratio in any of the environment.

For PAQA, the no unambiguous associations with T_a and RH were found, but a relationship to CO_2 mixing ratio was observed, especially at home and vehicle environments. Interestingly, an increase in the PAQA value with higher CO_2 mixing ratio was reported, which likely happened in homes with air-conditioning on and the window closed. In addition, a closed window could reduce the penetration of outdoor pollutants, thus producing a higher acceptability to household air quality, especially during the haze period in Singapore (Zhou et al., 2015). The worst PAQA was found inside vehicle cabins, where more dissatisfied air quality votes were found at CO_2 mixing ratios above 1000 ppm. Unacceptable air quality could be due to low outdoor air flow rate per person and close proximity among occupants (Moreno et al., 2015). The workplace was found to have the highest PAQA among all environments (i.e. 90% of the votes were acceptable). The few dissatisfaction votes could be attributed by many possible reasons, but no evidence emerged to show a clear relationship between PAQA and the measured parameters at the workplace. Comparing Figures 2 and 3, location was considered as an important factor in identifying the associations between the perceived acceptabilities of indoor environments and corresponding objective physical parameters.

Figure 4 shows boxplots for the TA and PAQA performance in relation to the air-conditioning on/off status at home and in restaurant (left). It also presents (right) acceptability results for home and workplace with subjects sorted according to whether they slept with air conditioning on (AC) or with windows open (AV). The data suggest that not operating an air conditioner may reduce thermal acceptability in restaurants (p < 0.05, Wilcoxon rank sum test). An analogous result is seen in homes with improved acceptability measures with air conditioning operated (TA and PAQA: p < 0.05), which limits exposure to warm and humid outdoor air together with limiting the penetration and persistence of outdoor pollutants. These results are consistent with the previous discussion of Figure 3. The data in Figure 4 also suggest that there is no significant difference between air-conditioning ventilated (AC) or adventitiously ventilated (AV) groups for TA and PAQA outcomes at home (p > 0.4). However, somewhat surprisingly, subjects who slept with air conditioning judged that their workplace had significantly lower acceptabilities (TA and PAQA, p < 0.05). It may be that the AC group was accustomed to control their sleeping environment, and may have been more unsatisfied than the AV group with the uncontrollable ventilation and thermal environment in their workplaces.

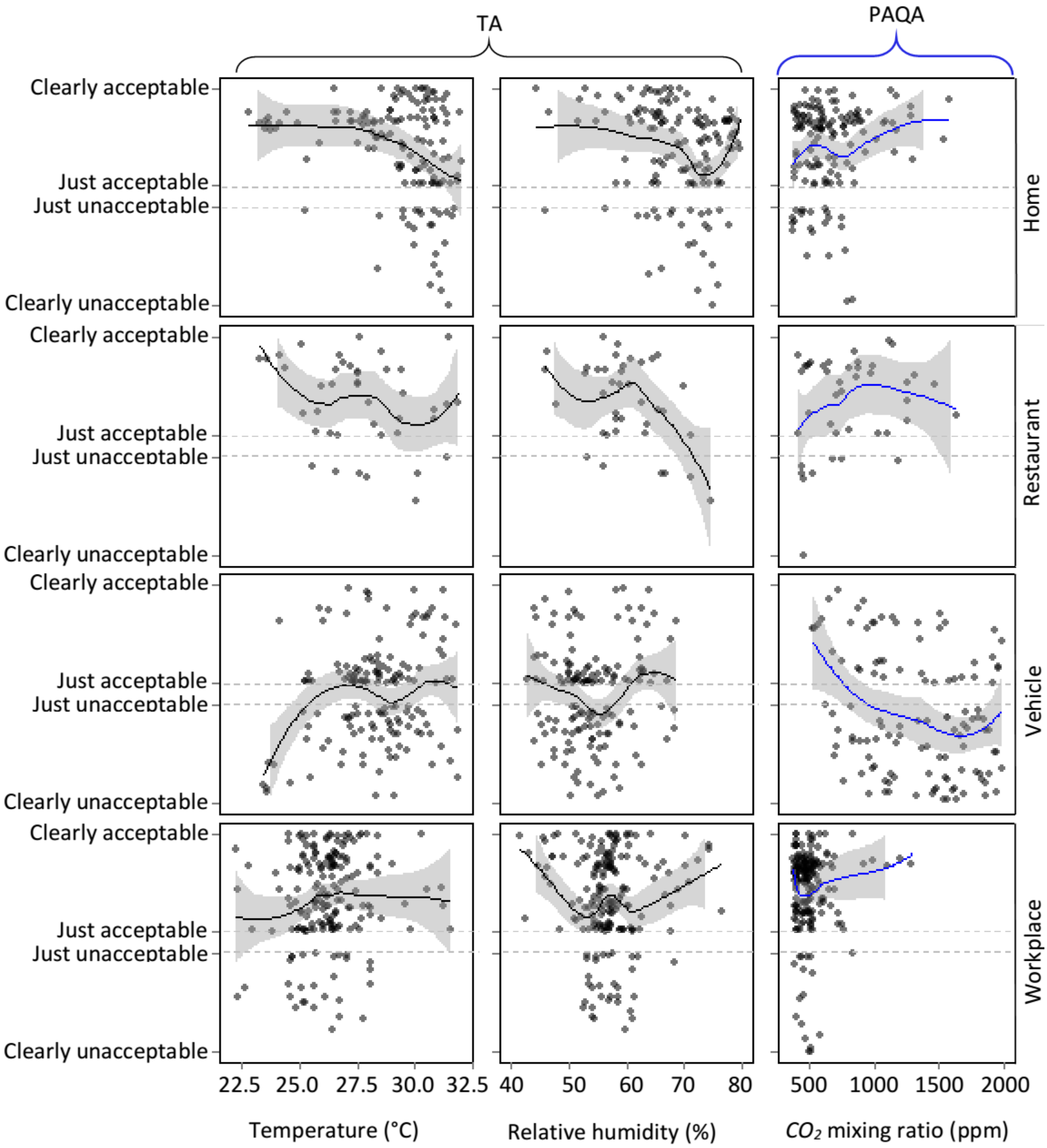

Figure 3 Relationship between thermal acceptability (TA) to measured environment parameters (T_a, RH, CO_2) in different environments

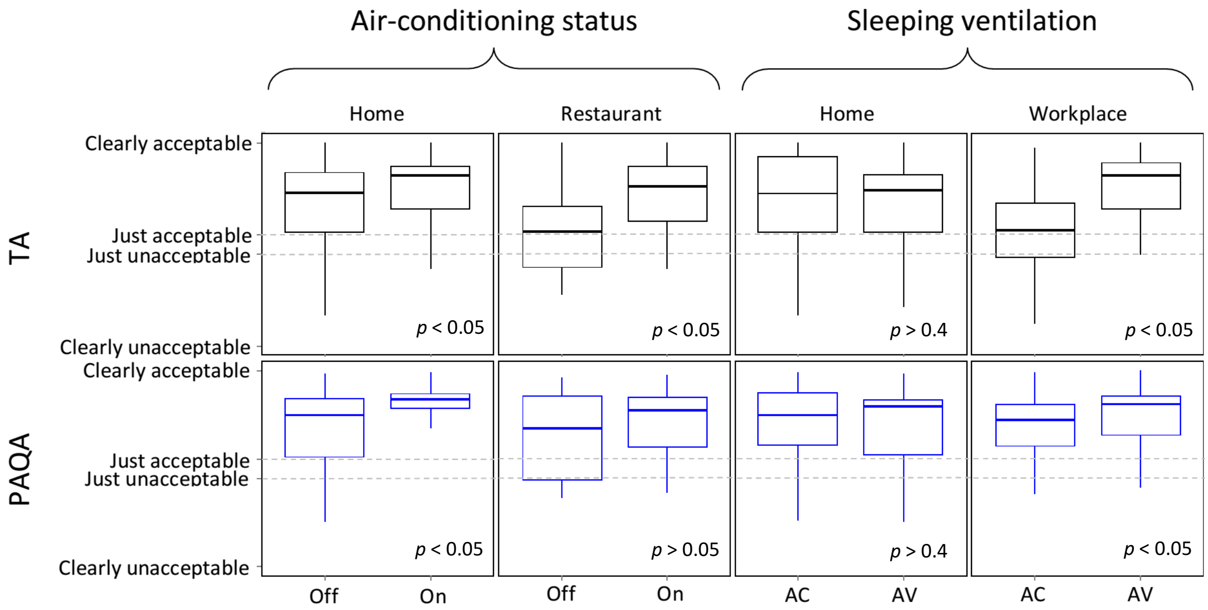

Figure 4 TA and PAQA performance for air-conditioning operating status and sleeping ventilation habits

4 Conclusion

Personal longitudinal monitoring experiments were conducted to investigate participants' assessment of thermal acceptability (TA) and perceived air quality acceptability (PAQA) in different locations with respect to objective physical parameters (T_a, RH and CO_2), air-conditioning status and occupant's sleeping ventilation habit. The findings suggest that clustering locations is important to better understand the associations between the environmental acceptabilities (TA and PAQA) and the measured physical parameters (T_a, RH and CO_2). The acceptability ratios of both TA and PAQA were greater than 80% in locations where people spent most of their time (home, workplace, and restaurants), but not outdoors and not in transportation vehicles. The worst PAQA, with acceptability ratio of 36%, was report in vehicle cabin, where an association of decreasing PAQA at higher CO_2 mixing ratio (median value = 1327 ppm) was observed. Greater acceptabilities were found when an air-conditioner was operated at home and in restaurant environments. In addition, both the air-conditioning ventilated (AC) and adventitiously ventilated (AV) sleeping groups were also satisfied with controllable ventilation at home, whereas the AC group assessed the thermal acceptability to be lower in the workplace than did the AV group. The database developed in this longitudinal experiment was capable to identify the thermal and perceived air quality acceptability trend under different environments. The next step of study would be focused on individual environment exposure analysis to assist future works on personal acceptability prediction.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

A Comparative Analysis of Thermal Acceptability in Offices in India and Japan

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Abstract
India's building energy consumption is increasing rapidly. Fukushima disaster reshaped Japan's energy perspective. Adaptive comfort standards need to be developed for these countries. We conducted a fourteen-month thermal comfort survey in India and a summer season study in Japan. This data was analyzed to develop an algorithm to predict thermal acceptability (TA). A direct question resulted in higher TA, than otherwise in Japan, perhaps due to deep-rooted cultural ethos. This trend is reversed in India. At 24 – 30 °C and at 27 – 28 °C of indoor temperature, 80 % thermal acceptability could be achieved in Japan and India respectively.

Keywords: Thermal Comfort; Adaptive Model; India; Japan; Thermal Acceptability

1 Introduction

After the Fukushima meltdown, Japan's energy perspective has undergoing a paradigm shift. Japan implemented '*setsuden*' (energy saving) measures for large electricity reductions, leading to 1.4% building energy reduction per year (IEA 2011). Tanabe et al., (2013) discussed the occupant satisfaction and Indraganti et al., (2013) the thermal comfort in offices under the *setsuden* conditions.

On the other hand, India's building energy consumption increased by about 3% per year. It was 196.04 million tonnes of oil equivalent in 2011, of which heating ventilation and air-conditioning (HVAC) and lighting contributed a major portion (IEA 2011). Moreover, India has a serious energy deficit and it is essential for its building sector to adopt non- energy intensive systems. India and Japan do not have adaptive comfort standards (BIS 2005). The current codes in India (BIS 2005) advocate narrow and uniform temperature ranges, leading to overcooling and wastage.

Arens et al., (2010) found that the precisely controlled thermal environments of ASHRAE's (American Society of Heating, Refrigerating and Air-Conditioning Engineers) (ASHRAE 2010) 'Class A' buildings were undesirable and impractical, offering no improved satisfaction to the users, when compared to the Class B or C buildings. Similarly, de Dear et al. noted the subjects under much lesser discomfort in naturally ventilated apartments in Singapore, even when the indoors were warmer than the standard prescriptions by about 3 K (de Dear and Leow 1991).

Therefore, thermal comfort is not a temperature set point. Being a complex adaptive system, the equilibrium can be achieved under several combinations of variables. Thermal comfort is indispensable for user satisfaction, which in turn decides the way a building is used, maintained and sold. Thermal acceptability is often used as a metric to assess user satisfaction. The ASHRAE Std-55 (ASHRAE 2010) mentions thermal acceptability as 'the condition where 80% of the occupants vote within the three central categories on the seven-point thermal sensation scale.'

Researchers often record thermal acceptability (TA) through a direct question (McCartney and Nicol 2002, M. Indraganti, R. Ooka, et al., Adaptive model of thermal comfort for offices in hot and humid climates of India 2014, Han, et al. 2007). However, thermal acceptability is quite a controversial construct as it can also be assessed with respect to many other comfort scales like thermal sensation (TS), and overall comfort (OC). Several physiological and psychological factors like sweating, expectation levels, thermal history, and others like adaptive opportunities contribute to this (Fountain, Brager and de Dear 1996). Baker and Standeven (1996) even strongly argue that the pursuit of strict temperature standards is an inappropriate goal to achieve acceptance in buildings.

Therefore, more important than thermal sensation is the question of how a given change in the environment would affect thermal acceptability of a space or modify the percentage of persons dissatisfied within a room (Berglund 1979). Many researchers found evidence that neutrality was not primarily ideal for a significant number of people and that the temperatures beyond the central three categories were judged satisfactory (Fountain, Brager and de Dear 1996). Thus, procedures to evaluate and estimate the integrated feelings of the users have to be established.

Therefore, this paper makes use of two field study data (M. Indraganti, R. Ooka, et al., Adaptive model of thermal comfort for offices in hot and humid climates of India 2014, Indraganti, Ooka and Rijal, Thermal comfort in offices in summer: Findings from a field study under the 'setsuden' conditions in Tokyo, Japan 2013) and aims to (1) propose a method to predict the thermal acceptability in offices in India and Japan using logistic regression and (2) compare and discuss thermal acceptability metrics derived through various thermal comfort scales. These logistic regression equations can be used in building performance simulations.

2 Methods

2.1 Survey areas

Figure- 1. (1) The instrument setup (2) The survey environments in India and Japan (A) Thermo-hygometer (TR 76Ui) (B) Anemometer (Testo 405 and Kanomax) (C) Globe thermometer (Tr-52i)

Hyderabad (N17°27’ and E78° 28’) has composite climate and Chennai (N13°04’ and E80° 17’) has warm humid wetland coastal climate. These have four distinct seasons: summer, monsoon, post monsoon and winter. The survey was conducted for 14 months during the period 2012- 13 in 28 office buildings. We undertook another survey in four office buildings (83 office spaces) in Tokyo (N35°41’ and E39° 41’), for three months in summer 2012 (Fig.1). Both surveys used paper-based questionnaires.

2.2 Survey areas

We surveyed fourteen buildings in each city in India. These are of three types: (1) fully naturally ventilated (NVall), (2) mixed mode (MM) and (3) air-conditioned throughout (ACall). We had thirteen MM buildings, fourteen ACall buildings and one NV building. We recorded the data when the offices were running in two modes: naturally ventilated (NV) and air-conditioned (AC). Some of the buildings are mixed mode buildings which operated in both NV and AC modes as chosen by the occupants. All the buildings in Japan are MM buildings which functioned either in AC or NV modes.

In India we collected 6042 sets of data from 2787 office occupants and in Japan 2402 sets from 435 subjects. An occupant’s unique thermal responses at a point in time, together with the thermal measurements of his/ her immediate surroundings is regarded as a data set. About 22% and 18% of the data were collected in NV mode in India and Japan respectively.

Table- 1 Details of the thermal scales used (ASHRAE 2010, McCartney and Nicol 2002)

THERMAL SENSATION	OVERALL COMFORT	THERMAL ACCEPTABILITY
Hot (3)	Very comfortable (1)	
Warm (2)	Moderately comfortable (2)	Unacceptable (1)
Slightly Warm (1)	Slightly comfortable (3)	Acceptable (0)
Neutral (0)	Slightly uncomfortable (4)	
Slightly cool (-1)	Moderately uncomfortable(5)	
Cool (-2)	Very uncomfortable (6)	
Cold (-3)		

The questionnaires included direct thermal enquiries on sensation, preference, acceptability and overall comfort (Table 1) (Indraganti, Ooka and Rijal 2013, Indraganti, Ooka and Rijal 2013). The surveyors noted down the use of environmental controls, clothing and activity.

Simultaneously while the occupants responded, we recorded all the four environmental variables: air and globe temperatures (T_a and T_g), air movement (V_a) and relative humidity (RH) using standard protocols (ASHRAE 2010). Females constituted about 1/4th and 1/3rd of the sample in India and Japan respectively. The subjects' age ranged between 20 – 70 years. We interviewed the respondents once or twice, and a dozen times a month in India and Japan respectively. The methods are detailed in Indraganti et al. (Indraganti, Ooka and Rijal 2013, M. Indraganti, R. Ooka, et al. 2014).

Table- 2 Mean and Standard Deviation of the indoor and outdoor thermal variables in NV and AC modes (Ind: India, Jap: Japan)

T_g		RH		V_a		T_{om}		T_{comf}	
Ind	Jap	Ind	Jap	Ind	Jap	Ind	Jap	Ind	Jap
28.8	29.4	44.7	52.6	0.17	0.20	25.5	25.9	28.0	27.0
2.0	1.6	11.7	6.4	0.25	0.15	3.0	2.2	2.6	2.5
26.2	27.9	48.2	50.8	0.11	0.25	28.4	28.0	28.0	26.4
1.6	1.2	9.3	4.4	0.17	0.16	3.4	1.7	2.6.	2.8

3 Results and Discussion

3.1 Thermal conditions and comfort responses

Hyderabad (N17°27' and E78° 28') has composite climate and Chennai (N13°04' and E80° 17') has warm humid climate. The indoor and outdoor conditions in India were warm throughout the survey, and in summer very humid as well, much similar to the Tokyo summer (Table 2). Winters in India were very mild. Therefore, it makes the data tenable for comparison. We obtained the outdoor mean temperature (T_{om}) for all the days of the survey from the local meteorological databases and estimated the outdoor running mean temperature (T_{rm}).

Researchers have made use of the running mean temperature as it represents people's responses to the outdoor environment better than the outdoor daily mean temperature. Humphreys et al. (2013) further show that the exponentially weighted running means give greatest weight to temperatures in the most recent past, and progressively less weight to those in the more remote past.

The exponentially weighted running mean of the daily mean outdoor temperature is obtained from the mathematical expression:

$$T_{rm\ (tomorrow)} = (\alpha)\ T_{rm\ (yesterday)} + (1-\alpha)\ T_{om\ (today)} \ldots \quad (1)$$

Where, T_{rm} is the running mean temperature (°C) and T_{om} is the outdoor daily mean temperature (°C) while α is a unit less constant between 0 and 1 and is usually taken as 0.8. It indicates a half-life of approximately 3.5 days (Humphreys, Rijal and Nicol 2013). We estimated T_{rm} for all the days from January 2012 to February 2013 for India data and also similarly for the Japan data.

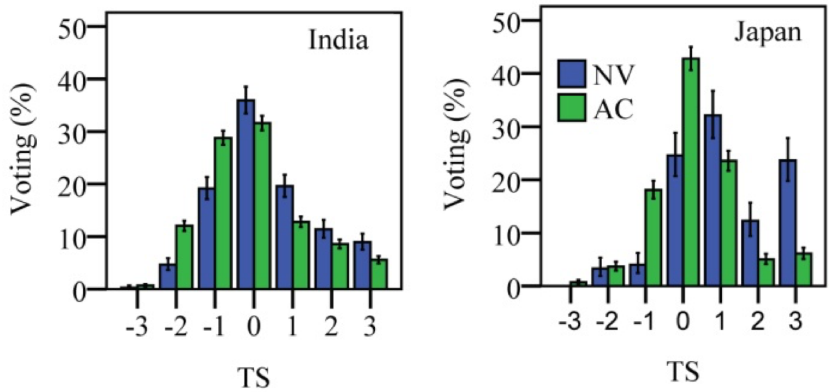

Figure- 2. Distribution of thermal sensation vote in India and Japan (error bars indicate 95% confidence interval)

A majority voted towards the central band of the sensation scale in both India and Japan as shown in Fig.2. However, in NV mode, a higher percentage voted on the warmer side of the sensation scale throughout. In Japan, Mean sensation in NV mode was 1.17 (SD = 1.3) and AC mode was 0.24 (SD = 1.2). Tanabe et al. noted greater variability in TS in Japan. They found it varying between -0.7 (SD = 1.1) to 2.0 (SD = 1.3) (Tanabe, et al. 2013).

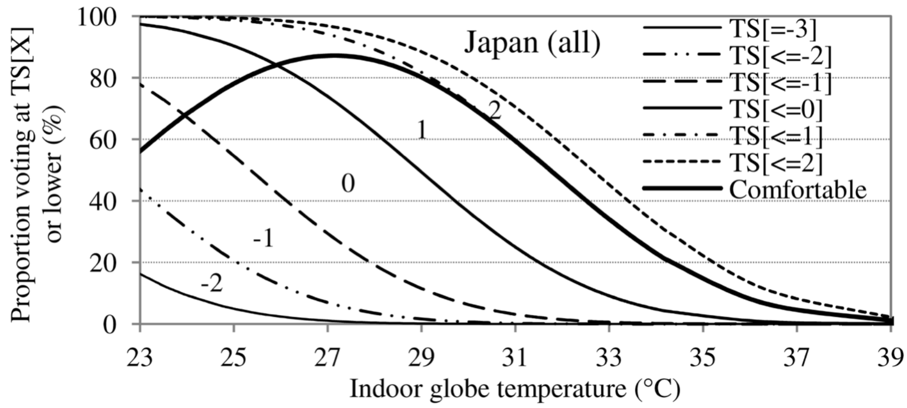

Figure- 3. Probit curves indicating subjects voting at a TS scale point or lower and the proportion comfortable (-1 to +1) (Japan all data)

From Fig.3 we can observe that when the indoor temperature was around 29 °C, 80% subjects feel comfortable (voting on TS -1 to +1). Also, at temperatures higher than this, the proportion voting comfortable rapidly plummets. Similar phenomenon was observed on Indian data also.

3.2 Comfort temperature

The correlation between TS and T_g was significant in both Japan and India. However, in Japan the modal difference was not significant. TS varied with T_g at a gradient of 0.33 K^{-1} in both the modes in Japan. Using this relationship, we noted a regression neutral temperature of 25.4 °C and 26.8 °C in NV and AC modes respectively for Tokyo in summer.

Using 0.5 as the Griffith's coefficient we estimated the comfort temperature (T_{comf}) for all the data sets (Griffiths 1990, M. Indraganti, R. Ooka, et al. 2014, Indraganti, Ooka and Rijal 2013). Table 2 features these values. Interestingly, comfort temperatures in Indian offices are similar to those of Tokyo in summer. Comfort and indoor temperatures of this order are not uncommon in the subcontinent. Acclimatized population in warmer tropics achieve comfort at usually higher temperatures than those experienced in the West. For example, a residential building study in Hyderabad noted comfort conditions being reported at as high as 32 °C (Indraganti 2009). Nicol et. al., made similar observations on Pakistan subjects (Nicol, et al. 1999).

We noted a significant adaptive relationship between the outdoor running mean and indoor comfort temperatures. For example, in AC environments, the rate of change of comfort temperature with respect to the outdoor running mean temperature was 0.10 K^{-1} in Japan and 0.15 K^{-1} in India, coming close to 0.09 K^{-1} of Europe (CIBSE, (The Chartered Institution of Building Services Engineers) 2006, M. Indraganti, R. Ooka, et al., Adaptive model of thermal comfort for offices in hot and humid climates of India 2014).

3.3 Thermal acceptability (TA)

We measured thermal acceptability using a direct question (0: acceptable; 1: Unacceptable). Two indirect acceptability binary scales were derived from TS and OC: voting comfortable on TS and OC scales as acceptable (a) (TA_{ind} = 0), and (b) (Comfort Acceptance: CA = 0) respectively, and vice versa (de Dear and Brager 1998). Table 3 shows the mean non-acceptability as measured through these scales.

Interestingly in India, a direct enquiry (TA) resulted in lower acceptance while indirect estimates gave higher acceptability respectively (TA_{ind} and CA). This contrasts the Japanese pattern of voting, perhaps due to innate Japanese cultural ethos.

Table- 3 Mean thermal non-acceptability (%)

Variable		Mode		
		NV	AC	All
India	N	1273	3936	6048
	TA	28	29	30
	TA_{ind}	25	27	27
	CA	23	19	20
Japan	N	423	1979	2042
	TA	24	8	11
	TA_{ind}	39	16	19
	CA	57	29	34

Comparing the performance of the direct and proxy acceptability scales revealed various nuances of these scales. The indirect questions also perhaps related to some physiological conditions while in a direct question, psychological factors overrode these, resulting in subjects' lower acceptance in India. In Japan, the modal differences in acceptability were not significant, while they were, in India.

3.4 An algorithm to predict thermal acceptability

Table 4 Logistic regression analysis for acceptability ($p<0.001$)

NO.	CASE	EQUATION	$R^2_{(Negelkerke)}$
3	TA_Japan	logit(p) = 0.454 T_g - 15.007	0.07
4	TAind_Japan	logit(p) = 0.459 T_g - 14.431	0.08
5	CA_NV.Japan	logit(p) = 0.325 Tg - 9.222	0.07
6	CA_AC.Japan	logit(p) = 0.480 T_g - 14.334	0.07
7	TA_NV.India	logit(p) = 0.218 T_g - 7.241	0.06
8	TAind_NV.India	logit(p) = 0.310 T_g - 10.063	0.01
9	TA_AC.India	logit(p) = 0.114 T_g - 3.888	0.11
10	TAind_AC.India	logit(p) = 0.111 T_g - 3.913	0.01

Logistic regression best suits the analysis of binary data such as TA, TAind and CA, probability of which varies with a stimulus such as Tg. Logistic regression of thermal non-acceptance was done with indoor globe temperature. This relationship is governed by the logit relationship:

$$Logit\ (p) \quad = \quad log\ (p/(1\text{-}p)) = bT+c \qquad (2)$$

Whence

$$p = e^{(bT+c)}/(1+e^{(bT+c)}) \quad (3)$$

Where,

p is the probability that the environment is unacceptable, T is the temperature (in this case indoor globe temperature), b is the regression coefficient for T and c is the constant in the regression equation.

The results of the logistic regression with direct acceptability (TA), indirect acceptability (TA_{ind}) and overall comfort acceptance (CA) are shown in Fig. 4 and Table 4. The actual proportion of acceptability at various temperature bins is also super-imposed on these curves (shown as points). The actual data matched very closely with the logistic regression lines. The slope of the regression lines in AC mode in India is much lower. It perhaps indicates many other non-thermal factors influencing acceptability. Some of these could be frequent outages, inadequate access to environmental controls as noted (Indraganti, Ooka and Rijal 2013).

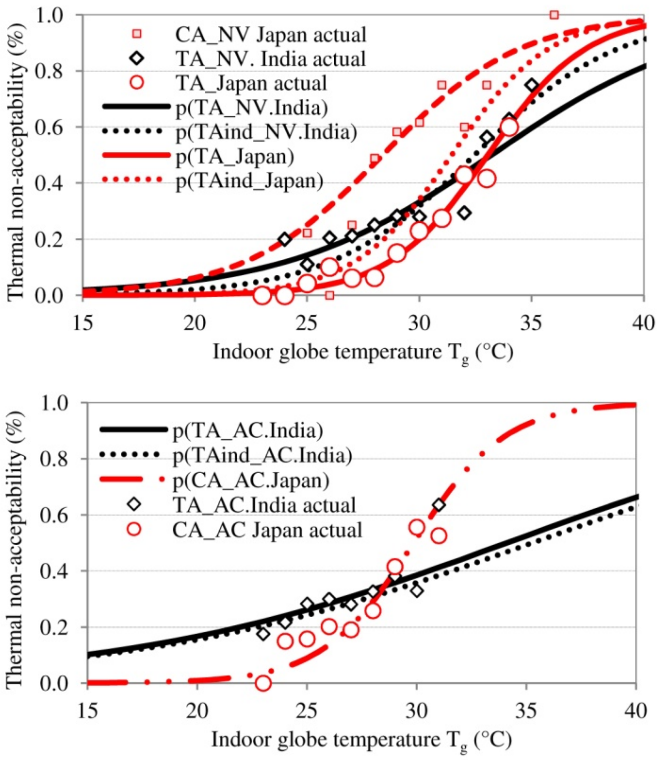

Figure 4. Logistic regression of various metrics of acceptability with indoor globe temperature for India and Japan in NV mode (above) and AC mode (below)

Using these curves, we can predict 80% acceptability in Japan (1) through a direct question at 30 °C, and (2) at 24 – 28 °C in NV and AC modes with indirect scales. On the other hand in India in NV mode, 80% acceptability could be predicted with a direct question, when the indoor temperature is at 27 °C. An indirect enquiry would yield the same at 28 °C. The temperature ranges for 80% acceptability obtained here are very close to the comfort temperature reported in Table 2. Importantly these are much higher than the ranges specified in the standards (BIS 2005). Likewise, de Dear and Brager (1998) found little resemblance between the actual levels of acceptability expressed by the subjects and those specified in the ASHRAE Standard 55-92. Arens et al., (2010) also noted no major variation in the acceptability outcomes of three different classes of buildings with varying levels of predicted mean vote (PMV) ranges of (-0.2 to + 07). Therefore, it may not be prudent to overdesign the systems to meet with the stringent narrow temperature standards.

Brager and de Dear (2000) demonstrated that people who were exposed to a narrow range of temperatures (mostly through HVAC systems) developed high expectations for homogeneity and cool temperatures, and were soon critical of the subsequent thermal migrations indoors. Contrastingly, they noted occupants of NV buildings appearing tolerant of – and in fact preferring wider thermo-hygro regimes, as also noted by Mallick (1996) and in this study (NV in India). These logistic regression equations can be included in the building performance simulations to predict the thermal acceptability vis-à-vis the indoor temperature.

4 Conclusions

A direct enquiry on thermal acceptability yielded higher acceptability in Japan and lower acceptability in India than through indirect methods of assessing acceptability. Logistic regression predicted 80% acceptability in Japan at indoor temperatures of 24 – 30 °C and at 27 – 28 °C in NV mode and at 22 – 23 °C in AC mode in India. Frequent outages, access to controls also could have affected the acceptability in AC mode in India.

Acknowledgements

The Japan Society for Promotion of Science and The University of Tokyo funded these surveys. We thank them. We also thank all the subjects and Mukta Ramola for their help in the surveys. The analysis in part was supported by Qatar University through NPRP-7-143-2-070. We acknowledge their support.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Improving the thermal performance and energy efficiency of NSW Demountable classrooms using a community led retrofitting strategy. A proposal for Broken Hill.

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Abstract
A community led retrofitting strategy involves the use of a design methodology to improve thermal performance that can be implemented by the community. This is a bottom up approach where designers work with children, parents and teachers to effect change in their built environments. Broken Hill provides an example of a remote community that represents the challenges of building and living in rural Australia in an extreme climate that is hot and dry. Whilst there are many strategies that can be used to improve the performance of the buildings, the practical passive strategies of insulation, fly roof and thermal mass using fibre cement sheeting where selected. Computer simulation is used to model these strategies and they found to halve the energy consumption of the building, however the energy consumption still exceeds the current target for this type of building.

Keywords: Demountable classrooms, energy efficiency, community

1 Introduction
Lightweight construction systems are used in hot climates around the world and often create internal environments that are too warm. In New South Wales (NSW), Australia, 12% of all government classrooms are lightweight demountable classrooms. These transportable classroom buildings provide the NSW government with an innovative system of physical infrastructure that allows schools to expand and contract in response to population fluctuation as well as providing emergency accommodation. However, they are commonly regarded as offering inferior teaching spaces due to their poor thermal performance. The existing solution to this challenge is to air-condition the classrooms. Whilst this might create thermal comfort it also creates high CO_2 emissions (in NSW 1kWh of electricity produces 1.05 kg.CO_2-equivelent (Department for climate change, 2013).

Prior research carried out in the milder cool temperate climates of NSW concluded that improving the fabric of the classroom could improve the thermal performance. However little work has been carried out in other climate types in New South Wales. This paper explores how the thermal performance of demountable classrooms can be improved when they are located in the extreme hot and dry climate of Broken Hill in the far west of NSW. The first part of this paper examines the climate characteristics of Broken Hill. The second part explores the utility and thermal performance of the demountable classroom typology is discussed. Third, the design led methodology is discussed. The methodology has three parts. (i) a qualitative assessment. (ii) the development of "Solution Sets", and finally (iii) a quantitative assessment of the proposed solution sets using a computer simulation model.

The development of the Solution Sets includes the development of a framework that will allow these strategies to be implemented by school communities and allow them to develop a greater understanding and knowledge of thermal comfort and the strategies that can be employed to achieve it. The fourth and final part of the paper discusses the results of the computer simulation and evaluates which of the solution sets are effective in improving the thermal performance, thermal comfort and reducing energy consumption and associated CO_2 emissions.

2 Site and Climate of Broken Hill

The site chosen is an existing situation at a school in Broken Hill. The demountable classrooms on the site sit in a row adjacent to some permanent buildings as illustrated on the site plan (FIG 1). the single highlighted classroom is used for the simulation. The classroom is fitted with a fly roof to reduce insolation.

Broken Hill is located 1159 km NW of Sydney close to the South Australian border, in the New South Wales (NSW) outback. The closest large town is Mildura, located 300km south of Broken Hill. The closest major city is Adelaide approximately 500km southwest. Broken Hill is the largest regional centre in western NSW; it is an isolated mining town and the largest producer of zinc, lead and silver in Australia. The population is approximately 19,000. The town is dominated by the 'line of load' rock formation, which is now largely made up of the slag from mining (NSW Wales Public Works Architects Department, 2011)

2.1.1 Climate:

The climate is illustrated in figure 2 (BOM, 2014). The climate has very hot arid summers and cool winters with average summer temperatures of 33^0 C and average winter temperatures of 15.6^0 C. The average rainfall is 200mm per year. There are cooling summer winds from the south and cold winter winds from the west. The environmental quality is dry and dusty. Figure 2 shows the features of this climate and the thermal comfort zone based on the adaptive model (Humphreys, 1978, de Dear and Brager, 1998). This shows for the summer months (November to February) that the mean temperatures are within the comfort zone however the mean minimum and maximum temperatures are outside the comfort zone. This large diurnal range is typical of hot dry climates. There is a short cross over period in spring and autumn when the climate is relatively mild although the mean minimum temperatures are consistently below the comfort zone. Mean relative humidity levels are low in summer month (<60%) and high during the winter (May 65%,, June 73%, July72%). Also note that there are extreme temperature events both for under heating and over heating; there are over 90 days per year when the temperatures are over 30^oC and 7 days a year when the temperatures are above 40^oC. (BOM, 2016). This building is largely an external load dominant building, which necessitates passive strategies to the mitigate the external heat gains and losses.

The next section explores the utility and thermal performance of the demountable classroom typology.

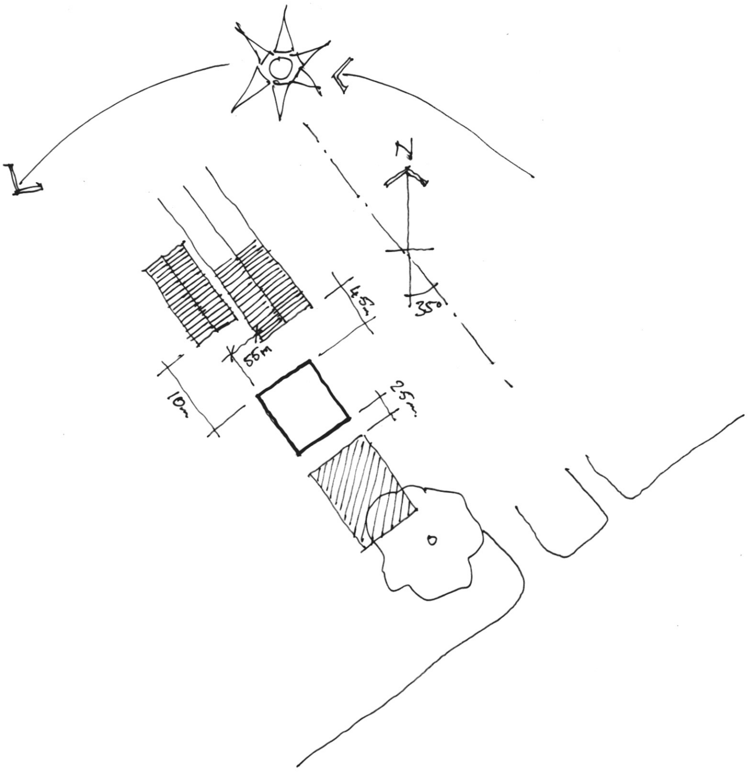


Figure 1: Site Plan (not to scale)

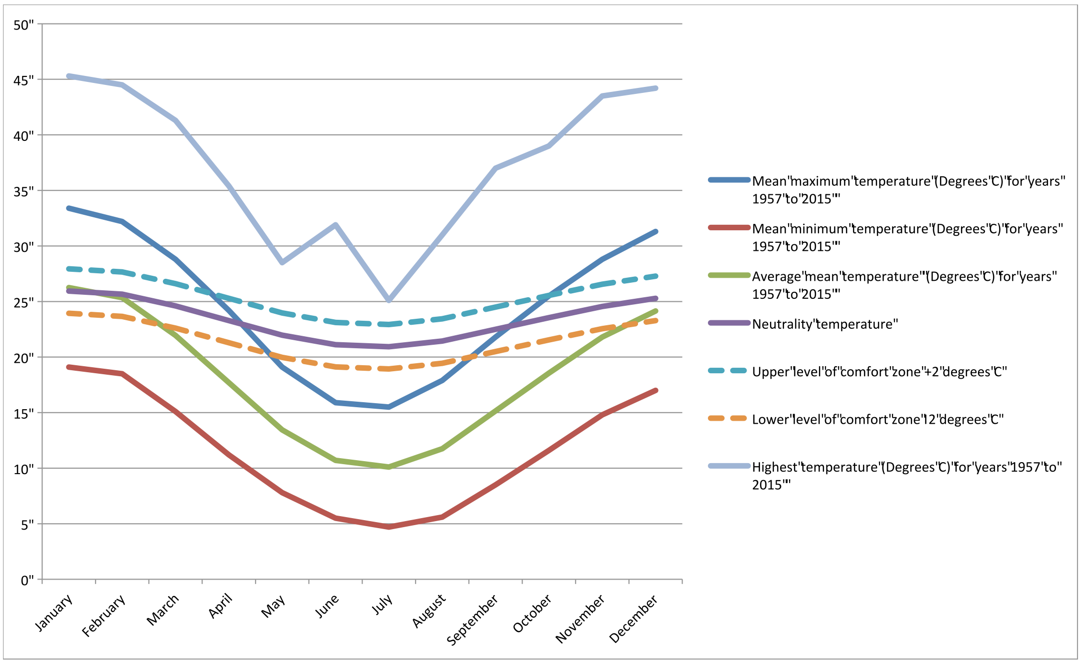


Figure 2. Broken Hill annual climate statistics (BOM, 2014) and comfort zone based on the adaptive model of human comfort (de Dear 1997)

3 Demountable Building Typology

The objective of the original NSW demountable classroom was to provide the NSW government with an easily re-locatable and adaptable classroom building that would allow the government to respond to changing school populations, demographics and local disasters such as bushfire, floods or arson (Underwood, 1972).

3.1 The original solution: A lightweight modular building

Originally designed in 1965 (Underwood, 1972) with a modified version created in the 1980's (NSW Government Architects, 1983). The NSW government Architects Office designed a building system that is based around a series of volumetric steel frames. The frames, constructed from steel sections approximately 200 x 75mm, are extremely robust. "Bomb proof" as an interviewee described them (Interview A, 2014). The frames are designed to be in-filled with a selection of prefabricated lightweight panels for the floors, roof and particularly the walls. It is clear from the original drawings that these panels are intended to be interchangeable and that the volumetric units are intended to be assembled in different configurations depending on the particular building that is required on a particular site at a particular time.

The volumetric units, approximately 8.8m long, 2.4m wide, 3.2m high and are designed to be delivered on the back of standard flat bed lorries without the need for an escort on the road. Originally they were unloaded using jacks although these have since been superseded by the use of cranes. The classroom units sit on a series of piles or plinths that minimise the foundations. This means that construction on site is minimised and when the classrooms are removed the site can be returned to its original state. The services required for the classrooms are also minimal restricted to electricity and sometimes water and simple waste.

A review of the original drawings and a detailed survey of existing classrooms undergoing refurbishment at Cessnock jail reveal a building fabric with substantial thermal bridging and minimal insulation. Detailed modelling of the construction using Therm 7 software (THERM 7.3, 2015) demonstrates the very poor U-values that the system achieves. The connections between the infill panels and the primary steel frame and the connections between the volumetric classroom units are all vulnerable to air infiltration (Figures 3 & 4).

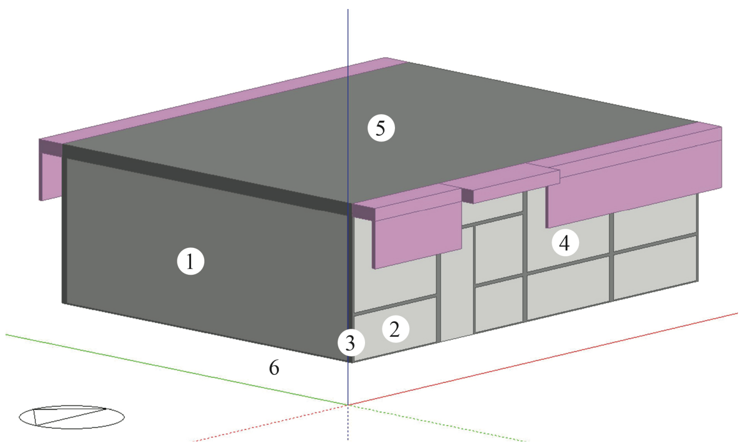


Figure 3: The demountable classroom building Design Builder model. (1) end wall (2) infill panel, (3) steel frame, (4) window, (5) roof

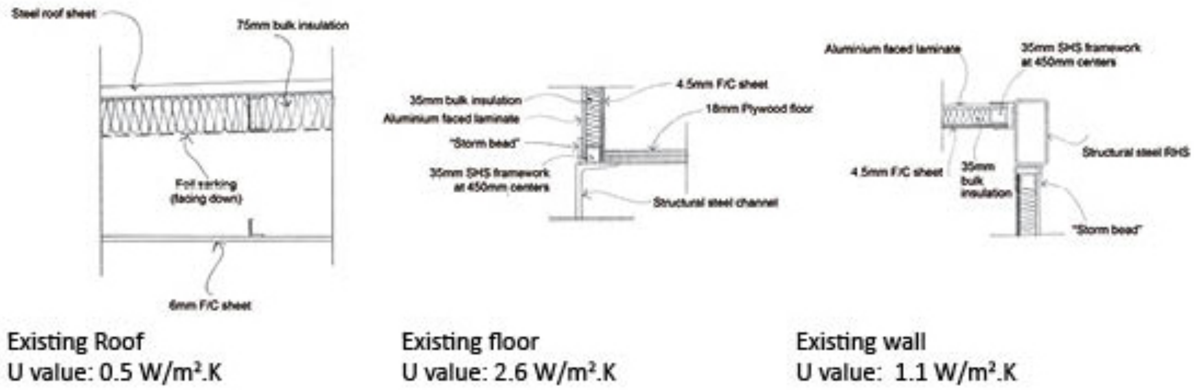


Figure 4. Existing construction details

3.2 The NSW Demountable classroom in use

The NSW demountable classroom was employed in a school design strategy called "Core-Plus". During the 1970’s, 80’s and 90’s the NSW Government developed the “Core-Plus” approach to school design where between 60 and 70% of the school is built as permanent facilities and the remainder of the classrooms are re-locatable demountable classrooms (Gan and Newton, 2012, Interview B, 2014, Underwood, 1972). The concept allows teaching capacity in these schools to be adjusted rapidly to accommodate changing demand. The demountable classroom allows the NSW government to expand and contract the school buildings in response to this changing population.

3.2.1 The current situation

The original demountable classrooms remain in use; a testament to their longevity and usefulness. They are occasionally refurbished but only to the original specification. the most significant change has been the introduction of split cycle air-conditioning units to all demountable classrooms between 2003 and about 2005 (Hansard NSW) (08/03/2003). They continue to fulfil a vital roll providing the communities of NSW with teaching accommodation.

Today the NSW Department for Education statement on Demountable classrooms (NSW Government, 2014) explains that the purpose of the demountable is to:

- provide accommodation for peak enrolments
- meet accommodation needs in schools from increased enrolments
- meet emergency needs as a result of fires or natural disasters
- meet needs arising from capital works or maintenance projects in schools.

The same role and objectives they were designed to meet 50 years ago. One example of this is the replacement of 80% of St Clair's High School in just 17 days following a fire in 2014 (Hansard NSW)(05/08/2014).

The interviewees tell a similar story, over the 35 years of their collective experience, explaining that the need for and purpose of the NSW demountable classroom has been and remains the provision of emergency accommodation and accommodating fluctuating school populations.

3.2.2 The current challenge

Unfortunately communities across NSW regard the demountable as a second rate classroom providing inadequate teaching accommodation. They have become "a pejorative" (Interview B, 2014). A view exemplified by a debate in the NSW parliament in 2003 with a motion calling for the House to acknowledge "that the learning environment of a permanent classroom in regional New South Wales is a better learning environment than a demountable classroom." (Hansard 8/09/2003).

3.2.3 Changing pedagogy

One interviewee explained that "a 21st century classroom is unrecognisable compared to a 20th century classroom" (Interview E, 2014). Pedagogy has transformed from a "talk and chalk" approach where rows of children passively absorb instruction into an interactive, exploratory and constructive experience that is expected to be engaging. This new approach places new demands on classroom spaces and there is a perception that the demountable is unable to provide the flexible spaces that are required. A review of the original drawings shows that such modern "innovations" as the moving partition between classrooms or the fully opening external walls were in fact designed for these buildings. The opportunity to implement them is not being taken. These buildings were designed to be modular at several levels from the volumetric classroom module to individual façade modules. They were designed to adapt and be adapted to changing needs and expectations.

3.2.4 Appearance

In his influential report Professor Vinson (Vinson et al., 2002) observed that

"the quality of school buildings and their surrounds can also be a potent symbol of the regard (or otherwise) in which public education is believed to be held by governments and the community"

In a section dedicated to the demountable classroom he notes that

"Demountables have been the subject of incessant criticism throughout the Inquiry. …..[in] the absence of air conditioning they are too hot; …. their insubstantial character detracts from the appearance and confirmed identity of a school."

3.3 Thermal performance and Internal Environmental Quality (IEQ)

There are no detailed studies of IEQ in NSW demountable classrooms or more broadly across Australia however there are numerous anecdotal reports in the press, parliament (Hansard NSW) and Professor Vinson's report (Vinson et al., 2002). There are also anecdotal reports from similar buildings across Australia (Fuller and Luther, 2003, Future Proofing Schools ARC Linkage Project, 2011). More detailed studies of relocatable classrooms in California (Jenkins et al., 2003, Whitmore CA, 2003) have found significant problems with thermal performance, CO2 levels and associated air quality. A baseline study by Slee and Hyde (2015a) using a detailed survey and thermal modelling demonstrated the thermal performance challenges these lightweight, poorly insulated building present in the diverse climates across the state with high solar radiation levels.

The negative impact of poor IEQ on the performance of pupils and teachers has been well documented. Notably by Mendel and Heath (2005) who conducted a detailed literature review and concluded that lower student performance can be linked to poor indoor air quality and thermal conditions. A more recent study by Wargoki and Wyon (2007) showed a correlation between "comfortably cool" conditions and the highest levels of pupil performance. Higher ventilation rates have been shown to improve student and teacher performance in studies by Bako-Biro (2012), de Guili (2012) and Clements-Croome (2008).

3.4 The challenge: Obsolescence

Pinder and Wilkinson (2000a) argue that buildings are utilities rather than assets and that obsolescence is a measure of their changing usefulness (utility) over time. Following Burton (1933), Pinder and Wilkinson (2000b) argue that there are two classes of causation for obsolescence:

1. Locational (extrinsic) causes (e.g. changing demographics, population movement or density and changing climate)

2. Building performance (intrinsic) causes (e.g. the thermal performance of the building)

Using Pinder and Wilkinson's categorisation of obsolescence the re-locatable classroom was specifically designed to avoid the locational, extrinsic causes of obsolescence by being re-locatable, possibly with the exception of tight inner city sites (interview E). The second-class, intrinsic building performance causes, have been shown to be a fundamental problem for the building typology. These intrinsic challenges are associated with the fabric of the building (the thermal performance) and the social utility of the building, that is the usefulness of the space for contemporary pedagogy and the esteem in which the buildings are held.

The social utility of these versatile buildings, deployable and operational across the state within days, is demonstrated in part by the fact that they have lasted for 50 years and continue to provide an economically and socially sustainable solution to the NSW government and the communities the government serves. Improving the social perception of these buildings is, however, challenging. The challenge of improving the thermal performance of the building is also significant since it has been shown that lightweight building envelopes tend to exacerbate rather than moderate the diurnal temperature range in warm and hot climates (Slee and Hyde, 2015a, Pearlmutter and Meir, 1995). Strategies do, however, exist and it is the combination and implementation of these strategies to significantly improve the thermal performance of the NSW demountable classroom, its perception within the community and utility as a means of teaching communities about comfort and thermal performance that the remainder of this paper explores.

4 Methodology

Buildings are an intrinsically complex system and exist within other complex environmental and social systems.

This paper uses a design led methodology for resolving the problem of poor thermal comfort in these classrooms and their poor social acceptance by developing a series of strategies that can improve the environmental performance of the demountable classrooms. These strategies are tested using computer simulation and the results analysed using thermal comfort metrics. The methodology facilitates the resolution of the complex problems of environmental performance, social acceptance, construction and financial cost. The methodology contains three stages:

1. A qualitative assessment of the existing situation

2. The selection of "solution sets" using a design led methodology

3. A quantitative assessment of the various proposals.

4.1 Qualitative analysis

The first part of this methodology is qualitative. A series of detailed and open ended interviews were conducted with people associated with the design, maintenance and administration of the NSW demountable classroom program. Additional anecdotal information was collected from original drawings and various academic, political and media reports. Finally detailed observations of classrooms before, during and after refurbishment were undertaken as well as the deployment method.

The qualitative aspect of the method allows the researchers to understand the social context and purpose of the NSW demountable classroom. the results of this assessment have been reported in more detail elsewhere (Slee and Hyde, 2015b) and are summarised in the introduction to this paper. These results inform the strategies proposed for improving the performance of the classroom.

4.2 Selecting solution sets

Solution Sets are descriptive models of a combination of systems that can be used to improve the performance of an existing or a new building to meet a set of objectives (Hyde et al., 2009, Bastien et al., 2013). The individual systems are sometimes referred to as interventions. The nature of the problem means that there can be no single or optimal solution. Each set of objectives can lead to multiple Solution Sets. These can in turn be categorised by cost, “buildability” or degree of innovation (Slee et al., 2014a).

The qualitative assessment of NSW demountable classrooms (Slee and Hyde, 2015b) concluded that (i) the thermal performance of the classrooms must be significantly improved and (ii) the communities appreciation of these remarkable buildings needs to be increased. To do this an overall approach needs to be defined which will inform the individual technological solutions that are proposed as "solution sets".

4.3 Three approaches

The principal of the modular demountable and relocatable classroom building has been shown to be important and useful. The following three strategies for significantly improving the thermal performance of this typology have been identified and are discussed briefly below:

- Replacement of existing demountable with a new design
- The “deep” refurbishment of the existing demountable classrooms
- On site modification

A number of social, practical and economic issues need to be considered.

4.3.1 Replacement – create a new design

The 6000 classrooms owned by the NSW government represent a significant asset. They are generally in a reasonable or good state of repair and their replacement would represent a considerable financial and environmental cost in terms of embodied CO2 and CO2-equivelent.

4.3.2 Deep refurbishment

Currently the demountable classrooms are refurbished at Golburn and Cesnock jails through a contract with the NSW Correctional Service Industries providing employment, training and rehabilitation to inmates. This process involves stripping the classrooms back to their structural frame and rebuilding them using original and new components. The process offers the opportunity to significantly improve the design and specification of the building envelope however only about 3% (100 – 200) classrooms are refurbished each year. This means that at the current rate a complete upgrade of the stock would take about 30 years. A substantial increase in the rate of refurbishment would reduce the number of classrooms available for teaching at a time when school populations are increasing.

4.3.3 On site refurbishment

On site refurbishment presents its own challenges as well as a number of opportunities for the use of climate specific adaption, social engagement and the development of practical education experiences that can be integrated into the school curriculum:

In developing a series of climate specific strategies that can be implemented at a local level it is important to recognise that the demountable portable nature of the classroom buildings and their existing robust construction must not be compromised.

The diversity of climates across NSW suggests that solutions appropriate in Coffs Harbour are unlikely to be appropriate in Broken Hill or Penrith.

The SEED project (The SEED Collaborative, 2015) and the work of Peter Hubner (Blundell Jones, 2007) both demonstrate how school communities of all ages can become involved in and learn from the process of designing and implementing bio-climatic school buildings. And that this learning process can continue long after construction is complete.

The decentralisation of responsibility to the users for improving the environmental performance of their school may be seen as socially and economically more efficient. It creates the opportunity to engender a sense of ownership and reinforce the significance of the school within the broader community. To quote Professor Vinson: “the quality of school buildings and their surrounds can also be a potent symbol of the regard (or otherwise) in which public education is believed to be held by governments and the community” (Vinson et al., 2002).

4.3.4 The advantages of community led refurbishment

A collaborative approach that integrates the process of design and construction into the school curriculum so that it is aligned with cotemporary/modern pedagogy (constructivist, student centred) (Ben Cleveland, 2015) enhances students interdisciplinary thinking, presentation and negotiation skills, and team work, as well as empowering students, teachers and the community. The process creates a sense of engagement and pride in the school and, importantly, encourages everyone to learn about Environmental Performance and Thermal Comfort. (Ben Cleveland, 2015, Wake, 2015, Parnell et al., 2008)

4.3.5 Technological solutions for community implementation

The use of community labour and skills means that the proposed technological Solution Sets need to be simple to implement using materials that are readily available. This strategy precludes the use of highly innovative systems such as phase change materials or the modification of the existing mechanical ventilation and cooling system. The proposals must also ensure that they do not reduce the portability of the building units or damage them. Consequently the proposals need to meet the following four criteria:

- Be relatively low cost
- Be simple to implement

- Use readily available building products
- Must not impede the relocation of the classroom units.

Three solution sets are proposed:

4.3.6 Whole building shading

Whole building shading has also been shown to be a very useful strategy. While the strategy has a number of high profile precedents and is a common approach on static caravans around Australia empirical research in this area seems to be limited. Cardinale et al (2010) used a validated simulation model of a mobile home in Bari, southern Italy, to explore the effectiveness a whole building shading strategy. In their simulation model they placed a second roof above the primary (original) roof with a (unspecified) space between the two. Of the various improvement strategies they tested this strategy was the most effective reducing the internal air temperature by about 7oC compared the unshaded version.

4.3.7 Resistive or bulk insulation

The current classroom buildings have very little resistive thermal insulation and so many thermal bridges that the insulation that is present is almost redundant. Resistive insulation is generally regarded as useful however there appears to be limited studies into its use in different conditions. Several studies exploring the use of resistive insulation in medium to high mass buildings have shown that, after a certain point defined by various parameters, additional insulation has no effect (Taylor et al., 2000, Jaffal et al., 2012) or it can actually increase cooling loads where air conditioning systems are used (Masoso and Grobler, 2008). Li et al (2013) observed that resistive insulation tends to be more effective in heating dominated rather than cooling dominated buildings and climates.

4.3.8 Thermal mass

The climate of Broken Hill with a large diurnal range and relatively extreme temperatures is a place typically associated with the effective use of thermal mass. These buildings are designed to be lightweight so that they can be transported easily. This operational objective precludes the use of substantial quantities of thermal mass however it has been shown that relatively small quantities of thermal mass can make a significant contribution to reducing internal temperature fluctuations and improving the thermal performance of a building (Slee et al., 2014b).

5 Proposed solution sets

5.1.1 Whole building shading

This modification has already been implemented on the site using a standard prefabricated system that has the same footprint as the roof. Prior to the use of air-conditioning in demountable classrooms these were apparently common but are not used now because they require an extra lorry to transport them to site and thus increasing transport costs by 25%. We will evaluate the contribution this "fly roof" makes and test a larger "fly roof".

Because we have adopted a pragmatic design led approach to this research where we are investigating the efficacy of possible interventions the following interventions will all be in addition to the existing fly roof (figure 5).

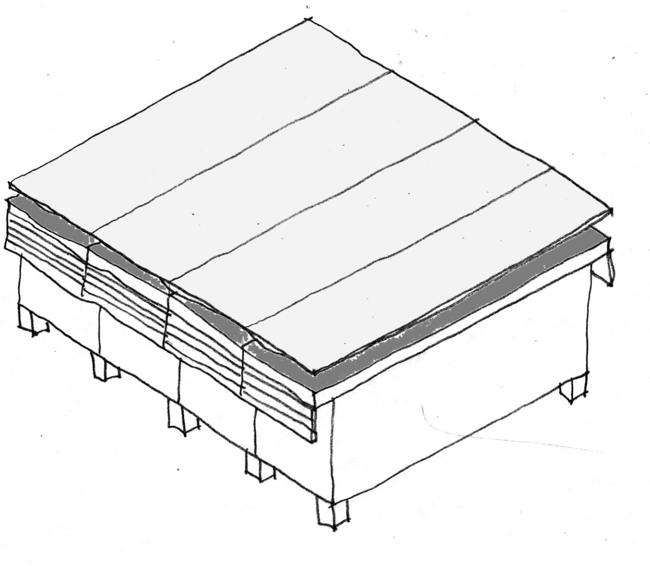


Figure 5: Illustration of the fly roof on a classroom

5.1.2 Resistive insulation

Using boards of PIR insulation foam we will add 40mm and then 80mm of insulation to the existing walls and ceiling. The insulation will be protected using a 6mm fibre cement sheet to form the internal finish. The existing floor that, is currently un-insulated will have R2.5 insulation fitted between the joists. PIR insulation board is widely available in builder's merchants and easy to handle (figure 6).

5.1.3 Thermal mass

The internal fibre cement board will be increased from 6mm to 18mm and then 36mm on the walls and ceiling to increase the thermal mass inside the space. Fibre cement board is widely available in builders merchants and easy to handle (figure 6).

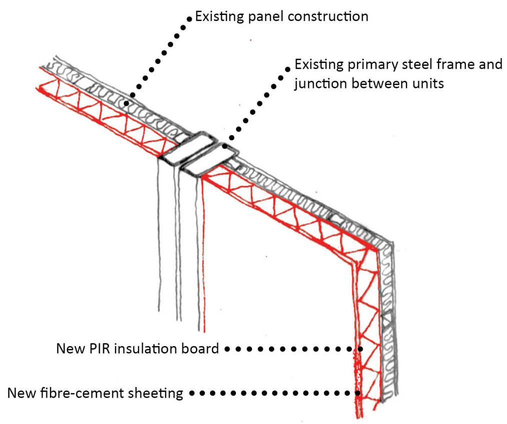


Figure 6: Illustration of solution sets 2 (insulation) and 3 (thermal mass) in a wall at the junction between two steel frames. Original construction shown black, proposed additions shown red.

Table 1: U-values and description of existing construction and proposed modifications for solution sets 2 and 3.

Solution Set	Floor	U-value W/m^2.K	Walls	U-value W/m^2.K	Roof	U-value W/m^2.K
AC01 & 2 EXISTING	Plywood floor	2.11	Steel framed panels	(1) 1.04 (2) 0.90	Foil-faced blanket	1.25
AC 03	R2.5 insulation between existing steel joists. Fibre-cement soffit to underside.	0.70	40mm PIR insulation board 6mm Fibre-cement sheet Fixed to inside on walls.	(1) 0.32 (2) 0.73	40mm PIR insulation board 6mm Fibre-cement sheet Fixed to existing ceiling.	0.42
AC 04	R2.5 insulation between existing steel joists. Fibre-cement soffit to underside.	0.70	80mm PIR insulation board 6mm Fibre-cement sheet Fixed to inside on walls.	(1) 0.20 (2) 0.42	80mm PIR insulation board 6mm Fibre-cement sheet Fixed to existing ceiling.	0.26
AC 06	R2.5 insulation between existing steel joists. Fibre-cement soffit to underside.	0.70	40mm PIR insulation board 18mm Fibre-cement sheet Fixed to inside on walls.	(1) 0.32 (2) 0.73	40mm PIR insulation board 18mm Fibre-cement sheet Fixed to existing ceiling.	0.42
AC 08	R2.5 insulation between existing steel joists. Fibre-cement soffit to underside.	0.70	40mm PIR insulation board 36mm Fibre-cement sheet Fixed to inside on walls.	(1) 0.31 (2) 0.72	40mm PIR insulation board 36mm Fibre-cement sheet Fixed to existing ceiling.	0.41
AC 010	R2.5 insulation between existing steel joists. Fibre-cement soffit to underside.	0.70	40mm PIR insulation board 36mm Fibre-cement sheet Fixed to inside on walls. Large fly roof	(1) 0.31 (2) 0.69	40mm PIR insulation board 36mm Fibre-cement sheet Fixed to existing ceiling. Large fly roof	0.40

6 Quantitative analysis

The detailed observations of the classrooms undergoing refurbishment allowed a detailed measured survey of the fabric of the Mk I classroom to be undertaken including the construction of the inside of wall, floor and ceiling panels and systems. This, combined with access to the original drawings and specification allowed a detailed computer simulation model to be constructed.

6.1 Simulation strategies

Two simulation strategies exist:

1) A computer simulation model validated using empirical data

2) A computer simulation model constructed from the available information.

The first of these strategies involves the construction of a model of an existing building that is then checked against data measured in real time in the actual building.

The second strategy is simpler and relies on the quality of the information available, the quality of the simulation model and software package to ensure a reasonable degree of accuracy.

The first strategy has the apparent advantage of being "validated' against "real" data. The difficulty of undertaking a robust validation process is significant and discussed at length by Raferty et al (Raftery et al., 2011a, Raftery et al., 2011b). Raferty et al highlight the tendency of researchers to use "ad-hoc" tuning processes rather than the robust systemic process they advocate. A second challenge for the validated model is the time required to collect a useful body of empirical data in different conditions and the time needed to calibrate the model.

The second strategy has been used by many researchers to explore the performance of different construction systems in Australia (Gregory et al., 2008, Bambrook et al., 2011, Slee et al., 2014c) the resilience of construction systems to climate change in the UK and Europe (Hacker et al., 2008, Zangheri et al., 2009, Causone et al., 2014, Ford et al., 2007). It offers the significant advantage of speed at the cost of a loss of empirical validation and this may be considered a significant shortcoming. The choice of approach depends on many factors, in particular the ability to access or collect empirical data, the time and resources available for the study and the purpose of the study. For this study we have chosen to use the second approach because of the difficulty of obtaining access to occupied classrooms for the collection of empirical data and the time available for the study.

This paper reports on one part of a broader study exploring the use and performance of the demountable classroom in the wide range of climates that exist across the state of NSW. The study explores how the construction and operation of the classrooms can be modified to improve their performance and so each simulation model will be significantly different from any original base case model. It is argued that where the simulation model is intended to be used to explore the relative impact of these parametric modifications and of climate on the thermal performance of the classroom building rather than to develop absolute values that this form of study is valid. The model is used for this purpose however the findings are grounded with reference to existing GreenStar benchmarks for energy consumption in this type of school buildings (GBCA, 2009). However these benchmarks are generalised to NSW and are not necessarily specific to Broken Hill.

6.2 A two stage process

The simulation model was created in two stages based on the information gathered during the survey and from the original drawings.

Stage 1: Individual parts of the building, for instance the wall panels, contain relatively complex thermal bridges formed from different steel sections used in primary and secondary structural frames. These were modelled using Therm 7 (THERM 7.3, 2015) to calculate an overall U-value for each panel system (table 1).

Stage 2: The classroom was modelled using Design Builder 4.6 (Design Builder Ltd) using U-values calculated in stage 1 for particular constructions of panel (figures 1 & 2, table 1). other important assumptions are listed in table 2.

Table 2: Simulation assumptions

Climate data:	A climate file based on data collected at Broken Hill Airport (Exemplary Energy, 2014) was used
Occupancy:	A standard school day was devised from 9am - 3pm with the teacher and some students arriving at 8am and leaving at 6pm. 30 students and 1 teacher. Occupancy was modelled for a 7-day week through the whole year 9365 days).
Thermostat settings	The NaTHERS thermostat settings were selected because they reflect the closest approximation to standard practice in people's homes. (NatHERS, 2012). Heating: 20 deg. C / Cooling: 26.5 deg. C
Ventilation	Ventilation is based on 8 l/s per person and calculated based on the occupancy schedule.

6.3 Evaluation criteria

The primary objective of the research is to develop proposals that will improve the thermal performance and consequential indoor environmental quality of the classrooms. The second objective is to reduce the annual energy consumption which is electrical and measured in kilowatt Hours (kWh). The Green Star Council target energy consumption for heating and cooling in classrooms is 26.8 kWh/m^2.year (GBCA, 2009).

In order to assess the thermal performance in the simulation model we have chosen to use the adaptive comfort model to predict comfort. Specifically we have used the daily running mean formula proposed by de Dear and Candido (de Dear and Candido, 2012) for naturally ventilated buildings in NSW.

The demountable classrooms operate in a mixed mode. Some may argue that the presence of the split cycle cooling system means that the adaptive model is not appropriate. We have chosen to use it for the following reasons:

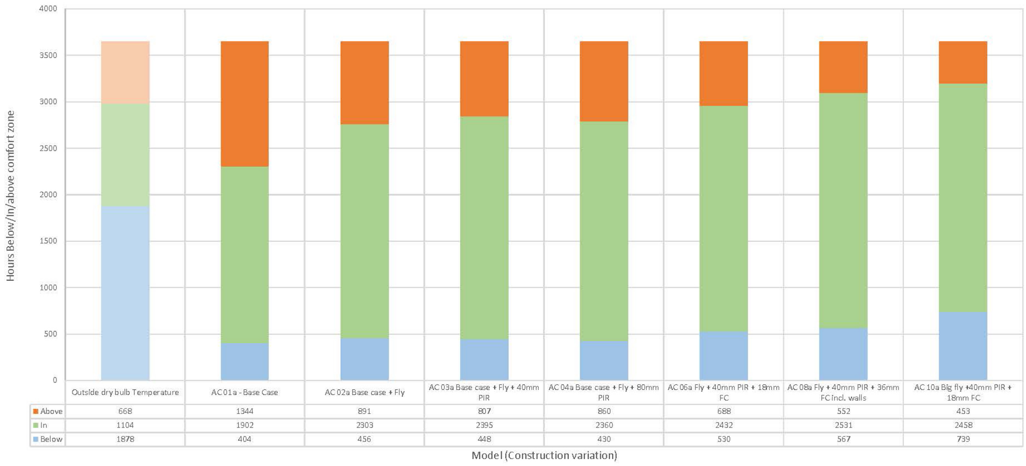
- The adaptive comfort method considers comfort in response to the local outdoor climate that the students and teacher experience frequently because they are entering and leaving the classroom for school breaks or to move to other classrooms.
- The ventilation to the classrooms is direct from the outside either through open windows or a mechanical fan in the wall. There is no air handling unit.
- the split cycle unit cools or heats the air in the classroom. it does not supply conditioned air to the classroom.
- The classrooms were originally designed as free running buildings
- NSW government policy is that all classrooms should be naturally ventilated or operated using a mixed mode strategy.
- The addition of split reverse cycle airconditioning system provides mechanical cooling and heating when limits of the passive strategies is reached, Controlled variables and settings:

7 Findings

Figure 7 illustrates the annual number of working hours (08.00 - 18.00) that the classroom is predicted to be below, in and above the comfort zone, which is taken to be 3 degrees each side of the predicted mean comfort temperature.

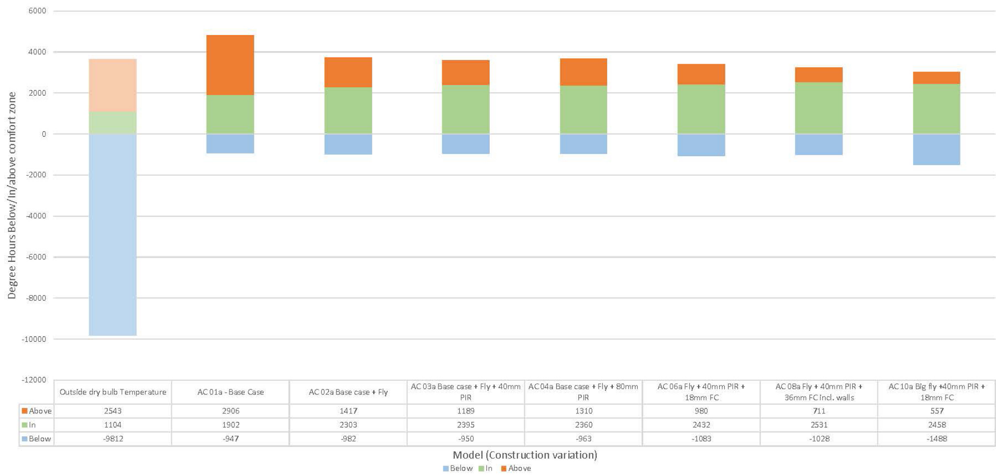
The second graph, figure 8, illustrates the number of degree-hours the classroom is predicted to be below, in and above the comfort zone. Viewed together they illustrate the amount of time and the magnitude of the periods that are outside the comfort zone and the relative impact of the various interventions.

The third graph, figure 9, shows the amount of energy in kWh used each year for heating and cooling the space with the total kWh for each intervention noted as a number. Table 3 combines this information and lists the total energy consumption as gross annual energy, annual energy consumption per square meter, and the mean annual energy consumption per day.



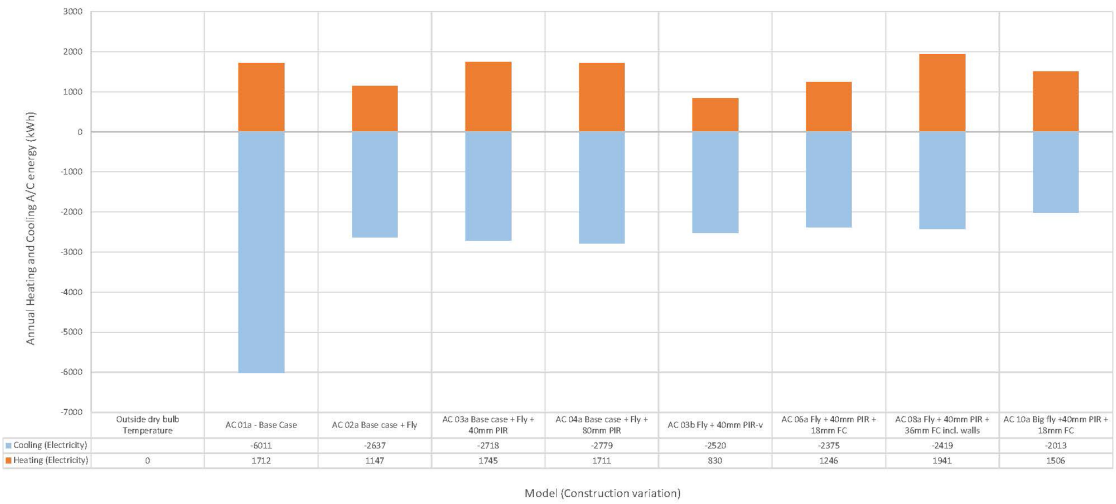
	Outside dry bulb Temperature	AC 01a - Base Case	AC 02a Base case + Fly	AC 03a Base case + Fly + 40mm PIR	AC 04a Base case + Fly + 80mm PIR	AC 06a Fly + 40mm PIR + 18mm FC	AC 08a Fly + 40mm PIR + 36mm FC incl. walls	AC 10a Big fly +40mm PIR + 18mm FC
Above	668	1344	891	807	860	688	552	453
In	1104	1902	2303	2395	2360	2432	2531	2458
Below	1878	404	456	448	430	530	567	739

Figure 7: Total annual hours below, in and above the comfort zone



	Outside dry bulb Temperature	AC 01a - Base Case	AC 02a Base case + Fly	AC 03a Base case + Fly + 40mm PIR	AC 04a Base case + Fly + 80mm PIR	AC 06a Fly + 40mm PIR + 18mm FC	AC 08a Fly + 40mm PIR + 36mm FC incl. walls	AC 10a Big fly +40mm PIR + 18mm FC
Above	2543	2906	1417	1189	1310	980	711	557
In	1104	1902	2303	2395	2360	2432	2531	2458
Below	-9812	-947	-982	-950	-963	-1083	-1028	-1488

Figure 8: Total annual degree-hours below, in and above the comfort zone. Hours inside the comfort zone are described as hours multiplied by one: (Hours in x 1)



	Outside dry bulb Temperature	AC 01a - Base Case	AC 02a Base case + Fly	AC 03a Base case + Fly + 40mm PIR	AC 04a Base case + Fly + 80mm PIR	AC 03b Fly + 40mm PIR-v	AC 06a Fly + 40mm PIR + 18mm FC	AC 08a Fly + 40mm PIR + 36mm FC incl. walls	AC 10a Big fly +40mm PIR + 18mm FC
Cooling (Electricity)		-6011	-2637	-2718	-2779	-2520	-2375	-2419	-2013
Heating (Electricity)	0	1712	1147	1745	1711	830	1246	1941	1506

Figure 9: : Total annual heating and cooling energy consumption (kWh)

Table 3: Annual energy consumption presented in three metrics. The GreenStar benchmark for NSW is 26.8 kWh/m^2.year (GBCA, 2009)

Total annual heating and cooling energy use	AC 01 Base case	AC 02 Existing (with fly)	AC03 Fly + 40mm PIR	AC 04 Fly + 80mm PIR	AC 06 Fly + 40mm PIR + 18mm FC	AC08 Fly + 40mm PIR + 36mm FC	AC 10 Big fly + 40mm PIR + 18mm FC
Total (gross) (kWh)	7723	3784	4464	4490	3621	3518	3519
Per sq.m (kWh/m^2)	107.3	52.6	62.0	62.4	50.3	48.9	18.9
Per day (kWh/day)	21.2	10.4	12.2	12.3	9.9	9.6	9.6

The following observations can be made:

The existing intervention, the fly roof, is the most effective reducing annual energy consumption by 51% compared to the base case model.

The addition of 40mm of resistive insulation reduces the magnitude (degree hours) of the periods when the classroom is warmer than the predicted comfort zone but made little difference (4%) to the amount of time in the comfort zone.

The addition of further insulation (80mm) made negligible improvement to the thermal performance or comfort in the space.

The additional insulation increased the amount of energy needed for both heating and cooling the space. This is a surprising result but in line with the conclusions of Masoso and Grobler (Masoso and Grobler, 2008) who simulated the thermal performance of an office building in the hot dry climate of Botswana. They varied the insulation levels of the walls and the set point temperature of the cooling system. The results demonstrate that as the U-value of the walls increases there comes a point when the cooling load also starts to increase. The point at which this occurs depends on the set point temperature for the cooling system and the change becomes more pronounced as the set point temperature is increased.

The addition of thermal mass in addition to the 40mm of PIR insulation (AC03, AC06 and AC08) makes a difference to the number of hours predicted above or below the comfort zone but only a small difference to the number of hours in the comfort zone: 1.5% (18mm AC06) and 5.7% (36mm, AC 08). The additional thermal mass does reduce the annual energy consumption by 19% (AC06) and 21% (AC08). However this brings the energy consumption back in line with the current situation because the additional insulation increased the energy consumption.

Finally, the addition of a larger fly roof projecting 2.5m from the buildings walls and providing additional shading to the walls with down stand shades was modelled on the building with 40mm insulation and 18mm thermal mass (FC Sheet). the large fly roof has a similar impact to doubling the thermal mass in the space to 36mm (AC 08). Compared to the current situation the magnitude of the overheating is reduced and the corresponding cooling energy also reduced. The cold period and heating energy increase. The period in the comfort zone increases by nearly 7%. The highest thermal mass proposal (AC08) increases the number of hours in the comfort zone by 10% compared to the existing situation (AC 02).

These results suggest that the external solar loads are the major driver for comfort in these spaces. A conclusion supported by an earlier baseline study undertaken by the authors (Slee and Hyde, 2015a) and work of others, for instance Pearlmutter et al (Pearlmutter and Meir, 1995) who observed that the internal surface temperature of lightweight houses in the Negev Highlands fluctuates “with the slightest input of energy”. These buildings are a similar construction to the demountable classrooms but with significantly more (although still modest) levels of insulation. This creates a particular challenge for improving comfort because the perception of comfort is understood to be a combination of thermal experiences (convection, conduction and radiation etc.) and the relative values of radiant temperature and air temperature. In these classrooms the radiant temperature is often high even if the air temperature is maintained below a set point by the split cycle system. A further challenge is presented by the ventilation and cooling strategies. The ventilation is all directly from outside and high levels of ventilation (5+ ach) are required to maintain adequate air quality even if that air is entering the classroom at more than 35 degrees C. The split cycle air conditioning unit simply cools the air in the space by circulating it past chilled pipes.

The results suggest that the current modification is the most important and most effective and that other modifications such as increased insulation and increased thermal mass can also make a contribution. The results also suggest that further more technological solutions need to be investigated and developed particularly around how the spaces are ventilated. Luther and Horan (2014) point out that CO2 levels in classrooms are dynamic rather than static and that there may be opportunities to "flush" the space during breaks rather than continuously ventilate the space at the maximum rate. The use of small heat exchangers in the ventilation system similar to those used in Passiv Haus designs may also be useful (Ford et al., 2007).

8 Conclusions

The paper describes the complex social and technological problem presented by the NSW demountable classroom. The classroom is considered by many to be inadequate and therefore obsolete. A closer examination of the purpose of the classroom, the community's needs and the ability of the classroom to fulfil those needs suggests that it is performing a valuable function for the government and the communities they serve. The qualitative review concluded that (i) the thermal performance and consequential indoor environmental quality of the classrooms must be significantly improved and (ii) the communities appreciation of these remarkable buildings needs to be increased. It is proposed that both of these objectives can be achieved most efficiently by creating strategies that allow communities to retrofit the classrooms in their own schools. This strategy has three important benefits (i) it engenders a sense of ownership and pride in the buildings, (ii) it improves the thermal performance of the buildings at the lowest cost and fastest rate, and significantly (iii) creates an opportunity to help school communities learn about and understand thermal comfort and thermal performance in buildings.

The paper evaluated a number of simple strategies and concluded that whole building shading (a fly roof) is the most effective immediate intervention. The addition of some insulation and some thermal mass will further improve the performance of the classrooms. Finally the paper highlighted the need to investigate how these very simple classroom buildings can be provided with adequate ventilation without using air that comes from outside if it is at a relatively extreme temperature.

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Cumberland Lodge, Windsor, UK, 7-10 April 2016.
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An exploration of the selection of design summer years to define the overheating risk of buildings

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Abstract
Building engineers are faced with a difficult problem: how to design habitable spaces that conform to planning constraints, building regulations and low levels of energy use, whilst at the same time making them comfortable for us to live in. Thermal comfort assessments are an essential part of the design process in building construction, which in the UK involves using summer weather reference data called design summer years (DSYs) in building simulation models. Recent work has reformulated the DSYs based on probable return periods of overheating events to better describe their relative severity. However these events are still based on external temperatures alone and may not translate to the full risk to occupants. The work presented here considers how warmth metrics used to choose probabilistic design summer years can be extended to include weather variables such as solar radiation and relative humidity. It is found that the relative ranking of the warmest years and thus the selected overheating year depends on the metric used. The choice of which, has consequences for the assessment of overheating due to the underlying weather patterns within the selected year and could impact on building design.

Keywords: Design summer years, extreme events, overheating.

1 Background

Overheating in buildings is a growing issue as the climate changes and warmer weather is predicted. Meanwhile construction methods and materials are being designed to increase thermal performance which has the potential to exacerbate the risk of overheating in extreme weather in badly designed buildings. Engineers can assess the robustness of a building's design with the use of building simulation. The thermal assessment typically considers the maximum amount in which the internal environment can exceed a certain threshold. Such thresholds can take the form of the number of hours over which a parameter rises above a certain threshold such as a temperature (BB101 2006) or predicted mean vote (ANSI/ASHRAE 2013) alternatively they may be given in terms of an absolute limit (CIBSE 2013). However, to assess for such events or the probability of such events occurring requires appropriate weather data.

It has been shown that average weather files which take the form of TRYs (Eames et al. 2015) or TMYs (Wilcox & Marion 2008) are appropriate for the determination of the average energy use of a building. However, since these files represent average weather, they would be expected to produce very few overheating events if any. Very few countries have weather files for use with building simulation which represent more extreme weather events. For many locations, the only data available are the tables of external design conditions provided by the American Society of Heating, Refrigerating and Air Conditioning engineers (ASHRAE) (ASHRAE 2009). These tables consist of a limited set of information including degree days, dry bulb and dew point temperature corresponding to the 99.6 and 99% annual cumulative frequency and return periods values for the maximum extreme dry bulb temperature. Whilst these tables are suitable for use in simple or steady state calculations, they have limited use in many building performance simulation tools where annual weather files are required.

There have been a number of methods proposed for the creation of annual reference weather consisting of near extreme events. Frank (Frank 2005) created 'a warm reference year' composed of the months with the highest mean dry bulb temperature from a multi-year observation weather series of 20 years. Recently a new methodology for deriving extreme weather has been developed for both average and extreme weather conditions in Germany (BBR n.d.). Here the 90th percentile of the hourly dry bulb temperature and the number of days where the 95th percentile of the regional maximum temperature is exceeded (with weightings of 70% and 30% respectively). In the UK Design Summer Years were originally developed in 2002 (Anon 2002) and updated in 2006 (Levermore & Parkinson 2006) for determining the summer overheating of buildings in naturally ventilated buildings. The year selected was determined by the third warmest year based on the mean April to September dry bulb temperature. However, overheating in buildings is defined by the experience of thermal discomfort by its occupants, such that the internal environment is not comfortable. Using a statistic such as mean temperature over such a long period of time has the potential to give weighting to years which are just a little bit warm and contain no such period which could cause discomfort. To take better account of more extreme events, a different metric is required. Given that people spend an average of >80% of their time indoors(Basu & Samet 2002), the consequent internal environment in buildings during extreme weather conditions should form part of the overheating criteria in determining specific design weather data.

More recently probabilistic design summer years have been proposed for London (Anon 2014). The relative severity of a given year was determined by summing the weighted exceedance of the dry bulb temperature at a given hour over the comfort temperature at the same hour. This method not only determined the reference year but also designated it with a return period thus, providing an estimate of the severity or the likelihood of the event occurring. This method has been expanded (Eames 2016) to produce probabilistic files for the rest of the UK.

In each of these cases the key climatic variable used to determine the reference year is the dry bulb temperature, ignoring several other weather variables that affect the thermal impact on the human body(Moran et al. 1998). It is unknown if such metrics incorporating just temperature alone adequately describe the complete overheating risk or which metrics could be used if they were extended to incorporate more key weather variables such as solar ration, humidity and wind. Nor if weather files which have been determined using a single metric, are representatively warm in another metric. In this work return periods will be determined for warm weather events based on seven metrics for external conditions. Both near extreme and extreme weather years will be presented with a return period of 1 in 7 years and 1 in 21 years respectively for the 14 typical CIBSE locations (Eames et al. 2015). Return periods will then be determined for the internal environment for London using a simple building to demonstrate the effect of the building/internal environment on the determination of overheating. Overheating from building simulation is usually compared against a benchmark for compliance with building regulations; the possible impact on these benchmarks will then be discussed.

2 Method

The purpose of this work is to investigate the effect of the choice of overheating metric on the determination of design extreme weather years for use in overheating analysis within building simulation. Furthermore this work will investigate the effect of using either the external weather or the internal environment to determine such weather years and to see if there is any correlation between using external weather, the internal environment, or various overheating metrics. To achieve this, a number of different metrics will be determined to classify warm weather events during an observed weather series. Statistical analysis will then be used to define return periods for each observed year in terms of each overheating metric. The same observed weather series will also be used within building simulation to establish return periods for overheating events using the internal environment and the same overheating metrics. Finally the effect of the selection of extreme weather years on determining the level of overheating within a building will be investigated. For both the extreme weather years determined from weather observations and the internal environment (for London), building simulation will be used for a building with a range of glazed percentages to show the effect of the building on the amount of overheating.

2.1 Classification of hot events

Extreme weather already causes difficulties for the built environment, and with the possibility that these conditions could become the norm, engineers need to respond by incorporating this type of weather into their building performance simulations. The impacts of heat waves on health are treated very seriously by Public Health England and other bodies around the world, and annual heat wave response plans are published each year [10]. In the UK, probabilistic weather data for building simulation has been widely used since the publication of the Prometheus weather sets (Eames et al. 2010). These weather sets incorporated the effects of climate change and the probabilistic nature reflected the proportion of simulation runs which were either cooler or warmer than a given file. Redevelopment of the DSY into a probabilistic form gives building modellers the option of selecting a reference year of weather data based on the likely return period of whichever level of hot conditions they wish to test. For instance the original DSY in the UK is found by taking the 'third hottest' year for each geographic region from recorded data over a 21-year period(Levermore & Parkinson 2006). A probabilistic 'third hottest' DSY would therefore have a return period of 1 in 7 years. A benefit of this DSY reformulation is that it can be extended to test for more extreme weather, by selecting a reference year with a longer return period. Likewise the analysis can easily be extended to other metrics of performance.

Common metrics used in assessing over heating within buildings consider the number of hours over a given threshold e.g. 28°C. These simple temperature thresholds are easy to implement and relate to potential discomfort within buildings(Anon 2015). The first two overheating metrics considered here are the number of hours where the air temperature is firstly greater than 25°C (HRS>25) and secondly greater than 28°C (HRS>28).

Although simple, such a static metric does not take into account the ability of a person to adapt to changes in their environment(Nicol & Humphreys 2002): If a change occurs such as to cause discomfort, people react in ways which tend to restore the comfort. From a climatic point of view this means that the comfort temperature is not static. It has been shown that the adaptive comfort temperature is related to the recent outdoor temperature via running mean temperature which is calculated by

$$T_c = 0.33T_{rm} + 18.8\ , \quad (1)$$

where

$$T_{rm} = 0.8T_{rm-1} + 0.2T_{mean-1}, \quad (2)$$

T_{rm} is the daily running mean temperature, $T_{rm\text{-}1}$ is the running mean temperature of the proceeding day and $T_{mean\text{-}1}$ is the average temperature of the proceeding day. However, there is a limit to which a given person can respond. For normal persons this limit is defined as 3K above the comfort temperature at any given time. The third metric is given by the number of hours where the temperature is greater than the comfort temperature plus 3K (ACH).

The ACH metric better reflects the true response of people to warm events and greater departures from the average conditions but, like the static metrics does not account fully for severity. It would make no difference in each case if the threshold were exceeded by 0.1˚C or by 10˚C. However it is likely that the latter would cause greater discomfort. A simple extension to the simple thresholds which can account for severity is a measure of the number of hours over which the temperature exceeds the base threshold and by how much as used to calculate the number of cooling degree hours. The number of cooling degree hours is typically used to give an indication of the amount of cooling energy required in a given year from external conditions where the base line is dependent on the building. However, deviations far from the base temperature are counted equally. It is more likely that bigger deviations will have a bigger impact on human health and should ideally be reflective in the metric of overheating. The redevelopment of probabilistic DSYs for London within TM49 categorises hot weather events in terms of the number of hours over which the internal operative temperature exceeds the adaptive comfort temperature. A simple weighting function, given by a simple quadratic expression, is then implemented for each hour of exceedance such that greater influence is given to the more extreme exceedances. The total exceedance over a year is then given by

$$\mathrm{WCDH} = \sum_{all\ hours} \Delta T^2\ , \quad (3)$$

where

$$\Delta T = T_{op} - T_c\ , \quad (4)$$

and T_{op} is the operative temperature. The fourth metric is the number of weighted cooling degree hours ($WCDH_1$).

The factors which cause people heat stress in the internal environment are sustained high temperatures, and the combined effect of several weather variables which could include the effects of the solar radiation, air flow and humidity. The Predicted Mean Vote (PMV) is one such index commonly used globally for assessing overheating (ANSI/ASHRAE 2013). The PMV is an index that predicts the mean value of the votes of a large group of people on a seven-point scale ranging from hot (+3) to cold (-3) based on the heat balance of the human body (BS EN ISO 7730 1995). A well-functioning building should minimise the number of hours where the PMV lies outside the range of -0.5 to 0.5. The fifth metric considers the number of hours where the PMV is greater than 0.5 (PMVH).

Studies have shown that the UTCI is potentially more suitable than air temperature for measuring the impact of weather on health(Błażejczyk et al. 2010; Urban & Kyselý 2014). The UTCI, similar to PMV, is based on the human physiological response to environmental variables and the heat stress that a human body feels (table 1), which is a complex combination of air temperature, humidity and solar radiation(Moran et al. 1998). The UTCI is described by the equation

$$\mathrm{UTCI} = T_a + offset(T_a, T_r, V, p_a)\,, \tag{3}$$

where T_a is the air temperature, T_r is the mean radiant temperature, V is the air velocity and p_a is the vapour pressure (Bröde et al. 2012). The sixth overheating metric considers the number of hours where the UTCI is greater than 25°C (similar to metric one). It is likely that the reference year chosen depends on the metric used. For example if more weighting is given to solar radiation then sunnier years will be ranked as the most extreme. So as a simple extension to the metric four, the operative temperature in equation 4 will be replaced by the UTCI and the seventh metric considers the weighted cooling degree hours based on the UTCI ($WCDH_2$).

2.2 Return periods

The return period of an event refers to the frequency of the event with an associated exceedance value. This means a hot year which has a return period of 10 years, is predicted to occur every 10 years, or a given year will have a 1-in-10 chance of being equal to or hotter than it. The Generalised Extreme Value (GEV) distribution(Coles 2011) is frequently applied to climatological data to model the most extreme value within a period such as the extremes of rainfall(Katz et al. 2002) or to evaluate the effects of climate change(Nikulin et al. 2011) and assign return periods.

Assuming the observed threshold events are independent and uniformly distributed the probability density function of a set of events (x, such as ACH) is given by,

$$f(x|k,\mu,\sigma) =$$

$$\begin{cases} \left(\frac{1}{\sigma}\right) exp\left(-exp\left(-\frac{x-\mu}{\sigma}\right) - \frac{x-\mu}{\sigma}\right), & k = 0 \\ \left(\frac{1}{\sigma}\right) exp\left(-\left(1 + k\frac{x-\mu}{\sigma}\right)^{-\frac{1}{k}}\right)\left(1 + k\frac{x-\mu}{\sigma}\right)^{-1-\frac{1}{k}}, & k \neq 0, 1 + k\frac{x-\mu}{\sigma} > 0 \end{cases}, \tag{7}$$

where μ is the location parameter, σ is the scale parameter and k is the shape parameter. The events are typically fitted to the distribution using a maximum likelihood estimator method. The T-year return values X_T are then estimated from,

$$X_{Tgev} = \begin{cases} \mu - \sigma \ln\left[-\ln\left(1 - \frac{1}{T}\right)\right], & k = 0 \\ \mu - \frac{\sigma}{k}\left(1 - \left[-\ln\left(1 - \frac{1}{T}\right)\right]^{-k}\right), & k \neq 0, \end{cases}. \tag{8}$$

The return periods for the seven metrics are calculated for all 14 CIBSE locations for external weather data(Anon 2015). The return periods for the seven metrics will then be calculated for inside a reference building model for London as London has very little data missing across the entire observation data set. Using the fitted distribution two weather years will be determined; the near extreme weather year with a return period of 1 in 7 years and the extreme weather year with a return period of 1 in 21 years which is three times less likely than the near extreme year. The chosen year will have the return period closest to the desired value. All statistics (extreme value distributions) are determined from this base period of 1984 – 2013 for all locations but all years from the given location (as available) from 1960 onwards will be used to determine the extreme and near extreme weather years.

2.3 The building model

A simplified single storey building model was considered (see figure 1) consisting of a single zone with only the south face glazed and was simulated in EnergyPlus. The building has a square plan with an area of 91.2m^2 and a volume of 255m^3. The building operates in free running mode between June and August and is heated to 21°C the rest of the year. The window is opened when the building is occupied and the internal temperature is greater than 25°C with an effective openable area of 20% of the total glazed area providing ventilation by wind and stack effect only. The electrical gains are varied following the distribution as suggested by the Energy Savings Trust (Owen & Foreman 2012).

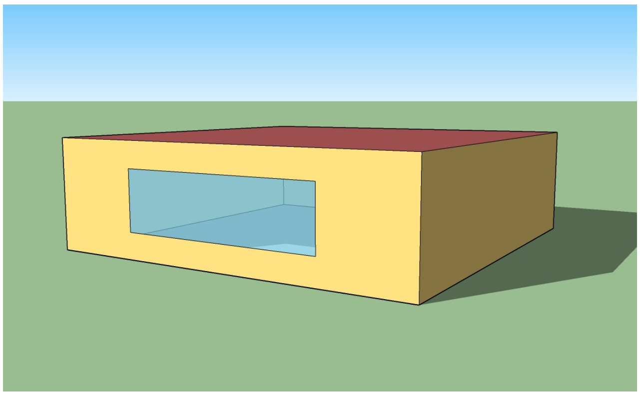

Figure 1: The building model consisting of a single room with glazing only on the south facade.

A realistic electrical load profile is derived from a real dwelling as monitored in the Micro CHP Acceleration project of the carbon trust (Anon 2011). Occupancy was also included in the model and was derived from the electricity profile. The same profiles are used for every simulation with a total of 7116 either partly or fully occupied hours. The infiltration rate is, as specified, the uncontrolled leakiness of the building with a constant rate of 0.2ach^{-1}. Additional ventilation of 1.7ach^{-1} is provided during occupied hours. The building model is constructed to comply with building regulations with U values for all windows and walls equal to 0.2Wm^{-2}K^{-1}. The U value of the external floor is 0.19 Wm^{-2}K^{-1}Wm^{-2}K^{-1}. The window has a U value of 1.39Wm^{-2}K^{-1} and g-value of 0.586. When testing the effect of the built environment on overheating using the extreme weather years, the glazed percentage will be varied between 0 and 90%. Many aspects of the building construction and how it is used can affect the amount of overheating experienced within the building. As part of this work is to compare simple temperature metrics with metrics which depend on the radiant temperature, the amount of solar gain would be critical for this comparison and therefore for simplicity is the building parameter which is changed. Modelling uncertainties and assumptions such as discharge coefficients, static pressure distribution and static infiltration have not been considered and are out of the scope of this work. The overheating metrics are determined using standard methods. For example, where applicable, occupants are only subjected to the mean radiant temperature rather than direct radiation and only occupied hours are counted. The building is set up so that it will overheat to some extent however this work is not to investigate the effect of overheating or how to minimise it in a specific building but what is the effect of the building or metric for determining extreme weather years for use in overheating assessments.

3 Results

The results of the return period analysis for the seven metrics using the external observations are shown in table 1 and table 2 for all locations for near extreme and extreme weather years respectively (the years closest to a 1-in-7 and 1-in-21 year). Across all metrics there are 16 possible near extreme years (table 1) and 9 possible extreme years (table 2). Of these years 1975, 1989, 2003 and 2013 are the most frequent for the near extreme years and 1976, 1995, 2006 are the most frequent extreme years. There is very little consistency across the different metrics and across the locations such that a year which is determined to be extreme in one metric is not necessarily extreme in another. For some metrics such as hours over 28°C there is often too little data at each location to robustly fit the extreme value distribution. Furthermore, for 9 of the 14 locations, years which are near extreme for certain metrics are determined to be extreme for other metrics. For example, 2006 is a near extreme weather year for Edinburgh for PMVH but extreme for $WCDH_1$ and UTCIH greater than 25°C.

Repeating this analysis for the internal environment, the near extreme and extreme return periods for the seven overheating metrics inside the building model for London are shown in Table 3. Here the building's south façade is 43% glazed. In this case there are four weather years which exactly match the results of tables 1 and 2. However most years except 1989, 2003, 2005 and 2011 appear in both sets showing good overall agreement between the external and the internal environment. It is clear however that the choice of hot year depends on the overheating metric which is used.

Changing the building configuration (the glazed percentage is used here) has a very similar effect to changing the metric used to define overheating. In this case the order of the hottest years does not change by much, by the return period associated with the years does change. Increasing the glazed percentage for this building model has the effect of increasing the solar gain into the space and increasing the potential for natural ventilation. An example of the building performance of two building configurations (the south façade is 33% and 66% glazed) is displayed in figure 2 for a design week in July for during 1976, namely, the external temperature and direct solar radiation, the internal temperature (including comfort temperature), and the overheating metrics of WCDH, PMV and UTCI. Increasing the glazed percentage for a warm weather event has the effect of increasing the level of overheating for all metrics. Even in this case where the hottest day is coincident with a more overcast day, the amount of overheating is recorded higher in the building with the greater amount of glazing. In all cases the buildings are not found to excessively overheat. For example less than 2.5% of all hours are greater than 28°C and less than 4% of all hours are greater than the comfort temperature plus 3K. For the original DSY (1989) only up to 1.04% of all hours are greater than 28°C and 2.85% of all hours are greater than the comfort temperature plus 3K.

Given that extreme weather years can be determined from a number of sources, next the effect of determining the years from the internal or external environment will be determined. The effect of the building model configuration on the selected weather years from table 1 and table 2 is displayed in Figure 3 for London. The glazed percentage of the south façade is varied between 0 and 90% with all other building parameters held constant.

The selected weather year again depends on the metric. For five of the seven metrics (HRS>25°C, HRS>28°C, ACH, $WCDH_1$ and $WCDH_2$) the extreme year produces more overheating within the metric than the near extreme year for all building configurations. However, the difference between the years is not consistent and can vary depending on the glazed percentage. Only for the $WCDH_2$ metric is the difference linearly dependent on the glazed percentage (R^2 > 0.99). For UTCIH, the near extreme year (2013), as determined externally, produces more overheating than the extreme year (1989) for all building configurations. For PMVH the near extreme year (1989) produces more overheating than the near extreme year (2003) for glazed percentages greater than 75%.

Repeating this analysis using the extreme years determined from the internal environment as shown in table 3, the effect of the building configuration on the selected weather years is shown in figure 4. In this case nearly all building configurations give more overheating using the extreme weather year than the near extreme years. The only exception is ACH for glazed percentages less than 10%. Similar to the weather years determined from the external weather data, the differences between the metrics for the near extreme and extreme weather years are not consistent. Again, only for the $WCDH_2$ metric is the difference linearly dependent on the glazed percentage (R^2 > 0.99).

Table 1. Selected near extreme weather years for all locations using all metrics and external weather.

Location	HRS > 25	HRS > 28	ACH	$WCDH_1$	PMVH	UTCIH >25	$WCDH_2$
Belfast	-	-	1989	2013	1997	1997	2003
Birmingham	2005	-	1976	1990	1995	1975	1975
Cardiff	2013	-	2006	1970	1995	1983	1990
Edinburgh	-	-	1999	1975	2006	2013	1976
Glasgow	-	-	1975	1983	1997	1983	1984
Leeds	1997	-	-	2003	2006	2003	1990
London	2013	1983	2011	2013	1989	2013	2013
Manchester	1984	-	2003	2003	-	1975	2003
Newcastle	-	-	1975	1995	-	1997	2013
Norwich	1999	1990	-	1989	-	1989	2003
Nottingham	1990	-	1976	1989	-	1970	1989
Plymouth	-	-	-	2013	-	1989	1983
Southampton	1999	-	1995/ 2001	1990	1989	2003	1990
Swindon	1975	-	1989	2003	2006	1975	1975

Table 2. Selected extreme weather years for all locations using all metrics and external weather. Values highlighted in bold indicate the year was the most extreme for the metric.

Location	HRS > 25	HRS > 28	ACH	WCDH	PMVH	UTCIH >25	$WCDH_2$
Belfast	-	-	1995	**1995**	**2000**	1976	1995
Birmingham	2006	-	**1989**	**2006**	**2003**	2003	**2006**
Cardiff	1983	-	**1989**	1975	**2006**	1976	1975
Edinburgh	-	-	**1995**	**2006**	**1995**	**2006**	1995
Glasgow	-	-	1984	**1995**	1976	1976	**1995**
Leeds	**1995**	-	-	**1995**	**2003**	1995	2006
London	2006	1995	1976	2006	**2003**	1989	1995
Manchester	1983	-	**1995**	1976	-	1976	1976
Newcastle	-	-	1976	1976	-	1995	1975
Norwich	1975	**1976**	-	2006	-	**2006**	1995
Nottingham	2006	-	1989	2006	-	1975	2006
Plymouth	-	-	-	1989	-	2003	1995
Southampton	1989	-	1976	1995	**1995**	1976/ 1995	**1995**
Swindon	1995		1976	2006	2003	1976	**1976**

Table 3. Selected near extreme weather years for London using all metrics and the reference building with the south face 43% glazed.

	HRS > 25	HRS > 28	ACH	$WCDH_1$	PMVH	UTCIH >25	$WCDH_2$
Near extreme	2013	1983	1983	2013	2013	2003	2005
Extreme	2006	1976	2006	1995	2006	2006	1976

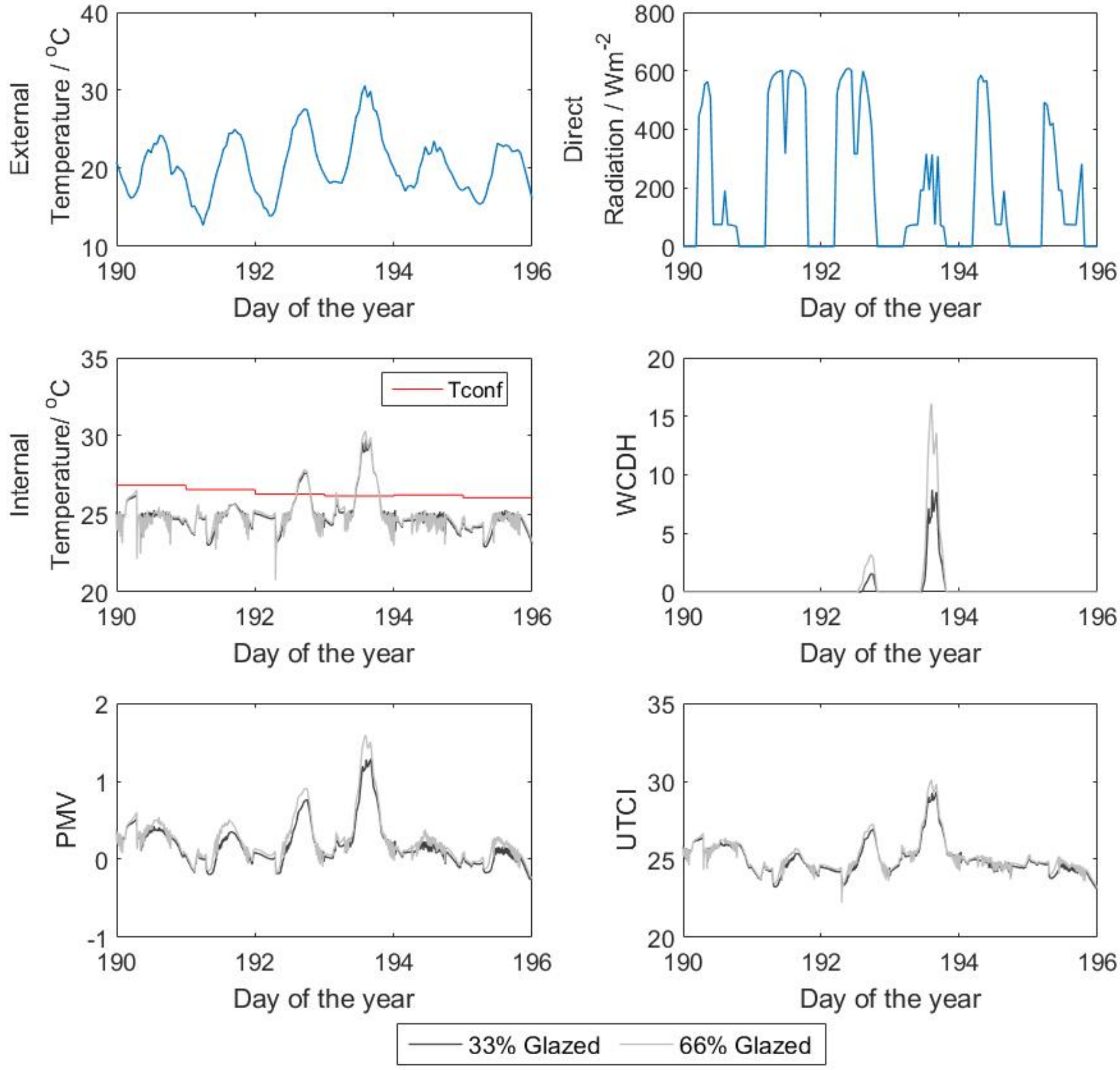

Figure 2. External weather (temperature and direct solar radiation) and building performance data of internal temperature and the overheating metrics of WCDH, PMV and UTCI for a week in July 1976 for a building in London with the south face glazed to 33% and 66%.

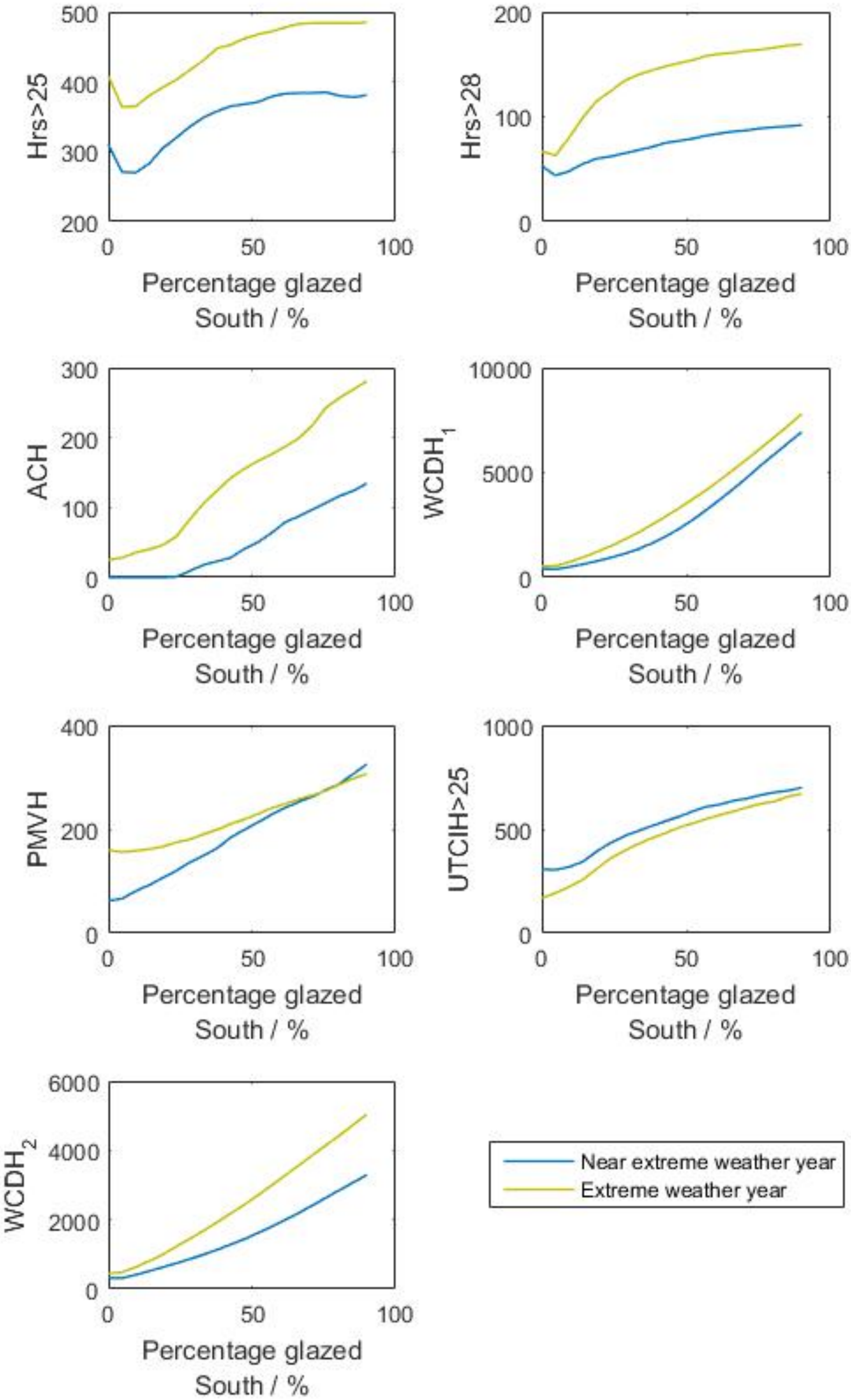

Figure 3. The effect of building configuration on the seven overheating metrics. The weather years are selected from external weather data as determined in table 1 and table 2.

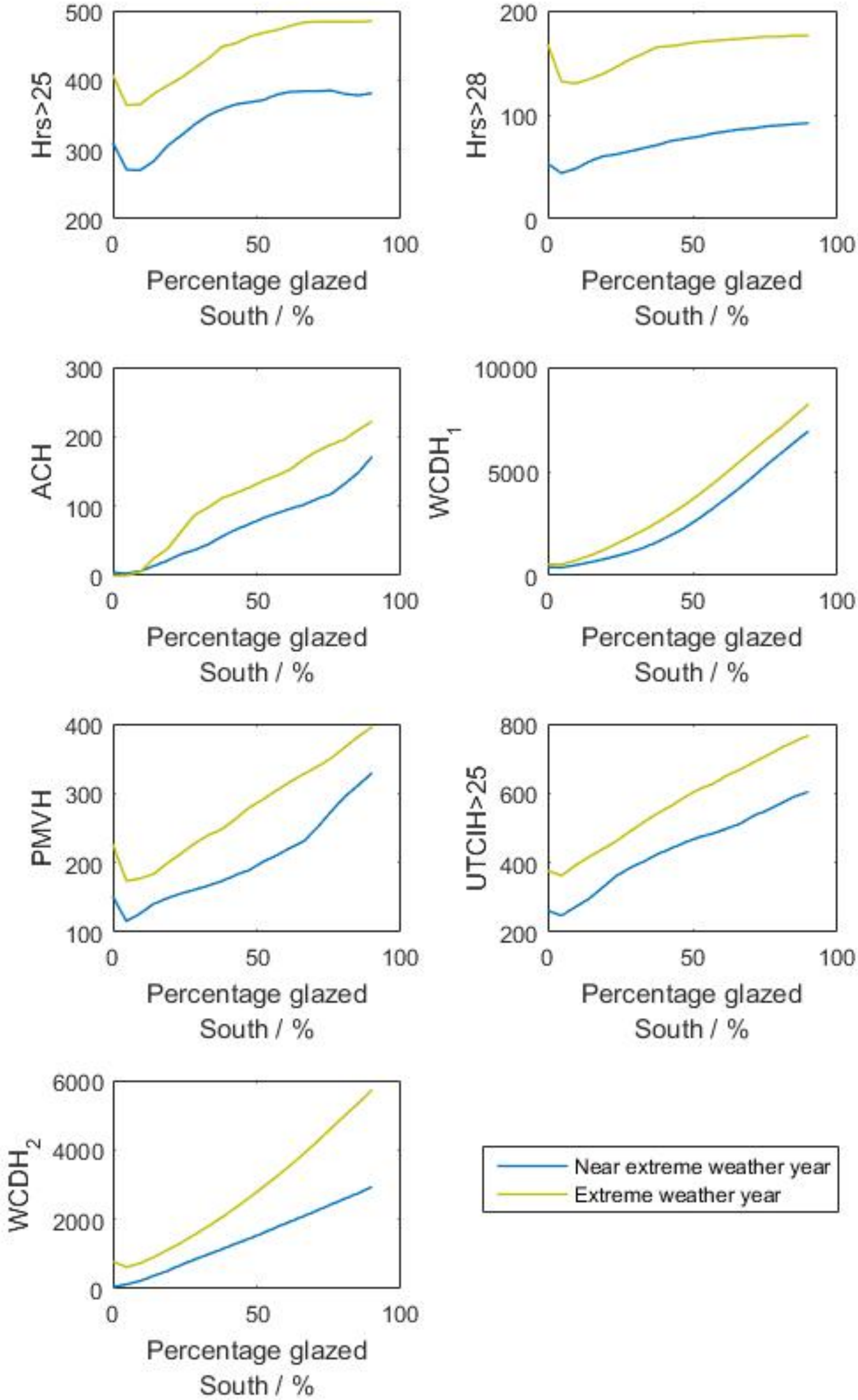

Figure 4. The effect of building configuration on the seven overheating metrics. The years are selected from the internal environmental as determined in table 3.

4 Discussion

The shortcomings of the original DSY have been known for some time (Jentsch et al. 2013) and prompted a redevelopment of the reference year construction method which resulted in the development of probabilistic DSYs (PDSYs) for London (Anon 2014) and this method was expanded for the rest of the UK(Eames 2016). Although the original DSY methodology was found to not guarantee any overheating events, the issues only appeared with certain building designs, hence why it probably took so long for the issues to be formalised. With the new PDSY methodologies, years were selected on the basis that they did contain warm events which might cause a degree of overheating within a building. This work has further researched into the determination of probabilistic weather model overheating within the built environment. In this case seven different metrics were used to model overheating and the weather years have been determined from both the external and the internal environment allowing results to be directly compared.

Results from tables 1, 2 and 3 show that, the selected weather year depends on the overheating metric used and whether the external or internal environment is used. The most frequent extreme weather years include 1976; a year which is typified by a prolonged period of sustained warmth, 1995; a year which typically contained two periods of intense warmth between late June and August and 2006; which typically contains a long warm spell in July as well as a having warm periods earlier in the year. Although these are considered to contain some of the warmest periods in recent times, 2003 appears much less frequently and in fact is more common as a near extreme weather year. Yet interestingly, 2003 was the year of the extreme heat wave that caused around 50,000 deaths across Europe(D'Ippoliti et al. 2010). If such years are used testing overheating within buildings, engineers would be testing their building designs against warm conditions that are known to cause human heat stress and serious health risks.

The issue of which year to choose is compounded by the changes to weather patterns across the country. So some of these hot years are actually less extreme in some locations hence other years feature within both tables 1 and 2 for different locations. It should be of no surprise that the definition of the extreme weather year is dependent on the metric as different metrics are using different coincidences of warm events. In some cases such as the number of hours where the temperature goes above a threshold, the metric is not concerned by how much the threshold is exceeded or by when. In other cases where there are rapid increases in the temperature above the running mean temperature a weighting can ensure that deviations which are far from the running mean temperature count more. In this example warm weather itself would not necessarily count as overheating but years which have events where weather changes suddenly (gets warmer) over a short period of time will be determined as the most extreme. Finally, overheating metrics are considered which include the coincidence of temperature and other variables such as solar radiation. Here weather years which have the greatest coincidence of these weather variables are determined to be the most extreme, although, they are still likely to be dominated by instances of the warmest temperatures.

Figures 3 and 4 demonstrate some of the difficulty of selecting a single weather year for assessing overheating. In each case the two extreme years were selected from table 1 and 2 or 3 and the building configuration was altered to investigate the effect on overheating. The difference between amounts of overheating given from the extreme and near extreme weather years is not consistent across all building configurations. For externally derived weather years, the least robust metric was found to be PMVH where the near extreme year actually provided more overheating than the extreme year. However looking deeper into the results it is found that there is no combination of weather years which consistently find the extreme year which predicts more overheating, for all metrics, for all building configurations. For this work the building model was chosen such that it would overheat for many of the building configurations and therefore not entirely realistic. This was necessary to create a large enough data set for each metric and location to be able to determine the return periods although there were still locations where the return periods could not be determined. However, the overheating was not found to be excessive and most buildings would pass many of the standard overheating tests (CIBSE 2013).

These results suggest that there are potential issues with using probabilistic weather years for the derivation of overheating, especially if a designer is using what is determined as a more extreme year and for their building model it is found to produce less overheating. This is likely to be the case where real observations and contiguous years are chosen for determining the overheating risk where different weather patterns can affect different buildings. There are three possible solutions. The first solution considers a series of the warmest years as based on a number of metrics. A building designer should then model their building using all years to ensure the building is robust to all weather scenarios. In this solution the set of weather years from TM49 or the new DSYs from CIBSE would be appropriate. However separate benchmarks may be required for the more extreme years, but, this solution is most similar to current practice and only requires a couple of extra simulations. The second option would require parameterising the building model (and overheating metric) such that the correct year is used for the required overheating metric. It is clear though that such parameterisation would be non-trivial and any optimisation methods used to minimise the overheating could mean a new building parameterisation and the need for a different weather file. The third solution would replace real weather data with synthetic weather. Here weather files would be produced such that bespoke weather patterns, based on real weather events, are stitched together to replicate warm spells with different characteristics. By using synthetic weather, more overheating events could be considered within the same simulation reducing the simulation overhead. The weather events would represent examples of weather known to commonly cause issues for the internal environment and could be generated to exactly replicate the 1-in-x event which may not be available in the observation set ensuring consistency across the UK.

5 Conclusion

In this work metrics for determining extreme weather years have been investigated for both external weather data and the effect of this data inside a simple building model. It is found that the extreme years depend not only on the overheating metric used but also whether they are determined from external or internal data. Although there is little consistency across locations and across metrics, for a given location, characteristically hot years tend to rank highly regardless of the metrics. A building designer would require consistent design weather data to assess the risk of overheating independent of metric and location. This leaves a couple of pragmatic options for determining design weather years; either the use of some of the warmest years which consistently produce overheating to some degree with appropriate benchmarks or synthetic weather years which contain weather events known to cause issues for the built environment.

Acknowledgements
The authors would like to thank the EPSRC for their support [grant ref: EP/J002380/1 and EP/M022099/1]

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

A study of thermal comfort and thermal preferences in the upland tropical climate of Uganda

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Abstract
Upland tropical climates, are often regarded as 'benign', but are of increasing concern, particularly with regard to thermal comfort in the context of climate change induced temperature rises. Further, in light of increased economic prosperity and associated lifestyle changes, that suggest a trend toward the use of mechanical ventilation and air-conditioning equipment, how people perceive, respond and adapt to climatic conditions emerges as an area of interest in these regions.

This paper reports the findings of an ongoing study investigating thermal comfort of university students in the central region of Uganda. The study was undertaken in two parts: the initial phase (reported in this paper), looking at thermal comfort in student's accommodation, and the second in teaching spaces, both carried out during the dry (hot) season. Thermal comfort parameters collected include: Temperature, and Relative Humidity, as well as personal adaptations such as clo and Met. Questionnaires were used to garner student's perceptions and acceptability of their thermal environment and other subjective measures. The findings of this study indicate a neutral temperature of 26.8°C derived using the Griffiths method. The wide range of comfort votes suggest varied preferences and adaptations for this upland tropical climate and the complexities related to thermal comfort in naturally ventilated building.

Keywords: Naturally ventilated buildings, Upland tropical climate, Students, Uganda, Thermal comfort, Thermal preferences.

1 Introduction
Interest in studies of human responses to thermal environments in the tropics has grown significantly over the past few decades. With the increasing prevalence of air-conditioning equipment, and buildings designed 'in spite of' the prevailing climate, greater attention to the conditions people in tropical regions perceive as comfortable is needed to ensure comfort in naturally ventilated buildings, and to better manage demand for air-conditioning in mechanically ventilated ones. This has also been prompted by a recognition that application of thermal comfort standards such as ASHRAE-55 (2010), largely derived and promulgated from the temperate regions of the world, may contribute to increased demand for scarce energy resources with increased use of air-conditioning, through incorrectly set thermostats. In the context of Africa, research on the performance of buildings has been carried out for over 60 years, with landmark publications such as Fry and Drew (1964), and Koenigsberger et al (1973) making a significant contribution to the understanding of building performance in tropical Africa.

It is recognised however, that the focus of these early initiatives, and the genesis of what is now recognised as tropical modernism, was largely for the benefit of the expatriate populations, with little attention to the experiences of the general populace, particularly outside the administrative sphere, in a scenario much like that described by Ryan (2014) in Australia, and increasingly being questioned in the context of Africa (Le Roux, 2003 & 2004; Livsey, 2014). To date, only a few studies have attempted to engage with thermal comfort in sub-Saharan Africa, more so in upland tropical environments, or in relation to educational settings. With increased interest in education in the region, and a significant increase in the number of students attending educational institutions, crammed into existing small spaces, whatever thermal comfort conditions existed, are increasingly being compromised.

This paper presents the results of the initial phase of a thermal comfort study being conducted with students of the Uganda Martyrs University, Nkozi, during December 2015. Nkozi is located about latitude 0°0' and longitude 32°04' East at an altitude of 1,215m. This upland tropical setting has an average temperature of 21.3°C, with a mean maximum temperature is 26.8°C, a mean minimum temperature of 15.9°C. Average humidity is approximately 75%, with average rainfall of 1186mm per annum, with two distinct wet seasons: April - May and October - November. The broader study takes in student housing and teaching spaces, with this paper presenting the findings of the study of thermal comfort in student housing.

2 Background to the Study

Until recently little thermal comfort research had been carried out in Africa. A few studies had been carried out in West Africa during the 1950s and 1960s such as Peel (1961), and Terjung (1967). Peel's work in Nigeria can be regarded as the pioneering thermal comfort work in Africa, the first to actually investigate the thermal comfort conditions for an indigenous population. More recent, thermal comfort studies have been carried out across Africa, by Olweny (1996) in Uganda, Sharples & Malama (1997) in Zambia, Ogbonna & Harris (2008) in Nigeria, Djongyang et al. (2012) in Burkina Faso, and Kameni et al. (2013) and Nematchoua et al. (2014) in Cameroon. These along with various studies of comfort across the tropical zones of the world have found mixed results for thermal comfort across the different building types as presented in Table 1 and 2 below.

Table 1: Comfort studies in the housing in the tropics

Year	Researcher	Location	Building Type	Neutral Temperature
1996	Olweny	Uganda	Housing	28.0°C (NV)
1997	Sharples & Malama	Zambia	Housing	22.2°C (NV) (Winter)
2012	Djongyang, Tchinda & Njomo	Burkina Faso	Sleeping Rooms	27.0°C – 30.0°C (NV)
2013	Nematchoua, Tchinda & Orosa	Cameroon	Housing	23.0°C – 28.0°C (NV)

Table 2: Comfort studies in classrooms in the tropics

Year	Researcher	Location	Building Type	Neutral Temperature
2006	Hwang, Lin & Kuo	Taiwan	Classrooms	26.3°C (NV)
2007	Ogbonna & Harris	Nigeria	Classrooms	26.7°C (NV)
2013	Kameni, Tchinda & Djongyang	Cameroon	Classrooms	23.4°C - 25.8°C (NV)
2014	Karyono, Heryanto & Faridah	Indonesia	Classrooms	24.9°C (Mixed)

The current study of thermal comfort in Uganda is driven by a need to quantify comfort requirements in different building types as part of an ongoing desire to better understand the requirements for comfort and energy use in the context of energy efficiency, as promoted by UN-HABITAT (2014) among others. It is acknowledged that the use of air conditioning equipment, is on the rise, not only in response to the increasing frequency of hot spells, but also as a consequence of other environmental factors, such as noise and dust, as well as threats of terrorism, which have necessitate the sealing off of windows. Further, a perception that lower the thermostat set points will cool a space faster is common place, and it is not unusual to find thermostats set at 18°C, well below the mean temperature of the area generally regarded as the basis for thermal acceptability. Further, changing building use patterns have rendered obsolete accepted rules of thumb based on traditional architecture, making it necessary to engage in the a review of comfort requirements.

3 Methodology and Data Collection

This study acknowledges the definition of thermal comfort as being, "… that condition of mind that expresses satisfaction with the thermal environment" (ASHARAE, 2010), and in so doing, recognises that there needs to be an awareness of conditions that contribute to this satisfaction. This also points to the fact that "satisfaction with the thermal environment is a complex subjective response to several interacting tangible, and less tangible, variables" (Ogbonna & Harris, 2008; 2). Consequently a definition by Markus and Morris (1980) of thermal comfort seems more appropriate, and is stated simply as "the absence of discomfort." For this study of thermal comfort in East Africa, this is significant as the concept of 'thermal comfort' itself does not always translate into local languages and dialects, making general studies of thermal comfort somewhat challenging.

The study is aimed at gaining an understanding of the thermal comfort requirements of building occupants in familiar spaces. The selection of halls of residence as the focus of this initial study was to appreciate the idiosyncratic aspects of thermal comfort often taken for granted in climate chamber studies, but significant in the appreciation of adaptation to varied thermal conditions. The study was carried out during December 2015, traditionally the dry season for Nkozi. However, for much of the study period, weather conditions experienced could be described as anything but 'normal', with more than 50% of the days being cooler and wetter than is generally the case for that time of year. This in itself could impact on the nature of comfort experienced by subjects, given the changed weather conditions were outside what could be considered 'normal'. The study made use of a questionnaire-based interview approach as the primary data gathering instrument, with hand-held Hobo loggers used to measure temperature and humidity. Students in halls of residence across the university were interviewed, with the questionnaire designed to gather information on a range of aspects related to thermal sensation and thermal preferences, as well as background information on the subject's clothing levels, activity and other personal factors. Acclimatisation as a factor was assumed, given the study was being undertaken at the end of the academic semester, with students having been resident in the locale for at least three months.

As part of the questionnaire study, students were asked a number of questions about their response to hot and cold conditions as well as their attitude to climate. Questions were asked prior to thermal comfort vote to ensure subjects had been in and 'acclimatised' to the conditions of the space, and not been engaged in any strenuous activity prior to the vote. This enabled a key assumption to be made with regard to the activities of subjects at the time of the vote; seated and generally relaxed for approximately 30 minutes prior, thus their metabolic rate (Met) could be assumed to be about $70W/m^3$. Further, it could be assumed that conditions in the area in which the vote was take were the conditions experienced by subjects, and not a measure of transitory thermal sensation, as would otherwise have been the case.

Table 3: Thermal scales used

	Thermal Sensation	**Thermal Acceptability**	**Thermal Preference**
-3	Cold	Much Too Cool	
-2	Cool	Too Cool	Cooler
-1	Slightly Cool	Comfortably Cool	Slightly Cooler
0	Neither Cool Nor Warm	Comfortable	No Different
+1	Slightly Warm	Comfortably Warm	Slightly Warmer
+2	Warm	Too Warm	Warmer
+3	Hot	Much Too Warm	

The study made use of three thermal scales: the ASHRAE thermal sensation scale ("How do you feel?"); the Bedford thermal acceptability scale ("How do you find it?"); and, a modified McIntyre thermal preference scale ("How would you like to feel?") (Table 3). Thermal votes were taken at the end of the interview, with environmental parameters (Temperature and Relative Humidity) were recorded simultaneously on U12 Hobo loggers in a 'blind study' approach in order to reduce the chance of environmental information influencing the way subjects voted. The accuracy of the U12 logger is given as ±0.35°C for temperatures between 0°C and 50°C, and ±2.5% for relative humidity between 10% and 90%. Radiant temperature and wind speed were not recorded due to a lack of available equipment at the time. Use of ambient temperature in place of radiant temperature was however deemed appropriate for this study, as supported by earlier work by Williamson et al (1991) who found that that using ambient temperature to determine comfort levels would give satisfactory results. As far as was practically possible, protocols derived from Benton, et al (1990) were followed: measurements were taken as close to the subject as was practically possible; temperature and humidity data was collected continually during the interview (sampling at one minute intervals); and, the single logger used to collect data situated at a height of approximately 0.75 metres above the floor.

4 Results

The study was conducted over a three-week period during late November and early December 2015, when environmental conditions are typically dry, and warm to hot. A total of 111 subjects participated in the study carried out in student housing on and around the university campus. Buildings ranged from single storey to four storey blocks, and generally had concrete structures with clay brick or sand-cement compressed block infill. Roofing was either clay tile or steel sheeting as seen in Figure 1. Rooms were generally double banked, off a central corridor, typical of many student residential buildings worldwide. Room sizes ranged from a tight 8.4sq.m., to a generous 16.7sq.m., with most rooms shared by two students. Window to floor area ratios ranged from 9.6% at the low end, to a generous 35.7% at the high end.

Figure 1: Student’s accommodation

Subjects were all students of Uganda Martyrs University at the time of the study, in different programmes and years of study. The majority were undergraduate students between 20 and 22 years of age (75.6%), although for the study, ages recorded varied from 19 to 32 years, with a median age of 21. Respondents were split roughly 50:50 between male and female students (Table 4). Students were Interviewed separately so as not to bias individual responses (Figure 2).

Figure 2: Interview sessions

Table 4: Characteristics of Respondents

	Male	Female	Total
Number	55	56	111
Age (Max.)	29	32	32
Age (Min.)	19	19	19
Median	22	21	21
Std. Dev.	2.0	2.0	2.0

Table 5: Clo Values

	Male	Female	Total
Maximum	0.99	0.99	0.99
Minimum	0.10	0.14	0.10
Mean	0.32	0.36	0.34
Std. Dev.	0.15	0.15	0.16

As expected, given the study was conducted in student’s housing, a diverse range of clo levels was recorded, particularly as there was no set times allocated for the interviews, which were carried out between 09:00 and 23:59 (Figure 3). Clothing levels worn by respondents varied from 0.1clo to 0.99clo at the time of the vote (Table 5), differences that in part could be attributed not only to the time of interview but also to variances in weather experienced during the study. In general, it was uncommon to find student wearing shorts in public, doing so only within their halls of residence. During the day, most donned trousers, knee length dresses or long skirts, a consequence of societal norms that promoted particular level of clothing. Consequently, students were inclined toward higher levels of clothing during the day, than in the mornings or evenings, more so when in public. It was common to find student wearing cardigans during the mornings and evenings, discarding these in the middle of the day as it got warmer. Most students wore open-toe shoes or sandals, with many female students wearing these regardless of the weather conditions.

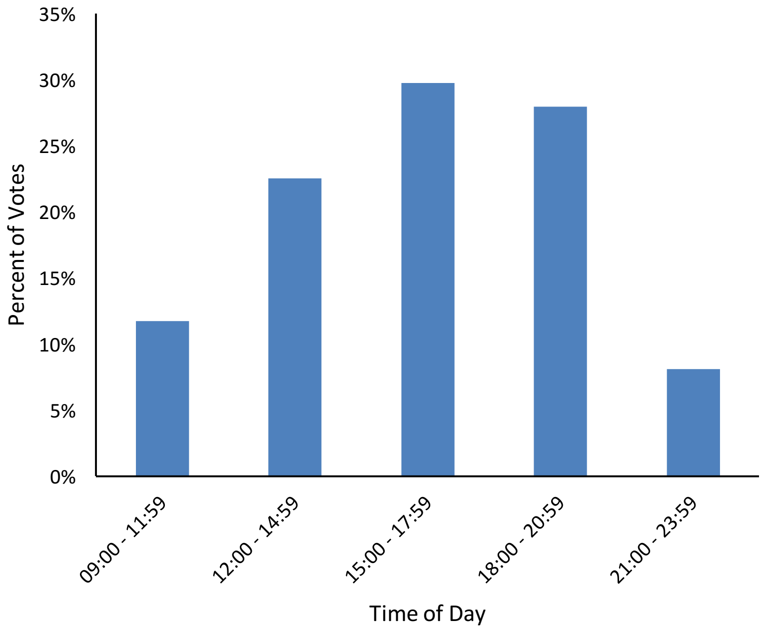

Figure 3: Time of Interview

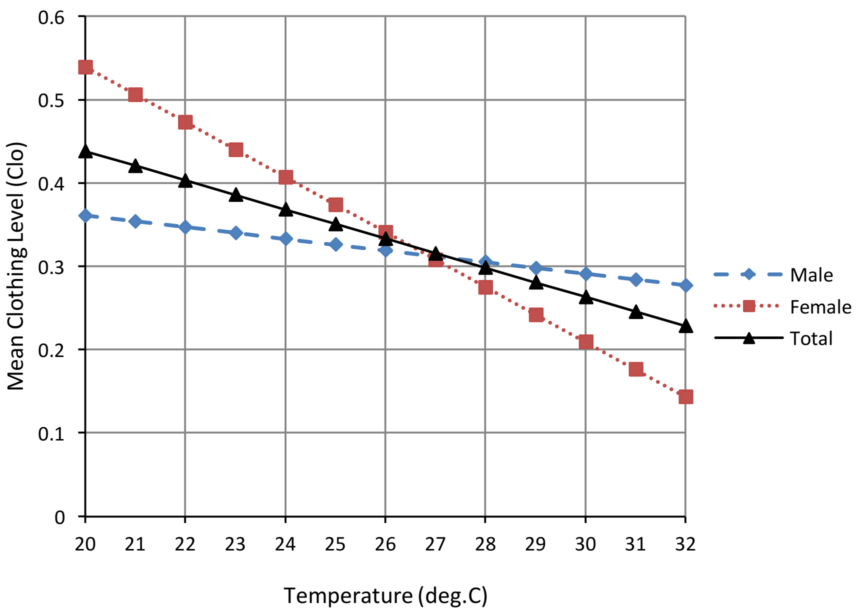

Figure 4: Clo Value vs Temperature

While mean clo values were somewhat similar between male and female students, regression analysis revealed variations at different temperatures (Figure 4). Female students had a wider range of clothing than male students, an indication that female students were more willing to alter clothing in response to discomfort conditions than was the case for male students. Male students typically donned trousers and short sleeve shirts, only adding a cardigan or changing from short sleeves to long sleeves and vice versa depending on the weather, with shorts rarely worn off the sports field. On the other hand, female students had much more diverse ensembles, ranging from short dresses and shorts or short skirts and singlets during warm and hot weather, to jeans and long sleeve tops and sweaters during cool weather, indicating greater aptness at personal adaptation than men.

4.1 Thermal Conditions

During the study period, external environmental temperatures ranged from 18.7°C, to 29.9°C, with a mean of 22.9°C. Relative humidity ranged from 53.5% to 93.4%, with a mean of 80.2%, an indication of the relatively wet conditions experienced at the time (Table 6). Indoor conditions were somewhat warmer, with the 22.5°C the lowest temperature recorded, while the highest was 31.6°C. Indoor relative humidity was on average lower, with a maximum of 77.5%, and a low of 56.5%, giving a mean of 70.2% (Table 7).

Table 6: External Environmental Conditions

	Nov.	**Dec.**	**Study**
Temperature			
Maximum	31.0°C	30.5°C	29.9°C
Minimum	17.8°C	16.3°C	18.7°C
Mean	23.3°C	23.3°C	22.9°C
Standard Deviation	2.83	2.66	2.45
Relative Humidity			
Maximum	92.5%	93.4%	93.4%
Minimum	53.5%	46.9%	53.5%
Mean	78.8%	76.6%	80.2%
Standard Deviation	8.39	9.71	7.86

Table 7: Environmental Conditions Experienced

	Male	**Female**	**Total**
Temperature			
Maximum	31.6	29.4	31.6
Minimum	22.5	23.8	22.5
Mean	25.7	25.9	25.8
Standard Deviation	1.47	1.33	1.40
Relative Humidity			
Maximum	76.4	77.5	77.5
Minimum	56.5	57.9	56.5
Mean	70.2	70.1	70.2
Standard Deviation	4.16	4.18	4.15

Analysis of the data indicated an Actual Mean Vote (AMV) of -0.73 (Table 8), or 'Slightly Cool' on the 7-point Thermal Sensation Scale, at a mean temperature of 22.9°C and Relative Humidity of 88.2%. Taking the votes about "0" (i.e. -1, 0 and +1), most respondents reported thermal sensation to be comfortable (52.2%), with Thermal Acceptability at 83.7% (taking votes between -1 and +1), with a mean Acceptability vote of -0.02 (Figure 5).

Table 8: Summary of Thermal Comfort Votes

	Male	**Female**	**Total**
Thermal Sensation	-0.78	-0.68	-0.73
Thermal Acceptability	0.05	-0.09	-0.02
Thermal Preference	-0.53	-0.30	-0.41

In seeking to derive the neutral temperature from the data, it was evident that liner regression would not be appropriate, given the data had been collected in different location, and at different times of the day over an extended period of time. In this case, linear regression revealed a weak correlation between thermal sensation votes and both indoor temperature (R^2 = 0.0188), as well as with external temperature (R^2=0.0463). A more appropriate means of interpreting the data was sought and found through the use of the Griffiths Constant (G_{cons}), which can be used to predict the Comfort Temperature (T_{comf}) from mean or individual Thermal Sensation Votes (*TSV*) and Globe Temperature (T_g) (Nguyen et al 2012). The equation for this purpose is defined as:

$$T_{comf} = T_g - TSV/G_{cons} \quad (1)$$

Using a Griffith's constant of 0.25, which provided the best fit to the gathered indoor and outdoor temperatures, it was possible to derive the neutral temperature for the study. For the purpose of this study, TSV is taken to be equivalent to the actual vote by subjects, with globe temperature substituted for ambient temperature. A strong correlation was found, with the following regression equations for indoor temperature (Equation 2) and outdoor temperature (Equation 3).

$$y = 0.22295x - 5.9723 \ (R^2 = 0.9480) \quad (2)$$

$$y = 0.2126x - 5.4604 \ (R^2 = 0.9127) \quad (3)$$

With the Griffiths constant, a neutral temperature of 26.8°C was found (Figure 7), slightly below the 28°C revealed by Olweny (1996) in Kampala, derived using probit analysis, with a comfort range of 26°C - 30°C. This was also similar to other climate studies in warm conditions across the tropics, as presented in Tables 1 and 2.

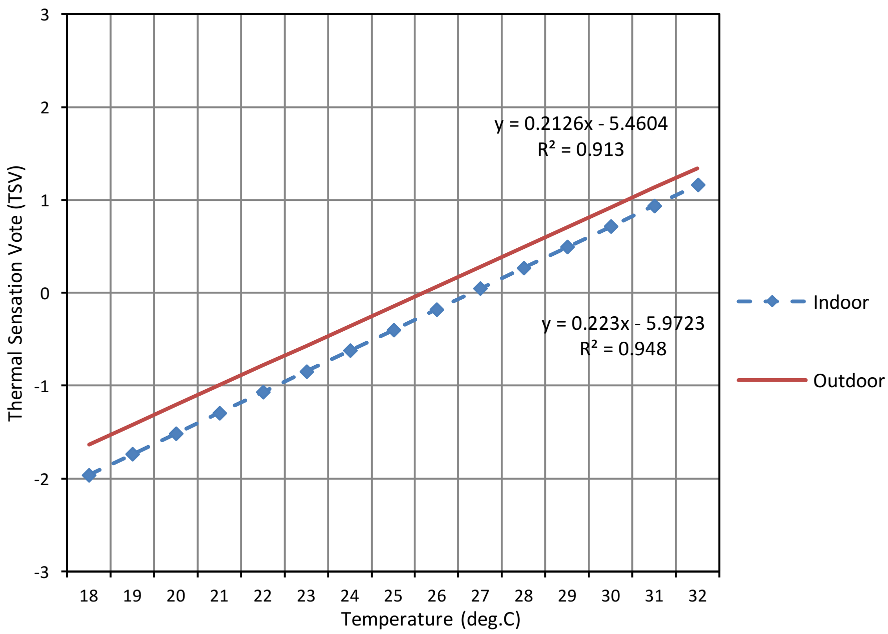

Figure 7: Regression of Thermal Sensation Vote vs Temperature

This neutral temperature of 26.8°C is higher than predicted by comfort equations by Humphreys (1978) ~ (24.1°C) Equation 4, and Auliciems (1983) for existing buildings ~ (24.9°C) Equation 5.

Humphreys (naturally ventilated) $T_n = 11.9 + 0.534T_m$ (4)

Auliciems $T_n = 0.48T_i + 0.14T_{om} + 9.22$ (5)

It is also higher than the Predicted Mean Vote (PMV) derived using data from the study: mean temperature (T_{om})= 22.9°C, mean clothing level (clo) = 0.34, Relative Humidity = 80%, Metabolic Rate = 1.0. Mean radiant temperature (MRT) was assumed to be equal to T_{om}, while air speed was considered negligible at 0.1m/s. Based on this data, PMV for Nkozi was determined to be -0.21, an over estimation of 0.52 points compared with a AMV, while the Predicted Percentage of Discomfort (PPD) of 6% is lower that the recorded discomfort of 16%. Variations in the predicted and actual neutral temperatures while expected were far greater than anticipated, and could not be explained solely through differences in methodological approaches. A more plausible explanation could relate to the unusually cool weather experienced at the time of the study, leading to an unconscious evaluation of transitional comfort as a reflection of 'anticipated thermal conditions', given this time of the year is traditionally hot and dry.

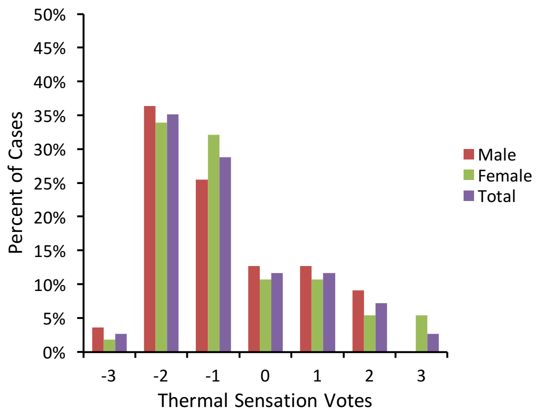

Figure 5: Thermal Sensation Votes

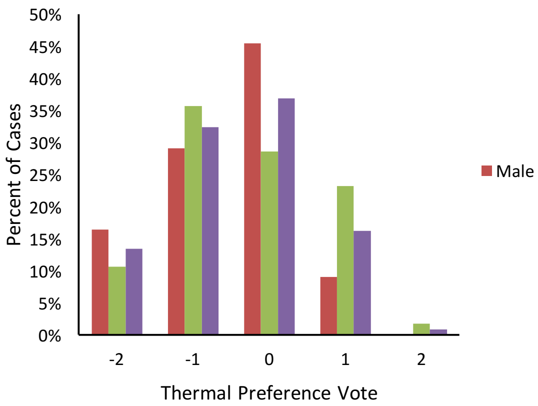

Figure 6: Thermal Preference Vote

More perplexing was an indication that the mean thermal preference vote was to be cooler (-0.41), despite the mean thermal sensation vote also being on the cool side (-0.73). Thermal preference votes indicating that 35% of subjects wanted to feel cooler, while only 11% wanted to feel warmer (Figures 5 & 6). A majority, 54% did not want to change their conditions at all. This however presents an important finding for human responses in naturally ventilated buildings, and the influence of adaptation in response to thermal conditions. To a degree the findings suggest a strong link between the clothing worn at the time of the study, the time of the vote, and the preferences exhibited by subjects. These are important factors that will be further investigated in this ongoing study.

Some answers to this apparent paradox were evident in the attitudes toward climate condition, through answers to the question, "What is your opinion about the weather and climate of Nkozi?" and a follow up question "Describe the conditions in this room at the current time." In response to these questions, students described general conditions as being hot and dry, in contrast to conditions in their rooms as cool and stuffy, suggesting a variance between expected thermal conditions versus conditions experience at the time of the study. How students responded to different weather conditions, and the mechanisms employed to cope with cool or warm conditions were thus of interest. None of the halls of residence were air-conditioned, with only a few rooms (14%) making use of fans as part of their comfort strategy. Where fans were used, students were largely satisfied with their ability to provide comfort, although it was stated that on some days, comfort was not always achieved. The majority of respondents relied on personal adaptations to achieve comfort, by: opening windows, taking a cool shower, reducing clothing levels, and leaving the room to somewhat cooler conditions (Table 9). Cool conditions prompted respondents to close windows, take a hot drink or enter their beds (Table 10). These findings were similar to those found by Olweny (1996) and showcase the importance of personal adaptation in times of discomfort.

Table 9: Response To Warm Conditions

Response	% of Cases
Open windows	27.6
Reduce clothing	24.1
Move to a cooler place	21.6
Take a shower	17.2
Turn on the fan	7.8
Drink water	0.9
Fan yourself	0.9

Table 10: Response To Cool Conditions

Response	% of Cases
Increase clothing	51.4
Enter bed	24.3
Close windows	16.2
Have a hot drink	8.1

5 Discussion and Conclusions

This study looked to investigate the thermal comfort requirements of university students for the dry season in Nkozi, Uganda. Through the study, a neutral temperature of 26.8°C was found, which is in line with thermal comfort studies in other tropical countries, and not markedly different. It was however evident that the mean thermal sensation vote in this study varied considerably, and both thermal sensation and thermal preference votes indicated a cooler than neutral. This in part could relate to the unusual weather conditions experienced at the time of the study, with high humidity levels, possibly contributing to an increased sense of discomfort among subjects. The study nevertheless has highlighted some of the challenges associated with field studies of adaptive thermal comfort in naturally ventilated buildings, an important considerations in this and other ongoing studies of thermal comfort, their unpredictability. This could be overcome with additional data and information, again which the follow up study will fulfil. Additional data from the ongoing study would be used to clarify these findings in weather conditions that are more 'typical', further reducing the possibility of measuring transitionary thermal comfort.

The study has confirmed the importance of personal adaptations in response to thermal discomfort in the context of naturally ventilated buildings in the context of Uganda. These adaptations reflect prevailing social norms and values, which are significantly important in an appreciation of thermal comfort in different contexts, and in contextualising responses, suggesting scope for further interrogation of thermal comfort in the context of up-land tropical environments. It is evident through this study that comfort itself is not a static element, but is a confluence of a diversity of factors and conditions. The follow up study of thermal comfort conditions in teaching spaces on the university campus should serve to clarify some findings, and in so doing go a step further in understanding thermal comfort in this upland tropical climate. While the current study made use of only temperature and humidity, the follow-up study will make use of additional high resolution data, including: dry bulb temperature, wet bulb temperature, globe thermometer, relative humidity, and air speed, using a Delta Ohm HD32.3 instrument specifically designed for the analysis of hot environments. It is also expected that the wider range of subjects, and larger number would provide a good basis for understanding thermal comfort in classrooms, relative to accommodation spaces.

Acknowledgments

This is to acknowledge the input of students of the Faculty of the Built Environment who participated in the data gathering exercise: Anita Ajuna, Arthur Baleeta, Christine De Guzman, Cynthia Ainomugisha, Dickens Kusemererwa, Emmanuel Geriga, Leslie Mugagga, Meshach Seruyange, Nathan Maling, Raymond Ainamani, Richard Migisha, and Tadeo Nedala.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Impact of workspace layout on occupant satisfaction, perceived health and productivity

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Abstract
Open-plan layouts have evolved significantly over the last decades with innovative concepts such as Activity-Based Working (ABW) becoming the norm in workspace layout. ABW by definition requires the creation of a variety of spaces for the occupants to select from, depending on requirements of the task at hand. While much research has been done in documenting the impacts of conventional open-plan layouts. Given the hyperbole around ABW coming from the industry, it is surprising that so little empirical research conducted in ABW has been performed to date. This paper aims to contribute to this knowledge gap by examining the impact of different workspace layouts on occupants' overall satisfaction on key IEQ dimensions, perceived productivity and perceived health. Post-occupancy evaluation results from 5,171 building occupants in 30 buildings from the Building Occupant Survey System Australia – BOSSA – database were used for this analysis. Floor plans were analysed and classified into three broad categories: Hive, ABW and Cell. Results indicated that occupants in ABW layouts were generally more satisfied with IEQ issues, such as space for breaks, interaction with colleagues, space to collaborate, air quality and building aesthetics, compared to those in Hive or Cell layouts. ABW was also in association with higher occupant satisfaction than the other two spatial configurations in terms of overall work area comfort and the overall building satisfaction. Not surprisingly, Cell layouts were more successful in producing higher satisfaction scores on sound privacy and visual privacy.

Keywords: Post-Occupancy Evaluation (POE), Indoor Environmental Quality (IEQ), Activity-Based Working (ABW), perceived productivity and health.

1 Introduction
The expression 'the new office' has been around since early 70s however it was only around mid-90s that a revolution towards flexible ways of working has been observed and its implications documented by researchers (Harrison et al., 2004; Joroff et al., 2003; Kampschroer and Heerwagen, 2005; Vischer, 2005, 2007; Stegmeier, 2008; van Meel, 2010; De Paoli et al, 2013). Open plan working has evolved alongside with changing trends observed in business management, including, the introduction of information and communication technologies and more flexible ways of organizing work processes (De Croon et al, 2005; De Been and Beijer, 2014; Miller, 2014). Several typologies in workplace design have been observed since (Becker, 1999; van Meel and Vos, 2001; Danielsson and Bodin, 2009; Duffy, 1997; Van Meel et al., 2010). Broadly these are grouped into cellular offices (Cell) or private workspaces for no more than one or two occupants and traditional

open plan layouts where a large number of workstations are co-located in a large office floor plate (Hive).

Activity-based working (ABW) is part of the latest wave of innovative workplace design and it has been the hot trend in Spatial Planning in recent years. ABW is a concept that requires the workspace layout to be designed to accommodate a variety or work-related activities. ABW expands the boundaries from the individual workstation to the entire office footprint by allowing workers to gravitate towards the best spot to develop the task in hand - it will provide workers with team desks, quiet concentration rooms, a variety of meeting rooms, brainstorm areas, multi media rooms and lounges, resulting in environments that have little or no resemblance at all to the traditional open-plan office as we know.

While a considerable body of research has been consolidated focusing on open plans offices, most of them reporting results from Post-Occupancy Evaluation (POE) surveys in open-plan offices (Visher, 1989; Cohen et al, 2001; Vischer, 2004; Zagreus et al, 2004; Leaman and Bordass, 2007; Loftness et al. 2009; Kim and de Dear, 2012; Candido et al, 2015), the same cannot be said about ABW. Likewise detailed studies providing much needed information about Indoor Environmental Quality (IEQ) (Visher, 1989; Vischer, 2008; Jarvis 2009; Loftness et al. 2009; Mui et al, 2009; Wong and Mui, 2009; Ncube and Riffat, 2012; Cao et al, 2012; Heinzerling et al, 2013; Deuble and de Dear, 2014; Kim et al, 2012; Kim and de Dear, 2013), productivity and performance (Leaman and Bordass, 1999, 2001; De Croon et al, 2005; Perettin and Schiavon, 2011; Frontczak et al, 2012; Liang et al, 2014; Thatcher and Milner, 2014; Hartkopf, Loftness and Mill 1986; Vischer 2008; Jarvis 2009; Heinzerling et al, 2013), health (Abraham and Greham-Rowe, 2009; Smith et al, 2013; Buckley et al, 2015; Graves et al, 2015; Marmot and Ucci, 2015) and other topics related to space planning (Duffy, 1997; Fawcet and Rigby, 2009; Oksanen and Stahle, 2013) remain focused on open plan settings.

Despite the fact that at least 10 million Australians spend most of their time at their workplace and the number of conventional open-plan offices being converted into ABW in this country, findings arising from research projects developed in such environments are in very need. The main mega-drivers behind the rapid incorporation of ABW are the ability to support business growth and objectives, brand differentiation and drives in talent attraction and retention. The introduction of ABW and shared workstations enables organizations to save office space, reduce general and technical services costs and increase flexibility of office use which when combined can serve to address the sustainability agenda of the business by saving energy in Heating Ventilation and Air-Conditioned (HVAC) systems and overall carbon foot-print of the building.

Apart from the obvious financial benefits from introducing ABW, advocates also claim that the resultant workspace is able to have significant, positive impacts on any organization's most precious asset – their workers. Significant gains in productivity, health and overall satisfaction, along with the ability of ABW spaces to increase collaboration and address intergenerational needs have all been reported by industry (sometimes backed up by case studies) when describing the advantages of ABW over conventional open plan counterparts. However, empirical evidence coming from research studies in ABW settings, particularly databases that may or may not corroborate the hyperbole observed in industry is scarce (De Paoli et al, 2013; Miller, 2014; De Been and Beijer, 2014; Remoy and van der Voordt, 2014).

This paper aims to contribute to this knowledge gap by providing empirical evidence of ABW performance. A comparative analysis of the impact of different workspace layouts (Hive, ABW and Cell) on occupant satisfaction in key IEQ dimensions, perceived productivity and health was carried out. By employing the effect size measurement, this study is able to tell how important these differences really are to the real practice, thus can provide references and guidance for future architectural designs and retrofits, from the perspective of promoting building occupant satisfaction.

2 Methodology

2.1 The BOSSA project

Since 2011 the BOSSA project has been developing and implementing research tools aimed to investigate IEQ performance in office buildings in Australia. The project has been conducted in close consultation and collaboration with key stakeholders of the property industry (buildings owners, tenants and consultants), government (National Australian Built Environment Rating Scheme – NABERS) and the Green Building Council of Australia (GBCA). BOSSA has tools for assessing IEQ via a Post-Occupancy Evaluations (BOSSA Time-Lapse) and high-resolution diagnostics via ‘right-here-right-now’ surveys (BOSSA Snap-Shot) along with *in situ* measurements of key IEQ parameters (BOSSA Nova). Details about the project’s tools and database have been outlined elsewhere (Candido et al, 2015).

Apart from background survey questions addressing participants’ gender, age, type of work, time spent in buildings, workspace arrangement, etc., there are thirty-one questionnaire items from the BOSSA Time-Lapse survey asking building occupants to assess their satisfaction with their workspace and building, covering nine broad IEQ dimensions, namely spatial comfort, indoor air quality, personal control, noise distraction and privacy, connection to outdoor environment, building image and maintenance, individual space, thermal comfort and visual comfort. There are also four overall satisfaction items in use: work area comfort, building satisfaction, productivity and health. The current analysis focus on the general impact of workplace layout on occupant satisfaction, thus the questionnaire items which are more building-related, such as external view, shading, personal control, building cleanness and maintenance were not included. Table 1 lists the BOSSA Tim-Lapse IEQ questionnaire items used in this study.

The current research database comprises a total of approximately 7,000 responses from BOSSA Time-Lapse surveys conducted in 65 buildings Australia-wide. Most buildings are fully air-conditioned with open-plan fit-outs (with/without partitions), fixed or flexi-desking workspace policies, including a mix of ABW, conventional open-plan and private offices. Building size range from 2,000m^2 to 62,000m^2 and the vast majority hold current energy performance and/or indoor environments ratings from the NABERS and/or the GBCA’s Green Star-Performance tool. Building metrics information and floor plans, including workspace layout, are collected for each building entering the database.

Apart from occupant surveys, BOSSA also collates building metrics information and floor plans, including workspace layout, depending on the availability. Details arising from this database enabled the workspace analysis presented and discussed on this paper.

Table 1 List of BOSSA Time-Lapse IEQ questionnaire items adopted in the current analysis

Dimensions and indices	Questionnaire items	Survey questions	Rating scale
Spatial comfort and individual space	Space for breaks	This building provides pleasant spaces (e.g. indoor or outdoor green space, break-out areas) for breaks and relaxation.	1= Disagree ~ 7= Agree
	Interaction with colleagues	How do you rate your normal work area's layout in terms of allowing you to interact with your colleagues?	1= Dissatisfied ~ 7= Satisfied
	Personalisation of work area	My normal work area can be adjusted (or personalised) to meet my preferences.	1= Disagree ~ 7= Agree
	Space to collaborate	The building provides adequate formal and informal spaces to collaborate with others.	1= Disagree ~ 7= Agree
	Comfort of furnishing	Please rate how comfortable your work area's furnishings are (including chairs, desk, equipment, etc).	1= Uncomfortable ~ 7= Comfortable
	Amount of workspace	Please rate your satisfaction with the amount of space available to you at your normal work area.	1= Dissatisfied ~ 7= Satisfied
	Storage space	Please rate your satisfaction with the amount of personal storage space available to you.	1= Dissatisfied ~ 7= Satisfied
Indoor air quality and thermal comfort	Air quality	Please rate your satisfaction with the overall air quality in your work area.	1= Dissatisfied ~ 7= Satisfied
	Temperature in winter	Please rate the temperature conditions of your normal work area in winter.	1= Uncomfortable ~ 7= Comfortable
	Temperature in summer	Please rate the temperature conditions of your normal work area in summer.	1= Uncomfortable ~ 7= Comfortable
Noise distraction and privacy	Unwanted interruption	The work area's layout enables me to work without distraction or unwanted interruptions.	1= Disagree ~ 7= Agree
	Visual privacy	My normal work area provides adequate visual privacy (not being seen by others).	1= Disagree ~ 7= Agree
	Sound privacy	My normal work area provides adequate sound privacy (not being overheard by others).	1= Disagree ~ 7= Agree
	Noise	Please rate your satisfaction with the overall noise in your normal work area.	1= Dissatisfied ~ 7= Satisfied
Visual Comfort	Lighting	Please rate your satisfaction with the lighting comfort of your normal work area (e.g. amount of light, glare, reflections, contrast)?	1= Dissatisfied ~ 7= Satisfied
	Access to daylight	Please rate your satisfaction with the access to daylight from your normal work area.	1= Dissatisfied ~ 7= Satisfied
Personal control and building image	Degree of freedom to adapt	All things considered, how satisfied are you with the degree of freedom to adapt your normal work area (air-conditioning, opening the window, lighting, etc.) to meet your own preferences?	1= Dissatisfied ~ 7= Satisfied
	Building aesthetics	Please rate the overall visual aesthetics of this building.	1= Dissatisfied ~ 7= Satisfied
Overall satisfaction	Overall work area comfort	All things considered, how satisfied are you with the overall comfort of your normal work area?	1= Dissatisfied ~ 7= Satisfied
	Overall building	How satisfied are you with this building overall?	1= Dissatisfied ~ 7= Satisfied
	Productivity	Productivity How does your work area influence your productivity?	1= Negatively ~ 7= Positively
	Health	How does your work area influence your health?	1= Negatively ~ 7= Positively

2.2 Workspace layouts

BOSSA Building Metrics and floor plans, when available, of 30 buildings were analyzed for this research paper. Based on the work of Duffy (1997) on spatial layout, workspaces were classified into three broad categories: conventional open plan (Hive, n = 2,301), multi-space workspace (ABW, n = 2,566) and private workspace (Cell, n = 304). The average size of buildings with ABW workspaces is almost twice as large as the ones with Hive layout (41,163m^2 and 21,820m^2, respectively). Since private workspaces are increasingly rare in Australia (and only existed in a few types of industries), there were much smaller sample size (304) in Cell layout than the other two. Nonetheless, the Cell sample size is still statistically large.

2.3 Statistical analysis

The one-way Analysis of Variance (ANOVA) was carried out to examine whether different workplace layouts significantly are associated with building occupant satisfaction. However, one of the problems with this null hypothesis testing is that even the most trivial effect will become statistically significant if enough people are tested (Field, 2013). As can be expected from the large sample sizes in the current BOSSA surveys (Table 2), the omnibus ANOVA tests revealed highly significant differences (p < 0.001) for all 22 questionnaire items. To solve this issue, the effect size[1](ES) measures were adopted to answer the research question of how important these statistically significant differences really are.

In this analysis, a common measure of ES—*Cohen's d* (Cohen, 1988, 1992), was adopted when comparing two means. It is calculated by Equation (1) and (2).

$$d = \frac{\mu_1 - \mu_2}{\sigma} \tag{1}$$

$$\sigma = \sqrt{\frac{(N_1 - 1)\sigma_1^2 + (N_{21} - 1)\sigma_2^2}{N_1 + N_2 - 2}} \tag{2}$$

where μ_1 and μ_2 refer to the mean value for two groups, N_1 and N_2 refer to the sample size of two groups.

Another common effect size, the Pearson correlation coefficient r, was also employed in the analysis when examining the association between two parameters. It is measured on a standard scale ranging between -1.0 and +1.0. As such, the absolute value of the correlation coefficient is an effect size that summarizes the strength of the relationship. All the statistical analysis was conducted in IBM SPSS, Version 22.

3 Results and Discussions

The mean occupant responses are illustrated in Figure 2, with a breakdown of three different workplace layouts. ABW was associated with higher satisfaction ratings than the other two in 12 IEQ questionnaire items, except for storage space, unwanted interruption, visual privacy, sound privacy, noise and lighting; ABW also outperforms the conventional open-plan and private workspace in all four overall satisfaction questionnaire items. However, the causality of these associations *cannot* be stated firmly due to the existence of potential confounding variables, mostly building-specific features, such as architectural and interior design quality, building facility quality and standard of maintenance, etc.

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[1] Effect size is an objective and (usually) standardized measure of the magnitude of the observed effect. (Field, 2013).

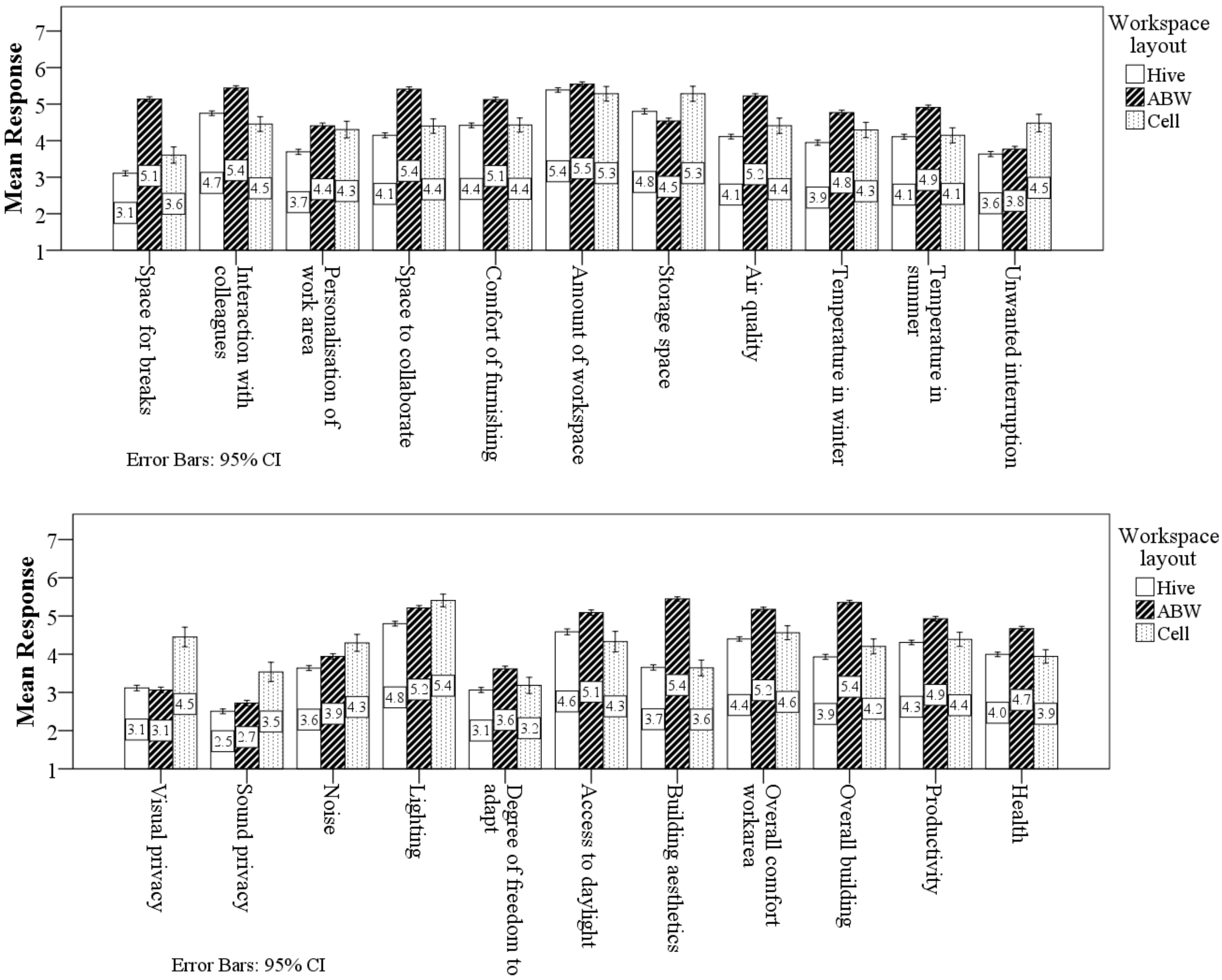

Figure 2 Breakdown of mean occupant responses in IEQ questionnaire items in three workplace layouts.

3.1 Workplace layout & occupant satisfaction with IEQ dimensions

ANOVA suggested highly significant mean occupant satisfaction across three different workplace layouts in 22 questionnaire items. To measure the magnitude of the effects, Cohen’s *d* was calculated for the ABW vs. Hive and ABW vs. Cell pairwise comparisons; the Hive vs. Cell comparison was of no interest in this study, thus was not calculated. Cohen suggested that *d*=0.2 be considered a *small* effect size, 0.5 represents a *medium* effect size and 0.8 a *large* effect size (Cohen, 1988, 1992). This means that if two groups' means don't differ by 0.2 standard deviations or more, the difference is **trivial**, even if it is statistically significant (Statistics for Psychology, accessed 07-01-2016). In Cohen's terminology, a *small* effect is one in which there is a real effect but can be observed only through “careful study”; a *large* effect is consistent enough that could be obvious to the “naked eye”. The authors thus believe that a medium or large size effect is of more practical meaning in the real world than the small size one. Table 3 reports the 7 questionnaire items that returned medium or large effects ($d \geq 0.5$) for either comparison.

Table 3 demonstrates that occupant satisfaction with space for breaks and building aesthetics was much higher in ABW than in Hive or Cell (representing large effects); ABW also exceeded the other two in respect to interaction with colleagues, space to collaborate, and air quality (medium effects); Cell performed better than ABW and Hive in terms of visual and sound privacy (medium effects).

Table 3 The effect of workplace layouts on occupant satisfaction in BOSSA IEQ questionnaire items (only medium or large effects are reported)

IEQ questionnaire items		Hive	ABW	Cell
Space for breaks	Mean	3.11	5.14	3.61
	ES (Cohen's *d*)	ABW vs. Hive		1.18
		ABW vs. Cell		0.92
Interaction with colleagues	Mean	4.75	5.44	4.45
	ES	ABW vs. Hive		0.45
		ABW vs. Cell		0.66
Space to collaborate	Mean	4.15	5.41	4.40
	ES	ABW vs. Hive		0.76
		ABW vs. Cell		0.64
Air Quality	Mean	4.11	5.22	4.41
	ES	ABW vs. Hive		0.71
		ABW vs. Cell		0.54
Visual Privacy	Mean	3.12	3.06	4.45
	ES	Cell vs. Hive		0.70
		Cell vs. ABW		0.73
Sound Privacy	Mean	2.50	2.72	3.54
	ES	Cell vs. Hive		0.61
		Cell vs. ABW		0.46
Building aesthetics	Mean	3.66	5.45	3.64
	ES	ABW vs. Hive		1.11
		ABW vs. Cell		1.25

Above results seemed to be intuitive and reasonable regarding visual privacy, sound privacy and building aesthetics—the enclosed/private offices with Cell layout are naturally of higher visual and sound privacy than the other open-plan ones; the innovative activity-based working break the rules of traditional workplace arrangement and fit-out contributing to a new and appealing appearance to the ABW buildings.

Regarding the three questionnaire items related to spatial comfort, specific spatial-related attributes of all sampled buildings in each type of workspace layout were examined and quantified, shown in Table 2. With the ABW buildings being specifically designed to integrate space for break out and both formal and informal spaces for collaboration, it may be unsurprising that ABW returned higher satisfaction when compared to both Hive and Cell. On the other hand occupant satisfaction with respect to "How do you rate your normal work area's layout in terms of allowing you to interact with your colleagues" suggests that specific amenities integrated in ABW do succeed in facilitating the desired interaction with colleagues. Although surveyed buildings with ABW layout have higher amount of floor area available per desk (16 m^2) than ones with Hive layout (13 m^2), the average work area per desk for ABW (5 m^2) is less than that for Hive (8 m^2). This could result from the nature of flexi-desk arrangement in ABW settings where the same desk is supposed to be shared by different people, or the fact that desks (flexi or fixed) equipped in buildings with ABW layout are simply not enough, or both.

ABW's superiority to Hive and Cell in achieving higher satisfaction with air quality may probably due to the prevalent flexi-desk arrangement in this layout. In a separate analysis of the 7 ABW buildings (Kim et. al 2015), the authors found that flexi-desk arrangement achieved significantly higher occupant satisfaction regarding air quality than the fixed-desk arrangement. Those participants reporting flexi-desk arrangement as their primary workspace arrangement were directed to another question about whether the indoor environmental quality influences their seat selection (seven-point scale with 1= disagree and 7= agree). The results showed that over 80% of the respondents agreed (the top three levels on the rating scale) that IEQ affects their decision of seat selection. Due to the nature of activity-based working, a flexi-desk arrangement is prevalent in ABW buildings. Among all 7 buildings with ABW layout, 87.3% of the participants have reported that flexi-desk is their primary workspace arrangement. Participants' enhanced level of perceived control over the indoor environment, as discussed in Kim and de Dear (2012), goes some way towards explaining why ABW achieved higher satisfaction ratings in air quality than the other two types.

3.2 Workplace layout & overall satisfaction

Similarly, Cohen's *d* was calculated for ABW vs. Hive and ABW vs. Cell pairwise comparisons for the four overall satisfaction items, shown in Table 4. ABW surpassed the other two in the overall building satisfaction, representing a large size effect; ABW also lead in the three types of workplace layout with respect to work area comfort, productivity and health, representing (near) medium size effects. Again, one should be cautious not to overstate this conclusion since the confounding variables were not controlled in the analysis.

Table 4 The effect of workplace layouts on four BOSSA overall satisfaction

Questionnaire item		Hive	ABW	Cell
Work area comfort	Mean	4.40	5.18	4.56
	Effect Size (Cohen's *d*)	ABW vs. Hive	0.54	
		ABW vs. Cell	0.45	
Building Satisfaction	Mean	3.93	5.35	4.20
	Effect Size (Cohen's *d*)	ABW vs. Hive	0.92	
		ABW vs. Cell	0.83	
Productivity	Mean	4.31	4.93	4.39
	ES (Cohen's *d*)	ABW vs. Hive	0.42	
		ABW vs. Cell	0.36	
Health	Mean	4	4.67	3.94
	ES	ABW vs. Hive	0.44	
		ABW vs. Cell	0.48	

Candido et. al (2015) employs multiple regression analyses to quantify how occupants' ratings on the 9 IEQ dimensions contribute to the ratings on the IEQ dimensions all significantly predict general satisfaction to different degrees. In this study, correlation analysis was carried out to examine how the superiority of ABW in promoting occupants' general satisfaction is related to its advantage/disadvantage in 18 IEQ questionnaire items. Figure 3 illustrates Pearson's *r* between 4 overall satisfaction and 18 IEQ questionnaire items for the ABW buildings. To interpret these effect sizes, an *r* of 0.1 represents a weak or *small* association, 0.3 represents a *medium* correlation and 0.5 or higher represents a strong or *large* correlation (Cohen, 1988, 1992).

The overall work area comfort and overall building satisfaction generally have higher correlation with IEQ items compared with productivity and health. Specifically, overall work area comfort and overall building satisfaction have a stronger correlation (r > 0.5) with respect to the IEQ items in which ABW outdistanced Hive and Cell (large or medium size effects) namely: space for breaks, interaction with colleagues, space to collaborate, air quality and building aesthetics. It is evident that the advantage of ABW over Hive and Cell is more conspicuous in terms of work area comfort and building satisfaction (medium or large size correlation) than in respect to productivity and health (near medium size correlation).

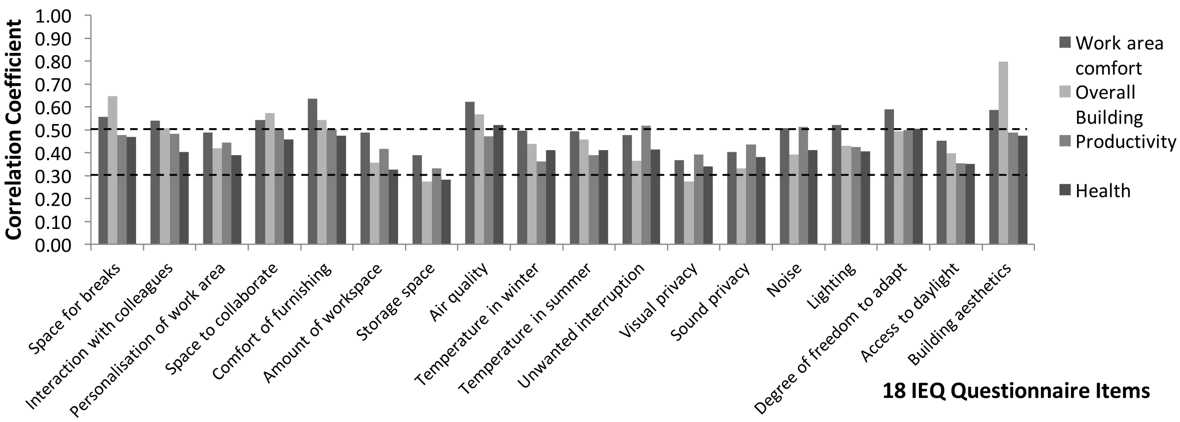

Figure 3 Correlation between IEQ questionnaire items for ABW.

4 Conclusions

This paper analyzed post-occupancy evaluation results from 5171 building occupants in 30 buildings from the Building Occupant Survey System Australia—BOSSA, specifically looking into the impact of different workspace layouts on building occupant satisfaction in key IEQ dimensions, perceived productivity and health. The following results can be obtained from this study:

- buildings occupants, generally, were more satisfied with ABW layout than Hive and Cell layouts in IEQ related issues, especially on space for breaks, interaction with colleagues, space to collaborate, air quality and building aesthetics, all representing medium or large size effects.
- ABW is also in association with higher occupant satisfaction than the Hive and Cell in the overall work area comfort (medium size effect), the overall building satisfaction (large size effect), perceived productivity and health (near-medium size effect).
- Not surprisingly, Cell layouts that afford private workspaces are associated with higher satisfaction scores in sound privacy and visual privacy.
- Although one should be discreet in generalizing the above mentioned trends, sampled buildings with ABW layout do provide more spaces for breaks, meetings and collaboration than the other two. Furthermore, flexi-desk arrangement that is popular in ABW also gives occupants more flexibility and control in choosing their workstation indoor environment with ideal air quality.

Acknowledgements

This research is supported under the Australian Research Council's Linkage Projects funding scheme (grant number LP1102000328).

The authors thank Associate Professor Martin Mackey from The University of Sydney's Faculty of Health Sciences for our discussions about healthy workplaces.

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Thermal performance of indoor spaces of prefabricated timber houses during summertime

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Abstract
Prefabricated timber houses are built with modern construction methods and have low-U value building components to meet improved regulations for thermal performance. However, the improved performance and the lack of thermal mass increase summertime overheating risk. Using Bridport and Oxley Woods in Southeast England, this paper discusses summertime temperatures obtained through monitoring and simulation to evaluate overheating. The analysis was done under free-running conditions and considered occupants' comfort using the CIBSE and the adaptive (BSEN15251) thermal comfort models. The monitored temperatures varied from 18.0ºC-30.5ºC in the summer (June-July) of 2012. The analysis of the CIBSE comfort model showed the monitored temperature exceeded 1%>28ºC in 3 of the 6 living areas (50%) and 1%>26ºC in 6 of the 9 bedrooms (67%). For the simulations, temperature exceeded 1%>28ºC in 1 of the living areas (17%) and 1%>26ºC in 2 of the bedrooms (22%). Analysis of the dynamic adaptive comfort model showed the monitored temperatures exceeded 5% of hours above the Category II upper marker in 1 of the living areas (17%) and in 6 of the bedrooms (67%) suggesting warm discomfort. The simulation showed the predicted temperature exceeded the indicator in only 1 of the bedrooms (11%) and none in the living areas. The monitoring results revealed overheating occurs, especially at Oxley Woods while the simulations did not suggest extreme overheating, which demonstrates that monitoring provides a more reliable dataset for assessing the thermal performance of buildings. Finally, although occupants take further adaptive measures to improve their thermal conditions reducing the impact of overheating, the lack of thermal mass in prefabricated timber developments increases the overheating risk, even in mild summer weather conditions.

Keywords: thermal performance, adaptive comfort, summertime overheating, monitoring, simulations, prefabricated timber

1 Introduction

Energy conservation to reduce carbon emissions has become a major issue in every sector including housing (IPCC, 2007; DECC, 2012). From 1970 to the mid 2000s, carbon emissions generated mainly from various actions by people have increased by at least 70% (IPCC, 2007); and the amount of energy used across the world is estimated to rise for the next three decades (from 2010-2040) by at least 56% (US EIA, 2013). In the UK, there are on-going efforts to cut carbon emissions and limit further exploitation of fossil fuels for various purposes by at least 80% in the 2050s (DTI, 2003). However, the targets set to cut carbon emissions are yet to be met.

Over the last few years, at least 26% of the overall UK carbon emissions are generated from the housing sector (DEFRA, 2007) considering the recent housing stock of 26.2 million (ONS,

2011) and the 61 million people with the estimated population to reach 65.4 million in 2016 (RICS, 2012). This shows construction of more low-carbon emission dwellings using sustainable materials such as timber with appropriate renewable energy integration to minimise carbon emission in housing is very important.

Several innovations to achieve energy-saving houses have been included in many developments to improve overall thermal environments. Sustainable materials have been increasingly used especially for dwellings in recent years. Literature has discussed summertime overheating as a crucial issue in buildings and proffered potential solutions for occupants to minimise its impact within indoor environment (CIBSE 2010). In addition, numerous studies have investigated the risk of overheating in buildings (Lomas and Giridharan, 2012) and highlighted that UK buildings are prone to summertime overheating. However, investigations on the performance of internal spaces of prefabricated timber houses have not been fully explored to understand occupants' comfort in prefabricated timber dwellings. As a result, this paper presents the findings of field surveys carried out in 9 households at two different developments in the Southeast UK, supplemented by dynamic thermal simulations to evaluate thermal comfort conditions and overheating.

2 Description of the case study buildings

The two case study buildings (Bridport and Oxley Woods) considered in this paper are located in the south-east of England and built with prefabricated structural timber panels. The buildings developed in the last decade have won different awards in terms of sustainability and low-energy rating. Bridport, completed in 2011 is located in Hackney, East London and built with prefabricated cross-laminated timber (CLT) panels. Construction of Oxley Woods, located in Milton Keynes, started in 2005 and was built with structural insulated panels (SIPs). It comprises of 145-dwelling units with 29-dwelling units yet to be completed as at the time of the survey. The internal spaces of the buildings were considered for the environmental monitoring during the summer of 2012. The table below summarises the thermal properties and features of the case study buildings.

Table 1: Thermal properties of the components and important features of Bridport and Oxley Woods

Case study	Components	U-values for the different components (W/m^2K)	Density (kg/m^3)	Heat capacity (J/kg-K)	Thermal conductivity (Wm-K)	Floor-to-ceiling height (m)
Bridport	**Walls:** high quality brown bricks for external walls, cavity, polyurethane rigid insulation board, breather membrane, CLT panel, gypsum plasterboard.	0.13 (internal wall) 0.14 (external wall)	500	1600	0.13	2.65
	Roof: brown/green roof substrate for bio-diverse planting, damp proof layer, rigid insulation, CLT panel.	0.12				
	Floor: timber finished floor layer, screed, rigid foamboard insulation layer, CLT panel, cavity, insulation, gypsum plasterboard.	0.16				
	Windows: low-e double glazed timber/aluminum composite.	1.37				
Oxley Woods	**Walls:** Trespan cladding, structural insulated panels (SIPs), 145mm cavity, non-toxic Warmcel insulation produced from recycled newspaper, gypsum plasterboard.	0.10 (internal wall) 0.12 (external wall)	450	1600	0.12	2.35
	Roof: roof panel over 100mm thick solid polyurethane insulation, timber cassettes.	0.17				
	Floor: timber finished floor layer, screed, rigid polyurethane insulation layer, timber cassette.	0.10				
	Windows: timber framed with low-e double glazing.	1.7				

3 Methodology

The research methods considered for this study include environmental monitoring and dynamic thermal simulations. The complementary comfort surveys were examined and discussed in Adekunle & Nikolopoulou (2014). The information on the case study buildings' designs such as shape, orientation, arrangement of spaces, construction methods used, services and integration of environmental controls was collected from architectural and construction drawings, specification documents and further discussions with the developers, architects, financiers and residents. The spaces monitored during the surveys were selected from different orientations as representative spaces in agreement with the residents that participated in the survey and where applicable, with the facilities' managers. (Table 2). Also, different occupancy patterns were also considered for selection of the spaces selected. The HOBO and Tinytag sensors, which were calibrated in advance, were used for the monitoring of air temperature and relative humidity, recording at 15-minute intervals.

Overall, 15 spaces in 9 households were monitored in the summer, five and 10 at Bridport (4 households) and Oxley Woods (5 households) respectively. The buildings are operated as free-running in summertime. The internal spaces of the buildings were monitored for at least two weeks from June-July 2012 to provide an equal basis for the monitoring periods at the buildings. The monitoring of the spaces could not be carried out during the hottest month (August) in the summer as the residents and appropriate authorities in charge of the case study buildings only granted access to the buildings between June and July 2012. The sensors were installed at 1.1m height above the floor level, away from high source of internal heat gains, the sun and close to where the occupants usually sit or work to measure the temperatures near the subjects. The outdoor weather data were collected from the nearby weather stations to the buildings. For Bridport, outdoor weather data were collected from London City Airport weather station while weather data from Luton Airport weather station were considered for Oxley Woods.

Since the environmental monitoring was carried out for only two weeks in the summer, it is important to understand the thermal performance of the building for the whole summer period (i.e, from May-September), through dynamic thermal modelling and simulation. The weather files (Test Reference Years- TRYs for the 2000s) used for the simulations were sourced from the Prometheus Group based at the University of Exeter, UK. The TRYs weather files were considered for the simulation as opposed to the future weather files due to the focus of the study, which was to investigate the thermal performance of the spaces monitored in the summer for comparison with the simulated data, and availability of the weather files used.

4 Performance of the internal spaces monitored during the summer (June-July 2012)

A sensor used for the environmental monitoring was placed in each of the spaces monitored in the summer. At Bridport, a maximum temperature of 25.0°C was recorded on 5/7/2012 in FL35SFL-BD (living area) when the external temperature reached 23.5°C on the same day. At Oxley Woods, a maximum temperature of 30.5°C was observed on 25/7/2012 in A162HAFFBB-OW (bedroom) when the external temperature reached 27.0°C on the same day. A peak temperature of 24.7°C was recorded on 5/7/2012 in FL1FFB-BD (bedroom), the second warmest space at Bridport. A maximum temperature of 30.0°C was recorded on 24/7/2012 in A1WLGFL-OW (living area), the second warmest space at Oxley Woods when the external temperature reached 27.0°C. The analysis showed higher indoor temperatures were recorded in the bedrooms than the living areas monitored at Oxley Woods and vice-versa at Bridport in the summer. An evaluation of the design of Oxley Woods showed the bedrooms of the dwellings investigated are located on the upper floors due to the temperature stratification on the upper floor, which may contribute to higher temperatures recorded in the bedrooms. Maximum temperatures were observed in all the spaces monitored at Bridport on 5/7/2012 while peak temperatures were recorded in all the spaces monitored at Oxley Woods between 24/7/2012 and 25/7/2012 due to a minimum lag of one day earlier observed in the external temperatures at the buildings. A summary of the data is presented on the table below.

Table 2: Summary of the data monitored at Bridport and Oxley Woods recorded in the summer.

Space-location	Orientation	Floor area (m²)	Floor level	Mean indoor temp (ºC)	Max. indoor temp (ºC)	Max. outdoor temp (ºC)	Date	Min. indoor temp (ºC)	Min. outdoor temp (ºC)	Date
FL1GFL-BD	South-facing	29.7	GF	22.9	24.6	23.5	5/7/12	21.7	11.0	11/7/12
FL1FFB-BD	Southwest-facing	13.1	FF	22.8	24.7	23.5	5/7/12	21.3	9.0	12/7/12
FL7FFFB-BD	East-facing	15.2	FF	22.3	23.8	23.5	5/7/12	21.2	13.0	11/7/12
FL8FFSB-BD	Northeast-facing	7.7	FF	22.0	23.6	23.5	5/7/12	20.1	9.0	12/7/12
FL35SFL-BD	West-facing	28.8	SF	23.7	25.0	23.5	5/7/12	22.7	9.0	12/7/12
A1WLGFL-OW	Southwest-facing	20.9	GF	23.5	30.0	27.0	24/7/12	19.8	8.0	30/7/12
A1WLFFFB-OW	Southeast-facing	12.2	FF	23.9	28.7	27.0	24/7/12	19.4	9.5	21/7/12
A6MLSFBB-OW	Northwest-facing	8.7	SF	24.7	29.2	27.0	24/7/12	21.0	8.0	30/7/12
A38MLGFL-OW	Northeast-facing	20.9	GF	22.6	28.1	27.0	24/7/12	18.2	9.5	21/7/12
A38MLFFFB-OW	Southeast-facing	12.2	FF	24.5	29.5	27.0	25/7/12	20.0	9.5	21/7/12
A38MLFFBB-OW	Northeast-facing	9.1	FF	24.3	29.1	27.0	24/7/12	20.8	8.0	30/7/12
A142HAGFL-OW	Southwest-facing	18.3	GF	22.4	28.0	27.0	24/7/12	18.3	9.5	21/7/12
A142HASFBB-OW	Southeast-facing	9.1	SF	23.2	29.8	27.0	24/7/12	18.0	10.0	31/7/12
A162HAGFL-OW	North-facing	20.9	GF	23.7	27.3	27.0	24/7/12	18.6	9.5	21/7/12
A162HAFFBB-OW	Southeast-facing	8.7	FF	25.7	30.5	27.0	25/7/12	20.8	10.0	31/7/12

*GF- Ground floor, FF- First floor, SF- Second floor. *BD- Bridport, OX- Oxley Woods. The spaces ending with –FL are living areas and the spaces ending with –BB, -SB and –FB are bedrooms.

Throughout the survey, the maximum internal diurnal temperature within the spaces monitored varied on each day at Oxley Woods while a difference between 2.0°C and 3.0°C was observed within all the spaces at Bridport. A minimum temperature of 4.0°C was observed between the maximum and the minimum internal temperatures in the spaces monitored at Oxley Woods in the summer. The analysis showed high temperatures were observed more often within the internal spaces at Oxley Woods than Bridport in the summer (table 2).

The mean temperatures recorded in the living rooms were higher than the average temperatures recorded in the bedrooms at Bridport and vice-versa at Oxley Woods in the summer (Fig. 1). The analysis also showed the mean internal temperatures recorded were at least 0.8ºC higher in the living rooms than the bedrooms at Bridport. On the contrary, the average internal temperatures were at least 1.0ºC higher in the bedrooms than the living rooms at Oxley Woods. The overall analysis revealed a wide range of mean internal temperatures at Oxley Woods, which is likely to influence higher adaptation of the occupants at Oxley Woods to the thermal environment in the summer.

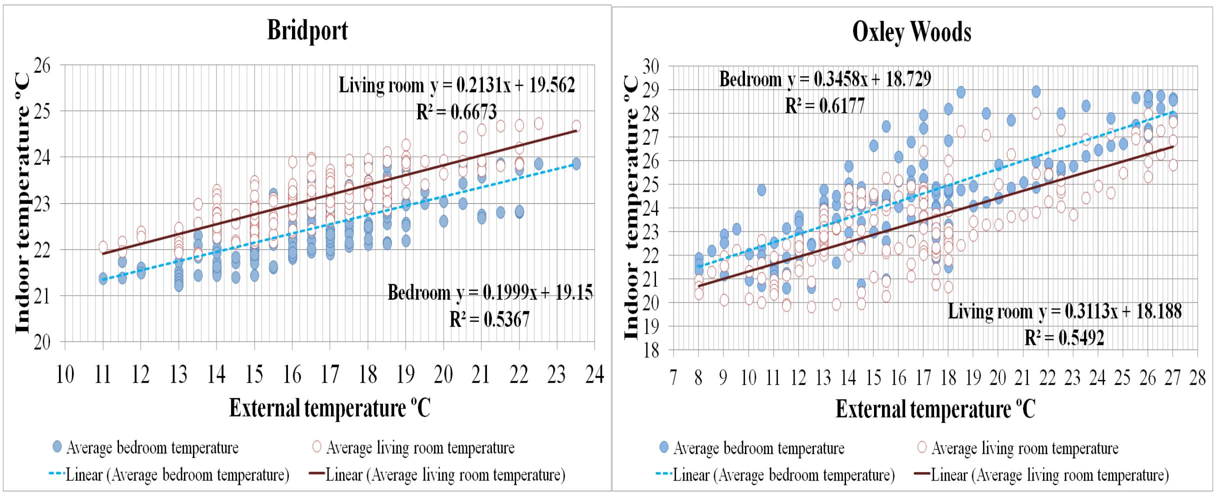

Figure 1: Relationship between the monitored mean temperatures in the living areas and the bedrooms at Bridport (left) and Oxley Woods (right) and the external temperatures

Further analysis of the total hours of monitored temperatures showed most of the living areas and the bedrooms exceeded the CIBSE and the BSEN15251 (Category II upper) thermal comfort models. The CIBSE thermal comfort analysis showed total hours of the monitored temperatures exceeded 5%>25ºC in 4 of the living areas (67%) considered and exceeded 1%>28ºC in 3 of the spaces (50%). The measured temperatures exceeded 5%>24ºC in 7 of the bedrooms (78%) and exceeded 1%>26ºC in 6 of the spaces (67%). For the BSEN15251 thermal comfort model, the analysis showed the temperatures exceeded the Category II upper limit above 5% of the total monitored hours in 1 of the living areas (17%) and in 6 of the bedrooms (67%). Figure 2 shows the recorded internal temperature in A1WLGFL-OW (the warmest living area) and in A162HAFFBB-OW (the warmest bedroom) compared to the BSEN15251 Category II boundaries. The findings showed extreme summertime overheating in the bedrooms than the living areas at the buildings, which may possibly affect the occupants' comfort especially during the nighttime. The table below summarises the findings on the risk of overheating using the static (CIBSE) and the adaptive (BSEN15251) comfort criteria and the spaces where extreme summertime overheating was observed are highlighted.

Table 3: Summary of the findings on the risk of overheating criteria of the monitored temperatures at the buildings

Name of space-location	Description	Total no of monitored hours	CIBSE: no of hours above 25°C	CIBSE: % of hours above 25°C	CIBSE: no of hours above 28°C	CIBSE: % of hours above 28°C	BSEN15251: no of hours above the Cat. II upper	BSEN15251: % of hours above the Cat. II upper
A1WLGFL-OX	Living area	166	35	21.10%	15	9.00%	15	9.00%
A38MLGFL-OX	Living area	263	39	14.80%	4	1.50%	3	1.10%
A142HAGFL-OX	Living area	263	32	12.20%	3	1.10%	6	2.30%
A162HAGFL-OX	Living area	263	65	24.70%	0	0	2	0.80%
FL1GFL-BD	Living area	316	1	0.30%	0	0	0	0
FL35SFL-BD	Living area	316	2	0.6	0	0	0	0
Name of space-location	**Type of space**	**Total no of monitored hours**	**CIBSE: no of hours above 24°C**	**CIBSE: % of hours above 24°C**	**CIBSE: no of hours above 26°C**	**CIBSE: % of hours above 26°C**	**BSEN15251: no of hours above the Cat. II upper**	**BSEN15251: % of hours above the Cat II upper**
A1WLFFFB-OX	Bedroom	263	118	44.90%	45	17.10%	18	6.80%
A6MLSFBB-OX	Bedroom	263	163	62.00%	62	23.60%	33	12.60%
A38MLFFFB-OX	Bedroom	263	147	55.90%	61	23.20%	34	13.00%
A38MLFFBB-OX	Bedroom	166	89	53.60%	32	19.20%	16	9.60%
A142HASFBB-OX	Bedroom	263	95	36.10%	42	16.00%	18	6.80%
A162HAFFBB-OX	Bedroom	166	122	73.50%	78	47.00%	37	22.20%
FL1FFB-BD	Bedroom	316	30	9.50%	0	0	0	0
FL7FFFB-BD	Bedroom	316	0	0	0	0	0	0
FL8FFSB-BD	Bedroom	316	0	0	0	0	0	0

*Location of the logger in the spaces: A1WLGFL-southwest facing, A1WLFFFB- southeast facing, A6MLSFFB- northwest facing, A38MLGFL- northeast facing, A38MLFFFB- southeast facing, A38MLFFBB- northeast facing, A142HAGFL- southwest facing, A142HASFBB- southeast facing, A162HAGFL- north facing, A162HAFFBB- southeast facing, FL1GFL- south facing, FL1FFB- southwest facing, FL7FFFB- east facing, FL35SFL west facing, FL8FFSB- north facing

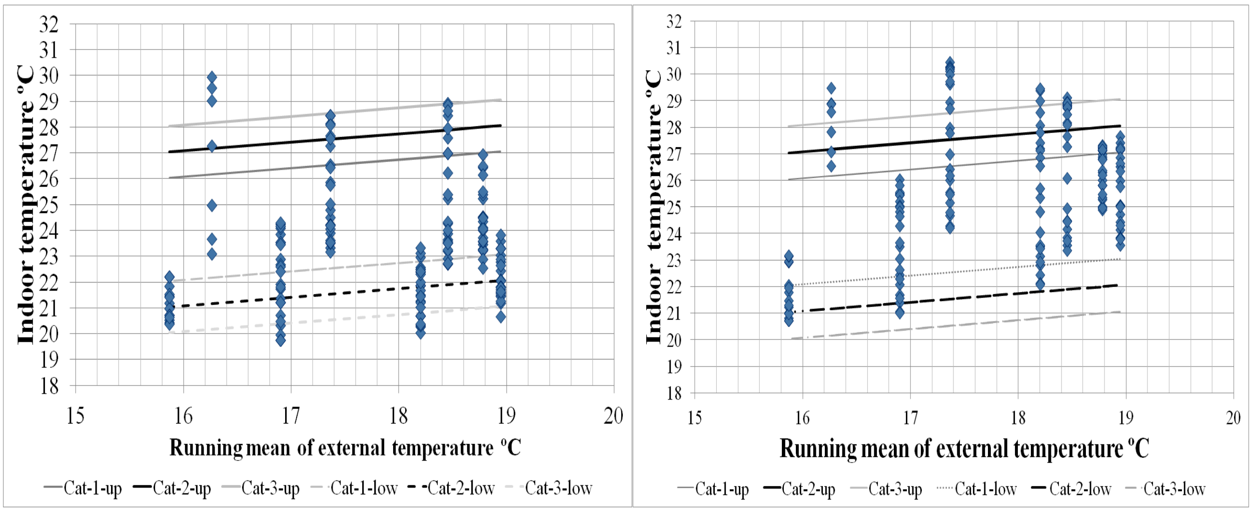

Figure 2: Indoor temperatures in A1WLGFL-OX (left) and A162HAFFBB-OX (right) at Oxley Woods compared to the BSEN15251 category boundaries.

5 Dynamic thermal simulations and calibration

For the simulations, assumptions regarding the infiltration rate, general lighting, task and display lighting were calculated from CIBSE (2006, 2010), operating free-running in summer, no assumptions regarding temperature set-points were made on mechanical cooling and heating of the spaces. The weather data files for the 2000s (Test Reference Year- TRY) were employed.

The infiltration rate was assumed at 0.12ach for Bridport (CLT panels) and at 0.15ach for Oxley Woods (SIPs). The outside air change (ach) rate for internal spaces in two storey dwellings with cross ventilation is recommended not to exceed 8ach (DECC, 2009). Dwellings with spaces that have no cross ventilation should not exceed 5ach (DECC, 2009; DesignBuilder 2009). The outside air change rate was assumed at 4.0ac/h for Oxley Woods and at 5.0ac/h for Bridport due to the additional floor area of spaces, larger size of windows and higher floor-to-ceiling heights at the latter.

For the calibration, preference was set on the rooms that provided a close range and similar pattern between the monitored and calculated temperatures over 26°C and 28°C, the CIBSE point of references for evaluating internal temperature of bedrooms and living rooms respectively (CIBSE 2006). All the spaces monitored at Oxley Woods and three of the spaces (FL1GFL-BD, FL1FFB-BD, FL7FFFB-BD) at Bridport were thus considered. The calibration was done using the two weather data files (London Islington TRY and St Albans TRY) for comparison and due to the proximity of the weather stations to the case study buildings.

The buildings were modelled with the DesignBuilder simulation software (version 3.2.1), based on the architects' drawings. Forecast regarding window opening actions of occupants during night-time are crucial and cannot be easily made (Lomas and Giridharan, 2012). However, priority must be given to reliable results with precise window opening actions that produce a similar pattern of results with measured data (Strachan, 2008). The window opening during night-time was modelled in accordance with the results obtained from the accelerators (state loggers) used to monitor windows' open and close sessions.

Since the models were set as free-running, the calculated internal temperatures were mainly influenced by window opening sessions and fabric of the houses. The calibration of the simulated and monitored temperatures showed the peak temperatures align with the data recorded during the monitoring. The differences between the maximum simulated and the monitored temperatures were usually within a range of 2ºC as mentioned by Lomas and Giridharan (2012) for most part of the calculated data to be considered credible (Lomas et al., 1997). The findings from the values obtained during calibration of calculated data and monitored data revealed a high degree of alignment between the simulated data and the monitored data for the average daytime and nighttime temperature in the living areas, the average nighttime temperature in the bedrooms, as well as the number of hours that exceeded the CIBSE point of reference (28ºC) within the internal spaces.

6 Simulation of the buildings' performance

The running mean temperature of the simulated outdoor temperature, T_{rm} of the weather files, as recommended in BSEN15251 (BSI, 2008) reached 20.4ºC on 15th August for London Islington TRY and 18.4ºC on 28th July for St Albans TRY. The average running mean temperature was 15.6ºC for London Islington TRY and predicted at 14.1ºC for St Albans TRY. The two weather files considered for this study were cooler when compared to the average running mean temperature observed during the monitoring periods at Bridport (17.5ºC) and Oxley Woods (16.8ºC) in the summer. Table 4 summarises the features of London Islington and St Albans TRYs for the current year conditions.

Table 4: Description of London and St Albans TRYs temperature for the current year (May-September)

2000s TRY	No of hours >25ºC	No of hours >28ºC	Max. temp. (ºC)	Min. temp. (ºC)	Mean temp. (ºC)	Max. running mean (ºC)	Min. running mean (ºC)
London Islington	62	4	28.4	2.5	15.6	20.4	8.7
St Albans	84	2	28.3	1.0	14.1	18.4	6.7

* The TRY external temperature for the 2000s is derived from the weather generator produced by the Prometheus Group (UKCP09)

The simulated mean temperature in the living areas at Bridport was 20.7ºC and 22.2ºC in the bedrooms for London Islington TRY while mean temperatures of 19.7ºC and 21.8ºC predicted in the living areas and the bedrooms respectively at Bridport for St Albans TRY. At Oxley Woods, the mean temperature of 20.8ºC was predicted in the living areas and 21.4ºC in the bedrooms for London Islington TRY. At Oxley Woods, the predicted mean temperature in the living areas was 20.1ºC and 20.7ºC in the bedrooms for St Albans TRY. The analysis showed the bedrooms are predicted to be warmer than the living areas at the buildings. Moreover, the spaces at Oxley Woods are predicted to be warmer than the spaces at Bridport.

The predicted mean temperature in the hottest living area (FL35SFL-BD) at Bridport reached 19.2ºC with a maximum temperature of 28.3ºC and a minimum temperature of 12.9ºC for London Islington. For St Albans, the simulated mean temperature in FL35SFL-BD reached 17.8ºC, a maximum of 28.4ºC and a minimum of 13.3ºC were predicted. At Oxley Woods, the predicted average temperature in A142HAGFL-OW (the hottest living area) was 22.0ºC with a maximum of 29.8ºC and a minimum of 19.5ºC for London Islington. The mean temperature of 21.4ºC, a peak of 28.6ºC and a minimum of 19.4ºC were calculated in A142HAGFL-OW for St Albans. An average temperature of 21.8ºC was predicted in the hottest bedroom (FL1FFB-BD) at Bridport while a maximum temperature of 30.4ºC and minimum temperature of 18.7ºC were simulated for London Islington. The peak temperature of 28.9ºC and a low of

17.7ºC and mean temperature of 21.4ºC were predicted for St Albans. At Oxley Woods, the mean temperature of 22.2ºC, a maximum of 31.4ºC and a minimum of 17.2ºC were expected in A142HASFBB-OW (the predicted warmest bedroom) for London Islington TRY. Likewise, a peak temperature of 31.1ºC, a minimum of 16.1ºC and the average of 21.6ºC were calculated in A142HASFBB-OW for St Albans TRY. Overall, the analysis showed lower temperatures were predicted in the living rooms and the bedrooms at Bridport than Oxley Woods. The table below summarises the predicted mean, maximum and minimum temperatures at the buildings.

Table 5: Description of the summary data from the simulations

Space-location	**Predicted mean indoor temp (ºC)**		**Predicted max. indoor temp (ºC)**		**Predicted min. indoor temp (ºC)**	
	LI-TRY	**SA-TRY**	**LI-TRY**	**SA-TRY**	**LI-TRY**	**SA-TRY**
FL1GFL-BD	18.6	20.6	26.8	26.7	14.8	15.3
FL1FFB-BD	21.8	21.4	30.4	28.9	18.7	17.7
FL7FFFB-BD	21.6	21.3	27.5	27.3	20.1	19.4
FL8FFSB-BD	20.8	20.5	27.2	27.0	19.8	18.7
FL35SFL-BD	19.2	17.8	28.3	28.4	12.9	13.3
A1WLGFL-OW	20.5	19.7	27.1	25.7	14.9	15.0
A1WLFFFB-OW	21.5	20.8	29.8	29.6	16.0	15.0
A6MLSFBB-OW	20.8	20.1	28.7	28.4	16.7	15.6
A38MLGFL-OW	20.2	19.4	27.3	25.9	15.0	15.1
A38MLFFFB-OW	21.8	21.1	30.6	30.4	16.3	15.2
A38MLFFBB-OW	20.9	20.2	28.9	28.5	16.1	15.0
A142HAGFL-OW	22.0	21.4	29.8	28.6	19.5	19.4
A142HASFBB-OW	22.2	21.6	31.4	31.1	17.2	16.1
A162HAGFL-OW	20.6	19.8	28.2	27.0	15.1	15.4
A162HAFFBB-OW	21.4	20.8	29.6	29.3	16.3	15.1

*LI-TRY= London Islington TRY, SA-TRY= St Albans TRY

Analysis revealed strong correlation exists between the simulated indoor and external temperatures in the living areas and bedrooms with higher level of relationships predicted in the living areas at the buildings (Figures 3-4). The predicted temperatures in the living areas and bedrooms at Oxley Woods are within a closer range than the predicted temperatures in the spaces at Bridport. However, the internal temperatures are predicted to be higher in the living areas than the bedrooms at Bridport when external temperatures rise above 22ºC which was not observed during the monitoring. With the cross over between the two lines observed at Bridport (Fig. 3), occupants are likely to experience higher internal temperatures in the living areas than the bedrooms during the hot summertime. On the contrary (Fig. 4), occupants at Oxley Woods are likely to experience the same range of internal temperatures in the living areas and the bedrooms during the same period.

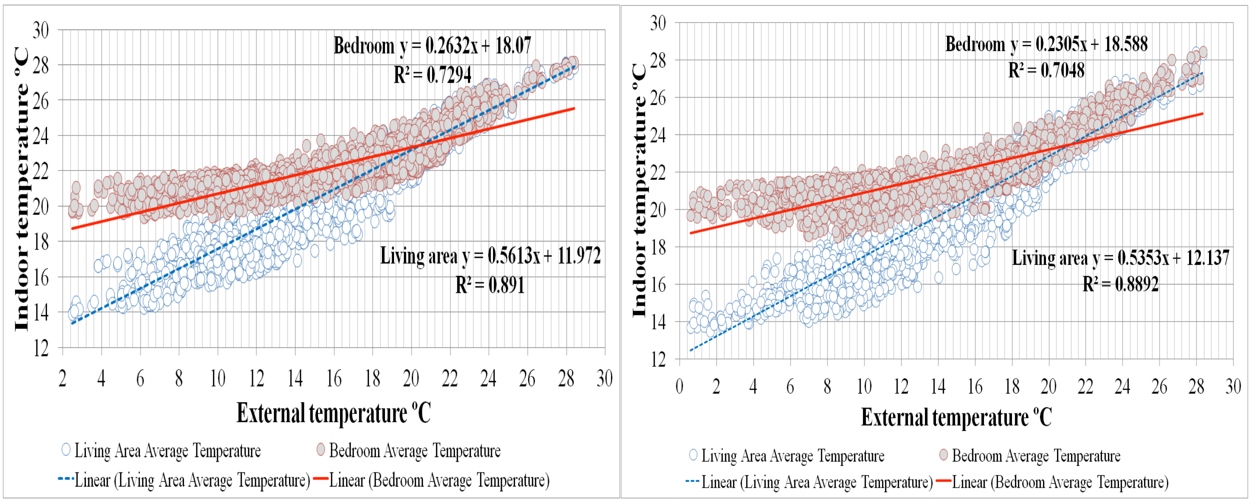

Figure 3: Relationship between the predicted mean temperatures in the living areas and the bedrooms at Bridport and the external temperatures London Islington (left) and St Albans TRYs (right)

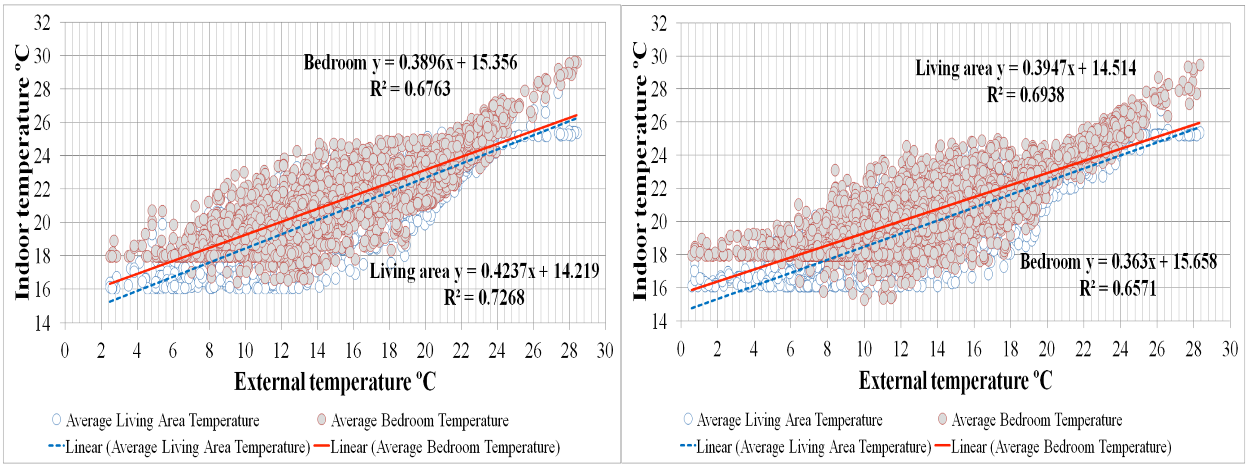

Figure 4: Relationship between the predicted mean temperatures in the living areas and the bedrooms at Oxley Woods and the external temperatures London Islington (left) and St Albans TRYs (right)

7 Overheating analysis of the predicted current performance

Analysis of the simulations using the CIBSE thermal comfort model at the buildings showed the total hours of the predicted temperatures exceeded 5%>25°C in 1 of the living areas (17%) considered and exceeded 1%>28°C in 1 of the spaces (17%). The predicted temperatures exceeded 5%>24°C in 1 of the bedrooms (11%) and 1%>26°C in 2 of the spaces (22%). For the BSEN15251 thermal comfort model, the analysis showed the temperatures exceeded the Category II upper limit for over 5% of the total predicted hours in none of the living areas and in just 1 of the bedrooms (11%). Figures 5 and 6 show the predicted temperature in A142HAGFL-OW and A142HASFBB-OW (the predicted warmest living area and bedroom respectively) compared to the BSEN15251 Category II limits. The findings showed extreme summertime overheating is not predicted in the spaces as observed during the monitoring. The table below summarises the findings on the risk of overheating using the CIBSE and the adaptive comfort criteria.

Table 6: Summary of the findings on the risk of overheating criteria for the monitored and the predicted temperatures at the buildings

Name of space-location	CIBSE: no and % of monitored hours above 25°C	CIBSE: no and % of predicted hours above 25°C		CIBSE: no and % of monitored hours above 28°C	CIBSE: no and % of predicted hours above 28°C		BSEN15251: no and % of monitored hours above the Cat. II upper	BSEN15251: no and % of predicted hours above the Cat. II upper	
		LI	SA		LI	SA		LI	SA
A1WLGFL-OX	35 (21.1%)	155 (4.2%)	138 (3.8%)	15 (9.0%)	0 (0%)	0 (0%)	15 (9.0%)	4 (0.1%)	0 (0%)
A38MLGFL-OX	39 (14.8%)	75 (2.0%)	61 (1.7%)	4 (1.5%)	0 (0%)	0 (0%)	3 (1.1%)	0 (0%)	0 (0%)
A142HAGFL-OX	32 (12.2%)	394 (10.7%)	266 (7.2%)	3 (1.1%)	28 (1%)	8 (0.2%)	6 (2.3%)	48 (1.3%)	34 (1%)
A162HAGFL-OX	65 (24.7%)	152 (4.1%)	121 (3.3%)	0 (0%)	1 (0.03%)	0 (0%)	2 (0.8%)	2 (0.05%)	1 (0.03%)
FL1GFL-BD	1 (0.3%)	92 (2.5%)	83 (2.3%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
FL35SFL-BD	2 (0.6%)	118 (3.2%)	92 (2.5%)	0 (0%)	5 (0.1%)	2 (0.05%)	0 (0%)	6 (0.2%)	8 (0.2%)
Name of space-location	**CIBSE: no and % of monitored hours above 24°C**	**CIBSE: no and % of predicted hours above 24°C**		**CIBSE: no and % of monitored hours above 26°C**	**CIBSE: no and % of predicted hours above 26°C**		**BSEN15251: no and % of monitored hours above the Cat. II upper**	**BSEN15251: no and % of predicted hours above the Cat II upper**	
		LI	**SA**		**LI**	**SA**		**LI**	**SA**
A1WLFFFB-OX	118 (44.9%)	129 (3.5%)	69 (1.9%)	45 (17.1%	20 (0.5%)	18 (0.4%)	18 (6.8%)	18 (0.5%)	36 (1.0%)
A6MLSFBB-OX	163 (62%)	29 (0.8%)	12 (0.3%)	62 (23.6%)	6 (0.2%)	2 (0.1%)	33 (12.6%)	6 (0.2%)	12 (0.3%)
A38MLFFFB-OX	147 (55.9%)	100 (2.7%)	56 (1.5%)	61 (23.2%)	68 (1.9%)	54 (1.5%)	34 (12.0%)	93 (2.5%)	91 (2.4%)
A38MLFFBB-OX	89 (53.6%)	66 (1.8%)	40 (1.1%)	32 (19.2%)	7 (0.2%)	3 (0.1%)	16 (9.6%)	6 (0.2%)	13 (0.3%)
A142HASFBB-OX	95 (36.1%)	219 (6.0%)	153 (4.2%)	42 (16.0%)	172 (4.7%)	127 (3.5%)	18 (6.8%)	197 (5.4%)	173 (4.7%)
A162HAFFBB-OX	122 (73.5%)	108 (2.9%)	61 (1.7%)	78 (47.0%)	30 (0.8%)	14 (0.3%)	37 (22.2%)	37 (1.0%)	53 (1.4%)
FL1FFB-BD	30 (9.5%)	2 (0.05%)	0 (0%	0 (0%)	19 (0.5%)	13 (0.3%)	0 (0%)	38 (1.0%)	48 (1.3%)
FL7FFFB-BD	0 (0%)	4 (0.1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	3 (0.1%)
FL8FFSB-BD	0 (0%)	2 (0.05%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

*Total number of the simulated hours- 3672. LI- London Islington TRY, SA- St Albans TRY. Monitored hours in the spaces as follow: 166 hours (A1WLGFL-OX, A38MLFFBB-OX, A162HAFFBB-OX); 263 hours (A38MLGFL-OX, A142HAGFL-OX, A162HAGFL-OX, A1WLFFFB-OX, A6MLSFBB-OX, A38MLFFFB-OX, A142HASFBB-OX); 316 hours (FL1GFL-BD, FL35SFL-BD, FL1FFB-BD, FL7FFFB-BD, FL8FFSB-BD)

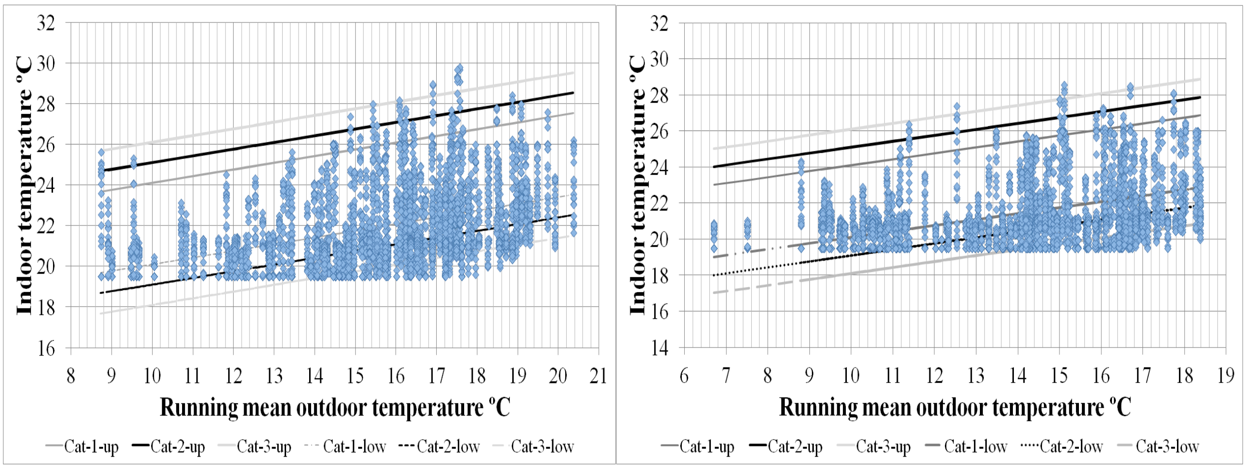

Figure 5: Calculated temperatures in A142HAGFL-OW suggesting warm and cold discomfort, compared to the BSEN15251 thresholds for London Islington (left) and St Albans TRYs (right)

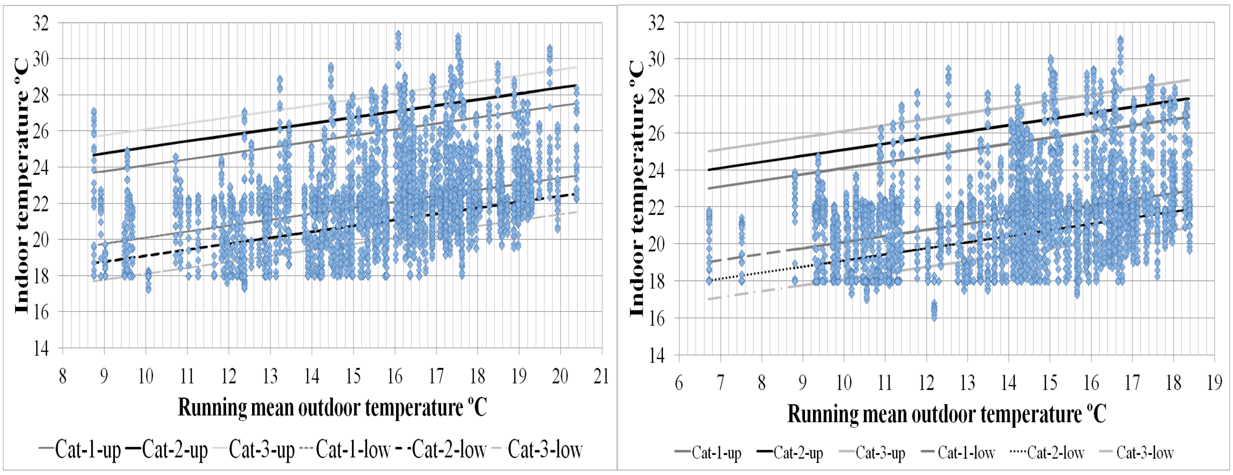

Figure 6: Calculated temperatures in A142HASFBB-OW suggesting warm and cold discomfort, compared to the BSEN15251 thresholds for London Islington (left) and St Albans TRYs (right)

Also, the analysis conducted on the buildings using the dynamic adaptive (BSEN15251) comfort criteria to evaluate the risk of overheating showed none of the buildings exceeded 5% of hours above the Category II upper threshold for London Islington and St Albans TRYs. However, the analysis suggests that all the buildings exceeded 5% of hours below the Category II lower marker for London Islington and St Albans. The analysis further suggests tendency of cold discomfort within the indoor spaces of prefabricated timber houses during summertime when the external temperature decreases. There is possibility of obtaining a different result if the TRYs weather files for future scenarios were considered which may predict occupants are likely to experience high summertime temperatures as observed in the monitoring results. However, the overall analysis showed the occupants of energy-efficient houses need to take further adaptive measures to reduce the hours of temperatures above the overheating criteria.

8 Conclusion and implications of the findings on future occupancy patterns

This paper discussed the thermal performance of prefabricated timber houses in summertime. The finding from the environmental monitoring showed extreme summertime overheating was observed in the spaces monitored at Oxley Woods and Bridport while the predicted temperatures using the two weather files (London Islington and St Albans TRYs) did not suggest extreme summertime overheating. Throughout the survey period (June-July, 2012), the monitored temperatures exceeded the CIBSE thermal comfort model of 1%>28ºC in 3 of the living areas (50%) and exceeded 1%>26ºC in 6 of the bedrooms (67%) at the case study buildings. The findings showed the bedrooms are warmer than the living areas as highlighted in Adekunle and Nikolopoulou (2014), which may affect the occupants' comfort especially at nighttime. Therefore, future design needs to consider how high summertime temperatures can be reduced in the spaces while occupants need to take further adaptive behavioural actions to improve the overall thermal environment of dwellings. For the simulations in summer (i.e, from May-September), the predicted temperatures exceeded the 1%>28ºC in 1 of the living areas (17%) and exceeded the 1%>26ºC in 2 of the bedrooms (22%). The results showed possibility of summertime overheating considering the current performance of prefabricated timber houses and potential of extended high summertime temperatures.

In addition, the findings revealed the occupants are more likely to be affected by summertime overheating in bedrooms than the living areas. The outcomes (i.e, bedrooms being warmer than living rooms) are likely to influence occupancy patterns and numbers of hours spend in bedrooms in future. The findings imply possibility of increase and frequent in use of controls such as opening of windows, fans and other cooling devices in bedrooms than living rooms in future especially during summertime. The results also imply possibility of frequent intake of cold drinks and difference in clothing put on (clo-value) by occupants in bedrooms when compared to occupants in living areas to minimise the impact of summertime overheating as bedrooms get warmer than living areas in different houses. The findings also showed occupants are likely adapt to higher temperatures in bedrooms than living rooms in future.

The analysis of the spaces using the BSEN15251 adaptive thermal comfort category limits showed the total hours of the monitored temperatures exceeded 5% of hours above the Category II upper limit in 1 of the living areas (17%) and exceeded the indicator in 6 of the bedrooms (67%) at the buildings. The outcome further showed high summertime temperatures were recorded in the bedrooms than the living areas which indicated warm discomfort of the occupants in summertime. The simulations showed the temperatures are predicted to exceed 5% of hours above the Category II upper limit in just 1 of the bedrooms (11%) while none of the living areas is predicted to exceed the indicator. The findings showed potential of higher temperatures observed in the bedrooms than the living areas.

The findings from this study indicated summertime temperatures are likely to occur in prefabricated houses. The monitored results showed extreme summertime overheating occurs in the buildings investigated and provided a better understanding on the thermal performance of the indoor spaces in summertime. On the contrary, the simulated results only provided an understanding that the buildings are prone to summertime overheating without indicating that extreme summertime overheating occurs in the buildings, which may not provide adequate information to designers. The simulated results can also mislead designers and researchers to investigate necessary adaptive actions various to reduce the impact of summertime overheating in order to improve occupants' comfort during summertime. However, the findings presented in this study by comparing the monitored with the simulated results will help designers in future to consider necessary design interventions at the design stage in reducing the impact of summertime overheating in prefabricated timber houses. This is important as the study revealed possibility of a gap between the actual and the predicted thermal performance of prefabricated timber buildings in summer. Overall, the monitored results revealed overheating occurs, especially at Oxley Woods while the simulations did not suggest extreme overheating, which demonstrates that monitoring provides a more reliable dataset for assessing the thermal performance of buildings. Finally, although occupants take further adaptive measures to improve their thermal conditions reducing the impact of overheating, the lack of thermal mass in prefabricated timber developments increases the overheating risk, even in mild summer weather conditions.

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Mechanical Ventilation & Cooling Energy versus Thermal Comfort: A Study of Mixed Mode Office Building Performance in Abu Dhabi

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Abstract

In hot climates, office building ventilation and cooling dual operation can cause high energy consumption in order to maintain thermal comfort limits. Using mixed mode ventilation and cooling operation, incorporation of natural ventilation strategies can offer significant reductions in annual energy consumption. Natural ventilation operation can be used with an external air temperature ranging from 24 to 28°C. Within this paper, a literature on thermal comfort is completed to understand temperature limits for hot climates.

This work details theoretical model analysis of a simple mixed mode office building located in a hot climate, Abu Dhabi, United Arab Emirates. This is completed using dynamic thermal simulation. The aim of this work is to evaluate the impacts on mechanical ventilation and cooling energy when raising internal comfort temperatures beyond 24°C; to a maximum of 28°C. Time/temperature analysis is completed for different months of the year to ascertain when thermal comfort temperatures are exceeded and full mechanical operation is required. Results from this analysis show yearly ventilation and cooling energy savings ranging between 21-39% and demonstrate that higher mechanical cooling set point operations can be achieved when human occupants have access to openable windows.

Keywords: Natural Ventilation, Mixed Mode, Mechanical Cooling; Thermal Comfort, Openable Windows.

1 Introduction

In hot climates, excessive mechanical ventilation and cooling energy is a significant issue and considerable amounts of cooling is required during daytime periods to maintain indoor thermal comfort levels. In order to save energy, reduce carbon dioxide emissions and operational expenditure, alternative ventilation strategies and control methods should be adopted within the initial building design i.e. natural ventilation. Where office buildings are capable of mixed mode ventilation operation (CIBSE, 2000), thermal comfort set points can be increased to allow internal spaces to become warmer, hence reduce operation of mechanical services plant. This issue identified is thermal comfort parameters are compromised (CIBSE, 1999) i.e. exceed 22-25°C range. This paper provides an analytical assessment method to assess how mechanical ventilation and cooling energy can be reduced by increasing the internal thermal comfort set point temperature in a hot climate, Abu Dhabi, UAE. Using a theoretical office building model and Dynamic Thermal Simulations (DTS) tool, impacts of external supply air temperature are completed using time/temperature curve analysis. Percentage energy consumption can be predicted for natural ventilation operation (per year) and compared against base case model i.e. full time operation. The aim of this work is to understand maximum potential mechanical ventilation and cooling energy savings and discuss the impacts on office thermal comfort (adaptive), as defined by Brager & De Dear (2000).

The aim is realised by the following four objectives:

- Literature review of maximum tolerable temperatures for neutral thermal comfort.
- Develop an theoretical office building base case thermal model using dynamic thermal modelling software located in a Abu Dhabi and calculate cooling energy per month
- Using daily time/temperature analysis, determine natural ventilation and mechanical ventilation/cooling systems operation times
- Calculate potential percentage energy reductions for each set point temperature

2 Literature Review

As humans regularly adapt to their environment (Physiological, Behavioural and Psychological), a wider range of temperatures are more tolerable in naturally ventilated building (Brager & De Dear, 2000). The ability to open windows allows individuals to have control of their environment hence allow higher internal temperatures. Individual's tolerance is largely dependent on level of clo as analysed by Krzysztof & De Dear (2001) where individuals reported on thermal neutrality at 23.3°C. A literature review completed by Brager & De Dear (1998) highlighted that a study completed in Hong Kong suggests that individuals achieved thermal neutrality at 24.9°C. Furthermore a study completed by Humpreys discovered that depending where located in the world, tolerable thermal comfort temperatures can be 28.7°C (Malay Peninsular) and 25.7°C in London (Brager & De Dear, 1998). This builds a case for increasing the mechanical system set point temperature beyond recommended thermal conditions (CIBSE, 2015) hence increasing the mechanical ventilation and cooling set points to a higher value.

For control of an indoor environments, Iftikhar et al (2001) discovered that the most important factor was openable windows with drawn or half drawn blinds. This study shown extensive use of windows when internal temperature exceeds 20°C with 100% windows open at 27°C. Furthermore, De Dear & Brager (2002) define building scope for naturally ventilated space cooling as openable windows should be ease and access as primary means of thermos-regulation and cannot have a mechanical cooling systems.

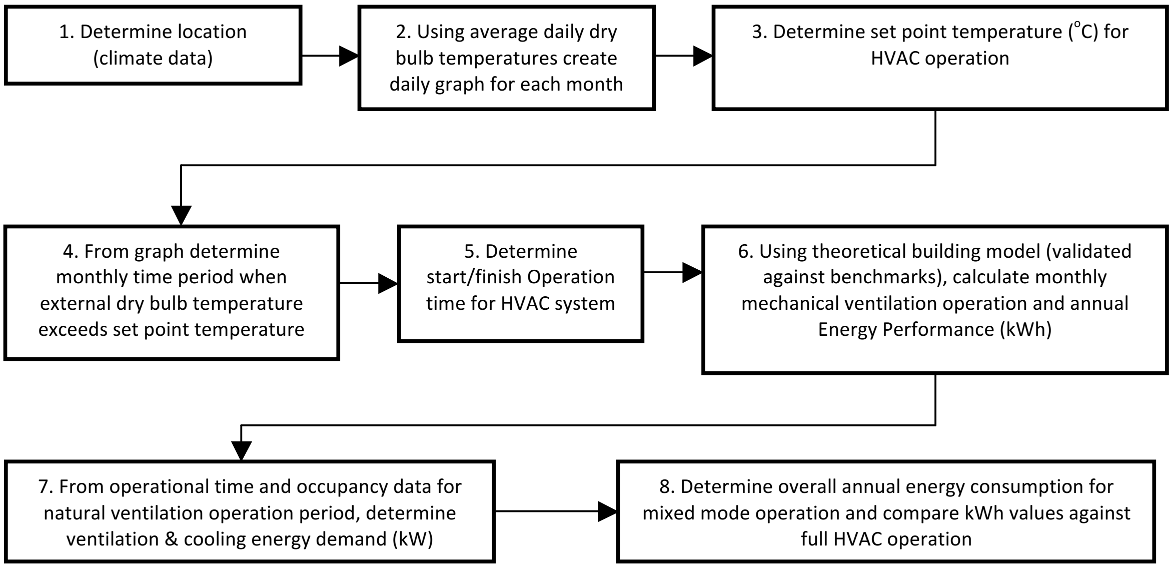
Guidance is also set out in British Standard (2005) when attempting to calculate PMV vs PPD however the calculated percentage dissatisfied may be higher than actual hence adaptive approach is better suited to this study.

3 Methodology

3.1 Mixed Mode Operation Performance Assessment

This section review the impacts of increasing HVAC set point be increasing thermal comfort level from 24°C to 28°C. For each temperature the time period is taken from the graph and converted into energy for each month assuming 100 percent fresh air for both modes of operation. This method of performance assessment is shown in Figure 1 below.

Figure 1. Mixed Mode Performance Assessment Methodology Flow Diagram



This flow diagram has been created to develop a new approach for assessing natural ventilation effects on reducing HVAC performance by calculating time external dry bulb air temperature exceeds HVAC set point. The time periods will determine HVAC times of operation between each mode. The amount of energy saved by varying set points can be used to calculated ventilation and cooling energy consumption. To calculate total time save, the following correlation applies:

$$QV_{(t)} = MV_{(t)} - NV_{(t)} \tag{Eq. 1}$$

Where; $QV_{(t)}$ is total time reduction available at a given time period, $MV_{(t)}$ is full time operational time of mechanical ventilation system in hours and $NV_{(t)}$ is operational time of natural ventilation in hours.

The building ventilation strategy is mixed mode where base case HVAC operation temperature is set when internal air temperature exceeds 24°C using 100 percent fresh air delivery for both modes. HVAC operational time is detailed below in Table 1.

Table 1. Office Operational Hours

Hours of Office	Pre-cool Period	Office Closing	Total office Hours for Day
Start (Time)	Time (Hours)	Start (Time)	Time (Hours)
0800	1	1800	11

3.2 Theoretical Building Model

A theoretical commercial building model was created and dynamic thermal simulations were completed to calculate room cooling load (kW) over a yearly period. The building is single height open office plan (theoretical model) has been created 20m (L) x 10 (W) x 3m (H) with a flat roof. Figure 2 shows graphic of building.

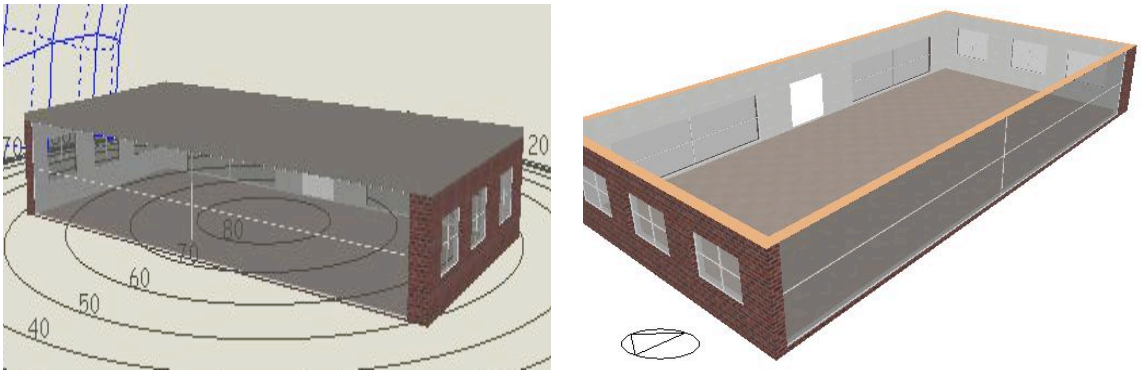


Figure 2. South View of Office Building & South South West View of Office Building illustrating interior (Graphic)

The south façade consists of a full height window 3m (H) x 19m (W). The East and West walls contain 3No. 2m (W) x 1.5m (h) and North wall contains double doors which are 2m (H) x 1.9m (W) and 2No. windows 6m (W) x 2m (H). The graphic generated by the software is shown in figure 2 below which shows the South facade view. Figure 3 indicate the building without the flat roof show highlighting the interior. The test building is based upon a generic building design identified by 1 North Bank, Sheffield, Yorkshire (e-architect, 2014). The metrics used (SI Units) in this analysis are mechanical cooling input energy consumption (kWh), sensible cooling load (kW) and Latent Heat Gains (kW). Sensible and latent heat gains are combined to determine annual mechanical cooling energy. For building parameters, see Table 2 below.

Table 2. Building Parameters

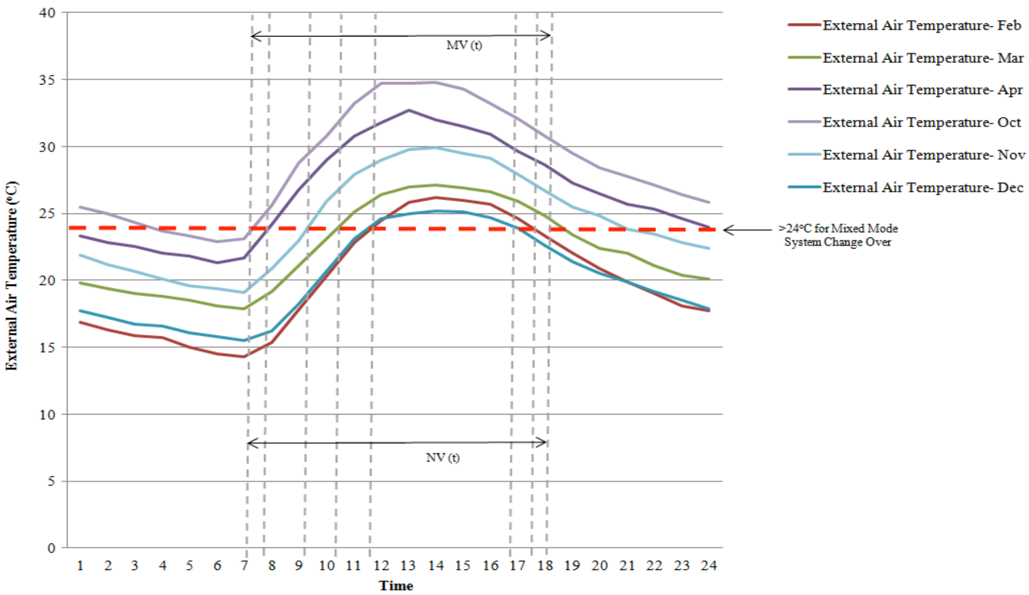
Type	Description
External Walls	Brickwork, Outer Leaf (105mm), XPS Extruded Polystyrene (118mm), Medium Concrete Block (100mm) & Gypsum Plastering - U value of 0.25W/m^2 K
Roof (Flat)	Asphalt (10mm), MW Glass Wool (200mm), Air Gap (200mm), Plasterboard 13mm- U Value of 0.186W/m^2 K
Floor	Urea Formaldehyde Foam (200mm), Cast Concrete (100mm), Floor Screed (70mm) & Timber Flooring (30mm) - U Value of 0.176 W/m^2 K
Glazing	Pilkington North America Solar-E Arctic Blue (7.9mm), 12mm Argon Filled Gap & Pilkington North America Eclipse Advantage Clear (5.91mm)- U Value of 1.685W/m^2 K
Doors	Metal Framed Doors with Infill to match glazing- Pilkington North America Solar-E Artic Blue (7.9mm), 12mm Argon Filled Gap & Pilkington North America Eclipse Advantage Clear- U Value of 1.685W/m^2 K
Air Permeability	0.25 Air Changes Per Hour
Ventilation	Normal Operation (Base Case)- 10 litres/second per person Supply Air condition 12°C Supply Air Humidity Ratio (g/g)- 0.08 Vents for Natural Ventilation- Large Grille (Dark Slates)- 0.5 Co-efficient of Discharge
Indoor Environmental Conditions (Summer Time Cooling)	Nominal Cooling-24°C Cooling Set Back- 26°C
Internal heat gains are based on occupancy and lighting heat gains only	Lighting – 12W/m^2 Occupancy Density- 10m^2/Person Activity- Light Office Work/Standing/Walking Computers 25W/m^2 Other Equipment- 0W/m^2 (Non Selected)
Mechanical Cooling Fuel Source	Electrical

The building is simulated using Design builder software version 3.0.0.105 incorporating DB Sim v1.0.2.1 as this enables dynamic thermal building simulations for mechanical cooling loads and input energy required for the cooling system operation over monthly and a yearly period. Climate data used is Design Summer Year (DSY) data within DesignBuilder. The building location selected is Abu Dhabi, UAE, as this provides one global extreme of a hot climate. A solution algorithm of finite differencing and adaptive convection algorithms are used for interior convection including McAdams algorithm used for exterior convection. Within the simulation air velocities for comfort are 0.1370 m/s.

4 Time/Temperature Analysis

Natural ventilation mode is in operation when external air temperature is less than the internal space set point temperature. Where external air temperature exceeds the set point temperature (24-28^{o}C), mechanical ventilation/cooling mode is in full operation. For example, actuation conditions of natural ventilation where external dry bulb temperature does not exceed internal set point temperature (T_o<SP). Once the set point temperature is exceeded, HVAC operation (T_o>SP) will activate. For mixed mode operation, energy consumption is revised accordingly as mixed mode system time periods change hourly hence operation and automatically adjusted accordingly via building energy management system (BEMS). The important factor is to determine the operational times for both modes of operation, which are mechanical ventilation operational time ($MV_{(t)}$) and natural ventilation activation time ($NV_{(t)}$).

Figure 3. Average Daily Dry Bulb Temperatures >24^{o}C During Occupied Hours



To calculate the effects of timed operation of mechanical plant, time/temperature graphs are generated for hottest day in each month, see Figure 3 below. The plots show maximum average dry bulb temperature experienced using weather data from DesignBuilder software. A horizontal line is added for each set point temperature and time is identified on the graphs intersect point within the curve, start and finish points. $NV_{(t)}$ is identified below the horizontal set point line and $MV_{(t)}$ is above. The graph also detail where external air temperature for February, March, April, October, November and December exceeds internal set point temperature. From the calculations for January, theoretically the set point is not exceeded therefore HVAC operation would not be required, however this may not be the case in practice. For months that temperatures that clearly exceeds 24^oC, full time HVAC operation is required.

The occupied office time period for natural ventilation operation (NV $_{(t)}$) and mechanical HVAC operation (MV$_{(t)}$) is taken from the graph (Figure 3) and revises base case HVAC energy consumption calculating total kilowatt hours per month, using corrected times detailed in Table 3. Normal HVAC operation for the base case is 11 hours per day (MV$_{(t)BC}$).

Table 3. Time Period for External Air Temperature Exceeding 24^oC

Month	MV (t) Start	MV (t) Stop	Time Difference (Hours)	Occupied Hours (Converted)		Available Working Days For Month (Mon - Fri)
				MV (t)-Time	NV (t)-Time	
February	11:30:00	17:00:00	05:30:00	5.5	5.5	20
March	10:15:00	18:00:00	07:45:00	7.75	3.25	20
April	07:45:00	18:00:00	10:15:00	10.25	0.75	22
October	07:00:00	18:00:00	11:00:00	11	0	23
November	09:10:00	18:00:00	08:50:00	8.87	2.13	20
December	11:30:00	17:00:00	05:30:00	5.5	5.5	17

This method was applied for the remaining set point temperatures 25^oC, 26^oC, 27^oC and 28^oC. As the external air temperature increases natural ventilation operational time decreases; indirectly proportional.

5 Results

Using base case mechanical ventilation and cooling energy results, Figures 4 and 5 below shows energy performance values for mechanical fan energy/cooling energy of each external set point temperature base on the hours of natural ventilation operation (NV$_{(t)}$) deducted from mechanical ventilation operation base case model (MV$_{(t)}$). As shown from monthly energy profiles, increasing internal thermal comfort set point temperature has a significant impacts on reducing mechanical ventilation and cooling energy from February to April and October to December in Abu Dhabi. The graph also shows in all cases full mechanical ventilation is required for May to September.

Figure 4. Mechanical Ventilation Energy Reduction (Mixed Mode) for Mechanical Fan Energy

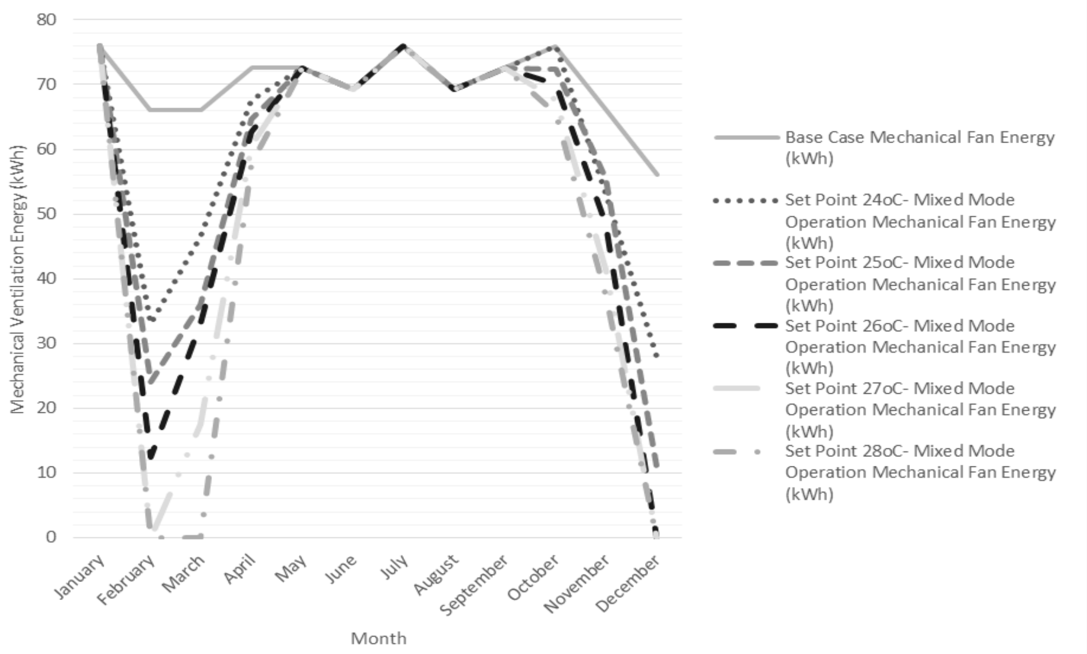


Figure 5. Mechanical Cooling Energy Reduction Using Mixed Mode Operation

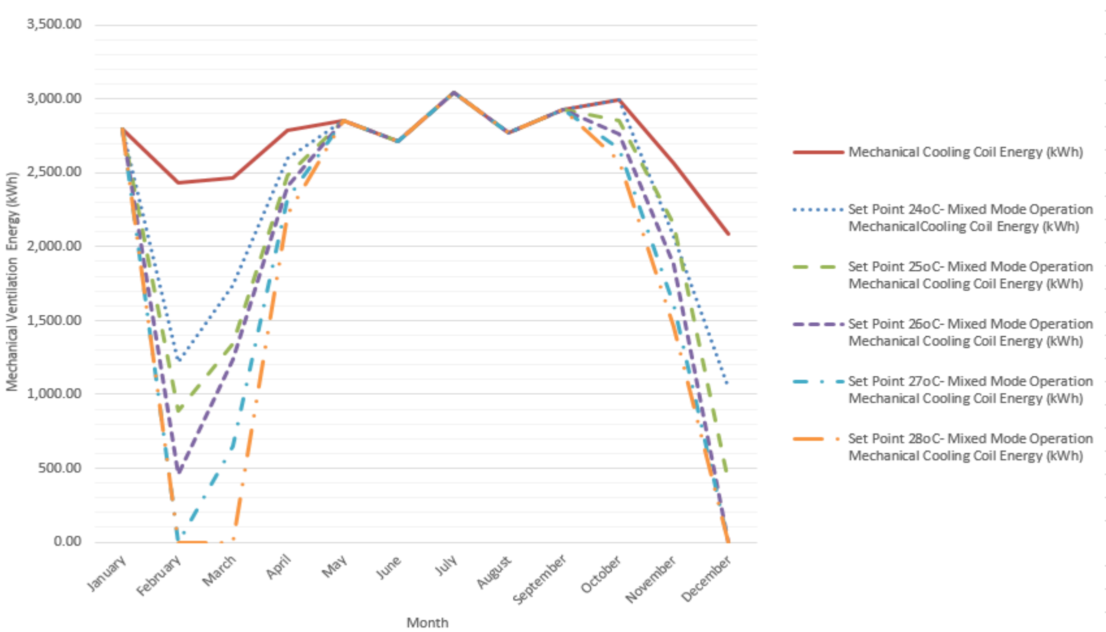


Table 4 below show calculated reductions that can be achieved. For Abu Dhabi climate, the greatest HVAC reductions for February and December by reducing the energy consumption by half.

Table 4. Percentage Reduction Using Mixed Mode Ventilation & Cooling at 24^{o}C Set Point

Month	Total Ventilation and Cooling Plant Energy (kWh) for Mechanical Operation (Base Case)	Total Ventilation and Cooling Plant Energy (kWh) for Mixed Mode Operation (Hybrid)	Percentage Reduction Using Mixed Mode Operation
February	2,501.68	1,250.84	50.00
March	2,529.73	1,782.31	29.55
April	2,857.82	2,662.97	6.82
November	2,628.45	2,119.48	19.36
December	2,144.19	1,072.10	50.00

From the results highlighted in Figures 4 and 5, annual energy reductions can be determined as an average percentage (Table 5 below). The percentages expressed show the total amount of mechanical ventilation and cooling energy that can be saved.

Table 5- Annual Energy Reduction when Adapting Mechanical Ventilation

Set Point Temperature

Month	Reduction (%) (SP<24°C)	Reduction (%) (SP<25°C)	Reduction (%) (SP<26°C)	Reduction (%) (SP<27°C)	Reduction (%) (SP<28°C)
% Reduction/Annum	21.31	26.72	31.57	36.53	39.77

The results show that adopting this method can achieve an energy reduction ranging from 21.31 to 39.77 percent.

5.1 Validation

The method of analysing natural ventilation and impacts of HVAC energy performance is completely unique in its approach. Validation proves somewhat difficult as many natural ventilation research conference papers, journal and books only review the performance of air flow, air temperature and heat gains. Inter-comparison of energy performance is difficult to empirically validate due to lack of readily available bias building HVAC performance data. This method of approximated time/temperature is a solid and fundamental approach that provides calculated effects of natural ventilation on mechanical ventilation and cooling energy performance and operation. From this analysis, calculated monthly values can be used and compared against an actual building BMS system (monitored outputs) and provide a benchmark how the building should be performing.

6 Discussion

The results show that during cooler climatic months greater energy savings can be achieved. In summer time periods, energy reduction is minimal or not achievable. There are significant savings available when adopting natural ventilation temperature/time methodology and can be easily implemented within a RIBA design process (RIBA, 2016) and new/existing BEMS. In hot climates, energy reductions are only achievable in cooler months of the year as summer months would be considered intolerable for both humans and office equipment i.e. computers, photocopiers, printers. Natural ventilation however is limited to office spaces as communications rooms need 24 hour mechanical ventilation and cooling strategies.

When attempting to assess mechanical ventilation & cooling energy versus thermal comfort, difficult arise as each individual has different thermal comfort levels based on age, gender and metabolic rate. For example, hypothetically higher set points such as 26°C may be suitable for 60% of occupants and improve energy reduction but the remaining 40% will be considerable dissatisfied with their environment, hence lowering by 1°C can possibly reduce dissatisfaction to lower percentages, toward 5% dissatisfied (British Standard, 2005).

7 Conclusion

This study provides a new approach to estimating mixed mode ventilation and cooling energy performance using time/temperature assessment methodology. The results from the method highlight the following:

- Time/Temperature assessments allow suitable energy predictions for mixed mode operation and provide suitable information for engineers at RIBA Stage 2 (Concept design) and stage 3 (Developed Design) (RIBA, 2014).
- Energy savings identified by time/temperature analysis (natural ventilation operational time deducted from mechanical ventilation operation) time range between 21.31-39.77%. By increasing internal temperature set point temperature annual energy savings are identified in these percentages. Savings are generally realised during cooler months of the year in Abu Dhabi.
- As determined by the literature review, higher set points can be applied provided the building has openable windows with clear access.

It is important to note that a constant higher temperature i.e. greater than 25^{o}C, will make the internal environment very uncomfortable for human occupation therefore the realistic values would a maximum set point temperature of 26^{o}C.

8 Further Works

Possible future research could be completed is as follows:

- Integrate method within dynamic thermal simulation software
- Develop BEMS algorithms to enable close temperature control by closely monitoring external air temperature and dry bulb temperature associated pattern (sinusoidal).
- Validate calculated percentages against real building operation in hot climate.
- Apply to existing building energy management systems (BEMS) and measure the level of discomfort and compare against energy savings.

Nomenclature

BEMS	Building Energy Management System
CIBSE	Chartered Institution of Building Services Engineers
DTS	Dynamic Thermal Simulation
HVAC	Heating Ventilation & Air Conditioning
PMV	Predicted Mean Vote
PPD	Percentage People Dissatisfied
$MV_{(t)}$	Mechanical Ventilation Operational Time
$NV_{(t)}$	Mechanical Ventilation Operational Time
$MV_{(t)BC}$	Base Case Mechanical Ventilation Operational Time
^{o}C	Degrees Celsius
kW	Kilowatt
kWh	Kilowatt-hour

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Thermal Responses of the Elderly in Summer Hot-Humid Climates

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Abstract

This paper investigates how the elderly in hot-humid latitudes respond to heat exposure and what adaptive action they take to be comfortable. Data was collected from 135 elderly people who live in Chiangmai, Thailand. They were interviewed in a semi-outdoor space about three thermal perceptions: sensation, preference and acceptability. The survey covered subjective responses to temperature, wind, solar radiation, relative humidity and sweating. The results show that 36°C is a 'comfortably warm' temperature as measured by the thermal comfort vote (TCV), while 38°C is an 'unacceptable' temperature under the thermal acceptability vote (TAV). According to the adaptive thermal comfort model, 36°C is the comfort temperature (T_{comf}) for the elderly in summer. Multivariate analysis shows that the TCV is affected more by subjective thermal responses than directly by the physical environment. The solar radiation sensation vote (SSV) shows the highest impact on TCV. Regarding the factors impacting on thermal comfort, the elderly felt that sweating and temperature concerned them the most. Drinking water and showering are the most frequent adaptive behaviours employed to relieve the heat. Since the conditions recorded in this study are outside the adaptive thermal comfort zone, future research should focus on thermal stress.

Keywords: thermal responses, thermal comfort, elderly, hot-humid climates, adaptive behaviour

1 Introduction

Elderly people are the most vulnerable group to heatwaves. This is the conclusion of much research from many heatwave-related death events around the world (Baccini et al., 2011; Bell et al., 2008). This paper investigates how the elderly in the hot–humid latitudes respond to heat exposure and what adaptive actions they take to be comfortable.

Identifying thermal comfort conditions of the elderly will clarify their response to heatwaves. Evidence suggests that they have more limited opportunity to adjust themselves to heat exposure, physiologically, behaviourally and psychologically. Higher temperatures resulting from climate change are also affecting the elderly.

Normally the elderly are accustomed to the local environment since they have acclimatized to it and have employed many adaptive techniques, although their physiological condition has deteriorated. Also, ASHRAE (2009) states that the deteriorated heat loss mechanism could be compensated by lower metabolic rate and reduced activity. However, since the elderly lose thermal sensitivity, they also have a slow response to the heat threat. Even though the elderly have a slower metabolism and less heat gain (Piers et al, 1998, Lührmann et al, 2010), their body mechanism inhibits heat loss. The elderly's physiology has deteriorated in many ways such as less thermal sensitivity, less skin blood flow and less active sweat glands (Kenny et al, 2010, Novieto and Zhang, 2010). Although they are acclimatized to a hot environment (Maiti, 2014), slow thermal response reduces adequate heat loss by evaporation. Particularly, evaporative cooling by sweating is the key factor to relieve heat in hot-humid climates. Moreover, some chronic diseases, such as cardiovascular, respiratory, diabetes, hypertension and obesity are common in the elderly in the tropical climates and are exacerbated by prolonged heatwaves (Kenny et al, 2010).

The elderly also have several behavioural limitations related to heat. Both their saving habit and income level constrain their lifestyle. For example, the elderly tend to feel they cannot afford cooling energy during heatwaves (Lun et al., 2012). They also tend to wear conventional clothing regardless of discomfort (Liang et al, 2005). Research has found that the low income elderly were impacted more by heatwaves since they tend to have a poorer quality of house (Semenza et al, 1996). Low education level also contributes to vulnerability to heat (Bell et al, 2008), since the less educated have limited knowledge of heat relief techniques. In addition, the elderly who are socially isolated or live in an institution have higher risk of heat-related health problems (Semenza et al, 1996).

Psychological factors affect the elderly's expectations. Field-notes from the exploratory, pilot and main surveys suggest that the elderly have low expectations of the weather being comfortable. The same is found particularly in the outdoors (Brager and De Dear, 1998). This leads them to accept thermal discomfort easily. The elderly also are thermally experienced and feel they can manage discomfort. However, their deteriorated health may lead them to overestimate their ability to adjust to difficult weather conditions like heatwaves which contributes to neglect of active adaptive behaviour against the heat threat.

Moreover, the physical environment has become more critical. Providing the optimum thermal comfort range for housing design may not be adequate in a warming climate, particularly in summer. The 30-year average minimum and maximum temperatures from 1981-2010 in Chiangmai were 20.8 and 32.2°C respectively, with 42.4°C the recorded peak maximum (Informatics Technology Meteorological Sector, 2015). Moreover, the number of very hot days (>34°C) and hot days (>31°C) increased approximately 10%, defined by the Thai Meteorology. Over one-third of the very hot days occurred in the last three years (Figure 1). Although the current conditions may be quite acceptable for the study participants since they are accustomed to it, future conditions may be more extreme for the vulnerable elderly. According to the Intergovernmental Panel on Climate Change (IPCC) (Kirtman et al, 2013), South East Asia will experience an increase in the average summer temperature of at least 0.5°C in 2016-2035 and 1°C in 2036-2055 above the 1850-1900 mean. The 25.5-31.5°C thermal comfort range across all adults in Thailand (Jitkhajornwanich, 2007), is similar to Malaysia (Djamila et al, 2013) and the monsoon season in India (Indraganti, 2010). Even though the comfort range of Thailand is still within the 30-year average temperature, the 42.4°C peak temperature already exceeded the comfort zone. Occupants will need even more sophisticated techniques to maintain their comfort in the extreme summers of the next decades. Particularly, low-income people in lower quality housing and the less literate people may have less ability to cope with this situation.

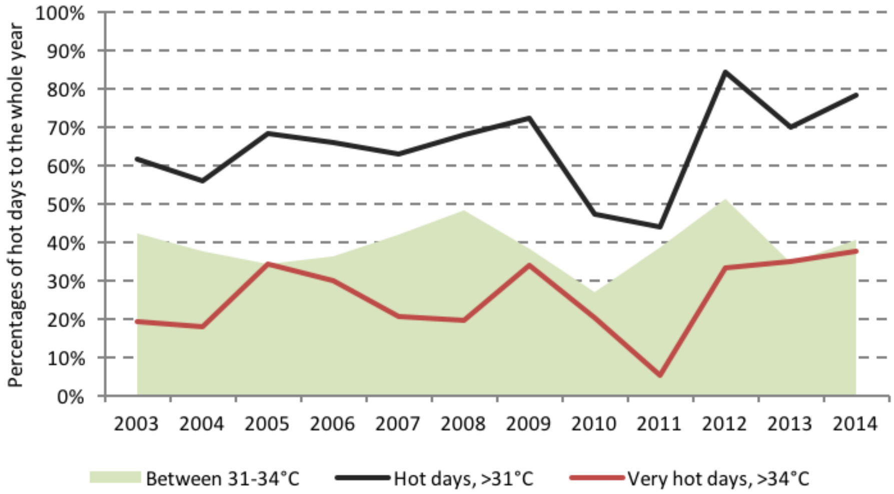


Figure 1 Percentages of hot-days throughout the year in Chiangmai

2 Methodology

A field survey was conducted in the hot dry season in April 2015 in Chiangmai, Thailand, which is hotter than the following rainy season. Chiangmai is in northern Thailand in the tropical monsoon climate zone. The mean day temperature during the survey was 36.01±1.85°C, with relative humidity (RH) 46.75±6.32% and air velocity (V) 0.18±0.11 m/s (see Table 1). Data was collected from 135 elderly people who lived in four retirement homes in the urban and rural area. They were interviewed in a semi-outdoors pavilion in each home about three conventional thermal perceptions: sensation, preference and acceptability. The interview was carried out while simultaneously measuring the physical environment and interviewees' sweating levels.

A Kimo AQ200 meter (OneTemp Pty Ltd) was used to measure air temperature (T_a), globe temperature (T_g), relative humidity (RH) and air velocity (V) (Table 1). According to EN 15251:2007, the survey is a compromise between Class II, requiring three-level measurement and Class III requiring one level measurement for outdoor surveys. The sensors were installed at 0.6 and 1.1 metres. The data was recorded at five-minute intervals. The galvanic skin response (GSR) sensor (Vilistus Biofeedback Ltd) was installed on the interviewee's fingertip to measure sweating level (Figure 2). The measured GSR and the participant's qualitative sweating sensation from the questionnaire were correlated with comfort feeling. The subjective responses involved in this paper cover temperature, wind, solar radiation, relative humidity and sweating. The participants were also asked about their adaptive behaviour.

Table 1 The weather profile of the survey

	T_a (°C)	T_g (°C)	MRT (°C)	RH (%)	V (m/s)
Average	36.01	36.55	37.26	46.75	0.18
Maximum	38.85	39.45	40.49	65.72	0.39
Minimum	29.79	29.79	29.79	38.30	0.01
SD	1.85	1.95	2.17	6.32	0.11

Figure 2 The measurement instruments in the field work: left - Kimo AQ200; right - Vilistus GSR sensors installed on the fingertip

The interview took 20-30 minutes. A mini-mental assessment preceded the main questionnaire to establish the interviewee's ability to take the survey. The main questionnaire is in three parts. The personal information section includes age, education level, health condition and their clothing habits. The thermal comfort section includes sensation, preference and acceptability questions. The adaptive behaviour part provides a list of heat-relief techniques for the participants to select as appropriate.

Cultural characteristics mean that feelings of discomfort in the Thai elderly will not be readily admitted. The elderly could not express their unacceptability of thermal conditions in the pilot survey, for example. The difference between acceptability and unacceptability in the full survey hinges on employing adjustments to become more comfortable. The need for adjustment equates to unacceptability.

The linear regression and multivariate analysis of variance (MANOVA) are used for predicting the dependent variable. Linear regression predicting one dependent variable was used to predict the thermal sensation vote (TSV) and wind sensation vote (WSV). MANOVA was used for identifying the TCV predictors.

3 Results

The public retirement homes in this paper comprise low care housing. The occupants are low income people, but they need to be healthy and independent. The results are in three sections: personal information, subjective thermal responses and adaptive behaviour.

3.1 Personal information section

The personal information covering education level, health condition and clothing level helps explain the personality of the participant. More than half of the elderly were only educated to primary school level or year 4 (Table 2). Moreover, the research also found that over 50% of the elderly have hypertension and approximately one-fourth have diabetes. Some elderly have more than one disease.

The results of the non-parametric analysis fail to prove that less education and at least one chronic disease influence the elderly's thermal responses. Nevertheless, participants in this survey with poor education manifest less sophisticated adaptive behaviour and are less concerned about the possibility of discomfort.

Clothing is a very important factor in thermal comfort. Removing clothing is the most convenient adjustment in an uncomfortably hot environment. However, most Thai elderly are conservative about clothing. Conventional clothing includes a shirt with shorts for men and a shirt with a tube skirt for women. Despite heat discomfort, some elderly insist on dressing with conventional clothing, in particular the females. However, Thai costume is designed for the local environment. The garment is light and sheer. Therefore, the clo-value of the Thai female elderly is not much higher than one third of the common summer clothing for tropical people (Baker, 1987). The average male and female clo-values are 0.24 and 0.38, respectively (Table 2). The metabolic rate of the Thai elderly is lower than that of the Western adult as set out in ASHRAE 55 (2013). It is calculated from the aggregate method based on 17 equations as 43.10 W/m^2 for males and 38.57 W/m^2 for females. The calculation process applied the method used by Siervo et al. (2014).

Table 2 Personal information of the participants

	Participants (No.)	Age (yr)	Weight (kg)	Clo-value	Usual education level	Usual disease
Male	49	72±7.75	64.83±10.02	0.24	Primary School (43%)	Hypertension (51%)
Female	86	74±6.97	53.94±9.78	0.38	Primary (48%)	Hypertension (57%)
Total	135	73±7.02	58.80±10.63	0.33	Primary (46%)	Hypertension (55%)

3.2 Subjective thermal responses

Subjective thermal response results are explained through the responses relating to temperature, wind and sweating.

3.2.1 Responses related to temperature

Half of the elderly in Chiangmai survey voted that the conditions were acceptable. The results show that the majority of the elders (>90%) experienced 'warm' to 'hot' sensations (in TSV) with temperatures over 38°C. However at 36°C, more than half were 'comfortably warm' in the TCV (Figure 3). Interestingly, 48% of the elderly were still 'comfortable' (TCV 0 to +1) when they sensed it was 'hot' (TSV +3).

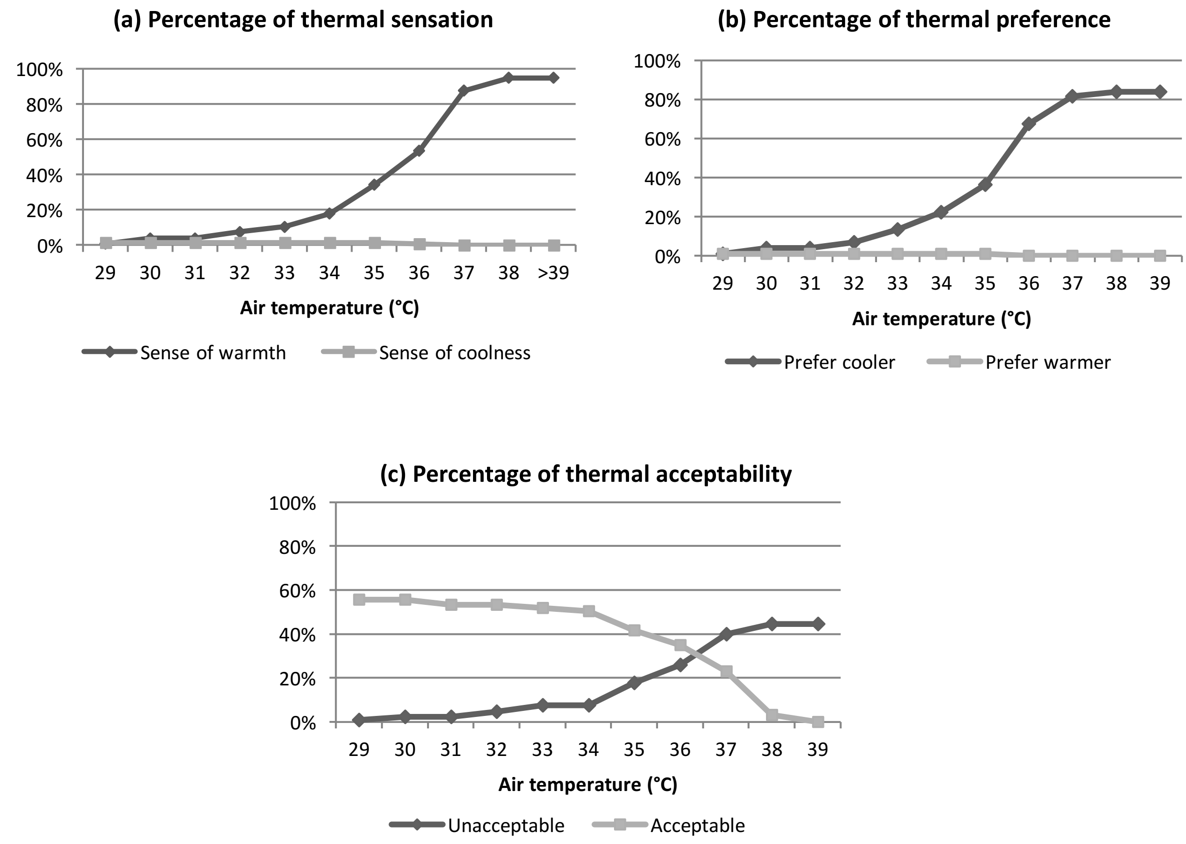


Figure 3 Charts of the frequency of subjective thermal perceptions and air temperature

Regarding the thermal preference vote (TPV), 80% of the elderly preferred cooler temperatures. The preferred temperature was 29°C. The accepted temperature was 36°C, with more than half of respondents feeling that 38°C was 'unacceptable' in the thermal acceptability vote (TAV).

Linear regression was used to predict semi-outdoor temperature (T_{semi}) in relation to outdoor temperature (T_{out}) with a significant relationship displayed (R^2=0.67; p=0.00), Equation (1). Figure 4 illustrates the TSV points shown in the linear regression, demonstrating that T_{semi} follows T_{out} and that there is no 'neutral' sensation (TSV '0') over 35°C.

$$T_{semi} = 0.425*T_{out}+20.351 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

However, when the linear regression was tested for TSV and TCV in relation to T_{semi}, only TSV shows a significant relationship (p=0.027), with R^2=0.04[1] in Equation (2). MANOVA shows that only SSV has a significant impact on TSV (p=0.00, R^2=0.4). TSV is affected by both T_{semi} and SSV, but the greater impact is from SSV (Equation 3).

$$TSV = 0.101*T_{semi}-0.987 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$TSV = 0.194*SSV+0.012*T_{semi}+2.114 \quad \ldots\ldots\ldots\ldots (3)$$

[1] This low R^2 distinguishes that there are other influential factors involved.

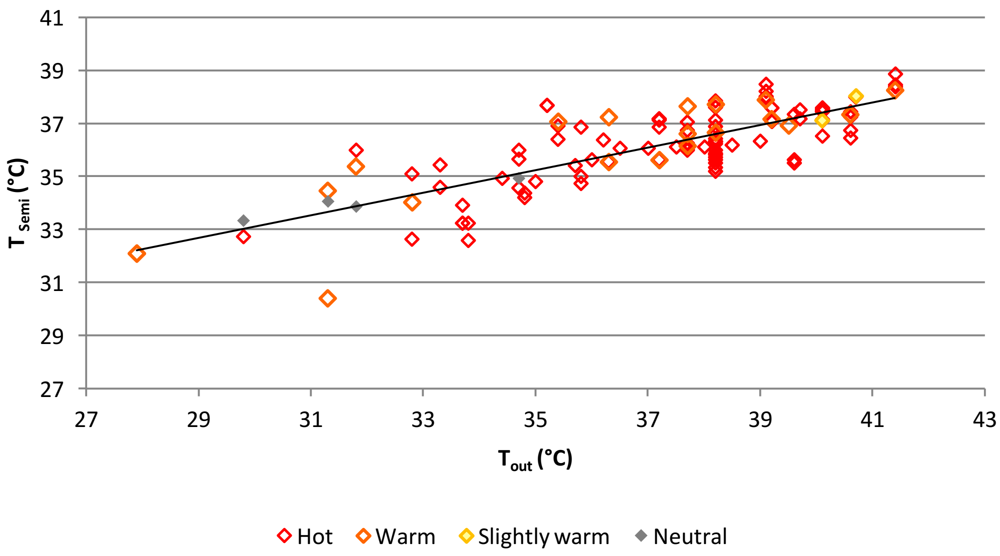
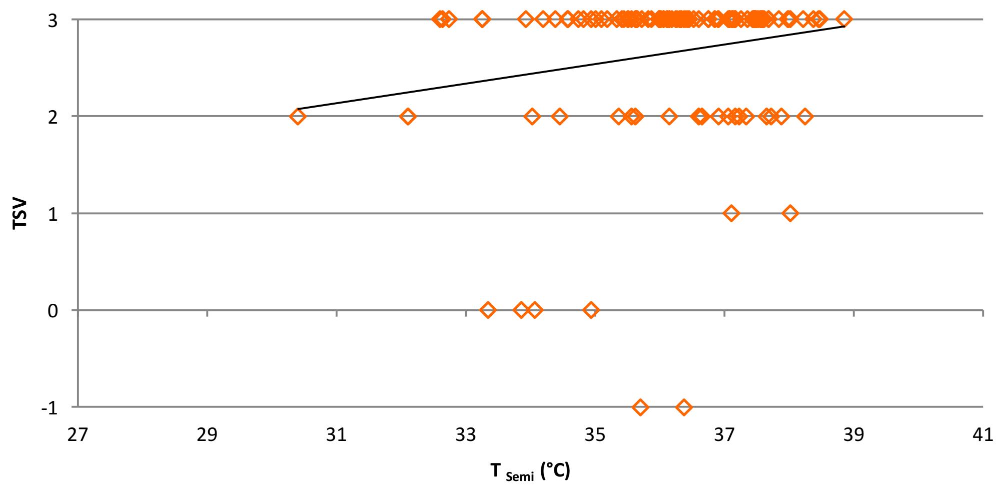


Figure 4 The linear relationship between semi-outdoor and outdoor temperatures

Figure 5 shows that an increase in sense of warmth will follow an increase in T_{semi}.



Note: Numbers denote TSV points; '0' = neutral, '1' = slightly warm, '2' = warm and '3' = hot

Figure 5 TSV in relation to T_{semi} (°C)

MANOVA shows that the TCV is affected more by subjective thermal responses than by the physical environment. Roy's Root illustrates a significant effect of WSV, solar radiation sensation vote (SSV), humidity sensation vote (HSV) and sweating sensation vote (SwSV) on TCV, with SSV showing the highest impact at p=0.005 (Table 3). However, TSV fails to show a statistical influence on the TCV. It consequently supports the previous result that even though the elderly sensed that it was 'hot', almost half of them insisted that they felt 'comfortably warm'. In addition, the physical environment parameters fail to show an effect on TCV through multiple regression and MANOVA. Consequently, the elderly's TCV in the tropical summer conditions cannot be predicted directly by physical environment parameters.

Table 3 The influence of parameters on TCV using MANOVA

Physical parameters	Significance	Subjective responses	Significance
T_{semi}	0.829	**TSV**	0.072
MRT	0.997	**WSV**	0.018*
Air velocity	0.100	**SSV**	0.005**
Relative humidity	0.899	**HSV**	0.022*
GSR	0.093	**SwSV**	0.034*

Note: ** p<0.01, * p<0.05

3.2.2 Responses related to wind

According to the summer conditions in Chiangmai, there were light breezes during the day but it was calm in the evening. However, the 0.22 m/s average wind during the day and 0.07 m/s average in the evening were very low for the semi-outdoors. One-fourth of the elderly experienced 'calm wind discomfort', with almost half of the discomfort experienced in the evening. Almost half voted 'unacceptable' since it was too calm. Since the maximum air velocity was only 0.3 m/s, 70% of participants voted for 'more breezes' both in the day and evening.

Linear regression was used to test WSV against air velocity (V). It shows a significant relationship (p=0.00), Equation (4) (Figure 6). However, when the multiple regression was applied, the relationship of WSV on RH and V produces a 0.001 significance value with low R^2=0.4, Equation (5).

$$WSV = 3.543*V-0.509 \quad \text{.................................} \quad (4)$$

$$WSV = 4.241*V+0.059*RH+0.098*T_{out}-7.018 \quad \text{.....................} \quad (5)$$

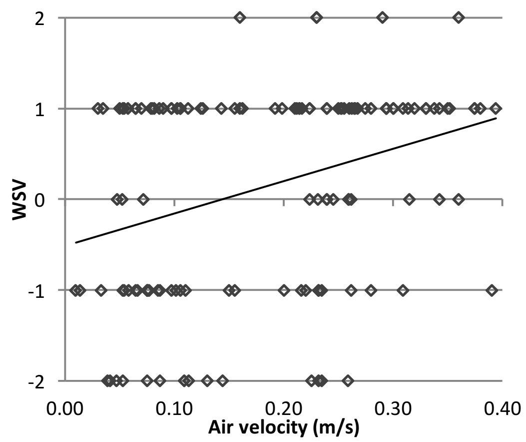


Figure 6 WSV in relation to air speed (V, m/s)

3.2.3 Responses related to sweating

Subjective sweat responses combined with the measured sweating level can indirectly indicate the effectiveness of sweat evaporation. For example, if people are uncomfortable, it is probably because they are sweating heavily but the sweat is not evaporating.

Sweating responses cover sensation, preference and acceptability related to sweating. Although there is no significant relationship between sweating responses and T_{semi}, RH and V, the relationship between physical parameters and the measured sweating level (GSR) is significant.

The Thai elderly preferred staying in high humidity although the recorded RH was rather low for the survey at 38-65%[2]. The research shows that half the elderly felt more discomfort in the dry conditions compared to the moderately humid environment. More than half of the elderly voted that their sweating was ‘acceptable’. More than half had ‘moderate’ to ‘heavy sweating’ in SwSV, and they wished to have ‘less sweat’ in sweating preference vote (SwPV). 18% confirmed that they experienced ‘heavy sweating’ (Figure 7). Another one-third of all participants voted ‘acceptable’ sweating, even though their subjective sweating conditions were ‘moderate’ to ‘heavy’.

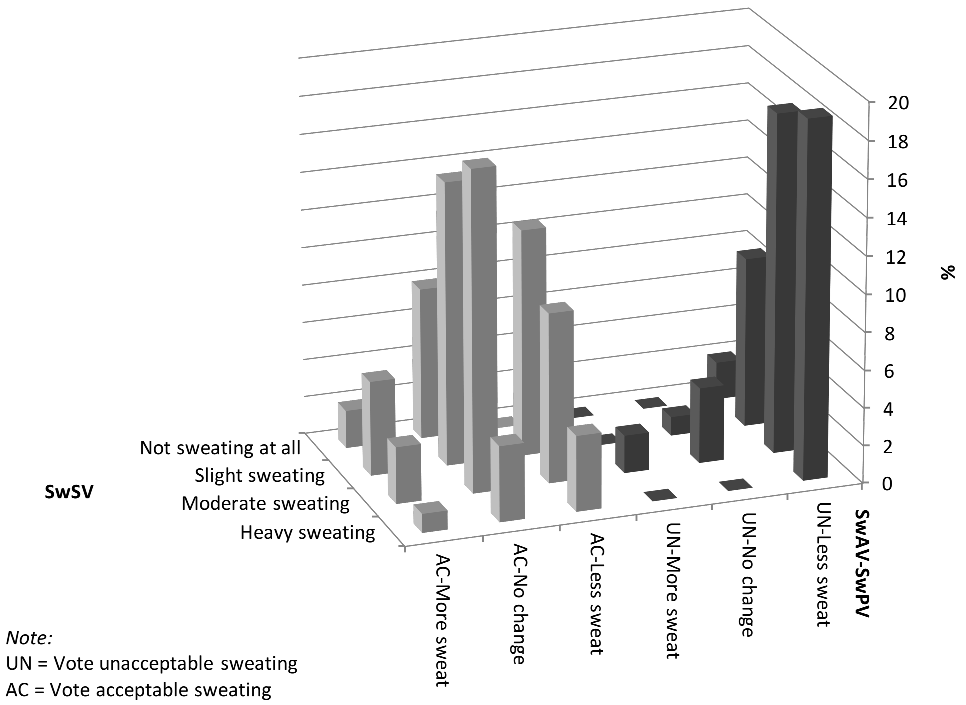


Figure 7 Sweat sensation vote in relation to sweat preference and sweat acceptability votes (%)

Measured sweating levels (GSR) are affected by both physical and physiological conditions and the correlations of four environmental parameters with GSR were moderately significant, tested by MANOVA in this paper (p=0.01, R^2=0.3). The GSR illustrates the quadratic relationship to RH, T and MRT and the exponential relationship to V (see Figure 8) indicating that the optimum sweating level lies in a limited range in regard to RH, T and

[2] The 30-year average daily relative humidity range is 51-87% in Chiangmai (Informatics Technology Meteorological Sector (2015)

MRT. Table 4 shows the equations and their significance values. Regarding MANOVA, GSR is affected by temperature (T and MRT), V and RH at $p<0.05$, $R^2<0.3$.

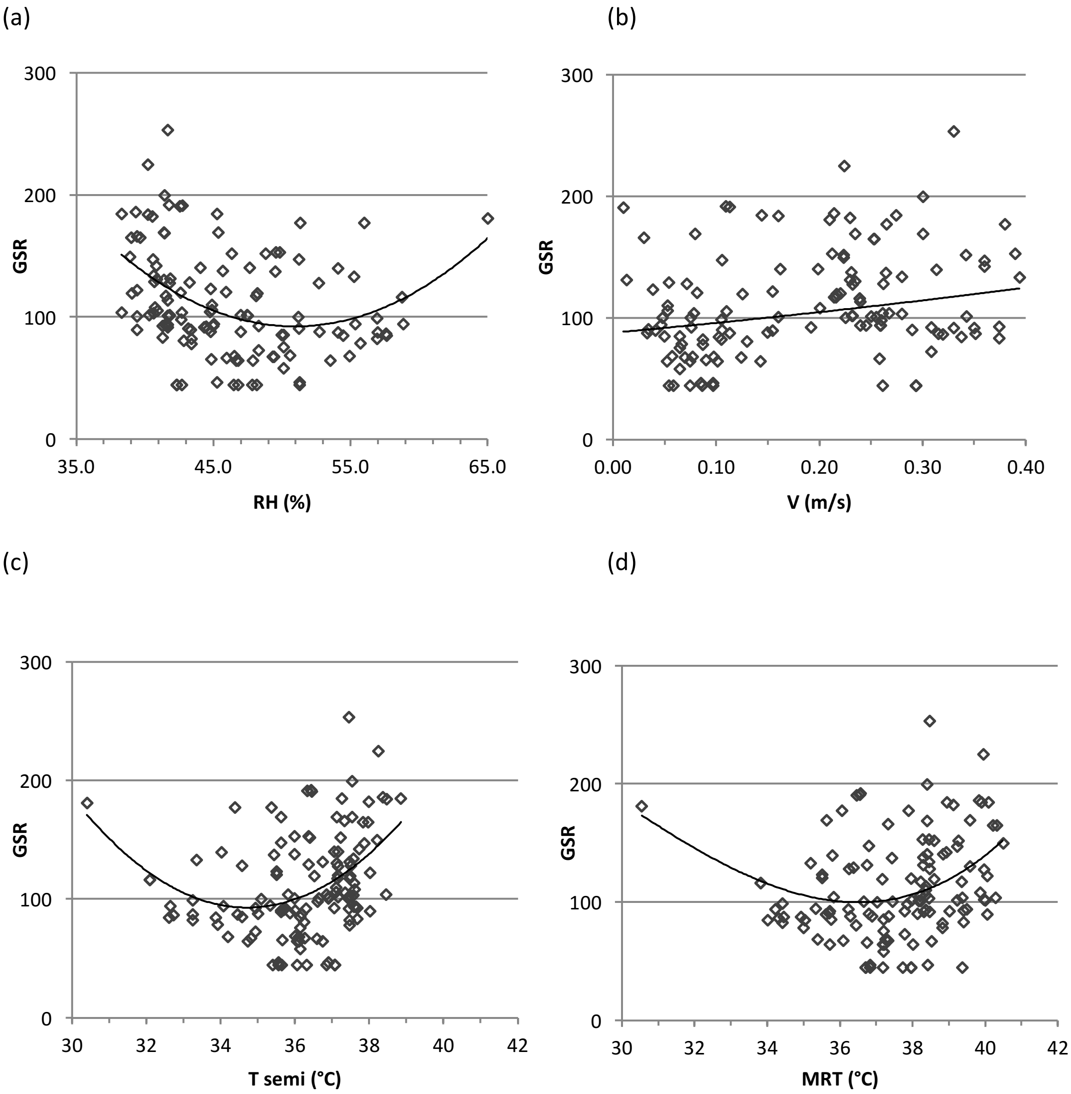


Figure 8 GSR (μSiemen) in relation to (a) RH (%); (b) V (m/s); (c) T_{semi} (°C); and (d) MRT (°C)

Table 4 Equations of galvanic skin response (GSR) in relation to physical environment parameters

Physical environment	**Equations**	***Significance***
(a) RH	$GSR = 1040.94 – 37.235*RH + 0.365*RH^2$	0.000
(b) V	$GSR = 88.04 + 0.865*V$	0.012
(c) T_{semi}	$GSR = 5153.76 – 291.563*T_{semi} + 4.199*T_{semi}^2$	0.000
(d) MRT	$GSR = 3592.01 – 192.791*MRT + 2.661*MRT^2$	0.002

The urban and rural areas exhibit some interesting contrasts about the effectiveness of evaporation. Firstly, although there was less extreme heat in the urban area, more elders reported an 'unacceptable' sweating condition than those in the rural area. Meanwhile, the GSR of the elders in the urban area was lower than those in the rural area (see Table 5). Urban weather conditions although slightly cooler, were more humid and less breezy. Hence, conditions in the urban area were less supportive of evaporative cooling by sweating so more participants experienced 'unacceptable heavy sweating' than those in the rural area (Table 5).

Secondly, the elderly in both urban and rural areas reported a similar comfort level (TCV), although rural conditions were hotter. It can be seen that evaporative cooling is the reason behind this. Table 5 shows higher GSR sweating levels in rural compared with urban subjects and lower percentages of 'unacceptable sweating' in rural subjects. Since the rural area was hotter but drier and breezier than the urban area, the elders could produce more sweat to relieve heat and lose more heat by evaporation.

Table 5 Conditions comparison between the urban and the rural areas

	Urban	**Rural**
Temperature (°C)	35.43±2.02	37.08±0.89
Relative humidity (%)	49.41±6.43	42.03±2.34
Air velocity (m/s)	0.15±0.11	0.23±0.08
GSR (µSiemen)	106.59±45.27	122.83±47.91
Heavy sweating	25%	36%
Unacceptable sweating	44%	35%
Thermal comfortable vote	15%	15%

3.3 Adaptive thermal comfort

Natural ventilation is included in ASHRAE's adaptive thermal comfort model since it can expand the comfortable range approximately 1.2°C (ANSI/ASHRAE Standard 55, 2013). According to Richard De Dear (*pers. comm.,* 2015) this model is applicable in the semi-outdoors and it was also used to identify thermal comfort in a tropical naturally ventilated house in Darwin, Australia (Daniel et al, 2015). Equations (6) and (7) (ASHRAE 55-2013) show the upper and lower 80% acceptability range of the theoretically neutral comfort temperature (grey area in Figure 9). This research was conducted in the semi-outdoors so T_{semi} represents the operative temperature in ASHRAE's equation. Equation (8) is the recorded comfort temperature for the elderly in Thailand. The mean comfort temperature in this research is 36.5°C.

$$\text{Upper 80\% acceptability limit} = 0.31*T_{out}+22.5 \quad (6)$$

$$\text{Lower 80\% acceptability limit} = 0.31*T_{out}+14.3 \quad (7)$$

$$T_{comf} = 0.375*T_{semi}+22.84 \quad (8)$$

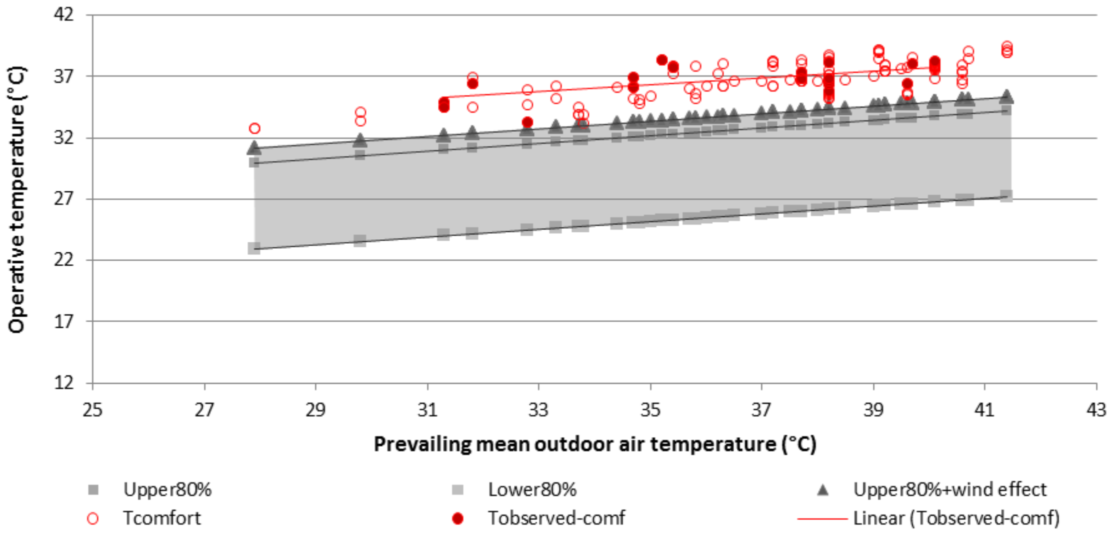


Figure 9 Comfortable temperature in the acceptable operative temperature ranges for semi-outdoor spaces

However, most of the comfort temperatures recorded in the survey do not fall within the adaptive thermal comfort zone (Figure 9). Theoretically, most elders should have reported heat discomfort which is relevant to the TSV and TCV results. Combined with acclimatization and low expectations of thermal comfort, exposure to extreme heat appears not to overly concern them. This may be caused by the deterioration of the elderly's body mechanisms. Additionally, the observed-comfort temperatures - the solid red dots in Figure 9 - are also above the comfort zone. The observed-comfort temperature was recorded when the elderly responded 'comfortable' in TCV. Equation (9) shows that the observed-comfort temperature is approximately 4°C above the upper 80% limit of acceptability.

$$T_{observed\text{-}comf} = 0.2757*T_{semi}+26.67 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

4 Adaptive behaviour

Adaptive behaviour is another key factor in comfort. If they are concerned by an extreme temperature, the sophisticated elderly can easily adapt their behaviour. However, in the very hot exposure, not all elderly can maintain their comfort due to factors like health conditions, conservativeness, economic status and perception.

The most common adaptive behaviour relates to temperature. One-third of the elderly usually 'drink water' and 'take a shower' in summer to deal with excessive heat. A less common habit is to increase local air speed. Over 25% usually 'turn on mechanical fans' or 'move outside' to get more breezes. Nevertheless, due to the Thai culture, some elderly tend to accept the conditions very easily rather than admit discomfort and feel miserable. One-fourth of them tolerate the unpleasantness until it ends.

Regarding the factors impacting on thermal comfort, the elderly felt that excessive sweat concerned them the most, followed by temperature and solar radiation (Table 6). In contrast, temperature change brings comfort most readily, followed by wind.

Table 6 Factors which lead to thermal comfort and discomfort

Factors	Solar radiation	Sweat	Wind	Temperature
Comfort	12%	13%	31%	36%
Discomfort	27%	30%	5%	29%

5 Discussion

5.1 Personal information

Although much research agrees that there is a relationship between thermal sensation and phenomena like education level and ailments like hypertension, cardiovascular disease, diabetes and stroke (Bell et al, 2008, Ir et al, 2010 and Kenny et al, 2010), this research did not support that. Since different diseases have different impacts on thermal sensitivities, it may be difficult to ascertain significant relationships. For example, the elderly with hypertension and heart diseases are susceptible to heat since their body will work harder to maintain thermal regulation (Ohnaka et al, 1993, Novieto and Zhang, 2010). Diabetes leads to reduced sensitivity and delayed responses which is accentuated in the elderly (Zanobetti et al, 2012).

5.2 Subjective thermal responses

The subjective thermal responses in the study show a higher range than other research in the last decade. Even though the preferred temperature in this research is similar to other research findings in Thailand, the accepted temperature is 4°C higher than the 31°C established in Thailand for combined elderly and non-elderly in 1992 (Busch, 1992). It shows that the elderly may have increased their tolerance to heat. However, the elderly have attenuated thermal sensation and the 4°C margin may be a result of this.

Jitkhajornwanich (2007) established a comfort range in naturally ventilated conditions for all adults in Thailand of 25.2-31.5°C. Applying similar methods in this research but focusing on the elderly in summer, a 36°C 'comfortably warm' temperature was recorded during the TCV. A 38°C 'unacceptable' ambient temperature was also recorded during the TAV. Both are well over the former comfort range. These two temperatures can be considered as a summer threshold temperature for the elderly. However, direct comparisons are not possible as a result of the focus since this research was conducted in summer and focussed on elderly people. The mean maximum summer temperature in Chiangmai is over 34°C, defined as "very hot" days by the Thai Meteorology (Figure 1). Therefore, people in Chiangmai actually face very hot days frequently and appear to cope with difficulty through high tolerance levels and slow responses.

Regarding factors influencing the TSV, TCV and WSV, the elderly's sensation and overall thermal comfort is affected more by their concern about how they should respond than the actual weather conditions would suggest. TSV, TCV and WSV have a significant relationship with physical parameters, but show a weak R^2-value. This suggests that there are other influential factors affecting these elderly's subjective thermal responses. Those may be more important for the elderly than the factors tested in this research, for example. factors like psychology, past experience and cultural background related to the elderly's low expectation of being thermally comfortable (Brager and de Dear, 1998). Nevertheless, subjective responses relate indirectly to physical parameters. The SSV shows the most influence on both TSV and TCV, presumably because radiant heat typically has a more significant influence than ambient temperature in all adults (Cheng et al, 2010).

According to the sweating responses, the elderly are accustomed to high humidity. Their body mechanism acclimatizes to the hot-humid climate. They could also adapt to be comfortable even in hotter conditions, if they could produce adequate sweat and stay in the effective evaporative conditions like low RH and breezes. It suggests that the sweating mechanism combined with acclimatization, are key factors in surviving in the hot-humid climate zone. However, conditions in the rural area may lead to higher risk of dehydration than those in the urban area since they were hotter, breezier and drier. The managers suspected nine elders in the rural home died from heatwaves during summer 2015, in which dehydration may have been a factor.

5.3 Adaptive thermal comfort

Most elders felt comfortably warm. However, when they report discomfort, it is usually too late to adapt (Bills and Soebarto, 2015). Regarding the comfort temperature (T_{comf}) for hot-humid Southeast Asia (Nguyen et al., 2012) in Equation (10), the adjusted equation in this research provides a 4°C higher T_{comf} than for Southeast Asia generally. It is also approximately 4°C higher than the equations suggested in ASHRAE 55-2013 in Equation (11) and EN15251 (2007) in Equation (12).

$$T_{comf} = 0.341*T_{out} + 18.83 \quad \text{.................................} \quad (10)$$

$$T_{comf} = 0.31*T_{out} + 17.8 \quad \text{.................................} \quad (11)$$

$$T_{comf} = 0.33*T_{out} + 18.8 \quad \text{.................................} \quad (12)$$

The recorded and observed-comfort temperatures in this research (Equation 9) are well above other research results. The current 36°C T_{comf} is approximately 8°C above the 28°C temperature claimed for Southeast Asia (Busch, 1992, Nguyen et al, 2012) and the noted standards. There may be four reasons: the hot summer season, migration to the semi-outdoors, the elderly nature of the participants and the warming climate. Since the T_{comf} relates to the T_{out} throughout the year (Brager and De Dear, 1998), the summer T_{comf} should also show the higher range than the overall noted T_{comf}. Moreover, equations in the Southeast Asia study and the abovementioned standards were in naturally ventilated *indoor* conditions, not the semi-outdoors. The 4°C higher temperature may result from the difference between indoor and semi-outdoor conditions.

There is also the evidence in the tropics that the elderly‘s sense of warmth is warmer than for younger adults. Rangsiraksa’s 2006 study of T_{comf} in the elderly in Thailand in summer 2006 shows that the 28°C comfort temperature of the elderly is 2°C higher than that for younger adults. Additionally, the elderly’s reduced awareness and increased level of psychological acceptability means when they feel ‘uncomfortably warm’ at 36°C they may not see a heatwave as a threat and there may be heat stress. The elderly are comfortable in high temperatures but it may be an illusion: if they are not concerned about heat they will not adapt to manage discomfort. In addition, warming climate may also influence thermal comfort. The 31°C summer mean indoor temperature recorded by Rangsiraksa (2006) was 5°C lower than the mean semi-outdoor temperature in this research. Consequently, the T_{comf} of the 2006 study is also 8°C lower than the 36°C comfort temperature in this research.

5.4 Adaptive behaviour

Most elderly use sophisticated techniques to adapt in the hot-humid climate. However, not all of the elderly cope with the heat. The interviews established that at least nine occupant elders may have died by heat stress in the excessive heat of summer 2015, as noted above. These elders might have had failing body mechanisms and less awareness, but considerable psychological thermal acceptability. In addition, adaptation techniques may not be adequate in climate change conditions. This paper disproves ASHRAE's statement (2009) that the particular Thai elderly in hot-humid climate could cope with their deterioration simply with slower metabolism and adaptive behaviour. *The elderly's experiences will not help them since the summers in future will bring more discomfort than they have experienced*.

6 Conclusion

The elderly in hot-humid climates are highly vulnerable to heat since they have more physiological, psychological and behavioural limitations than younger adults. Despite this, the elderly's sense of 'hot' is one of comfort in high temperatures. Their 'comfortably warm' temperature is 36°C, while the 'unacceptable' temperature is 38°C. The elderly's preferred temperature is 29°C. The adaptive thermal comfort temperatures exceed the expected adaptive thermal comfort zone based on the literature by 4°C. It is also 8°C warmer than the expected thermal comfort temperature noted in studies in hot-humid climates, although those studies are based on naturally ventilated indoor conditions and are not focused exclusively on the elderly, so a direct comparison is not possible.

The elderly's comfort range is surprisingly high partly because their physiological condition has deteriorated. In addition there are physiological, psychological and cultural reasons which prompt the elderly to accept a wide comfort range. Furthermore, increasingly warmer summers between 2006 and 2015 may have brought a degree of thermal tolerance for the elderly.

Three other conclusions are, first, SSV may have the most influence on TSV and TCV, whereas temperature has the most impact on elderly thermal perception. The elderly also prefer more breezes and humidity in the semi-outdoors. Regarding sweating conditions, this research shows that the elderly who can sweat sufficiently and stay in effective evaporation conditions will report thermal comfort. Secondly, this research also found that evaporation from sweating might have worked more effectively for the elderly in the rural area. Thirdly, education level and specific diseases do not seem to influence on thermal responses significantly in this research.

Acknowledgement

The GSR sensors (Vilistus Biofeedback Ltd) were provided by the Australian School of Business, University of New South Wales, Australia. The researcher greatly appreciates their kind support.

Appendix: The questionnaire of this research

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Questions (Talk about your feeling of the weather, please use the pictures to help your understanding)	Choices
1.2 How do you feel about the temperature at this moment?	[Cold/Cool/Slightly cool/Just right/Slightly warm/Warm/Hot] [-3 / -2 / -1 / 0 / +1 / +2 / +3]
1.3 How do you feel about the wind at this moment?	[Very calm/Slightly calm/Just right/Slightly breezy/Very breezy] [-2 / -1 / 0 / +1 / +2]
1.4 How do you feel about the solar radiation at this moment?	[Very weak/Slightly weak/ Neutral/Slightly strong/ Very strong] [-2 / -1 / 0 / +1 / +2]
1.5 How do you feel about the humidity at this moment?	[Very Dry/Slightly dry/Normal/ Slightly humid/Very humid] [-2 / -1 / 0 / +1 / +2]
1.6 How would you define your sweating at this moment?	[Not sweating at all /Slight sweating/Moderate sweating /Heavy sweating] [0 / +1 / +2 / +3]
1.7 Overall, how would you feel comfortable at this moment?	[Too cool/Comfortably cool/Comfortable/Comfortably warm/Too warm] [-2 / -1 / 0 / +1 / +2]

Probes: Do you feel the current temperature is hot? If it is not, how do you feel? Cool or Warm?

Questions (Talk about your preference, what the weather would you like?)	Choices
1.8 How would you prefer the temperature to be at this moment?	[A bit cooler/A bit warmer/No change] [-1/+1/0]
1.9 How would you prefer the wind speed to be at this moment?	[More calm/More breeze/No change] [-1/+1/0]
1.10How would you prefer the solar radiation to be at this moment?	[Less sun/More sun/No change] [-1/+1/0]
1.11 How would you prefer the humidity to be at this moment?	[Less humid/More humid/No change] [-1/+1/0]
1.12 How would you prefer your sweating to be at this moment?	[Less sweat/More sweat/No change] [-1/+1/0]

Probes: What would you like the weather to be at this moment? Why do you say that?

Complaints may be directed to the Ethics Secretariat, The University of New South Wales, SYDNEY 2052 AUSTRALIA (phone 9385 4234, fax 9385 6648, email : ethics.sec@unsw.edu.au).

Project: The Urban Heat Island and Elderly Thermal Comfort in the Hot-Humid Climate of Thailand page 3

Next, I would like to ask about the acceptability of the weather. I know that we cannot change the weather, but you feel that you could accept a strong wind easier than the strong sun, for example. Before asking, let me explain the definition of the words in this survey.

- *If you feel uncomfortable with the weather and you need some adjustments to be more comfortable such as using fans, it means that you feel it is "Unacceptable".*
- *If you feel comfortable with the weather itself without any adjustment, it means you feel it is "Acceptable".*

Questions (Then, let me ask the questions)	*Choices*
1.13 Is the temperature acceptable for you at this moment? (If you use the air-conditioner, it will be unacceptable)	[Acceptable/Unacceptable]
1.14 Is the wind speed acceptable for you at this moment? (If you use the fan, it will be unacceptable)	[Acceptable/Unacceptable]
1.15 Is the solar radiation acceptable for you at this moment? (If you use the umbrella, it will be unacceptable)	[Acceptable/Unacceptable]
1.16 Is the humidity acceptable for you at this moment? (If you have to drink water relate to dry weather, it will be unacceptable)	[Acceptable/Unacceptable]
1.17 Is your sweating acceptable for you at this moment? (If you use the handkerchief, it will be unacceptable)	[Acceptable/Unacceptable]
1.18 Overall, what would you define your degree of acceptability right now? If "1" is very unacceptable (very uncomfortable) and "5" is very acceptable (very comfortable). (Please use the pictures to help your understanding)	[Very unacceptable to Very acceptable] [1-2-3-4-5]

Probes: Do you accept this current temperature/wind or air speed/solar radiation or sun is comfortable?

1.19 What factors bother you the most when you feel uncomfortable?
☐*Temperature* ☐*Wind* ☐*Solar radiation* ☐*Sweat*

Probes: What is the biggest impact on you when you feel uncomfortable?

1.20 What factors bring a feeling of comfort easiest when you feel uncomfortable?
☐*Lower temperature* ☐*More wind* ☐*Shade* ☐*No sweat*

Probes: What is the easiest way for you to be comfortable?

Complaints may be directed to the Ethics Secretariat, The University of New South Wales, SYDNEY 2052 AUSTRALIA (phone 9385 4234, fax 9385 6648, email : ethics.sec@unsw.edu.au).

Figure 10 The questionnaire

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Relationship between children's comfort temperature and outdoor climate: some methodological issues

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Abstract
Several recent studies have focused on children's comfort criteria in schools, highlighting a need to develop an adaptive comfort model with application for children in naturally ventilated classrooms. This paper examines the influence of prior exposure to weather dynamics on children's indoor thermal comfort. The field study was performed in naturally ventilated primary school classrooms during the warm season in Shiraz, Iran. Child-specific questionnaires were administered while concurrent indoor and outdoor climate measurements were conducted. This study has set out to obtain the adaptive comfort equation for children based on the methods used to develop comfort equations in ASHRAE 55 (2013) and EN 15251 (CEN, 2007). A sensitivity analysis was performed to test the relationship between children's indoor comfort temperature and outdoor climate. Different measures of outdoor temperature were examined in order to identify a suitable metric for the outdoor climate, suggesting the strongest correlation coefficient with the comfort temperature. The result of the analysis shows that the running mean method with lower decay values (α=0.45) leads to higher correlation with children's comfort temperature. However, the 'true' value of α remains debatable. The gradient of the comfort equation in relation to outdoor temperature for children is shown to be shallower than that of adults.

Keywords: Thermal comfort, adaptive model, outdoor air temperature, indoor comfort temperature, children, school classroom

1 Introduction

Despite the importance of maintaining thermal comfort in schools (Wargocki and Wyon, 2007), thermal comfort studies have largely concentrated on adults. While children's thermal comfort requirements are not significantly included in the existing thermal comfort data, ASHRAE 55 (2013) suggests that recommendations of that standard could be applicable for children in classroom situations. A number of thermal comfort field studies conducted in classrooms have found that comfort predictions and requirements do not match those specified in adults' thermal comfort standards. Further, some authors suggest that children feel comfortable at cooler temperatures than predicted by adaptive comfort standards (Mors et al., 2011; Teli et al., 2012; de Dear et al., 2015; Teli et al., 2015).

This paper aims to evaluate the adaptive thermal comfort model for children based on a field survey conducted in naturally ventilated primary schools in Iran during the warm period of the school year. To obtain the relation between thermal comfort indoors and the outdoor climate, survey data were examined to derive comfort temperature for children and define a suitable metric for the prevailing outdoor temperature. A sensitivity analysis was performed and various approaches were adopted to calculate the comfort temperature for the sampled children, mainly because the methods previously described in the literature for deriving comfort temperature may not be applicable for children. To better understand the adaptive comfort relationships for children, this study tests different metrics of outdoor climate to identify a suitable metric that suggests the strongest correlation with children's neutral temperature.

2 Calculating the comfort temperature

The 'neutral or comfort temperature' (T_{comf}) is the temperature defined as "the Operative Temperature at which either the average person will be thermally neutral or at which the largest proportion of a group of people will be comfortable" (Nicol and Humphreys, 2010). The analytic method of determining the neutral temperature differs between the two adaptive comfort approaches, the global adaptive comfort standard (ASHRAE 55, 2013) and its European counterpart (EN 15251, 2007), mainly because of different sample sizes used (de Dear, 2011; de Dear et al., 2013).

2.1 Linear regression analysis

In the ASHRAE RP-884 project (de Dear and Brager, 1998), the buildings' indoor operative temperature (T_{op}) was binned into half-degree intervals, and the bins' mean thermal sensation responses were analysed. The neutral temperature (T_{comf}) was calculated for each building by solving the weighted linear regression model between thermal sensation and operative temperature for a mean sensation vote of zero. The large sample sizes in the ASHRAE database, about 9000 of total 21000 questionnaires in NV buildings (de Dear et al., 1997), allowed for statistically significant regression models for estimation of the optimum comfort temperature at the individual building level (de Dear et al., 2013).

2.2 The Griffith method

The regression analysis method requires a substantial amount of data and a wide range of temperatures to estimate the neutral temperature accurately (Nicol and Humphreys, 2010). Therefore, another analysis technique, the so-called Griffiths method, was employed to determine neutrality in the EN 15251 adaptive model in order to address the smaller sample sizes in the SCATs (Smart Controls and Thermal Comfort) database (1449 of total 4655 samples in free-running buildings) (Nicol and Humphreys, 2010).

Compared to regression analysis which calculates mean value of comfort temperature over the several days or weeks of the survey period, the proposed Griffith method used in EN 15251 estimates a comfort temperature "of a particular person in a particular building in that particular month" (Humphreys et al., 2013). Humphreys et al. argue that day to day drift of the daily mean room temperatures during the survey period could introduce some bias in estimation of the regression coefficient and consequently in calculation of the comfort temperature when regression analysis is used.

In order to assess neutral temperature in case of a small number of subjects (or comfort votes) or small range of temperature, the Griffiths method (1990) introduced a constant value for the linear relationship between thermal sensation vote and operative temperature; i.e. the so called 'Griffiths constant', G (/K) (Nicol et al., 2012, p.148). It is equivalent to the regression coefficient (Griffith slope) which relates the comfort temperature to the operative temperature and subjects' thermal sensation votes; based on the assumption that no adaptation has happened (Nicol and Humphreys, 2010; Nicol et al., 2012, p.149). The neutral temperature can be calculated using the following relationship (Humphreys et al., 2007) from operative temperature (T_{op}), thermal sensation vote (TSV), and a standard value of regression coefficient taken as the Griffiths constant (G):

$$T_{comf} = T_{op} – TSV/G \qquad \text{(Eq.1)}$$

This equation can be applied to calculate comfort temperature from individual comfort votes, or estimate average neutral temperature from a group of votes using mean thermal sensation votes ($TSV_{(mean)}$) and mean operative temperature ($T_{op(mean)}$) (Humphreys et al., 2007; Nicol and Humphreys, 2010; Nicol et al., 2012).

The estimation of the Griffiths constant is of importance in the precision of the estimated neutral temperature. However, it requires conditions which are not likely to be achieved in field studies where "…no adaptation to temperature changes takes place and measurement errors are excluded" (Nicol and Humphreys, 2010). Therefore, an optimum value for the Griffiths slope has been estimated (G=0.5) (Humphreys et al., 2007) using data from the SCATs and ASHRAE databases of comfort field studies (McCartney and Nicol, 2002; de Dear et al., 1997).

In EN 15251 (CEN, 2007), neutrality is calculated for each comfort vote assuming that a regression coefficient is equal to 0.5/K (Nicol and Humphreys, 2010), which corresponds to the rate of change in thermal sensation against operative temperature in situations where no adaptions take place. However, the validity of the presumed value of the Griffiths constant (0.50/K) in EN15251 (Nicol and Humphreys, 2010) is questioned (de Dear, 2011; de Dear et al., 2013). It is argued that Fanger's PMV/PPD model (1970) provides a more reasonable method to estimate the Griffiths constant in the absence of adaptive actions, given that PMV/PPD poorly estimates thermal sensation of occupants in buildings where they have thermally adapted. In the absence of adaptation, taking summertime data found in the SCATs database (typical office wear of 0.6 clo, metabolic rate=70 W/m^2, air speed=0.13 m/s, RH=50%, T_{op}=28.1°C when PMV=+1), Fanger's PMV/PPD model gives a value of 1/3.5=0.29/K which corresponds to a temperature decrease of 3.5 K to shift PMV from slightly warm to neutral (de Dear, 2011; de Dear et al., 2013). A recent study which examined the value of Griffiths constant in the comfort temperature calculation for school children shows that G=0.5/K could be applicable for children (Teli et al., 2015). However, more validation studies in different climates are required.

3 Expression of outdoor climate for use in the adaptive comfort model

The relationship of comfort temperature to the outdoor climate is expressed in terms of different measures of outdoor climate (Humphreys et al., 2013), predominantly as the monthly mean minima and maxima temperatures from meteorological records, the average of the minima and maxima daily air temperatures during the survey period, and a weighted running mean of the daily mean outdoor temperature prior to the survey day.

The monthly mean was commonly used as the expression for outdoor temperature (Humphreys, 1978; ASHRAE 55, 2004) primarily because it is readily available from meteorological data. According to de Dear (2011) the monthly mean outdoor temperature employed in ASHRAE's adaptive model is highly correlated with neutrality derived over a time-period of several days to weeks. Therefore, it is given to be the most logical expression of prevailing outdoor temperature for data in the ASHRAE RP-884 database (de Dear, 2011).

ASHRAE 55 (2013) and EN 15251(CEN, 2007) recognised the linear relationship between comfort temperature indoors and the prevailing condition outdoors; however, the two Standards adopted different metrics of outdoor temperature. The outdoor climate index in ASHRAE 55 (2013) represents the prevailing mean outdoor air temperature for a time period between 7 and 30 sequential days before the day in question (ASHRAE 55, 2013). It was previously expressed as the mean monthly outdoor air temperature (ASHRAE 55, 2010): i.e. average of the mean daily minimum and maximum outdoor temperature for the month in question. The recent version of the ASHRAE standard (ASHRAE 55, 2013) also permits a new metric for climate known as exponentially-weighted running mean of a sequence of mean daily outdoor temperatures prior to the day in question (T_{rm}).

The adaptive model in EN 15251 (CEN, 2007) adopted an exponentially weighted running mean temperature, which "…captures and puts more emphasis on the immediate, perceptual and behavioural layers of human thermal adaptation compared to the longer-term adaptive processes operating at the physiological level" (de Dear, 2011). According to Humphreys et al. (2013) an exponentially weighted running mean temperature (T_{rm}) is a more appropriate climate index compared to the daily mean or the monthly mean temperature. This is based on the assumption underlying the adaptive approach in which neutral temperature is influenced by a person's recent thermal experiences (Nicol and Humphreys, 2010). A running mean temperature gives weightings to temperatures based on their distance in the past and suggests that recent thermal experiences are more important than those further in the past (Nicol et al., 2012; Nicol and Humphreys, 2010). T_{rm} for any given day is calculated from the series:

$$T_{rm}=\{T_{od-1}+\alpha T_{od-2}+\alpha^2 T_{od-3}.....\}/\{1+\alpha+\alpha^2.....\} \qquad \text{(Eq.2)}$$

where constant α is <1, T_{od-1}= the daily mean outdoor temperature for the previous day, T_{od-2}=the daily mean outdoor temperature for the day before that, and so on (Nicol et al., 2012, p.38). Because α is <1, more weight is given to recent days' temperature than the more remote past (de Dear, 2011). EN 15251 (CEN, 2007) provides an approximate equation using the mean temperature for the last seven days with recommended value of α=0.8 (Eq.3):

$$T_{rm}=(T_{od-1}+0.8T_{od-2}+0.6T_{od-3}+0.5T_{od-4}+0.4T_{od-5}+0.3T_{od-6}+0.2T_{od-7})/3.8 \qquad \text{(Eq.3)}$$

The exponential weighting method to derive running mean outdoor temperature gives decaying weights to the past mean daily outdoor temperature which suggests that recent days are more influential to the occupants' comfort temperature than days in the more remote past (ASHRAE 55, 2013). The half-life (λ) of an exponentially weighted running mean is given in the following equation (Nicol and Humphreys, 2010; Humphreys et al., 2013):

$$\lambda = 0.69/(1 - \alpha) \qquad \text{(Eq.4)}$$

The running mean constant can vary between 0 and 1 and explains the speed of the running mean response to changes in the outdoor temperature (McCartney and Nicol, 2002). The constant α is a time-constant that shows a time-period needed for people's thermal adaptation to occur. This relation shows that larger values of α result in longer half-life days.

The recommended value of α in the ASHRAE standard (2013) varies within a range of 0.9 and 0.6 to calculate the exponentially-weighted running mean of outdoor temperature. These values depend on a slow and fast response running mean respectively. The α=0.9 is given to be more suitable for climates with minimal day to day temperature variation e.g. humid tropical climates, while lower values of α seems more appropriate for climates where people are more familiar with day to day temperature dynamics (ASHRAE 55, 2013).

The optimum value of α can established by deriving the strongest correlation between the indoor comfort temperature and the running mean outdoor temperature. To determine the best value of the running mean constant, McCartney and Nicol (2002) examined the correlation between the calculated comfort and outdoor temperature using different measures of the outdoor temperature. The result of that investigation using data from the SCATs project suggests that the best value of the running mean constant is 0.8 (McCartney and Nicol, 2002). Using a value of α=0.8 in Eq.4, represents a half-life of 3.5 days (λ=3.5) which suggests a period of a week for thermal adaptation of occupants to a step-change in the mean outdoor temperature (Humphreys et al., 2013).

The study by de Dear (2011) questions the 'true' value of α and highlights the importance of the α coefficient in the adaptive comfort temperature standard. According to de Dear (2006) and de Dear (2011) a seven-day integration period is "short enough to incorporate recent weather dynamics, yet long enough to capture 'weather memory and persistence' effects in human clothing behaviour".

4 Method

The field work was conducted in four boys' and girls' primary schools in Shiraz, in the south west of Iran, during the warm conditions of the local school year (May-2013). The entire sample included in the analysis constitutes 811 survey responses drawn from healthy children aged 10-12 years in 28 classrooms. All classrooms were in free running mode and naturally ventilated using operable windows. The participating school buildings all utilised medium-heavy weight construction systems. The four indoor environmental variables required for assessment of thermal comfort were collected in the selected classrooms, in accordance with the specifications relating to accuracy of measuring instruments and procedure set out in the standards (ASHRAE 55, 2013; ISO 7726, 2001) from an array of instruments placed at three levels, 1.1m, 0.6m and 0.1m, above the floor. Instrumentation was three sets of Kimo AQ200O units and related measuring probes. The instruments were placed at a mid-classroom location or near the centre, between the occupied rows of desks without impairing students' visual access and routine activity. The outdoor temperatures were collected from the local weather station, Maxkon® WH 3081, to obtain concurrent data representing the school outdoor microclimate during each survey. The weather station shows the outdoor temperatures in 30-minute intervals with sufficient level of accuracy and resolution anticipating possible comparison with the bureau of meteorology data.

Fieldwork procedures combined simultaneous measurement of physical variables of the classrooms with survey of students' subjective responses conducted on 'right here right now' basis. Questionnaires were specifically designed for the target age group based on developmental psychology (Haddad et al., 2012). The field survey and measurements were conducted during the last five minutes of the class session, before the next break to minimize any influence on thermal sensation caused by activities during the previous break. The survey participants were involved in sedentary activities (i.e. sitting quietly, writing-sitting, reading-sitting) during the 45 minute lesson period, after performing light to high intensity activities during each 15 minute school break. Since questioning students at the end of the class session may affect students' perception about thermal comfort, the relation between the students' tiredness and thermal sensation was examined. No statistically significant relationship was determined between the percentage of tiredness and sleepiness and the survey participants' mean TSV ($r^2 \leq 0.1$, p>0.05).

5 Results and discussion

5.1 Calculation of comfort temperature in each school

Both linear regression and the Griffiths methods were used to derive children's thermal neutrality in each school (Table 1). First, the neutral temperature in each school is calculated using simple linear regression analysis of the mean thermal sensation votes (TSV) as a function of classroom indoor operative temperatures aggregated into 0.5°C bins. Students' mean TSV per survey are taken for analysis rather than all individual votes. Data are then weighted according to the number of students making up each mean vote within each 0.5°C indoor operative temperature bin.

Table 1. Calculation of the neutral temperature using different methods during the warm season

School	Gender	*N*	Linear regression method					T_{comf}^{c} (°C) - Griffiths method		
			r^2	*P*	B^a	C^b	T_{comf}^{c} (°C)	G=0.50/k[d]	G=0.23/k[e]	G=0.29/k[f]
A	Male	233	0.41	0.00	0.17	-3.67	22.2	24.6	23.1	23.7
B	Male	219	0.87	0.00	0.28	-6.59	23.8	24.5	23.2	23.7
C	Female	192	0.84	0.00	0.29	-6.72	23.4	24.6	22.6	23.4
D	Female	167	0.87	0.00	0.28	-6.33	22.4	23.8	21.4	22.3

[a]*B*: Regression Coefficient
[b]C: Constant
[c]T_{comf} (°C): Neutral temperature based on linear regression of weighted binned mean TSV versus T_{op}
[d]: G=0.50/k based on the value used in EN15251 (Nicol and Humphreys, 2010)
[e]: G=$\delta PMV/\delta T_{op}$ based on data obtained in school surveys
[f]: G=$\delta PMV/\delta T_{op}$ taking data from SCATs database (de Dear et al., 2013)

Further, comfort temperature in each school is calculated based on the Griffiths method from Eq.1 using different constant values. First, the Griffiths method uses the value of the Griffiths constant (G=0.50/K) based on Humphreys et al. (2010), to predict neutrality of children. Secondly, the value of the Griffiths constant is obtained from the school survey data based on the rate of change of Fanger's PMV to operative temperature, $\delta PMV/\delta T_{op}$ (de Dear, 2011; de Dear et al., 2013). It is suggested that $\delta PMV/\delta T_{op}$ for the sampled children is equal to 0.23 when children's metabolic rate is taken as 1.2 during sedentary activities with average clothing level of 0.7 clo (Haddad et al., 2014). Notwithstanding that the Griffiths coefficient of 0.5/K is questioned in de Dear et al. (2013), the alternative value using the PMV/PPD model could not be determined with certainty for children, more likely because of the sensitivity of PMV/PPD model to variables like metabolic rate which are not validated for children (Haddad et al., 2014). The Griffiths constant is also taken as G=0.29/k based on de Dear (2011) and de Dear et al. (2013) for the comparative purposes.

Table 1 shows that the neutral temperature derived from Griffiths value of 0.50/K (Nicol and Humphreys, 2010) is higher than that calculated from the regression analysis of the mean TSV against T_{op} or predicted by $\delta PMV/\delta T_{op}$. However, due to the relatively small number of school buildings participating in this study compared to the ASHRAE database, the method used in the SCATs database using the Griffiths constant (G=0.50/K) seems to be appropriate for the calculation of thermal neutrality; application of the regression method to derive neutrality may fail to produce statistically significant regression models with the outdoor climate. The sensitivity of the results to the selected value of the Griffiths constant is examined in order to derive adaptive comfort equation for sample children.

5.2 The prevailing mean outdoor air temperature

This section examines different functions of the outdoor temperature calculated from the following methods for comparative purposes: the average daily air temperature, the arithmetic average considering the last 30 days prior to the day in question, and the exponentially weighted running mean temperature with various decay values (α set to 0.45, 0.65, and 0.8). Figure 1(a) shows the overlay of prevailing mean outdoor air temperatures during spring 2013; the grey shaded area refers to the survey period coinciding with the warm season of the school year. Outdoor mean daily air temperature shows the greatest variability, while arithmetic average of the last 30 days shows the smoothest oscillation. The running mean with α=0.45 and α=0.65 provide a faster response running mean to outdoor weather transients in more recent days than α=0.80. Figure 1(b) illustrates the impact of the different decay values (α) on the amplitude of the ASHRAE 55 upper 80% acceptable indoor temperature responses to outdoor weather transients during the survey period. It reveals that weather variability with α=0.45 and α=0.65 is greater compared to other functions. The curve corresponding to α=0.45 in Figure 1(b) indicates a warming response in the acceptable indoor temperature limit by about 2.5 K from day 225 to 235, while the rise is reduced to about 1.5 K when α=0.8 is used in the exponentially weighted running mean temperature.

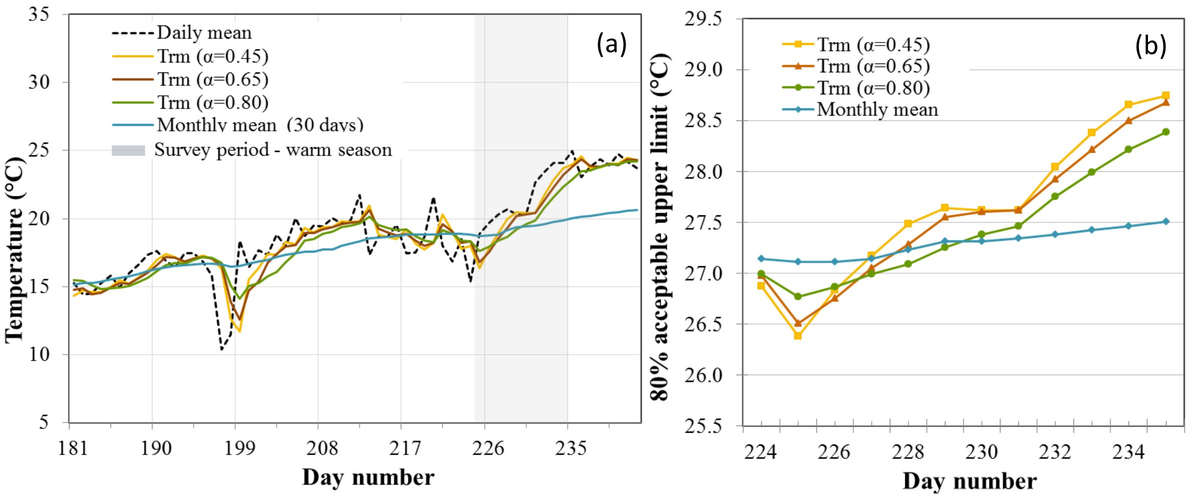

Figure 1. Various functions of prevailing mean outdoor temperature-variation from March to May 2013(a), Effect of different running mean outdoor temperature functions on the upper 80% acceptable temperature limit in ASHRAE 55 adaptive comfort standard-variation during the survey period between days 224 and 235(b)

5.3 Relationship between children's comfort and outdoor climate

5.3.1 Sensitivity of regression equation to the values of G and α

A sensitivity analysis is performed to obtain the appropriate values of G and the running mean constant (α) for the sampled children and better understand the relationship between children's indoor comfort temperature and outdoor climate. As Teli et al. (2015) noted, the optimum values of both constants G and α need to be determined for children since these values were derived from adult based adaptive comfort databases (de Dear and Brager, 1998; McCartney and Nicol, 2002). Although the context of this field study differs from European countries involved in the SCATs project, the analysis methods used for the study of SCATs data (Humphreys et al., 2007; Nicol and Humphreys, 2010; Humphreys et al., 2013) are adopted here. This is mainly because of the small sample of children compared to the ASHRAE database, and limited indoor operative temperature changes during the survey period.

In this study, the comfort temperature for each individual TSV is calculated based on Eq.1 using various values of 'G'. For the purpose of the sensitivity analysis, values of Griffith constant are taken as 0.5 and 0.4 (Nicol and Humphreys, 2010), 0.29 based on $\delta PMV/\delta T_{op}$ (de Dear et al., 2013), and 0.23 based on $\delta PMV/\delta T_{op}$ from data obtained in this study. A suitable measure of the outdoor temperature and the optimum value of α should be obtained using data from the children's thermal comfort survey to correlate with the calculated value of neutral temperature. Different values of α were employed to calculate the running mean of outdoor temperature, using Eq.2, ranging between 0.33 and 0.90 similar to values used in the analysis of the SCATs database (McCartney and Nicol, 2002); each value suggests different durations of adaptation (Table 2). Prevailing mean 7-days, daily and monthly mean temperatures are included in the analysis for comparative purposes (Table 3).

Table 2 summarizes the sensitivity analysis of chosen values of G and α as described above. It includes the correlation coefficient (*r*) between the exponentially weighted running mean outdoor temperatures resulting from different values of α and the comfort temperatures calculated from children's TSVs using the data from all sample schools combined. It should be noted that all reported values are statistically significant (P<0.001). Table 2 suggests that the correlation between the comfort temperature and the outdoor running mean temperature for all values of G is strongest when α=0.45. However, for each value of G, the values of correlation coefficients are not very sensitive to the values of α. As depicted from the table, G=0.5 appears to be the optimal value of G for the sample children; the higher values of the Griffiths constant provide the larger correlation coefficients. This is likely explained by the fact that occupants' comfort temperature derived from this value of G is related to the operative temperature, and that operative temperature correlates to the outdoor temperature in naturally ventilated buildings (Nicol and Humphreys, 2010).

Table 2. Pearson correlation of neutral temperature calculated for each individual student from Eq.1 with running temperature calculated from Eq.2 for NV school buildings using various values of G and α

G [a]	T_{rm} [b] using α					
	α=0.33 λ~1	α=0.45 λ~1.3	α=0.65 λ~2	α=0.7 λ~2.3	α=0.8 λ~3.5	α=0.9 λ~6.9
0.50[c]	0.355	0.363	0.361	0.360	0.354	0.347
0.40[c]	0.225	0.231	0.230	0.231	0.227	0.223
0.29[d]	0.061	0.070	0.067	0.070	0.068	0.067
0.23[e]	n.s	n.s	n.s	n.s	n.s	n.s

[a]:G = Griffiths constant
[b]:T_{rm} = Exponentially weighted outdoor running mean temperature
[c]: Values of Griffith constant are taken based on Nicol and Humphreys (2010)
[d]: Based on $\delta PMV/\delta T_{op}$ taking data from SCATs database (de Dear, 2011; de Dear et al., 2013).
[e]: Based on $\delta PMV/\delta T_{op}$ taking data from the sample schools

In addition to occupants' adaptive behaviour, outdoor running mean temperature could reflect the effects of the building fabric on the operative temperature (Nicol and Humphreys, 2010). According to Humphreys et al. (2015, p.306) the value of α is an indicator of "the thermal inertia of the building together with the delayed behavioural responses of the occupants to temperature changes within the building". Thermal inertia decreases the temperature swings and leads to some time-lag between the indoor and outdoor environment (Nicol and Humphreys, 2010). Due to the effect of building thermal inertia on the optimal value of α, more study in both medium and light-weight schools and within an expanded range of indoor and outdoor temperature is desirable to draw a conclusion on the appropriate value of α for children.

Table 3 compares different metrics of the outdoor temperature. The optimum value of G=0.5/K is selected to calculate thermal neutrality for each individual student as explained above. Children's comfort temperatures are regressed against various measures of the outdoor temperature including monthly mean, daily mean, prevailing mean 7-days, and running mean outdoor temperature where values of α vary between half-life (λ) of about one day (0.33) and seven days (0.90). Coefficients of determination (r^2) and regression coefficients are presented in Table 3.

As inferred from this table the maximum variance of comfort temperature explained by the outdoor climate occurs when running mean outdoor temperature with α=0.45 is used. It indicates a period of about three days for children's adaptation to outdoor temperature variation. However, it should be noted that the coefficient of determination (r^2) is not very sensitive to the values of α. The coefficient of determination using α=0.45 is just 0.007 higher than that when the recommended value of α for adults (α=0.80) is used. Similarly, the increment in r^2 over that obtained when α=0.65 or α=0.70 is negligible. As de Dear (2011) noted, this increment may not be statically significant.

Table 3. Comparison of different metrics of the outdoor temperature using G constant=0.5/K

Metric of outdoor temperature	**B[a]**	r^2
Monthly mean	1.426	0.130
Daily mean on which the survey took place	0.291	0.119
Prevailing mean 7-days	0.394	0.115
T_{rm}: α = 0.90 (2λ ~ 14days)	0.552	0.121
T_{rm}: α = 0.80 (2λ ~ 7days)	0.328	0.125
T_{rm}: α = 0.70 (2λ ~ 5days)	0.276	0.130
T_{rm}: α = 0.65 (2λ ~ 4day)	0.258	0.130
T_{rm}: α = 0.45 (2λ ~ 3day)	0.246	0.132
T_{rm}: α = 0.33 (2λ ~ 2day)	0.234	0.126

[a]: Regression coefficient of individual student's comfort temperature (G=0.5) on outdoor temperature

5.3.2 Regression equation between children's indoor comfort and outdoor climate

Two methods are employed to establish adaptive comfort equations for the sampled children as summarized in Table 4: regressing children's mean comfort temperature per survey on the running mean of outdoor temperature with the optimum value of the Griffiths constant and α (G=0.5, α=0.45), and with the same value of G and the recommended value for α of 0.80 (Humphreys et al., 2015; Humphreys et al., 2013).

The adaptive comfort equation was also derived based on the methods used in ASHRAE RP-884 where neutral temperature in each building is derived from regression analysis of the thermal sensation in relation to the operative temperature. However, regressing neutral temperatures obtained for each investigated school, from the linear regression model of the mean TSV against T_{op}, on the prevailing outdoor temperature failed to reach statistical significance (*p*-value>0.05). This is more likely because neutrality was derived from a small sample of schools. In other words, the sample size was not large enough to yield a robust and accurate relationship between school's indoor comfort temperature and the outdoor climate. More observations from several schools would be desirable to better understand the relationship between neutral temperature and the outdoor climate when school's comfort temperature is derived from the regression model.

For comparative purposes, Table 4 includes adaptive comfort equations outlined in Humphreys et al. (2015), ASHRAE 55 (2013) and EN15251 (2007) adaptive comfort standards, and regression equation proposed for adults from the same cultural background (Heidari, 2014). According to Heidari (2014, p.114) α=0.80 is a reasonable value for adult subjects in Iran. Children's comfort equation based on children's individual responses in a medium-weight school in the UK is also included in Table 4, where T_{rm} is calculated from a value of α=0.80 (Teli et al., 2015).

Comparison of the methods used to obtain adaptive comfort equation from children's mean comfort temperature per survey indicates that regression equation using Griffiths method with value of G=0.5, and α=0.45 provides a shallower regression slope and a higher coefficient of determination ($P<0.0001$, $r^2=0.583$) than the same method using α=0.80 ($P<0.0001$, $r^2=0.556$). As noted previously, despite a small difference between the r^2 statistics, α=0.45 seems to be suitable for use in the investigated schools. A similar result has been found when children's comfort temperature was calculated from each individual comfort vote and regressed against the outdoor running mean temperature.

Table 4. Adaptive comfort equation for different characterization of the outdoor temperature

Database	**Adaptive comfort equation**	**Metrics of climate**	
Humphreys et al. (2015)	$T_{comf} = 0.53T_{rm} + 13.8$	T_o [a]	-
ASHRAE55 (2013)	$T_{comf} = 0.31T_{pma(out)} + 17.8$	$T_{pma(out)}$ [b]	-
EN15251 (2007)	$T_{comf} = 0.33T_{rm} + 18.8$	T_{rm} [c]	α=0.80
Heidari (2014)	$T_{comf} = 0.36T_{rm} + 17.6$	T_{rm} [c]	α=0.80
Teli et al. (2015)[d]	$T_{comf} = 0.19T_{rm} + 19.1$	T_{rm} [c]	α=0.80
This study-warm season [e]	$T_{comf} = 0.34T_{rm}+17.6$	T_{rm} [c]	α=0.80
This study-warm season [f]	$T_{comf} = 0.25T_{rm}+19.1$	T_{rm} [c]	α=0.45

[a]:T_o: Prevailing mean outdoor temperature. In case of running mean temperature α=0.80.
[b]:$T_{pma(out)}$=Prevailing mean outdoor temperature. In case of running mean temperature: 0.6<α<0.9
[c]:T_{rm} :Weighted running mean of outdoor temperature
[d]: calculated T_{comf} from all individual responses ($r^2=0.029$)
[e]: calculated T_{comf} per survey based on Griffiths method (α=0.80- $r^2=0.556$)
[f]: calculated T_{comf} per survey based on Griffiths method (α=0.45- $r^2=0.583$)

The resulting regression equation with the value of α=0.45 in Table 4, was solved to find the operative temperature range that would be thermally neutral for the sampled children. It is revealed that the mean indoor comfort temperature per survey varies between 23.2°C and 25.2°C when the outdoor T_{rm} ranges between 16.5°C to 24.2°C during the survey period. The neutral temperature of 23.2°C at the outdoor running mean temperature of 16.5°C is the same as the comfort temperature calculated from the weighted regression model of the mean TSV as a function of the classroom operative temperature binned into 0.5°C intervals ($TSV_{(mean)}= -6.251 + 0.268\times T_{op}$, $r^2=0.82$, $P<0.001$). The adaptive comfort equation suggests that the sampled children were capable of tolerating indoor temperatures up to 25.2°C when the outdoor running mean temperature was high (T_{rm}=24.2°C); this is 2 °C higher than predicted neutral temperature from the above equation.

Table 4 implies that children's adaptive comfort equation using Griffiths method and α=0.80 is remarkably similar to that of adults from the same cultural background over hot conditions (Heidari, 2014, p. 109), although statistically a less reliable correlation compared to the former method when a value for α of 0.45 is used. Despite different indices used to represent outdoor climate, the comparison between the neutral temperatures derived for the sampled children and those predicted by the ASHRAE 55 adaptive equation as a function of the outdoor running mean temperature provides similar results. As can be seen from Table 4, the gradient of children's regression equation when α=0.45 is considerably shallower than those of adults in the EN 15251(CEN, 2007), and other adult-based studies (Heidari, 2014; Humphreys et al., 2015). This could be an artefact of the different measures of outdoor climate used in this study, α=0.45. The shallower regression gradient may indicate a weaker relationship between the children's neutral temperature and the outdoor temperature change. It can be noticed that in the same climate the sampled children feel comfortable at cooler temperatures than adult subjects. At higher outdoor temperatures, sampled children in the investigated schools showed up to 2°C lower neutral temperatures than adults in office buildings. Similar to the results of this study, Teli et al. (2015) found a shallower regression slope and a weaker climatic adaptation in the medium-weight schools compared to adults; however, a different measure of outdoor climate was used (α=0.80).

In Humphreys et al. (2015, p.309) the scatter of the points around the regression line relating comfort temperature to the prevailing mean outdoor temperature is not a random error but rather indicates real differences between the neutral temperatures of subjects at any prevailing mean outdoor temperature. According to the same study a temperature band is preferable to a line for representing the relationship between comfort temperature and prevailing mean outdoor temperature. However, this band may not be identical for children and adults based on Teli et al. (2015). Figure 2 shows the scatter plot of the comfort temperature per survey against the exponentially weighted running mean outdoor temperature when α=0.45 (r^2=0.58, P<0.0001). The band consists of 95% of the neutral temperatures per survey. The comfort temperature band seem to be narrower in case of sample children than that of adults as obtained in Humphreys et al. (2015, p.308). It can be inferred from Figure 2 that the upper limit of comfort temperature is lower for children, which is critical for classroom's thermal performance during warm days of the school year.

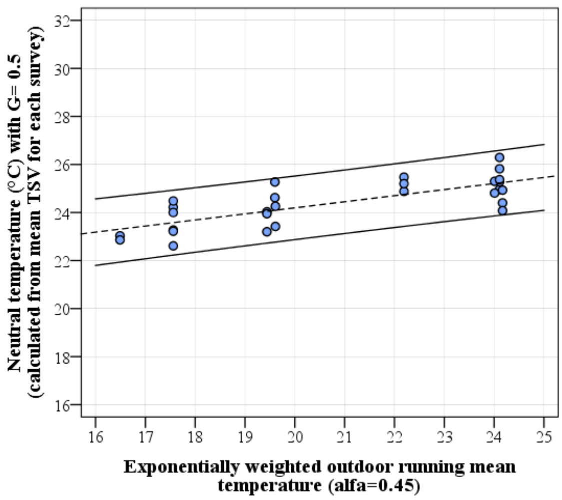

Figure 2. The classrooms' neutral temperatures (°C) per survey against the running mean outdoor temperature (°C)

6 Conclusion

This paper investigates the methods used to develop the adaptive thermal comfort equation relating children's neutral temperature to the outdoor climate. It draws on a total of 811 thermal comfort study responses gathered from naturally ventilated classrooms in 4 school buildings during the warm season in Iran. The differences between the methods used to develop adaptive comfort equations in ASHRAE55 (2013) and EN15251 (2007) standards are explained. The principal stages in the construction of the adaptive comfort equation based on children's responses from thermal comfort field survey are justified. Correlation analysis is performed to show the sensitivity of the derived equation to the choices made at each stage of analysis. The neutral temperature is obtained using various methods and a suitable metric for climate axis is defined from the survey data. The sensitivity of the results to the values chosen for the Griffiths constant and 'α' are examined. From the analysis result it seemed appropriate to choose 0.5 as the Griffiths constant for the sampled children; however, the need for a validation study is proposed. The analysis of data presented in this paper shows that the preferred metric for the prevailing outdoor temperature is the exponentially weighted running mean outdoor temperature, with a value of α in the region of 0.45. A running mean with an α of 0.45 seems to better correlate with children's comfort temperature which means that the range of running mean temperature is greater for children than for adults. This finding suggests that the children or their parents are responding to changes in the weather more quickly than adults (Nicol and Humphreys, personal communication, June 2015).

The adaptive comfort model derived for the sampled children has a shallower regression slope compared to adults' adaptive equations. The smaller regression coefficient may be explained by different explanatory variable, running mean temperature, in the two cases. Moreover, it may suggest that the children are adapting to the outdoor changes more quickly, but less completely than adults would. In this investigation, children's neutral temperatures ride lower than the ASHRAE 55 and EN 15251 models for NV buildings. At higher outdoor temperatures, the upper limit of indoor comfort temperature for children is up to 2°C lower than that for adults. It is therefore suggested that children might need different comfort criteria than those of adults with stricter upper temperature limits during warm seasons. The implications of additional comfort cooling could be significant for schools' energy demand. The results presented in this study contribute to a growing understanding of adaptive thermal comfort for children in school buildings. Further work in a larger sample of school buildings with different construction types, and reflecting different cultures and climates may improve the expression of outdoor temperature and comfort indoors for children which is important to understand the most logical explanation for different pattern of children's adaption to outdoor climate.

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Are Modellers literate? - studying the relation between literacy of building modellers and the performance gap.

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Abstract

One of the most discussed issues in the design community is the performance gap. In this research, we investigate whether part of the gap might be caused by the modelling literacy of design teams. 108 building modellers were asked to comment on the importance of obtaining and using accurate values for 21 common modelling input variables, when estimating annual energy demand by dynamic simulation. The questioning was based on a real domestic dwelling for which high resolution energy data had been recorded. A sensitivity analysis was then conducted using a model of the building by alternating one parameter in each simulation. The effect of each alteration on the annual energy consumption was found and a ranked list generated. The order of this list was then compared to that given by the modellers for the same changes in the parameters. A spearman-ranking value of 0.43 was found and an R^2 value of 0.28, which indicates little correlation between which variables were thought to be important and which proved to be. In addition, there was no correlation between modellers, with many ranking some parameters as important that other thought irrelevant. Using a three-part definition of literacy it is concluded that this sample of modellers, and by implication the population of building modellers, cannot be considered literate. This suggests an opportunity and need for both industry and universities to increase their efforts with respect to building physics education, and if this is done, a part of the performance gap could be closed.

Keywords: literacy, building modellers, simulation, performance gap.

1 Introduction

Many policies and actions are being implemented by governments with the aim of reducing greenhouse gas emissions. In developed countries, buildings commonly account for up to 40% of such emissions (Perez-Lombard, Ortiz and Pout , 2008), making them a clear focus. Unfortunately, there is a proven gap between the energy use generated by models of buildings used to aid their design and ensure compliance with national building codes, and monitored energy consumption of the buildings once built. Many researchers claim that the measured energy consumption is frequently twice or more than that of the design stage prediction (Johnstona et. al., 2014; Menezes et al., 2012; De Wilde, 2014), and although many studies have explored the performance gap from various perspectives, such as the role of poor workmanship or occupants' behaviour, the literacy of building energy modellers is rarely questioned. In addition, the literature indicates that in general professionals (architects, engineers, sustainability experts, etc.) do not tend to criticize themselves and thus a culturally embedded lack of reflection might contribute to the performance gap (Johnstona et. al., 2014; Menezes et al., 2012; De Wilde, 2014; Zero Carbon Hub, 2014).

Modelling professionals are limited in the time they can apportion to any project and hence need accurate inbuilt knowledge of the impact of modelling any element of the building in less than ideal detail might have. For example the impact of missing out a thermal bridge. The basis for these judgment calls might be in part based on experience, but it is likely to also be embedded within an organisation or just commonly accepted within the modelling community (van Knippenberg et. al., 2002; Sani, 2005). Professionals in general are known to be open to change if evidence is presented (Morton, Postmes and Jetten, 2007), and this paper attempts to provide this evidence in a robust way, by asking the question, how accurate in general are such professionals' judgments?

2 Background

2.1 Literacy

The United Nations Educational, Scientific and Cultural Organization (UNESCO) defines literacy as the "ability to identify, understand, interpret, create, communicate and compute, using printed and written materials associated with varying contexts. Literacy involves a continuum of learning in enabling individuals to achieve their goals, to develop their knowledge and potential" (UNESCO, 2004). Some have argued that this definition of literacy should be expanded to include the capability to use computerized tools efficiently and correctly (Kress and Gunther , 2003).

There is no single method to monitor and measure literacy levels, but there are various methodologies that can be followed depending on the aim of the study. According to UNESCO, "typically countries measure literacy levels by undertaking self-assessment questionnaires and/or by means of a proxy variable utilizing the number of years of primary schooling (i.e., 6 or 8 years of primary schooling equals a literate person), typically literacy rates are assigned so that people over 15 years of age are designated as literate" (Wagner, 2006). Unfortunately, this does not give a robust method for measuring literacy levels in other settings. An alternative is to use tailored questioning to assess literacy.

There are many ways one might define literacy with respect to building physics and thermal modelling, and we are after a measure which is more independent and about modelling in general, not about a certain simulation package or method. The assessment method also needs to provide a numeric result or a ranking in order that a quantitative assessment of literacy can be made.

Here we suggest a suitable requirement for literacy within a population to have been demonstrated is that we might expect that when given a real project the population of modellers should: **1.** approximately agree on the important parameters that need to be included in the model; **2.** approximately agree on the rank order of the importance of a list of possible input parameters; **3.** that their rank ordering of the impact of given changes (perturbations) to the values of these parameters should approximately agree with that given by a sensitivity analysis of the parameters within a thermal model.

2.2 Building Energy Modelling

Researchers have noted the influence that the building design industry has had on building performance simulation (BPS) tools and vice versa. This development has meant more complexity without evidence that the complexity is manageable by all professionals (Attiaa et al., 2012). For example, architects are regularly using BPS tools, despite them being described as generalists (Morbitzer et al., 2001; Ibarra and Reinhart, 2009; Schlueter and Thesseling, 2009; Augenbroe, 2002; Hand and Crawley, 1997; Mahdavi et al., 2003).

Many studies highlighted that most tools available are inadequate to deal with early design stages. Furthermore, they are not user friendly (Lam et al., 2004; Reither et al., 2009; De Herde et al., 2009B; Weytjens et al., 2010). The building simulation industry became aware of this and tried to tackle it by producing more friendly interfaces. However, many barriers still exist in using these tools (Attiaa et al., 2012).

It has been argued that the most important capabilities of these tools are *usability*, *computing ability*, *data-exchange* and *database support* (Tianzhen, Chou and Bong, 2000). Researchers have also stated the importance of what they called "functional criteria" of BPS tools, which again addresses the question of usability (Augenbroe, 2002). Despite researchers' concerns about usability, tools over the years have became more and more complex.

Attia et al. (2012) performed a survey with approximately 150 architects, with the aim of ranking the selection criteria of BPS tools according to their importance from the user point of view. Results showed that model intelligence had the highest priority (Figure 1). (The study defined model intelligence "as the ability to advise the user with design optimisation options based on a range of early stage input.") Accuracy was considered the least important (Attiaa et al., 2012).

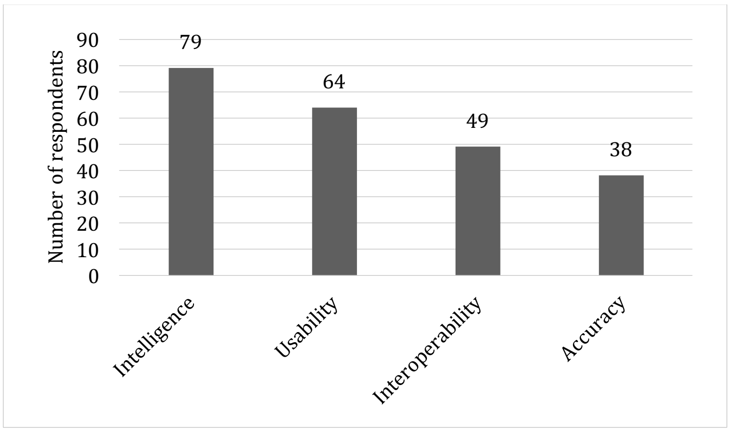

Figure 1: Architects' ranking to the importance of simulation tool features (data from Attiaa et al., 2012).

2.3 The Performance Gap

The literature indicates that a disconnect between modelled and actual performance can occur in each of the three broad stages of: design, construction and operation (Johnstona et. al., 2014; Carbon Trust, 2011).

- **The design gap**

Many studies have concluded that the design phase is a frequent cause of the gap (Carbon Trust, 2011; De Wilde, 2014). Reasons include misunderstanding of the design performance targets between design team and client, or even between the design team members (Newsham, Mancini and Birt, 2009). In addition, De Wilde (2014) pointed out that even if the design itself is properly outlined, underperformance can still occur if the design team did not take into consideration buildability, simplicity or the construction sequence. Other papers have focused on the specification of advanced systems and technologies due to the level of complexity of the system and its controls (De Wilde, 2014).

The 2014 Zero Carbon Hub report "Closing the Gap" observed that professionals have a limited understanding of the impact of their design decisions on the actual energy performance (Zero Carbon Hub, 2014). For example, how much might improving the U-value by 10% reduce heating energy consumption in a particular climate. But this observation was not based on a quantitative assessment, and is hence questionable.

Knowledge of the impact of uncertainties in the design stage is another level of literacy that is understudied, and it is unknown if practitioners gain the required knowledge to address this after many years of experience or not, but given that few buildings are monitored after construction by their designers, this seems unlikely.
It is known that incorrect use of simulation tools will result in unreliable predictions at the design stage, which will lead to the gap later on, therefore, the user has to have a minimum level of knowledge and skills to be able to use these tools properly (Dwyer, 2012). De Wilde (2014) pointed out that the required knowledge includes the ability to define correct input data within the model (De Wilde, 2014). Nevertheless, even with an experienced user, many predictions will still be inconsistent and lacking in certain areas, mainly arising from issues of uncertainties such as occupancy behaviour and weather data (Menezes et al., 2012).

- **The construction gap**

Another issue that can cause a performance gap is the construction process. Many studies, including industry reports and papers analysing various scales and types of case studies, have pointed out that the onsite construction quality often does not agree with design specifications. More particularly, there is a lack of attention to aspects related to insulation and airtightness (Menezes et al., 2012; Almeida et al., 2010; De Wilde, 2014). In many cases, both builders and engineers are responsible for the resultant discrepancy in buildings performance, but studies are not able to identify nor quantify the exact source of the gap.

- **The operational gap**

A building’s operational stage is repeatedly cited to be a major reason for the discrepancy with the design stage predictions. More particularly, studies often put the blame on occupants' behaviour (Korjenic and Bednar, 2012; Menezes et al., 2012; Haldi and Robinson, 2008; De Wilde, 2014). Menezes et. al. (2012) suggested that by using proper post occupancy evaluation data, more knowledgeable design stage assumptions might be possible in future and hence reduce this contribution to the gap (Menezes et al., 2012). However, such data is rarely collected.

3 Building simulation modelling

3.1 Case study building

The particular building chosen in this study was a typical UK semi-detached house, which was recently renovated to meet the L1B requirements (essentially an upgrade to the relevant building codes). The building was modelled in detail using IES and the model validated using hourly measured gas, electricity, occupancy and indoor temperatures.

3.2 Modelling approach and limitations

Weather input data: Observed weather was recorded for the project from a weather station approximately 3 miles from the house. This gave, dry bulb temperature, wet bulb temperature, atmospheric station weather, relative humidity, wind direction and wind speed. Radiation data were taken from the World Meteorological Organization's website for Camborne (the closest available location) with similar climate characteristics and hourly measured weather data (2004-2014). Other data were from the EPW for London.

Heating use: System use was determined based on observations of measured energy consumption, and indoor temperature variations for each space. The heating set-point ($21^{o}C$) was based on the measured indoor temperature.

Building geometry: Internal and external dimensions and openings of the case study building were modelled carefully using to-scale drawings.

Surroundings: The surrounding environment of neighbouring buildings were modelled in detail as they provide extensive shading. The case study building has no external self-shading except for 200 mm extrusions above doors, a 100 mm extended roof perimeter and a 100 mm recession around windows and doors.

Glazing ratio: The plans gave a glazing ratio of 25% overall with 21.8% on south and north facades respectively. The east façade contains only one window, representing 2.3% of the area. Doors area was 1.6 m^2 (solid doors with no glazing).

Natural ventilation and Occupancy: Modelling natural ventilation depends on assumptions, for example, it is highly unlikely a modeller can accurately determine when and which windows will be opened, and for what length of time. Therefore, modellers usually use assumptions that are under-descriptive of the actual behaviour of occupants. For the purposes of this research, and starting from reasonable assumptions, the ventilation and occupancy were adjusted to give a high correlation between measured and simulated heating energy demand and temperature (measured on an hourly basis).

Building's envelope: The air permeability of the building envelope was not measured but set as 10 $m^3/h/m^2$ at 50 Pa in order to comply with the standard set by the building code (Part L). U-values were as detailed in (Table 1).

Table 1. U-values of case study building

Element	Modelled U-values (W/m^{2}K)
External walls	0.35
Pitched Roof	0.26
Floors	0.25
Windows	1.6
Doors	1.8
Internal walls	1.8
Internal floor/ceiling	1.0

Internal heat gains: The sensible gains for people were set to 75 W/person in accordance with the ASHRAE handbook (2013). A maximum of four people were assumed to be in the house, with occupancy linked to the measured occupancy profiles of each space. Gains from lighting were controlled based on the illuminance level required for each space and occupancy period. Finally, internal gains from equipment and cooking were assumed as an average based on the ASHRAE handbook (2013). The appliances were linked to occupancy profiles of each space in order to provide an average value of consumption. This action was performed with an understanding that not all appliances are linked to occupancy profiles, for example fridges.

3.3 Model validation: Building simulation modelling vs measured data

In order to validate the model, one year of detailed gas consumption and indoor temperature monitoring was obtained and correlated with the simulated case study results. The data was compared on hourly intervals across the entire year. The correlation between measured monthly gas consumption and the simulated model gives an R^2 of 0.93 (Figure 2). While (Figure 3 and 4) indicates a strong correlation remains on hourly basis. As illustrated in (Figures 5 and 6) a strong correlation is found between both peak and average indoor temperatures in all spaces. The model can thus be considered as validated.

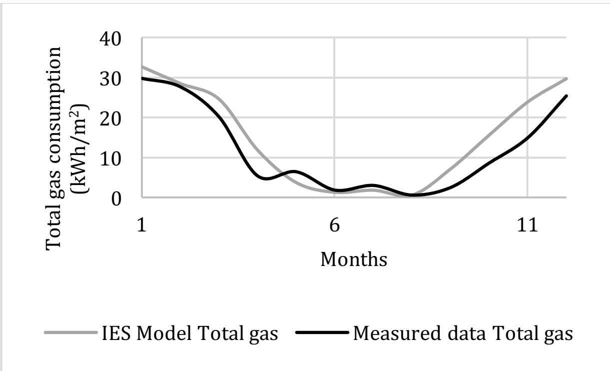

Figure 2. Monthly correlation between measured and simulated gas consumption for the case study building, *which indicates a close relation (R^2 value of 0.93)*

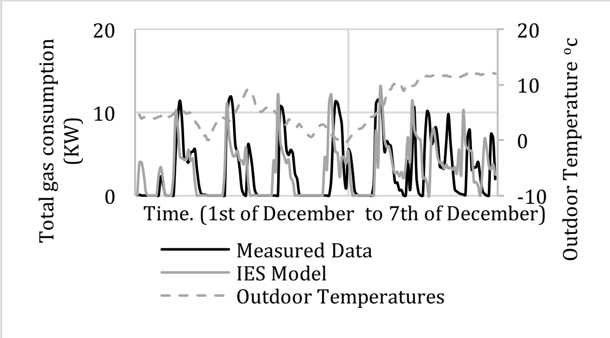

Figure 3. Simulated and measured hourly gas consumption for a week in December, in relation to measured outdoor temperatures (R^2=0.73).

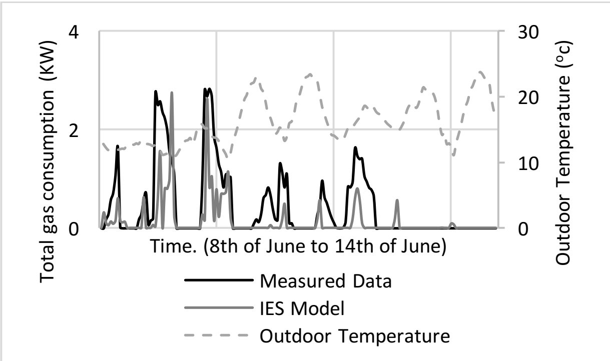

Figure 4: Simulated and measured hourly gas consumption for a week in June, which indicates a relatively close correlation (R^2 = 0.59)

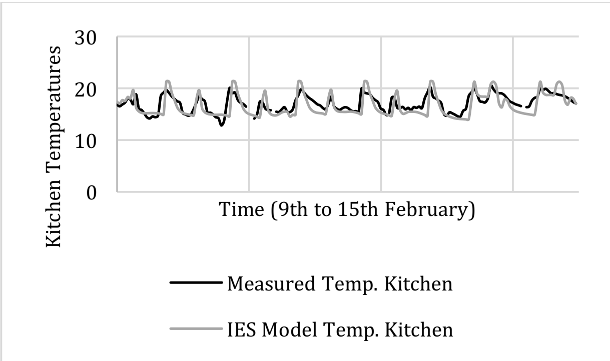

Figure 5: Plot of both simulated and measured indoor temperatures for the kitchen space for a week in February (R^2 = 0.61).

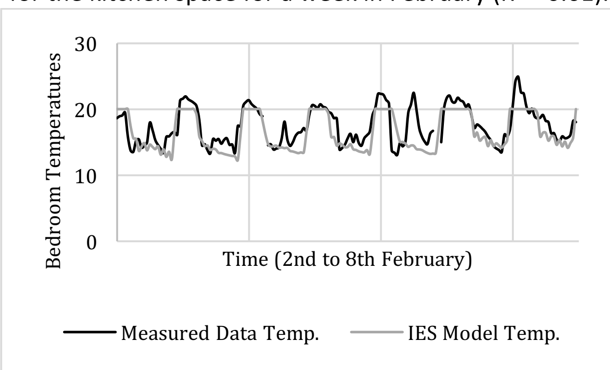

Figure 6: Plot of simulated and measured indoor temperatures for the bedroom space for a week in February (R^2= 0.63).

Table 2. Perturbations performed on each input parameter

Input parameter	Base value	Altered value	Scale of Alteration
Glazing ratio	17.3%	19%	10% > actual and modelled ratio
Installed window U-value	1.6W/m^{2}K	1.92W/m^{2}K	20% > installed and modelled value
Walls U-value	0.35W/m^{2}K	0.42W/m^{2}K	20% > installed and modelled value
Occupancy period	13hr/day	16.25hr/day	25% > the average measured and modelled period / day
Airtightness	0.25ach	0.3ach	20% > the assumed and modelled value
Roof U-value	0.26W/m^{2}K	0.31W/m^{2}K	20% > installed and modelled value
Thermal bridging	10% increase in each element U-value	Thermal bridges ignored	Ignoring thermal bridging
Winter indoor temperature set-point	21^{o}C	19^{o}C	The modelled value being 2^{o}C lower than reality
Natural ventilation	MacroFlo profiles	Constant airflow at 1ach	Assuming the air flow is constant at 1ach when occupied, against the base case of assuming windo-ws are open during occupied period, if (T_{in} > 25°C, RH > 65% or CO_2 concentration > 1000 ppm)
Ground floor U-value	0.25W/m^{2}K	0.3W/m^{2}K	20% > installed and modelled value
Building geometry	39.5m^2	32m^2	Using internal dimensions for the building rather than external
Ventilation rate	1ach	1.1ach	10% increase
Shading from surroundings	Modelled surroundings	Ignore their effect	Ignoring shading from the surround-ing homes, etc.
Windows recession	100mm	200mm	Assuming windows recessed 100mm further into the building

The position of windows in walls	Base-model position	0.5m downwards	Assuming a 0.5m vertical shift down from actual positions
Density of block used as inner leaf of wall	1.40Tonne/m^3	1.54Tonne/m^3	20% > installed and modelled value
Internal gains from appliances and lighting	52.8W/m^2	58.0W/m^2	10% > installed and modelled value
External doors opening	10 openings/day	Continuously closed	Ignoring the initial assumption that the external doors might be opened 10 times a day, each time for 30 seconds
Internal gains from cooking	12W/m^2	0W/m^2	Ignoring heat gains from cooking
Thermostat location	Thermostat only in the living room	Thermostat in each space	Assuming thermo-stats in each room
The use of curtains	Used at night	Ignore their effect	Ignoring the use of curtains at night

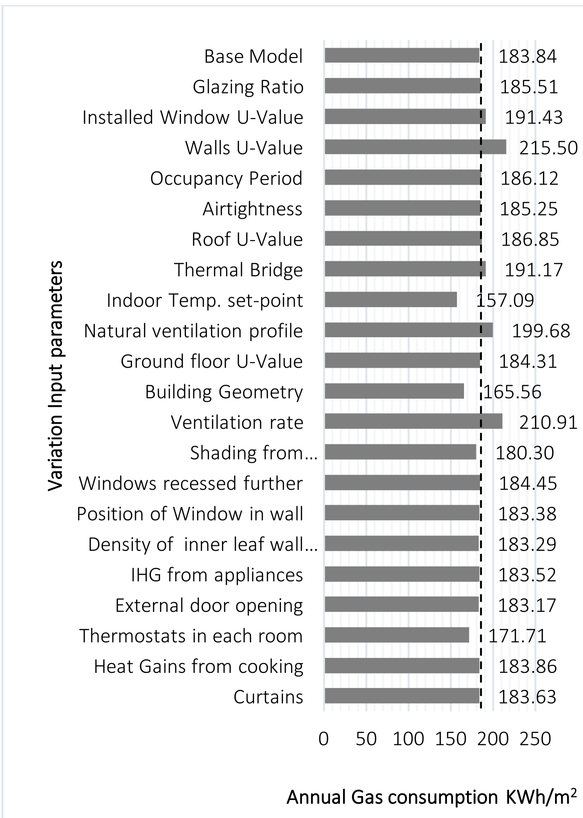

Figure 7: The impact of each perturbation on the annual gas consumption compared with the base model consumption

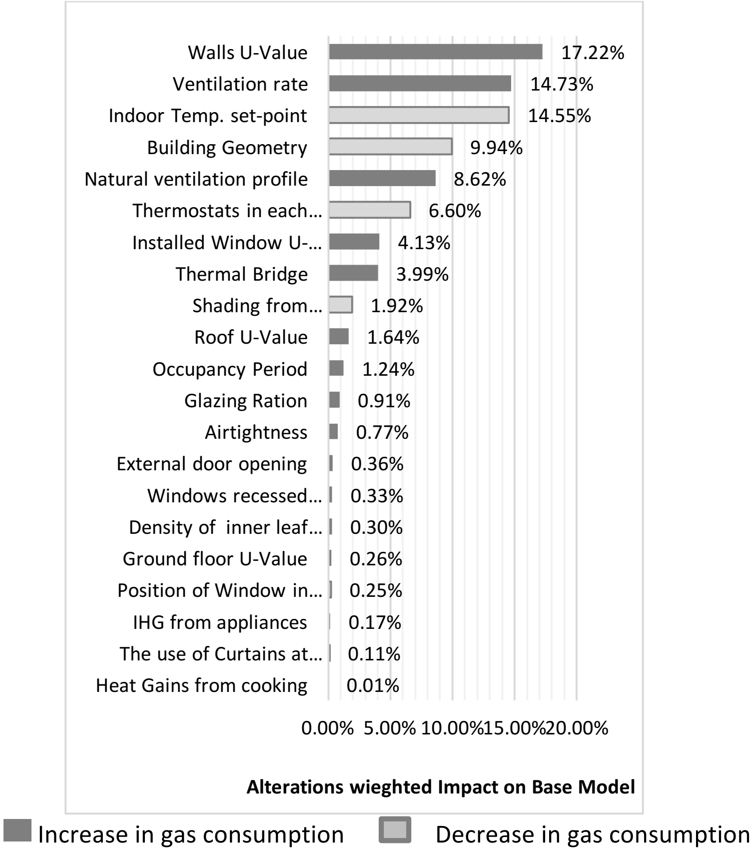

Figure 8: Weighted impact of each perturbations
on the annual gas consumption

4 Survey

4.1 Method

- **Survey design**

From a psychological perspective, "A person’s perception of how a system operates is often referred to as a mental model. This might come from educated understandings via literature and mentorships or simply from practical experimentation with the controls – and in both cases their mental model might or might not be accurate" (Gabe, Walker and Verplanken, 2015). Within this context, the survey conducted in this research aims to reveal the energy modelling "mental models" of professionals in the construction industry. This was done by asking questions using two standard social science approaches: *the free form method* and *the given list method* (Gabe, Walker and Verplanken, 2015), see (Table 3). A detailed description of the building and the surroundings (including photographs) was given to the participants.

Table 3. Survey questions and their purposes in respect to the research hypothesis

Free form method		
	Survey question(s)	**Purposes / Aims**
Q (1)	List the 3 most important parameters that if not included or included less accurately in a thermal model of the case study building, might affect the annual heating demand significantly.	To discuss any common input-parameters that participants might consider have a significant impact on the annual heating demand.

Q (2)	List 3 parameters that you might not normally include, as they do not have a great impact on the annual heating demand.	To encourage participants to include input-parameters that they might not normally consider. Hence, parameters not included in their answers, will more likely not used by participants in actual projects.
Q (3)	List any other parameters that you might include in a thermal model of the case study building and might have a moderate effect on the annual heating demand.	To give participants the chance to add any other input parameters that they might sometimes include in a thermal model of the case study building.
Structure concept	▪ Not providing users with a list of parameters - at this stage - was intentional, to not attract them to certain input-parameters that need to be included in the model. ▪ Clarify what participants can take or not take into consideration in a thermal model of the case study building and to identify their natural thoughts regarding the modelling stage assumptions. ▪ Dividing this section into 3 questions was to limit the answers to 3-5 options, making it easier for participants to understand [32].	
Given list of input-parameters method		
Survey question(s)		**Purposes / Aims**
Q (1)	Rate the list of parameters provided in the survey based on your judgement of impact on annual heating demand due to variations applied to each parameter (Table 2).	▪ Identify the perception of the design team of potential errors due to some parameters and their effect on the annual heating energy demand. ▪ The answers were obtained in a form of a "ranking list" and compared with the "accurate ranking" obtained from the validated simulation model. ▪ This comparison set forms the base for evaluating their modelling literacy.
Notes	▪ Details of the case study building was clearly illustrated to participants in the survey. ▪ Once participants proceeded from the "free form" question to the "given list" question, they were not able to return back and edit their responses. Hence, the case study description was repeated to be accessible while answering both questions. ▪ The "error factors" applied to each input-parameter were assumed to be due to lack of knowledge in the design stage or poor workmanship on-site.	

- **Sampling method**

The target respondents were chosen from professionals in the construction industry: architects, engineers and energy analysts. All of whom made regular use of dynamic thermal models. Random sampling (Bryman, 2013; Holt and Walker, 2009) was used to generate the population sample.

- **Participants**

Participating employees were from engineering and architectural firms involved in the design process of a range of national and international projects, and included some of the world's largest engineering and architecture practises. Emails were sent to directors to ask whether it was possible to visit their firm to ask employees to complete the survey. Many replies welcomed the idea, resulting in 31 respondents. The online questionnaire was also sent directly to professionals drawn from LinkedIn and respondents were also garnered by posting on online building energy modelling groups, resulting in an additional 77 respondents. The whole process resulted in 108 participants who completed the survey; a further 12 participants failed to fully complete it. Questionnaire results were anonymous. The names of the firms participating in the survey cannot be reported due to confidentiality.

(Figure 8) shows the nature of participants, in terms of years of experience in the construction industry. The highest academic degree achieved related to this field was reported as: bachelors (34 participants), masters (66), PhD (8). 81% of respondents selected IES VE as the simulation software they use for energy analysis.

Figure 9. Participants' years of experience in the construction industry

4.2 Results

- **Free form method**

In this form of the survey participants were not given a list of parameters to choose from, but asked to separately list parameters they considered highly important, moderately important, or unlikely to be important. Parameters listed by participants for this form are shown in (Figures 10, 11 and 12).

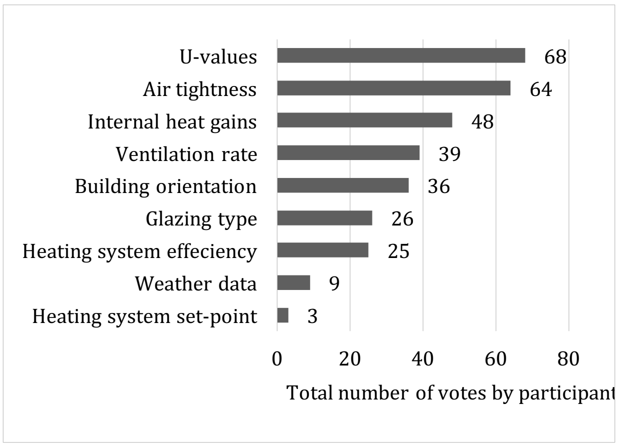

Figure 10. Question 1: Input-parameters assumed by participants to have a significant impact on the annual heating demand.

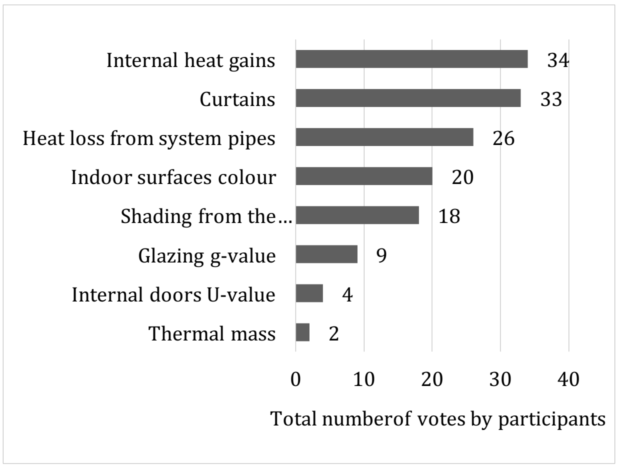

Figure 11. Question 2: Input-parameters that participants might not normally include in a thermal model of the case study building.

4.2.1

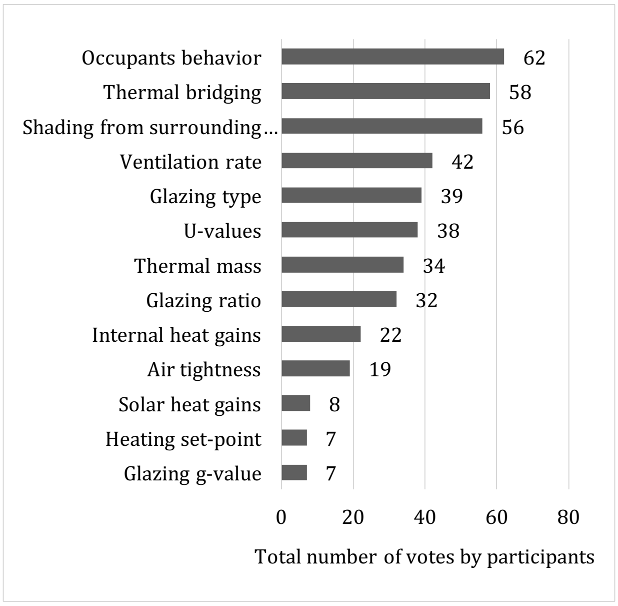

Figure 12. Question 3: Input-parameters assumed by participants to have a moderate impact on the annual heating demand.

- **Given list method**

For this part of the survey, participants were given a list of 21 input parameters and the perturbations used in the sensitivity analysis (see Table 2 and 3). Participants were asked to indicate the relative size of impact for each parameter variation on the annual heating demand by scaling them from 1 to 5. The ranking given by the participants is shown in (Figure 13). The weighted average for any parameter was calculated as:

$$\frac{x_1\,w_1 + x_2\,w_2 + x_3\,w_3 \ldots x_5\,w_5}{Total\ number\ of\ respondents}, \qquad (1)$$

where *x* is the response (1-5) and *w* is the response count.

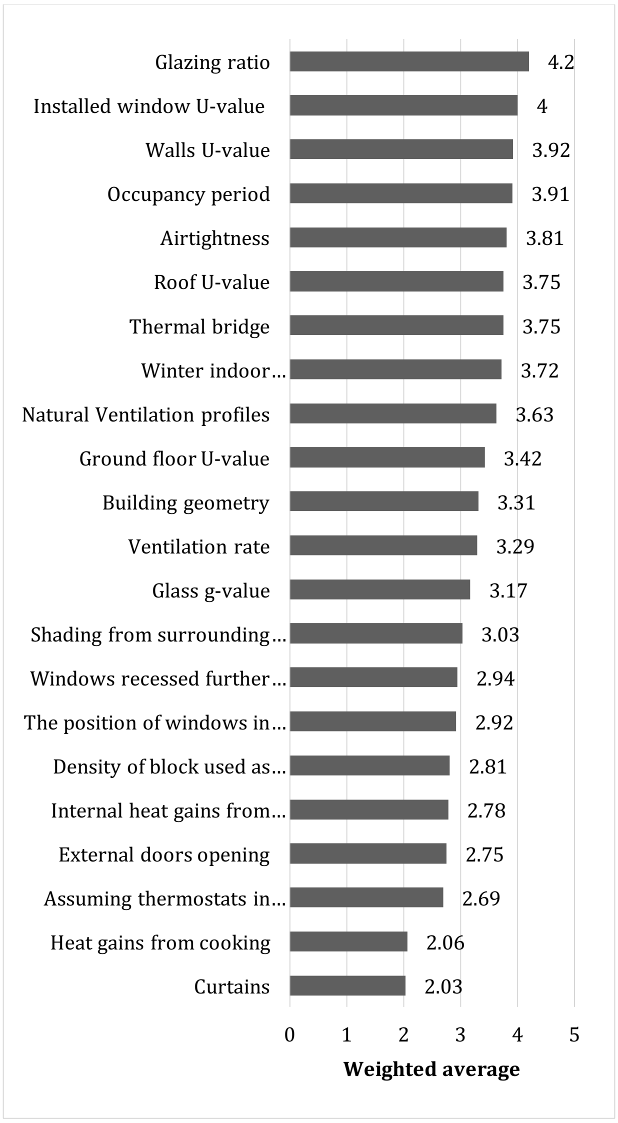

Figure 13. Ranking of the given parameters based on a total of 108 participants (Equation 1) when asked to indicate on a scale of 1-5 the relative size of impact for each parameter on the annual heating demand.

4.3 Results and discussion

- **Un-mentioned parameters**

Re-plotting the freeform results so as to concentrate on parameters not mentioned by one or more individuals provides some surprising results (Figure 14). All parameters were subject to being overlooked except U-values. For example, although "internal heat gains" was mentioned 104 times out of 108 responses, 34 participants considered it to be the type of parameter that they would not normally include in such a dynamic model. Similarly, 18 participants considered the inclusion of shading from the surrounding environment to not be worth including, whereas 56 respondents highlighted this parameter to be considerably important. This is still surprisingly low given that participants were provided with a photo of the surrounding area that shows the building is surrounded by buildings of a similar height.

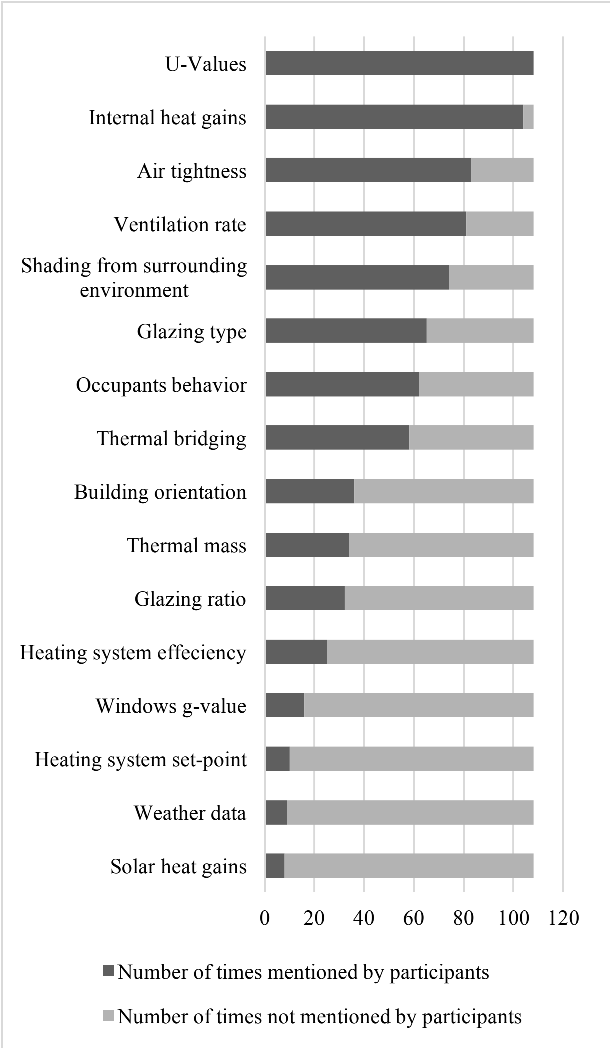

Figure 14. The most impactful input-parameters mentioned by participants in the freeform question highlighting the number of times each parameter was not mentioned.

- **Comparing and contrasting the results from both survey methods**

Comparing the results obtained from both methods highlights that a parameter's ranking can differ significantly. For example, in the freeform question, 70% of participants did not mention *glazing ratio*, while 42% and 23% did not include *occupancy period* and *airtightness* respectively. Whereas, the top 5 ranked parameters in the given list question included all 3 parameters as shown in (Table 4).

Table 4. Comparison between the Top 5 ranked input-parameters in the "given list" question and the number of times participants did not mention these parameters in the "free form" question.

Top 5 ranked input parameters	
Given list method	Number of participants who did not mention this parameter (Total of 108 participants)
Glazing ratio	76
Installed window U-value	0
Walls U-value	0
Occupancy period	46
Airtightness	25

One of the clearest differences between the participants and the ground truth provided by the model is in the impact of changing the glazing ratio (a 10% increase in glazing ratio was presented to the participants and modelled). Although assumed by the participants to be the parameter with the greatest impact, the modelling showed it to only be the 12th and giving an increase of only 0.91% in heating energy use (183.84 to 185.51 kWh/m^2/year). Similarly, installed window U-Value was given by the participants as the second most important, whereas, it was the 7th in the simulation model.

For a few cases the participants and the model are in better agreement. For example, the impact of changing the wall U-value was voted by the survey as 3rd, which is relatively close to the finding of the simulation study, which placed it 1st, with an increase of 17.22% in heating energy use. This outcome is probably logical, because of the large surface area of this element and the relatively large perturbation assumed (20%). Ignoring the use of curtains at night, ignoring the internal heat gains due to cooking and a 10% increase in heat gains due to appliances also showed agreement between the participants and the model. All are viewed by the participants and validated by simulation as being of little impact, securing the last 5 slots in the ranking of both the survey and the simulation model. However, in the case of indoor temperature set-point being reduced by 2^{o}C, the survey gave a rank of 8th, yet the simulation model shows it to be the 3rd; with gas consumption decreasing from the base case by 14.55%.

As discussed earlier, the sorted list of parameters given by the survey participants was in the form of a 1 – 5 scale. However, the ranking produced by the simulation model is listed from 1 – 21 based on the recorded impact on the annual gas consumption. In an effort to analyse the findings taking in consideration all individual responses, all parameters were organised according to the punctuation given by the survey and the 1 – 5 scale given by each individual was sorted to be in accordance with the 1 – 21 model ranking list. Additionally, the mean and standard deviation were calculated to each parameter. This action was performed with the understanding that a part of the precision was lost in this conversion, as some parameters will need to have the same score.

Nevertheless, It is clear that there is a large variability in the survey responses and in all cases, the means are far from being accurate with a Spearman ranking of 0.43 and an R^2 value of 0.28 (Figure 15). This suggests no correlation between the thoughts of designers and the modelled results and indicates that, when measured in this way, modelling or building physics literacy may not be high in the participants.

(Table 5) presents the Spearman ranking correlation and the R^2 value for each group depending on years of experience and the highest level of academic degree. It cannot be argued that for example: participants with less than one year of experience are proven to be more literate, as the number of participants in each category varied, yet, it is an indication that there is an urgent need for further investigations to understand the basis in which modellers' literacy can be improved.

Table 5. R^2 and spearman correlation values for each group depending on both years of experience and highest academic level

Group	R^2 value	Spearman correlation value
Years of experience		
< 1 year	0.36	0.59
1-3 years	0.33	0.56
3-5 years	0.24	0.47
6-10 years	0.37	0.59
> 10 years	0.20	0.42
Academic level		
Bachelors	0.35	0.58
Masters	0.33	0.56
PhD	0.20	0.42

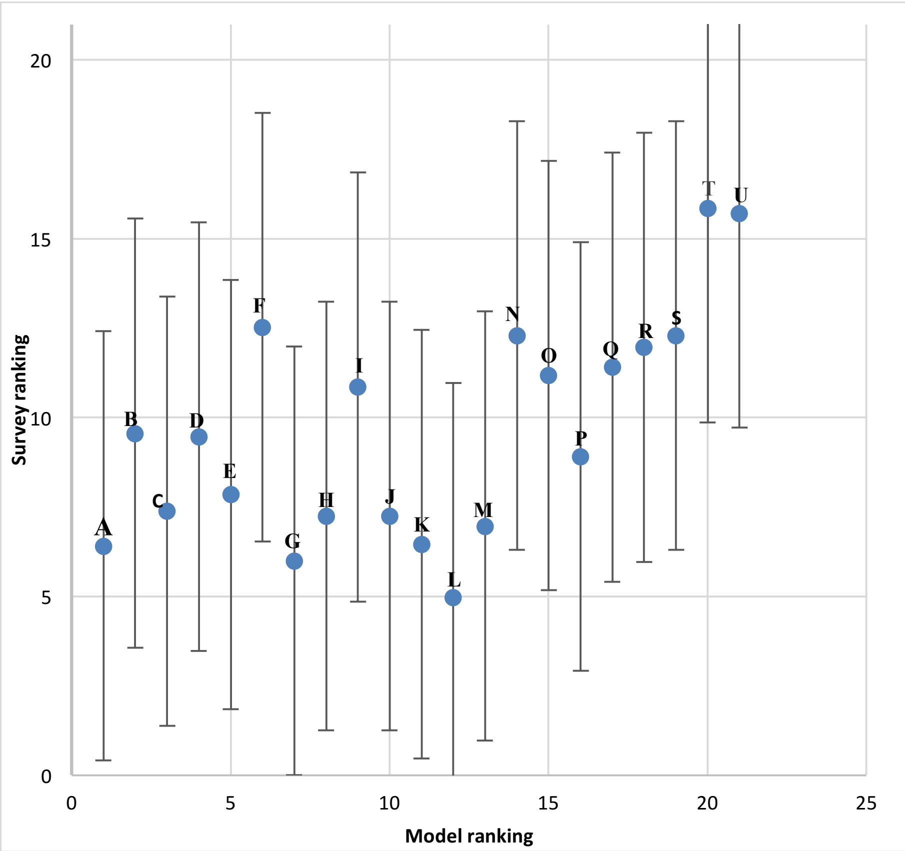

Figure 15. Scatter plot comparing survey results (mean and standard deviation) and simulation model ranking

A	Walls U-value (20% increase)	**L**	**Glazing ratio (10% increase)**
B	Ventilation rate (1.1 ach instead of 1 ach)	**M**	Airtightness (10% increase)
C	Inter indoor temperature set-point (2^{o}C lower)	**N**	External doors opening (Ignore)
D	Building geometry (Using internal dimensions)	**O**	Windows recessed (100 mm further)
E	Natural ventilation (change to constant ach)	**P**	Ground floor U-value (20% increase)
F	Heating set-point (thermostats in each room)	**Q**	Position of windows in walls (0.5 m down)
G	Installed window U-value (20% increase)	**R**	Density of inner leaf wall block (10% increase)
H	Thermal bridging (Ignore)	**S**	Internal heat gains from appliances (10%increase)
I	Shading from surroundings (Ignore)	**T**	The use of curtains at night (Ignore)
J	Roof U-value (20% increase)	**U**	Heat gains from cooking (Ignore)
K	Occupancy period (25% increase)		

5 Summary and conclusion

The performance gap is considered a problem that might affect all new buildings or the refurbishment of older ones. This creates a gap between reality and the policies implemented by governments to reduce energy use and greenhouse gas emissions. Previous studies tried to tackle this problem from various perspectives such as highlighting issues concerned with the role of poor workmanship or occupants' behaviour. The research reported here tackled this problem from the earlier stage of energy modelling, or, more precisely, the building physics literacy of building energy modellers. The literature indicates that this is an understudied area and is highly important as architects, engineers and modellers do not tend to consider themselves as a contributing factor to the performance gap, but rather consider construction quality and occupants to be the problem.

From the results reported here it is clear that all three tests of literacy suggested in section 2.1 have been failed by the sample of participants. Participants do not: **1.** approximately agree on the important parameters that need to be included in the model; or **2.** approximately agree on the rank order of the importance of a list of possible input parameters; or **3.** cannot rank order the impact of given changes to the values of 21 common parameters such that they approximately agree with that given by a sensitivity analysis of the parameters within an industry standard and validated thermal model.

Being that the sample size was reasonably large (108), this conclusion is likely to be valid on average also for the whole population of thermal modellers. Further research is needed to identify the current state of modelling literacy using a larger population sample and various building types as case studies. Furthermore, future research should identify new ways to teach building physics in both academic and industrial domains, as this clearly emphasises a potential gap that can be bridged.

Acknowledgement

We would like to thank all respondents who participated in the survey conducted in this research and express our appreciation for their valuable comments.

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Understanding the user-driven natural ventilation in Buildings: Can we benefit from the operationalisation of high-level human-ecological concepts?

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Abstract
Building inhabitants' presence and control actions are believed to considerably influence buildings' indoor environmental and energy performance. This has contributed to the recent increase in efforts toward developing dependable models of occupants' interactions with buildings' environmental systems. However, the quality and explanatory power of these models are mostly wanting. In this context, we discuss some human ecological concepts and their potential to contribute to a better understanding of the motivational background of occupants' control actions. Specifically, we explore the operationalisation of these concepts with regard to user-driven window operation in an office building. Long-term observations of indoor and outdoor conditions together with high-resolution data on the frequency of window operation actions provide the basis to test conjectures regarding parameters contributing to control action probability levels.

Keywords: natural ventilation, user behaviour, ecological potency, ecological valency

1 Introduction and overview

Buildings' indoor environmental and energy performance is thought to be considerably influenced by occupants' presence and control actions. This contention has contributed to the recent increase in efforts toward developing dependable representations of occupants' interactions with buildings' environmental systems. However, purely data-driven behavioural models may fall short of deepening the understanding of the underlying phenomena and processes. It thus seems useful to consider high-level psycho-physiological regulatory functions as the starting point of white-box or grey-box models of occupants' control-oriented action models in buildings. Toward this end, human ecological concepts such as (people's) "ecological potency" and (environment's) "ecological valency" could be of utility. In this context, the present contribution involves the following: First, we offer a brief critical background review of the current state of model development concerning inhabitants' presence and actions in buildings. Thereby, we identify the need to address a number of problems and fallacies of both conceptual and practical nature. Second, we further illustrate the problem of models' reliability based on an empirical case study focusing on the assessment of a number of existing window operation models. Third, we provide a very compact treatment of a few essential concepts in Human Ecology as the necessary preparatory step toward the exploration of their operationalisation potential in behavioural modelling. Fourth, we use again the aforementioned instance of user-driven window operation in an office building, where long-term observations of indoor and outdoor conditions together with high-resolution data on the frequency of window operation actions provided the basis to exemplarily test conjectures regarding parameters contributing to control action probability levels. Collected data was examined to see if there is a high enough signal to noise ratio to suggest that occupants' need for action and available degrees of control could explain the distribution of action probability data.

2 Background

Multiple models have been introduced in the past to capture building inhabitants' behaviour with regard to the operation of buildings' control devices (e.g., luminaires, windows, shades, and thermostats). The underlying motivation behind many of these efforts may be summarised as follows: *"The energy and indoor environmental performance of buildings depends not only on the buildings' fabric, systems, and microclimatic boundary conditions, but also on internal processes, which are, in a large part, triggered by occupants' presence and actions in buildings. A better understanding of these processes, and their representations as behavioural models can thus facilitate a more comprehensive basis for building performance assessment."*

While this statement is plausible as such, it is frequently stretched and amended imprudently leading to a number of misconceptions. For instance, reference to inhabitants' behaviour has been suggested to satisfactorily explain the so-called "performance gap". Inclusion of behavioural models in computational tools has been claimed to improve the "predictive ability" of such tools concerning buildings' future performance. Specifically, by the virtue of including models of probabilistic nature, certain kinds of behavioural models have been gratuitously claimed to be more "accurate". Worse, the same kinds of models have been unreasonably declared to be the only valid ones, independent of the actual purpose of model deployment. Such fallacies have been addressed in previous publications in more detail (Mahdavi, 2012, 2015; Mahdavi and Tahmasebi, 2015; Yan et al. 2015; Tahmasebi and Mahdavi, 2015), resulting in the insight that the confidence with which many behavioural models have been introduced as representing "reality" is by no means based on scientifically sound model testing and validation processes and criteria. To illustrate this point, we focus on selected models of natural ventilation via window operation. The following section provides a brief report on one of the recent studies that we have conducted to compare the results from three such window operation models with empirical observations.

3 An illustrative case study of behavioural model appraisal

To compare three existing window operation models (together with a modified version of one to these models and two additional benchmark instances), we used high-resolution data collected from an office area at TU Wien (Vienna, Austria). This area (see Figure 1 for a schematic plan) includes an open space with multiple workstations and a single-occupancy office. Inhabitants have access to manually operable casement windows. A number of variables are monitored on a continuous basis (e.g., indoor air temperature, carbon dioxide concentration, window states). Outdoor environmental parameters (such as air temperature) are also continuously monitored via building's weather station. For the present study, we used 15-minute interval data from a one-year period (1.1.2014 to 31.12.2014) to investigate the occupants' behaviour, and to adjust the coefficients of a number of window operation models. A separate set of one-year-long data (1.1.2013 to 31.12.2013) was used to evaluate the predictive performance of the occupancy models.

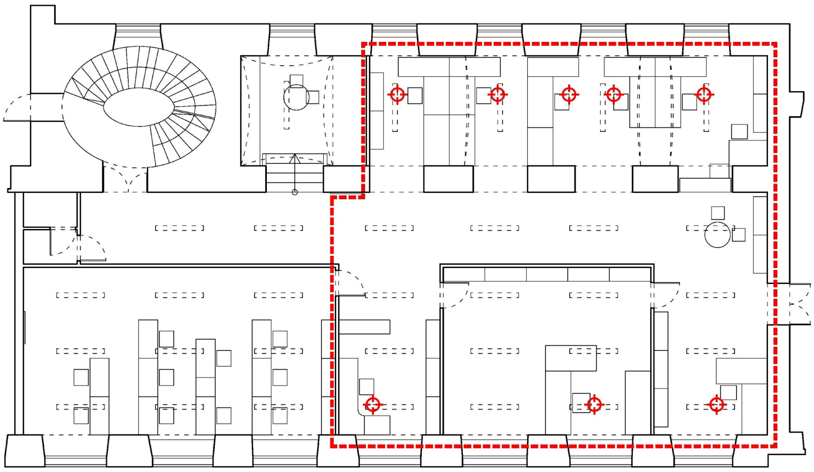

Figure 1. Schematic illustration of the selected office area with workstations and windows.

The selected three existing window operation models (referred here as A, B, and C) are widely referenced in the building performance simulation community. These are all Markov chain based logistic regression models that estimate the probability of window opening and closing actions based on the previous window state and a number of occupancy-related and environmental variables. Included in the analysis were also modified versions of models A and C (denoted as A* and C*) as well as two benchmark "pseudo-models" (denoted as D and E). We introduced models A* and C*, as the original models do not capture a key behavioural feature in the building under study where the inhabitants are requested not to leave the windows open when they leave the office (due to storm damage risk). The benchmark models are intended to put the performance of the selected models into perspective. A brief description of the aforementioned models is provided below:

- Model A, developed by Rijal et al. (2007), estimates the probability of opening and closing windows based on outdoor and operative temperature, when operative temperature is outside a dead-band (Comfort temperature ± 2°C). Given the proximity of measured indoor air and indoor surface temperatures in the present case, the operative temperature was replaced by indoor temperature.
- Model A*, a variation of Model A, always returns a closing action upon each occupant's last departure.
- Model B, developed by Yun and Steemers (2008), is specifically fitted to buildings without night time ventilation, and estimates the probability of window opening action upon first arrival and the probability of window opening and closing actions within intermediate occupancy interval (i.e. after first arrival and before last departure) based on indoor temperature.
- Model C, developed by Haldi and Robinson (2009), estimates the probability of opening and closing actions at arrival times (first and intermediate ones), intermediate occupancy intervals, and the departure times (the intermediate ones and the last one) based on a number of occupancy-related and environmental independent variables.
- Model C*, a variation of Model C, always returns a closing action upon each occupant's last departure.
- Model D, a benchmark pseudo-model that "predicts" windows are always open.

- Model E, a benchmark pseudo-model that "predicts" windows are always closed.

We evaluated the performance of these models to predict the inhabitants' interactions with windows in a one-year period (1.1.2013 to 31.12.2013), whereby we used both original and adjusted coefficients of the logit functions. Whereas the original coefficients are published by model developers, the adjusted coefficients are obtained from re-fitting the models to a separate set of data (1.1.2014 to 31.12.2014) obtained from the building under study. We specify the models with original coefficients with a subscript "O" and the ones with calibrated coefficients with a subscript "C". Note that the latter option (involving the possibility of adjusting model coefficients based on observations in actual buildings) has no relevance to model deployment scenarios pertaining to building design support, but may be of some interest in operation scenarios of existing buildings. Table 1 lists the independent variables, the original and adjusted estimates of coefficients for model A, B, and C. To compare the models' performance, we used the following metrics:

- Fraction of correct open state predictions [%]: This is the number of correctly predicted open state intervals divided by the total number of open state intervals.
- Fraction of correct closed state predictions [%]: This is the number of correctly predicted closed state intervals divided by the total number of closed state intervals.
- Fraction of correct state predictions [%]: This is the number of correctly predicted interval states divided by total number of intervals.
- Fraction of open state [%]: This is the total window opening time divided by the observation time.
- Mean number of actions per day [d^{-1}] averaged over the observation time.
- Open state durations' median and interquartile range [hour].
- Closed state durations' median and interquartile range [hour].

From the above indictors, the *fraction of correct open state predictions* ("true positive rate"), *fraction of open state*, *mean number of actions per day*, *median open state duration*, and *median closed state duration* have been suggested in previous studies to evaluate the predictive performance of window operation models (Schweiker et al., 2012; Fabi et al., 2015). We added three indictors to the previous work, namely *fraction of correct closed state predictions* to express models' states prediction performance, and the *interquartile range of open/closed state durations* to capture the spread of window states' durations.

The calculated indicator values are given in Table 2. Thereby, the first column provides, as benchmark, the monitored values. Numeric values of these types of indicators are frequently included in past publications without providing an interpretative context. Hence, to provide a "feel" for these numbers and put them in perspective, we included in Table 2 the results of the aforementioned "pseudo-models", one "predicting" that the windows are always open (D) or always closed (E).

Table 1. Selected window operation models, their independent variables, and the original and adjusted estimates of coefficients

Model	Type	Occupancy phase	Independent variables	Original coefficients	Adjusted coefficients
A	Opening & closing	-	Intercept	-6.430	-13.963 ± 1.733
			Operative temperature	0.171	0.461 ± 0.077
			Outdoor temperature	0.166	0.022 ± 0.020
B	Opening	First arrival	Intercept	-4.849 ± 1.075	-13.797 ± 1.014
			Indoor temperature	0.218 ± 0.045	0.501 ± 0.042
		Intermediate	Intercept	-0.629 ± 0.226	-11.049 ± 0.740
			Indoor temperature	0.030 ± 0.010	0.274 ± 0.031
	Closing	Intermediate	Intercept	0.209 ± 0.049	12.554 ± 1.112
			Indoor temperature	-0.007 ± 0.002	-0.651 ± 0.048
C	Opening	Arrival	Intercept	-13.700 ± 0.400	-10.120 ± 1.063
			Indoor temperature	0.308 ± 0.017	0.231 ± 0.050
			Outdoor temperature	0.040 ± 0.004	0.064 ± 0.014
			Preceding absences > 8h	1.826 ± 0.048	1.809 ± 0.130
			Occurrence of rain	-0.430 ± 0.120	-0.531 ± 0.464
		Intermediate	Intercept	-11.780 ± 0.300	-7.065 ± 1.252
			Indoor temperature	0.263 ± 0.014	0.070 ± 0.060
			Outdoor temperature	0.039 ± 0.004	0.080 ± 0.016
			Ongoing presence duration	-0.001 ± 0.000	-0.372 ± 0.076
			Occurrence of rain	-0.336 ± 0.088	0.072 ± 0.418
		Departure	Intercept	-8.720 ± 0.230	-6.101 ± 0.359
			Daily outdoor temperature	0.135 ± 0.008	0.126 ± 0.021
			Following absences > 8h	0.850 ± 0.120	NA
			Ground floor	0.820 ± 0.140	NA
	Closing	Arrival	Intercept	3.950 ± 0.390	3.963 ± 3.141
			Indoor temperature	-0.286 ± 0.018	-0.192 ± 0.152
			Outdoor temperature	-0.050 ± 0.005	-0.109 ± 0.040
		Intermediate	Intercept	-4.140 ± 0.240	7.044 ± 1.617
			Indoor temperature	0.026 ± 0.011	-0.323 ± 0.077
			Outdoor temperature	-0.063 ± 0.002	-0.142 ± 0.019
		Departure	Intercept	-8.680 ± 0.250	-0.337 ± 1.951
			Indoor temperature	0.222 ± 0.024	-0.049 ± 0.098
			Daily outdoor temperature	-0.094 ± 0.007	-0.066 ± 0.036
			Following absences > 8h	1.534 ± 0.077	1.587 ± 0.231
			Ground floor	-0.845 ± 0.074	NA

Table 2. The values of evaluation indicators for the window operation models

Models	Fraction of correct open state [%]	Fraction of correct closed state [%]	Fraction of correct states [%]	Fraction of open state [%]	Actions per day [d^{-1}]	Opening duration [hour]		Closing Duration [hour]	
						Median	IQ	Median	IQ
Observed	100.0	100.0	100.0	4.1	0.28	1.8	5.3	23.5	55.3
A_o	71.8	39.2	40.5	61.3	0.01	1180.0	2803.2	452.8	1442.3
A_o*	26.0	98.7	95.7	2.3	0.10	4.9	4.1	23.9	96.6
B_o	43.1	85.3	83.5	15.9	5.77	0.3	0.3	0.5	0.7
C_o	61.3	70.1	69.7	31.2	0.09	44.3	102.6	97.3	212.5
C_o*	22.2	97.9	94.8	2.9	0.15	4.2	4.7	76.3	157.5
A_c	80.9	46.4	47.8	54.7	0.01	1380.1	1318.2	635.0	974.1
A_c*	30.8	98.8	95.9	2.4	0.10	4.8	5.5	22.0	106.5
B_c	34.2	95.2	92.7	6.0	0.32	2.9	5.1	36.8	77.3
C_c	55.0	80.6	79.6	20.9	0.17	5.2	26.1	56.7	118.7
C_c*	33.7	97.5	94.9	3.8	0.22	3.2	5.6	54.2	110.1
D	100.0	0.0	4.1	100.0	0.0	8760.0	0.0	-	-
E	0.0	100.0	95.9	0.0	0.0	-	-	8760.0	0.0

A brief look at the data in Table 2 suggests that, even though the adjusted versions of the models performed somewhat better, none of the models yielded reasonable approximations of the reality of the observational data for the specific office area considered. It is both ironic and desponding to note that, for the indicator *fraction of correct state predictions*, the dummy pseudo-model E performed best. We may now engage in searching for detailed reasons and excuses for this arguably poor performance. However, it may be more useful to focus on a major flaw common to most model development procedures, which claim general applicability for models resulting from fitting (sometimes over-fitting) predictions to a limited set of observational data. If there is no explicit reasoning (involving for example, causal explanations) behind the inclusion of independent variables, iterative improvement and systematic generalisation of models' logic becomes a difficult challenge. To understand this challenge, one does not need to be a proponent of the stringent falsification paradigm in science (one counterfactual prediction suffices to declare a model invalid). As it has been demonstrated in other areas of scientific inquiry, what is needed is at least bare-bones explanatory story (e.g., a causal theory) for a meaningful, iterative, and cumulative model evaluation practice. Toward this end, the aforementioned human-ecological concepts may provide a suitable framework.

4 Some concepts in Human Ecology

As a discipline, ecology deals with the relationships between organisms and their surrounding world. Accordingly, human ecology may be simply defined as the ecology of the Homo sapiens. There are multiple traditions in human ecology. For the purpose of the present discussion, we consider the "Vienna School of Human Ecology" (Knötig, 1992a, 1992b; Mahdavi, 1996a) and focus on a couple of its essential concepts. Construction and operation of buildings and related artefacts may be viewed as an integral part of the totality of largely regulatory operations initiated by human beings as they interact with their surrounding world. Human ecology offers a useful way of thinking about these interactions via a number of high-level yet versatile concepts. Thereby, a central pair of concepts involves:

i. the human beings' *ecological potency*;
ii. the surrounding world's *ecological valency* (Knötig, 1992a; Mahdavi, 1996b).

Ecological potency refers to the human repertoire of means to deal (cope, interact) with the surrounding world. *Ecological valency* denotes the totality of that surrounding world's characteristics (resources, possibilities, opportunities, challenges, risks, hazards, etc.) as it relates to, confronts, or accommodates people's *ecological potency*. Coined initially by Uexküll (1920), the concept of *ecological valency* is akin to the Gibson's concept of *affordance* (Gibson, 1977, 1979).

Given this conceptual framework, the main consideration in human ecology pertains to the complex and dynamic relationships between the ecological potency of human beings and the ecological valency of their surrounding world. Given this perspective, buildings may be viewed as being constructed and maintained with the (implicit or explicit) intention to favourably influence the relationship between people's ecological potency and the ecological valency of their surrounding world. Such an intention expresses itself, for example, in the "shelter function" of the vernacular architecture (Mahdavi, 1996c, 1989). In contemporary building delivery processes, this intention is often expressed explicitly and formally, for example when desirable indoor environmental conditions are specifically defined and are expected to be maintained in the course of building operation. Provision of desirable conditions for the building users, or in other words, maintaining a high degree of "habitability", may be thus seen as the central utility of buildings.

Human ecology's concepts are also relevant to the evaluation of the habitability of the built environment. Specifically, a second pair of concepts should be mentioned, which concerns distinct aspects of the relationships between people and their surroundings. Thereby a high-level distinction is made between the *material-energetic* and *information-related* aspects of these relationships (Knötig, 1992a; Mahdavi, 1996a, 1992). To measure the habitability of the built environment we cannot disregard people's subjective experiences and attitudes. Subjective evaluation processes of the built environment arguably involve both material-energetic and the information-related aspects of the relationships between inhabitants and the built environment. A common approach to "operationalise" such evaluation processes in planning and operating involves the use of "psycho-physical" scales. The idea is that exposure to various levels of physical (material-energetic) stimuli translates – in a more or less predictable way – into corresponding subjective experiences. For example, exposure to increasing levels of sound intensity is said to result in an experience of increased loudness and associated stress (annoyance). But it would be highly problematic to postulate a deterministic relationship between measurable environmental factors and occupants' evaluation of environmental conditions (Mahdavi, 2011, 1996a, 1996b).

People's evaluation of exposure situations may be easier to describe and predict in when the material-energetic aspect of the environmental relationships dominates. It is, thus, not surprising that most efforts toward predicting the outcome of evaluation processes have focused on the identification of a measurable material-energetic scale (such as sound pressure level) to which subjective judgments (such as the degree of annoyance) are expected to correlate. However, the relevance of internal information processing for the degree of expressed dissatisfaction associated with various energetic levels of exposure has been demonstrated in experimental psycho-acoustic experiments (Mahdavi, 2011, 1996a).

5 Potential human-ecologically consistent independent variables in window operation models

We took advantage of the previously described long-term observation of indoor and outdoor conditions together with high-resolution data on the frequency of window operation actions in an office space. Specifically, monitored data from the period 1.1.2014 to 31.12.2014 was considered. This dataset provides the basis to test conjectures regarding parameters contributing to inhabitants' control action probability levels. Thereby, the choice of independent model variables can be shown to be based on an explicit and coherent underlying theory of the pertinent processes involving users' need for adaptive actions arising from a mismatch between inhabitants' ecological potency and the environment's ecological valency. A very simple operationalisation of this mismatch from the thermal point of view can be formulated in terms of the deviation of the prevailing indoor temperature (θ_i) from the inhabitants' preferred temperature (θ_c). A higher degree of mismatch is hypothesised to correlate with a higher adaptive action probability. On the other hand, under certain conditions, lower prospects for adaptive actions' success could presumably reduce their probability. The indoor-outdoor temperature difference ($\theta_i - \theta_e$) can represent – in case of natural ventilation – a means of approximating the actions' success potential. Next to the considerations pertaining to the thermal environment, indoor air quality can arguably play an essential role in window operation behaviour. A very simple indicator of an environment's deviation from the preferable air quality conditions may be operationalised in terms of the prevailing CO_2 concentration levels.

The result of the above queries are depicted in Figures 2 to 9 below. Figure 2 shows the distribution of the number of observed window opening actions upon inhabitants' first arrival at their workstations (during the aforementioned one-year observation period) as a function of the difference between indoor temperature (θ_i) and comfort temperature (θ_c). Thereby, θ_c was computed as a function of the running average of outdoor temperature based on Auliciems (1981). As alluded to before, we interpret this difference as the first approximation of the thermal environment's deviation from the "optimal" ecological valency. The same dependency is shown in Figure 3 for the duration of occupied hours at the workstations. Figure 4 shows the probability of window opening actions upon inhabitants' first arrival at their workstations as a function of the difference between θ_i and θ_c. Figure 5 shows the rate of window opening actions (per hour) during the occupied hours as a function of the difference between θ_i and θ_c. Likewise, Figure 6 illustrates the probability of window opening actions upon intermediate arrivals. These do not include first daily arrivals in the office but include all arrivals at the workstations after periods of intermediate absences lasting one or more hours. Figure 7 shows the probability of window opening actions upon first daily arrival at the workstations. In this case, the data is structured in terms of four categories as per Table 3. Thereby, categories 1 and 2 imply an insignificant human-ecological potency-valency mismatch. However, 1 suggests that actions are less likely to be effective, whereas 2 suggests a higher probability of actions' effectiveness. Categories 3 and 4 suggest a more pronounced potency-valency mismatch. However, in case of 3 actions are less likely to be effective, whereas 4 suggests a higher probability of actions' effectiveness. Figure 8 shows the probability of window opening action upon inhabitants' intermediate arrivals at their workstations as a function of prevailing CO_2 concentration. Figure 9 shows the rate of window opening actions during the occupancy period as a function of the prevailing CO_2 concentration. Again, the magnitude of CO_2 concentration is assumed to provide a first approximation of potency-valency mismatch as relevant to indoor air quality.

Table 3. Data categories considered in Figure 7.

Category	θ_i - θ_c [K]	θ_i - θ_e [K]
1	-1 … 1	-2 … 2
2	-1 … 1	<-2 or >2
3	<-1 or >1	-2 … 2
4	<-1 or >1	<-2 or >2

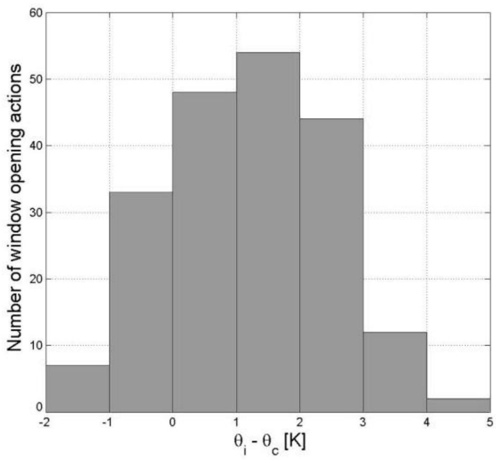

Figure 2. Window opening actions upon inhabitants' first arrival at their workstations as a function of the difference between indoor temperature (θ_i) and comfort temperature (θ_c).

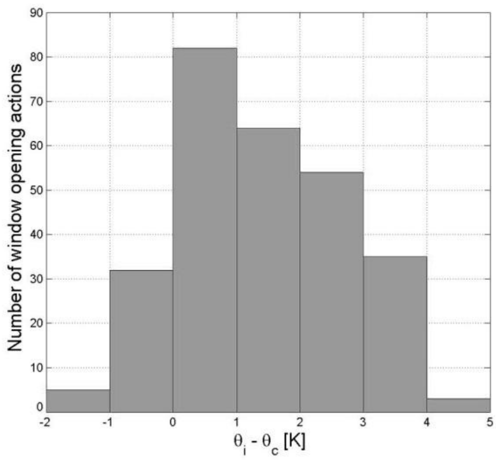

Figure 3. Window opening actions for the duration of occupied hours at the workstations as a function of the difference between indoor temperature (θ_i) and comfort temperature (θ_c).

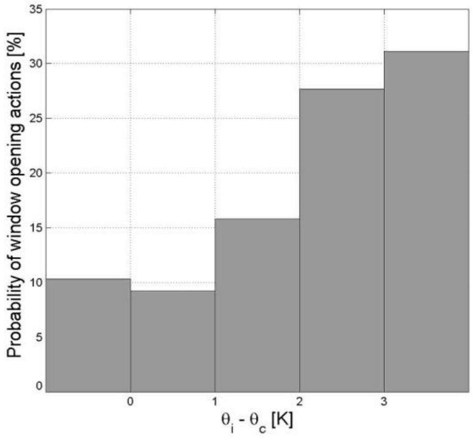

Figure 4. The probability of window opening actions upon inhabitants' first arrival at their workstations as a function of the difference between θ_i and θ_c.

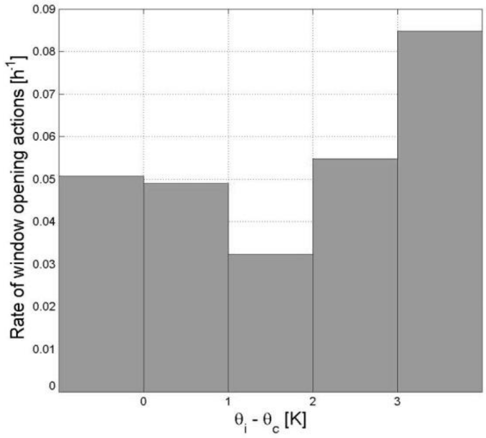

Figure 5. The rate of window opening actions (h^{-1}) during the occupied hours as a function of the difference between θ_i and θ_c.

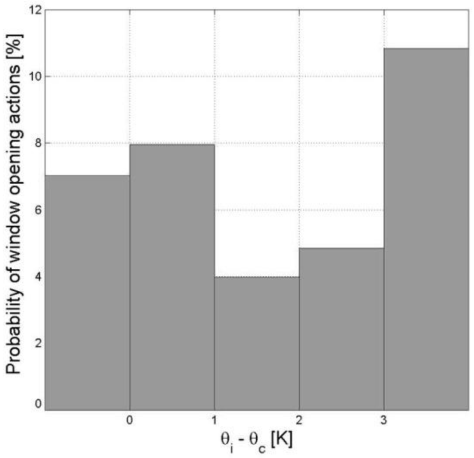

Figure 6. The probability of window opening actions upon intermediate arrivals.

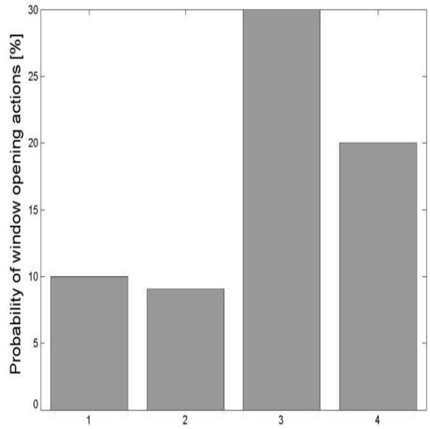

Figure 7. The probability of window opening actions upon first daily arrival at the workstations in terms of four categories as per Table 3.

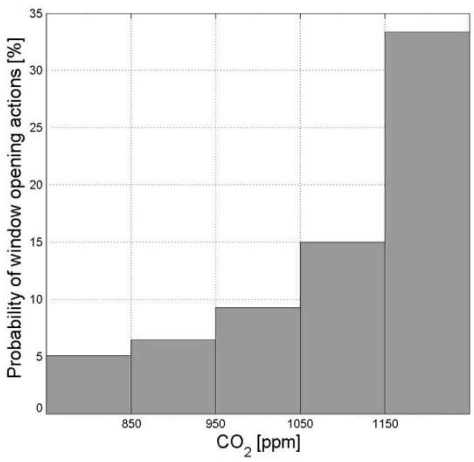

Figure 8. The probability of window opening action upon inhabitants' intermediate arrival at their workstations as a function of CO_2 concentration.

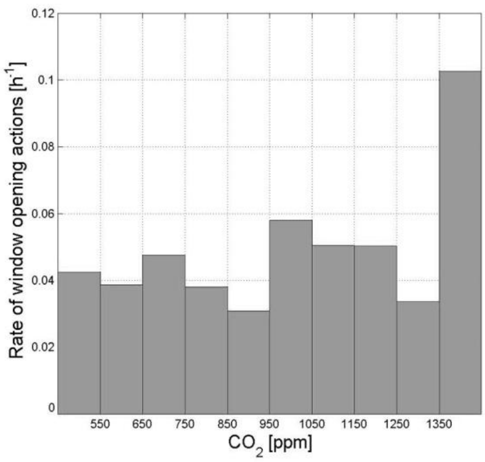

Figure 9. The rate of window opening actions during the occupancy period as a function of the prevailing CO_2 concentration.

The results point to the complexity of inhabitants' control actions in buildings, which can explain some of the limitations of many behavioural models introduced in the past. Given the "noise" generated by the simultaneous presence of a large set of possible contributing factors to user actions, it is anything but trivial to identify unambiguous and clear "signals" of individual causal factors. Nonetheless, concentration on human-ecologically relevant independent variables can offer some clues toward future model-making strategies. Firstly, we considered the dependent variables not only in terms of the absolute number of window opening actions (see Figures 2 and 3) but also in terms of the probability of actions or action rates. Consequently, Figure 4 displays a certain meaningful relationship between window opening action probability upon first daily arrival in the office and human-ecological potency-valency mismatch as expressed in terms of the "distance" to thermal neutrality. The rate of intermediate window opening actions (Figure 5) and window opening probabilities upon intermediate arrivals (Figure 6) reveals a similar signal.

Further analysis utilised the four categories of Table 3, whereby category 1 (small potency-valency mismatch and low action success prospect) was hypothesised to correlate with lowest action probability, whereas category 4 (large potency-valency mismatch and high action success prospect) was hypothesised to correlated with highest action probability. The results (Figure 7) appear to provide some evidence for this conjecture, as far as window action probabilities upon first daily arrival are concerned. However, similar tendencies were not discernible when analysing the rate of actions during occupancy and action probabilities upon intermediate arrivals.

In our study, the probability of window opening actions upon first daily arrival did not reveal any meaningful relationship to prevailing indoor CO_2 concentration levels. This is as such not surprising, as the CO_2 levels before the first daily arrivals are generally rather low. However, window opening actions upon intermediate arrivals were found to be more likely at higher CO_2 concentration levels (see Figure 8). The overall rate of intermediate window opening actions during occupancy did not appear to follow CO_2 concentration levels, until rather high values well beyond 1300 ppm (Figure 9).

6 Conclusion

Inhabitants' control-oriented actions in buildings can be triggered by a complex set of factors. To capture this complexity in behavioural models intended for use in computational building analysis applications is not trivial. It is of course possible to relate, mathematically, the rate or frequency of control actions with a number of environmental parameters based on a specific set of data for a specific building. But respective attempts have not resulted in convincing results. The aforementioned complex set of candidate influencing factors (including, but not limited to: indoor and outdoor environmental conditions, spatial configuration of inhabitants with respect to the location of control devices, type and technology of devices and their actuators, potential factors pertaining to social dynamics in a given spatial setting, inhabitants' health and comfort conditions as well as their cognitive state) create a kind of background noise in the observational and experimental data collection efforts, making it thus difficult to discern and identify clear signals in terms of straight-forward causal relationships between specific candidate independent variables and actions' probabilities and rates. This circumstance was exemplarily demonstrated in the illustrative window operation model comparison included in the present paper. Model developers appear to frequently fall into the "overfitting trap", proposing locally fitted multi-variable mathematical formulations that perform poorly as soon as they are confronted with new observational data. Regrettably, such models are often published – and occasionally even implemented in building performance applications – with unwarranted and imprudent claims regarding their general "validity" and applicability.

In the present study, we intentionally tested only a small number of hypothesised causal factors in view of their potential relevance for inhabitants' window operation behaviour and the resulting window opening states in an office area within an educational institution. Monitored indoor and outdoor environmental conditions together with monitored window opening and closing actions provided the baseline for the empirical exploration of the suspected causal factors. The results obviously do not provide definitive conclusions toward isolation of pertinent independent variables and causal mechanisms involved. But certain meaningful relationships between window opening actions and suspected contributing factors could be observed. For instance, window opening actions upon first daily arrival in the office (and, to a lesser extent, intermediate window opening actions) displayed a certain level of correlation with ecological potency-valency mismatch (operationalised in terms of the "distance" to thermal neutrality). Likewise, indoor air quality (as represented in terms of CO_2 concentration levels) and the probability of window opening actions upon intermediate arrivals at the workstations appear to correlate. Even if not particularly strong, such signals do encourage further efforts toward systematic exploration of inhabitants' control-oriented action in buildings in the context of a number of candidate causal factors. This is, in our view, an important prerequisite for the development of more generally applicable behavioural models. Until then, model developers and potential users would be well advised to exercise caution in the types of empirical and utilitarian claims made about behavioural models pertaining to inhabitants presences and actions in buildings.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Analysis of shading and usage of sun-lit areas in an urban square in a subtropical location

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Abstract
An urban square has been evaluated with the overall goal of aiding urban designers to plan more adequately resting areas on it. A preliminary analysis was performed from on-site footage over four distinct weekdays in winter in Curitiba, Brazil (25.5°S). The square is flanked by high-rise buildings to the north side, partially blocking solar access to the square during that season. Altogether 8435 scenes have been analysed from two views captured by standing cameras with time-lapse function, in 1.5-minute intervals. Zoomed images covered five different niches where the occupancy and length of stay were determined for each bench in respect of square visitors being in the building shade, partially shaded by trees or in the sun. A predominance of shaded situations has been found, closely followed by the usage of the benches. A more detailed analysis showed that in selected situations the length of stay varied with thermal comfort conditions measured at the time of the footage. The outdoor comfort indices PET and UTCI were calculated from data measured at the official meteorological station. It was concluded that the climatic conditions over the four winter days, mostly around the comfort range and one category above it ('moderate heat stress') did not suffice to elicit a climate-conscious usage of shaded/sun-lit areas.

Keywords: solar access, park attendance, time-lapse observations

1 Introduction

During the last decade, an increasing number of people moved to urban areas and this number is expected to keep on rising. In large urban centres, high-density standards can lead to environmental issues, as in the case of diminished solar access and ventilation potentials, which will consequently affect public health. In addition, from the point of view of urbanites, stress-related issues are thought to be commonly reduced in resting areas like parks and plazas (Kaplan & Kaplan, 1989). Such spaces are required for leisure and recreational activities, thereby exposing people to local microclimate. Evaluating and understanding local microclimate conditions in urban parks could thus contribute to sustainable urban planning and to life quality in cities (Nikolopoulou & Steemers, 2003).

Many studies have been carried out to understand space usage and human behaviour in green areas and parks located in different climate zones, suggesting a clear relationship between attendance and local microclimate conditions (Huang et al, 2015; Nikolopoulou et al., 2001; Gómes-Martín & Martínez-Ibarra, 2012; Lin, 2009; Kántor & Unger, 2010). Apart from thermal physical variables, the context-related, psychological aspects of pedestrians in their adaptation to the local environment are also considered to be of the same level of importance. Considering that thermal comfort in resting areas is related to time of exposure in such spaces, it is assumed that stressful thermal conditions may distress the occupants and induce them to leave the space in the short term (Nikolopoulou & Steemers, 2003).

Curitiba is located in southern Brazil and it is known as the “greenest” city in the country, boasting 422 squares, 13 groves and 16 parks distributed within its perimeter. However, the city also has many socio-environmental issues which remain unresolved. One of the most impacting urban plans for this city, from the 1970’s, intended to guide urban growth on the basis of so-called ‘structural sectors’, high-density areas served by an efficient, linear mass public transport. Buildings in those sectors had no clear height limitations defined in the master plan and ended up obstructing solar access and ventilation in the street canyons (Krüger & Suga, 2009). The city is located at 25°25’40” S, 49°16’23” W and is the coldest capital of the country, requiring solar access during winter (Goulart et al., 1998).

This paper aims to observe and explain human behaviour during square attendance in benches located at *Praça do Japão*, in a high-density area in downtown Curitiba, during the winter of 2014. A major goal of the study is to evaluate how adjacent buildings and trees may affect square attendance.

2 Method

The square is located in a structural sector surrounded by tall buildings which cast undesirable shadows in the square during winter. For the evaluation of square attendance in regard to solar access and thermal aspects and in order to avoid any influence over user’s behaviour, a non-invasive, observational study was carried out. Two time-lapse, digital cameras were placed inconspicuously in the porch of the second floor of the Japanese Memorial –a typical Japanese building, built to honour the Japanese immigration. Only footage was used, i.e. no on-site interviews have been made. There are 16 benches on the site, from which 10 have been evaluated.

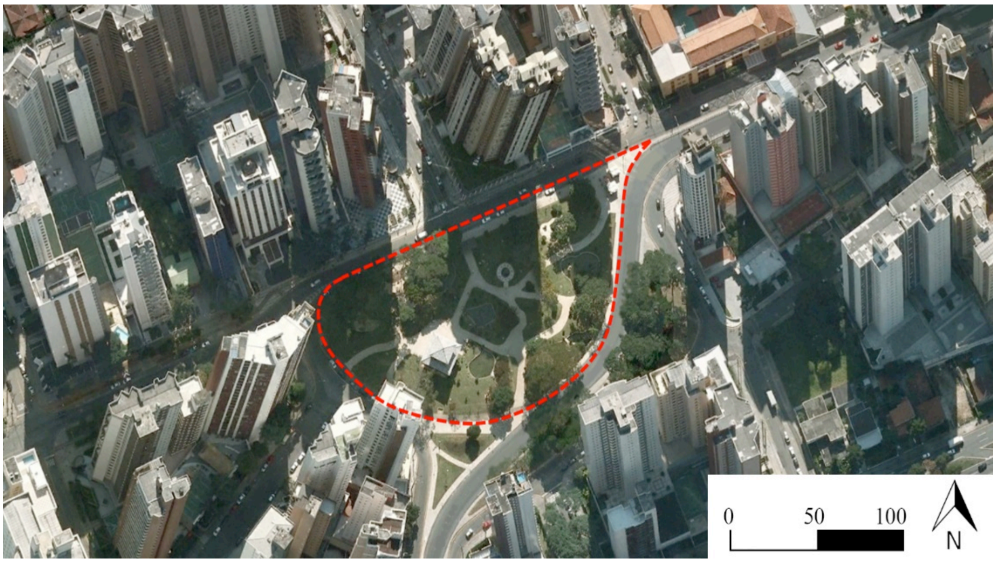


Figure 1: Google Earth aerial photograph of Japan Square location on May 21st

The footage was carried out during 4 days in winter: July 27th, 28th, 30th and August 15th, from 10:30am to 04:00pm, using a Nikon D80 and a Nikon D5200, in 1.5-minute interval, time-lapse videos. Obtained photos were edited in order to clearly depict 5 niches, whose shading profile was identified per image (‘not shaded’, ‘partly shaded by trees’, ‘shaded by buildings’, ‘reflected light from surrounding glazed facades’). The total of 8435 scenes was obtained over the four days of observation, resulting from the five niches and by the footage obtained from both camera viewpoints.

Shading profile, attendance and residency (length of stay) were evaluated. The thermal indices PET and UTCI were used as reference conditions for understanding relations between overall climatic conditions during footage and human behaviour. For that, air temperature, relative humidity, wind velocity and global radiation data were obtained from an official meteorological station (from the National Meteorology Institute – INMET), located at approximately 6 km from the evaluated square. Background (not on-site!) official meteorological data were thus used in the analysis. The reason is that by using official data, general predictions can be made at a future step for typical meteorological conditions, TMY data for instance.

Figure 2: Camera locations and corresponding views.

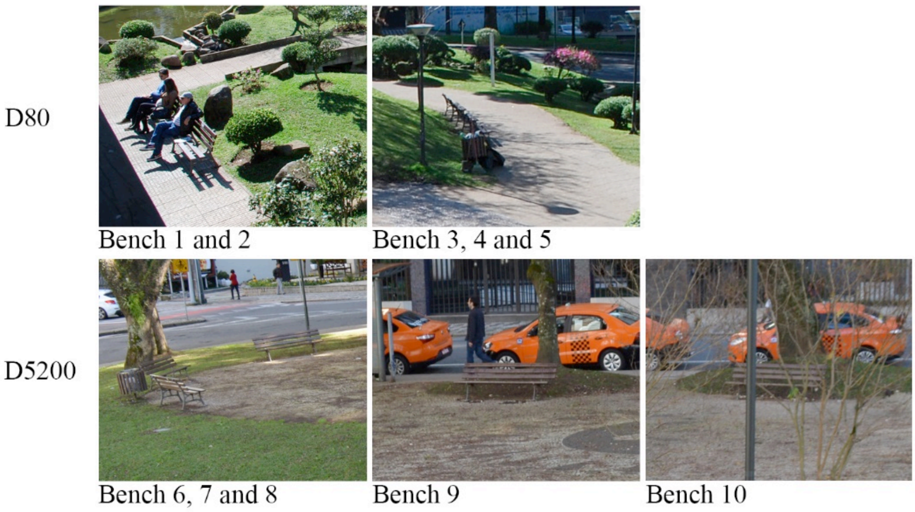


Figure 3: The five niches analyzed.

Meteorological data were converted to Physiological Equivalent Temperature (PET) units with the Rayman model for a standard person (ISO 8996: a 30-year old man weighing 70 kg and 1.75 m tall) with a low metabolic rate of 150 W. The individual thermal insulation was assumed to be 1.3 clo, supposing male winter clothing (ISO 9920).

The outdoor comfort index Universal Thermal Climate Index UTCI was additionally tested. UTCI units were processed from meteorological data used as input in the online version of the model (http://www.utci.org/utcineu/utcineu.php). For the analysis, we considered the UTCI thermal index as calibrated for Curitiba's climatic conditions from past outdoor thermal comfort surveys (Rossi et al., 2012).

Table 1 Thermal comfort and heat stress categories for PET and adjusted UTCI (Rossi et al. 2012)

PET	adj-UTCI	Thermal comfort/stress categories
18°C	*15°C*	--
		No thermal stress
23°C	*27°C*	--
		Moderate heat stress
29°C	*33°C*	--
		Strong heat stress
35°C	*39°C*	--
		Very strong heat stress
41°C	*45°C*	--
		Extreme heat stress

3 Results

Meteorological conditions obtained from the meteorological site during the four winter days observations and its respective medium PET and UTCI indices of the monitored period (10:30 am to 4 pm), are shown in Table 2.

Table 2 Climatic conditions and thermal comfort index results for the monitored period

	Ta (°C)	RH (%)	v (m/s)	Ig (W/m²)	Tmrt (°C)	PET (°C)	UTCI (°C)
Mean	20.6	48	2.1	541	41.7	26.0	25.9
Minimum	13.0	34	0.1	133	19.8	18.9	20.6
Maximum	25.0	92	6.0	778	53.1	35.5	30.6
Fluctuation	12.0	58	5.9	645	33.3	16.6	10.0

PET ranged between 'no thermal stress' and 'strong thermal stress', while UTCI varied less, between 'no thermal stress' and 'moderate heat stress' (such conditions apply to a sun-lit situation at the meteorological site). The question behind our analysis is whether under such climatic conditions, the need for shade or for sunlight would be decisive for making one choose another bench spot or even move from his original seat due to localized thermal discomfort. A preliminary analysis showed a predominance of shaded situations (52% of the scenes against 14% in the sun, with 33% of the situations in half-shade and also 1% with reflected light from buildings). This pattern is closely followed by attendance.

Figure 4 shows users' attendance over the various observation days, per bench (B1-B10). The percentage of people in a bench spot where the 'not shaded' condition occurs is frequent, whereas benches that are normally shaded or half shaded are less visited. The mean thermal index value for the each monitored period is given in the graph. Even in heat stress conditions, such as on Thursday, there is still some preference for not shaded bench spots.

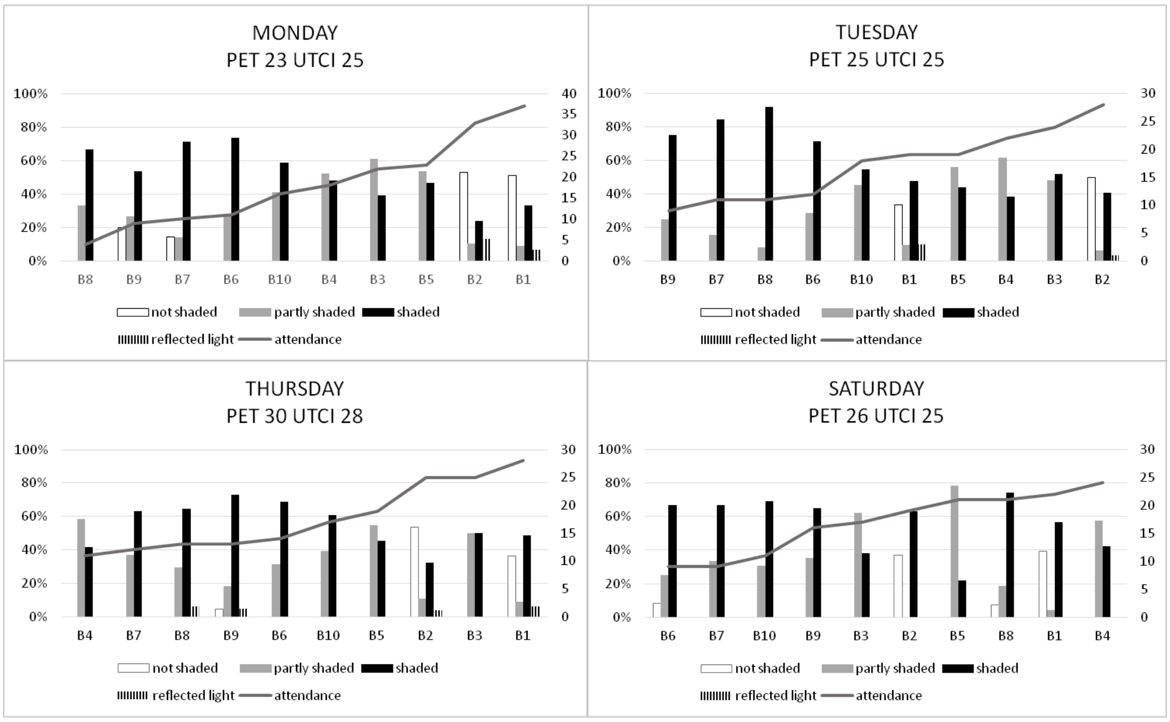


Figure 4: Relation between bench shading profile and attendance during the four days.

Aggregated results show that there is a prevalence of attendance in benches where 'not shaded' situations are frequent (106 individuals on bench 01 and 105 on bench 2), as shown in Figure 5 (right-hand side) for the complete period. This could be related to the open-air nature of such benches, which offer a less obstructed view of the square. Together with the subsequent benches B3-B5, this array of benches is central in the square and may be, at first glance, more inviting to the visitor. However, users' residency (i.e. length of stay) is increased in 'shaded' and 'partly shaded' conditions (Figure 5, left-hand side).

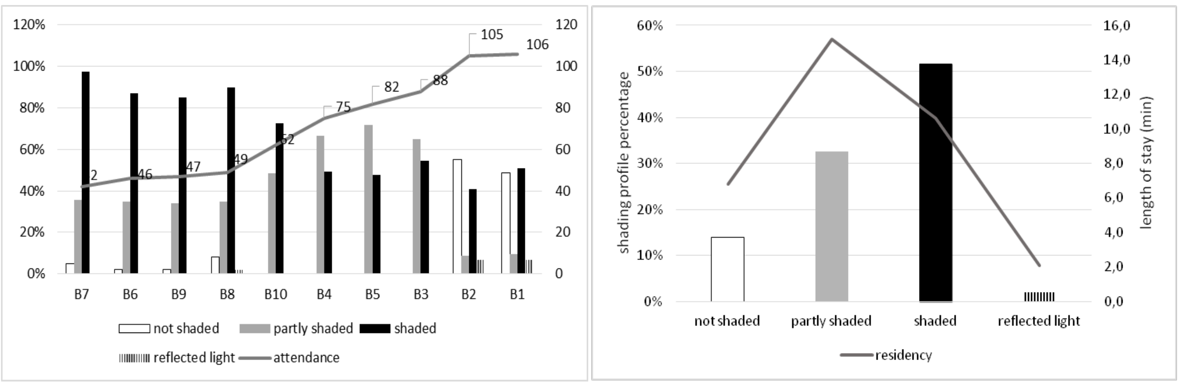


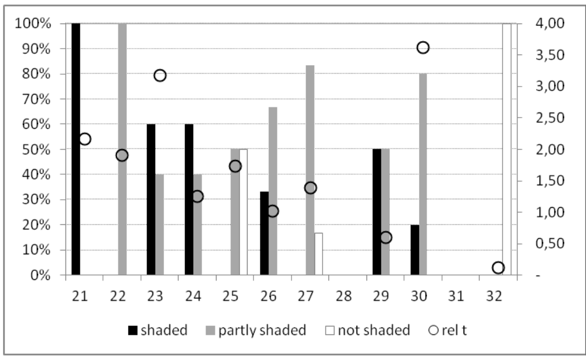
Figure 5: Summary of the four days of observation / relation between bench shading profile and length of stay (residency)

A more detailed analysis showed that in selected situations the length of stay varied with thermal comfort conditions measured at the time of the footage. Table 3 shows situations with long residency, where the person chose to move from the initial bench to another, thereby tracking the sun/shadow from vegetation and surrounding buildings. Shown here are the situations where there was a clear choice of two different contrasting conditions of shading. Results are for the first day of observations, where PET ranged 19-26 °C and UTCI 21-27 °C. Even though meteorological conditions on this day lied close to or just around the threshold of the comfort range in both indices, it seems there is a choice for reducing heat stress (by moving to more shade) when there is a rising trend over time in both index values (subjects A1, A2) and an opposite behaviour when there was a drop in both indices (subject L5).

Table 3: Moving patterns of square users and corresponding PET and UTCI values

Subject	Bench	Condition	PET (°C)	UTCI (°C)	Length of stay (min)
A1	B1	not shaded	21.0	25.5	5
	B5	partly shaded	22.0	26.0	23
A2	B1	not shaded	21.0	25.5	5
	B5	partly shaded	22.0	26.0	23
G4	B2	not shaded	25.0	26.0	17
	B1	shaded	25.0	26.0	32
G8	B2	shaded	25.0	26.0	3
	B5	partly shaded	25.0	26.0	12
G9	B2	shaded	25.0	26.0	3
	B5	partly shaded	25.0	26.0	12
L5	B4	shaded	23.0	25.0	1.5
	B3	partly shaded	21.0	23.0	5
P8	B6	partly shaded	23.0	25.0	11
	B9	shaded	23.0	24.0	6
S6	B9	shaded	23.0	25.0	3
	B10	partly shaded	23.0	25.0	5
S7	B9	shaded	23.0	25.0	7,5
	B10	partly shaded	23.0	25.0	5

However, the fact that observations were made on fairly comfortable days may have been responsible for diminished thermal awareness by the square users. Figure 6 below shows corresponding PET and UTCI values, measured at the meteorological site (in the sun) and the chosen bench location status in percent after subjects moved from one place to another. The preferred location does not show a clear relationship with thermal comfort expectations. The time relationship between length of stay in the last and in the first location is also depicted (mean values for 'rel t'). Even when we neglect the preference for a bench location in the sun at the highest PET and UTCI values as in this case the subject stayed for a tiny fraction of time of his original location in the new setting and then left, at the first PET and UTCI values, the person (again, a single individual) decided to stay longer in the shaded location.



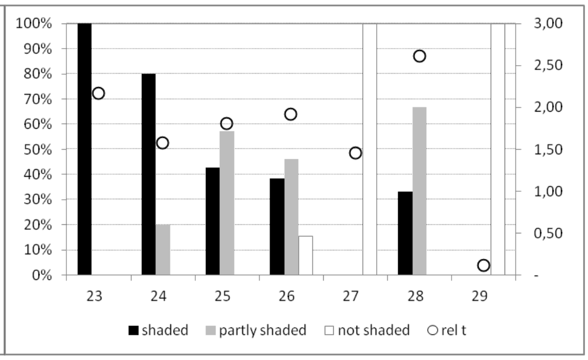


Figure 6: Percentage of preferred bench positions (status of shading) for overall PET / UTCI conditions at the meteorological station

4 Conclusion

It was concluded that PET and UTCI conditions over the four winter days, mostly concentrated around the comfort range (PET classes were 'no thermal stress', with 21% of the hours monitored, 'moderate heat stress', with 61% of the hours and 'strong heat stress', with 18%; UTCI varied from 68% 'no thermal stress' to 32% 'moderate heat stress') did not suffice to elicit a climate-conscious usage of shaded/sun-lit areas.

Interesting questions can be raised from this observational study. Are changes in bench locations more importantly driven by thermal discomfort or by the search for comfortable conditions than by aesthetic factors (the view from a particular spot, for example)? Would it be possible to define a 'comfort range' for a person in the shade or in the sun, from the behavior of square visitors for background meteorological conditions?

The study will be carried out in other climatic conditions throughout the year, looking at seasonal aspects of square attendance.

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Proceedings of 9th Windsor Conference: **Making Comfort Relevant**
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Virtual Energy for Comfort: To present discomfort and reward passive design in EDGE

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Abstract
EDGE (Excellence in Design for Greater Efficiency) is a green building certification for mass market application in developing countries. To meet the EDGE standard, a building must achieve a 20% reduction in energy and water consumption and embodied energy in materials, compared to a city-specific base case. Over half a million square meters of buildings have been EDGE-certified since October 2014 globally. EDGE has introduced a new concept to the analysis of energy efficiency and thermal comfort: "Virtual Energy for Comfort", measured in kWh equivalence. In order to calculate a building's energy efficiency, EDGE takes into account the impact of passive design on the projected use of heating or cooling to maintain thermal comfort, even when a building does not include related heating or cooling systems at present or designed as free-running building. As incomes rise and air conditioning becomes more popular in developing countries it is essential to encourage good design today which will minimize potential air conditioning load or chances of discomfort in the future. Hence the importance of this new concept. This paper presents the methodology of calculating "Virtual Energy for Comfort" and explains the benefits and challenges of putting such a concept into practice.

Keywords: EDGE, Virtual Energy, Thermal Comfort, Passive Design, Green Buildings

1 Introduction to EDGE

EDGE, a green building certification system, is available in more than 100 emerging markets (EDGE, 2015). An innovation of IFC, a member of the World Bank Group, EDGE has been used to certify more than half a million square meters of building floor space since October 2014. EDGE is a simple, smart and affordable certification applicable to residential, retail, hospital, hotel and office buildings across the price spectrum. To date, EDGE aims to certify 20% of new build in seven years in five countries of special initial focus: Costa Rica; India; Indonesia; South Africa; and Vietnam.

Using a free online application (www.edgebuildings.com) incorporating a simulation engine, EDGE empowers the discovery of technical solutions at the early design stage to reduce operational expenses and environmental impact. Based on the user's basic information inputs and then selection of green measures, EDGE provides projected operational savings and reduced carbon emissions within minutes. This overall picture of the financial and environmental performance of a building helps to articulate a compelling business case for building green.

Figure 1. Examples of EDGE certified projects, with countries where EDGE certification is available marked in green.

The suite of EDGE tools includes building type specific design simulation engines connected to user guides providing both technical explanations and also procedural guidance on certification.

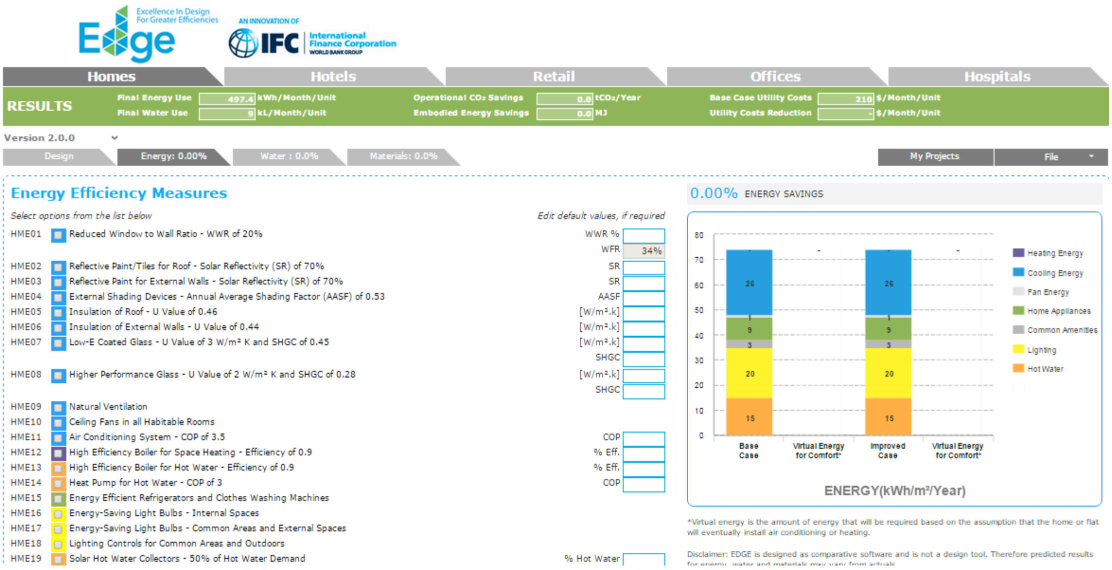

Figure 2. Screenshot of EDGE online application showing the energy section for homes

EDGE has been designed and developed by the in-house green building team of the Climate Business Department of the IFC (International Finance Corporation). IFC is the private sector investment arm of the World Bank Group. EDGE was originally designed to assess the IFC's own investment projects and help clients take the decision to build green. Now EDGE certification is being offered through a global network of certifiers and is being used across the emerging markets in Asia, Africa, Middle East, Eastern Europe, North Africa and Latin America.

1.1 The EDGE Standard

In order to meet the minimum requirements of the EDGE standard, a building project must achieve 20% energy savings, 20% water savings and 20% reduction in embodied energy in materials compared to a city-specific base case. The base case for each city is defined based on local construction techniques, building codes, building use patterns and climate. Thus, EDGE applies a uniform simulation methodology while adjusting the base case to the context of each location.

EDGE focuses in on resource efficiency for a streamlined approach that enables market adoption of green buildings at scale because most actions reduce operating costs. The process is simple, with only a handful of measures required to reach the minimum requirements. The result is lower utility costs, extended equipment service life and less pressure on natural resources.

1.2 How are energy savings calculated?

EDGE utilizes building physics calculations to determine the building's overall energy demand, including requirements for heating, ventilation and air-conditioning, as well as domestic hot water, lighting demands and plug loads. EDGE also estimates water demand and the embodied energy of materials related to non-structural building elements, in order to create a comprehensive analysis of projected resource usage.

Since a building generally uses more than one fuel from different carriers (i.e., gas, diesel, district cooling/heating, electricity, etc.), EDGE creates a link among the sources, converting primary energy into "delivered" energy values. The combined outputs for energy use are relayed as delivered energy (rather than primary energy or carbon dioxide emissions) in order to best communicate efficiency gains to users, who relate more easily to results when expressed as lower utility bills.

Accounting for renewable energy. For the sake of simplicity, renewable energy generated on site (i.e., electricity from solar photovoltaics or hot water from solar collectors) is deducted from the building's improved case and is expressed as "energy savings" on delivered energy.

Heating, ventilation and air conditioning calculations. EDGE uses a monthly quasi-steady-state calculation method based on the European CEN and ISO 13790 standards to assess annual energy use for the space heating and cooling of a residential or non-residential building. The method was chosen for its ease of data collection, fast response time, reproducibility and cost effectiveness of inputs gathering for the data base.

The energy efficiency calculation process. The first step in assessing the energy efficiency of a design is to establish a project specific base case. A designer enters basic project data (e.g. size, location, building type, expected occupancy level) into the EDGE software, which calculates the project "Base Case" by drawing upon location-specific databases for parameters such as climate, business as usual building practices and local usage patterns. To encourage early-stage planning of green options, the EDGE software provides many default (see the Design page of the EDGE software) options to a designer who has not yet decided on the details of a project. The base case includes "non-regulated" energy usage (such as from catering and appliances) in order to provide a complete picture of projected energy usage and savings.

An “Improved Case” is next created when the user selects technical measures for inclusion in the design. If Improved Case energy consumption is at least 20% less than that of the Base Case a building meets the EDGE standard. In addition to energy consumption savings, the EDGE software also reports water savings, reduction of embedded energy in materials, GHG emission avoidance and operational cost reductions. For non-residential buildings, incremental costs for the selected technical measures and the payback period from utility savings are also presented.

Figure 2 provides an example of how the energy saving in a hotel building is displayed in the EDGE software by presenting the Base Case alongside the Improved Case.

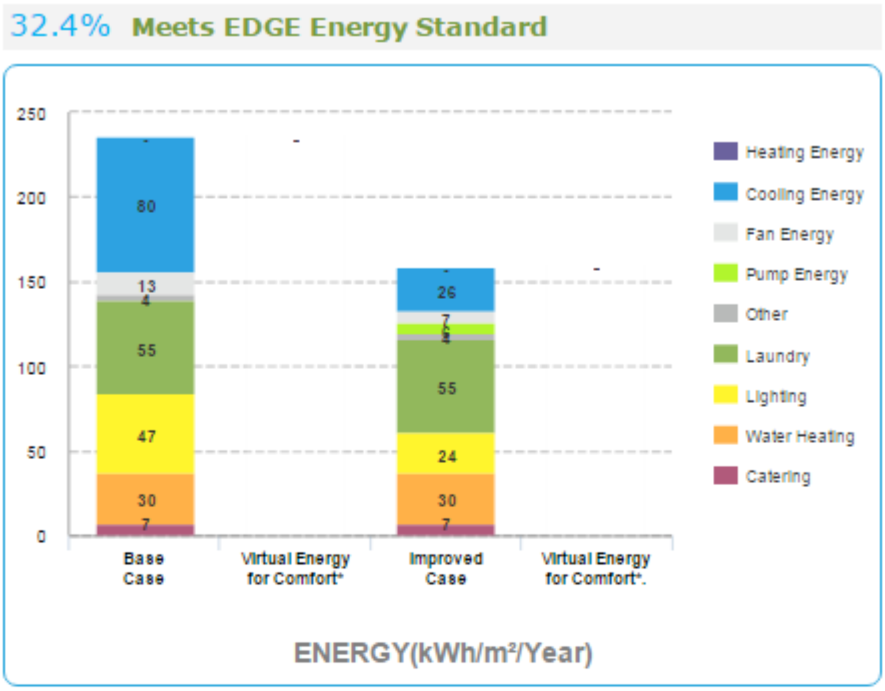

Figure 3. Showing energy savings in a hotel building amounting to 32.4% over the Base case

Thermal comfort assumptions. EDGE uses a fixed thermal comfort set point for heating and cooling systems. The set point is fine-tuned for cities where an in-depth market study has been performed, such as cities in India, South Africa, Costa Rica, Vietnam and Indonesia. Other country data will be added as data become available. The set point drives heating and cooling load calculations for base case and improved case. However when building uses natural ventilation the comfort set point changes to the adoptive thermal comfort conditions, see table 1.

Table 1. Heating and cooling set points for EDGE homes (EDGE 2014)

	Temperature	Notes
Heating set point (homes)	20^{o}C	With city specific calibration
Cooling set point (homes)	24^{o}C	With city specific calibration
Comfort conditions in natural ventilation mode	Use of adoptive comfort	Depending on cities climate condition and average monthly temperature

For additional information on the EDGE methodology see the report published online: www.edgebuildings.com/updates-and-guides/#methodology.

2 Why is Virtual Energy for Comfort important?

Passive design improves thermal comfort in a building, thus reducing demand for heating or cooling. In many developing countries, however, most occupants do not currently heat or cool, due to economic constraints, as well as climate conditions which border lines comfort conditions such as cold winters nights in Johannesburg South Africa or warm summer days in San Jose Costa Rica. At the same time, as incomes rise, there is a strong tendency to introduce cooling and heating systems. If we recognize and reward passive design features that improve thermal comfort today we diminish the risk of having to install HVAC systems in the future, or we at least ensure that such systems will be smaller and less frequently used. Or in case the heating or cooling system is not installed due to high cost, at least people should not suffer from discomfort indoors. To provide an example, in San Jose Costa Rica, if a house being designed with high level of glazing and small opening sizes, the internal temperature will easily rise above 30^{o}C and natural ventilation will not be enough to remove the internal heat gains and solar gains. This is why Virtual Energy for Comfort is important.

To illustrate how Virtual Energy for Comfort is calculated, consider a building without air conditioning today which uses a passive design feature like window shading to reduce solar thermal gain. The EDGE software calculates how much less energy the building would need ***if it had a virtual air conditioning system*** in order to maintain thermal comfort. That amount of energy used in the virtual system is the Virtual Energy for Comfort.

The graph bars in Figure 5 reflect Virtual Energy for Comfort for a project which does not have HVAC systems today but does incorporate passive design to reduce the need to heat or cool the building. It is important to clarify that Virtual Energy for Comfort savings of course have no impact on utility cost savings in the EDGE software.

Until now, green building efforts have centred on reducing energy consumption in designs that already consume large amounts of energy in the first place, and then presenting savings to show projects are green. Given the target of EDGE in all range of income categories, for example in low income housing, in many instances in developing countries today there is no HVAC but we can predict with high levels of probability that HVAC will be installed within the next decade or so if comfort conditions ignored. With the Virtual Energy for Comfort approach one can guide today's construction without HVAC towards efficiency over the buildings life taking into account the trend toward more cooling (or heating).

The Virtual Energy for Comfort virtual baseline. The heating[1] or cooling system baseline assumed in the EDGE software is in line with ASHRAE 90.1 2007 Appendix G, as the methodology for energy modelling for LEED and BREEAM international, which defines:

"c. Where no heating system exists or no heating system has been specified, the heating system classification shall be assumed to be electric, and the system characteristics shall be identical to the system modelled in the baseline building design.

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[1] EDGE uses heating energy source as per city conditions not necessarily electric

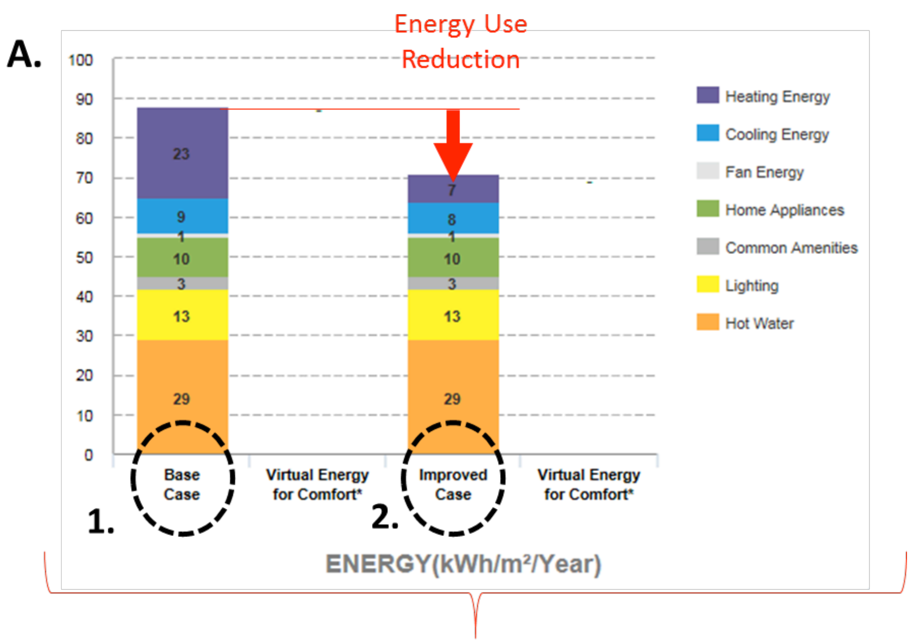
d. Where no cooling system exists or no cooling system has been specified, the cooling system shall be identical to the system modelled in the baseline building design." (ASHRAE, 2007)

The above shows that energy model protocol under ASHARE 90.1 2007 also uses similar concept to Virtual Energy, however savings in ASHARE are reported as energy cost savings and comfort issue is not highlighted as it is in EDGE. Discomfort conditions in ASHRAE 90.1 Appendix G, are counted as unmet hours for system sizing, however in naturally ventilated buildings, system sizing becomes irrelevant.

An award for thermal comfort. Despite using the Virtual Energy for Comfort concept in EDGE to assess energy efficiency, the EDGE certification does not set a minimum comfort level as part of its standard. Nevertheless, there is potential to use this concept in the measurement of thermal comfort in general. CIBSE states that less than 1% of operating/occupancy hours should go beyond 28°C for offices and schools and 26°C for Dwellings (CIBSE, 2006). However CIBSE does not lay out criteria regarding the maximum time indoor temperature can be below any specified level. For example how many hours per year indoor temperature can go below 18°C? If a over cooling requirement was clarified by CIBSE in addition to the existing over heating requirement, the overheating and overcooling could be also displayed in number of hours under EDGE results as a next step.

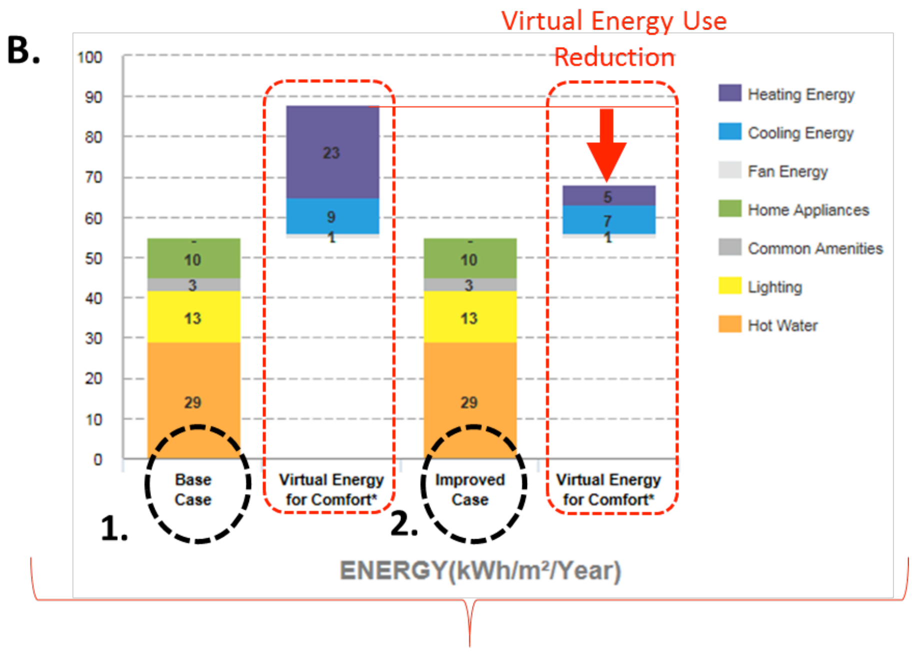
We do propose a similar rule to overheating:

"Less than 1% of annual operating/occupancy hours should go below 18°C for offices, schools and dwellings to prevent overcooling."



The bar graph **A.** shows the setting of one **(1.)** Baseline Building with HVAC compared with **(2.)** Improved Case where passive and active strategies have been used to improve the efficiency of the HVAC system in order to reduce energy consumption (kWh/m²yr). No Virtual Energy is analyzed in this graph.

Figure 4 Comparison of Base Case and Improved Case in a building with HVAC system



The bar graph **B.** shows the comparison of a **(1.)** Base Case building and an **(2.)** Improved Case with No HVAC system. The Virtual Energy appears as a separate bar from the main bar (dotted red) for both cases.
The **(2.)** Improved Case uses only passive strategies that improves comfort at the same time that reduces the potential energy consumption of the future need for HVAC. This is reflected in the reduction of the Virtual Energy.

Figure 5 Comparison of Base Case and Improved Case in a fully naturally ventilated building

3 Results:

As a green building assessment tool the EDGE software illustrates the potential issues with discomfort in buildings and has created the concept of Virtual Energy for Comfort which provides for a way to present potential thermal discomfort. This approach is used to award for design solutions which improves thermal comfort even in a fully free running building.

Despite the inclusion of requirements for overheating in CIBSE, overcooling has not been assessed. However, overcooling can be an issue, mainly in the developing world, for example in cities such as Lima, Bogota, and Delhi, where cooler indoor temperatures can occur frequently. This may be a new area for research and design guidance for reduction of discomfort.

EDGE has taken a step toward measurement of potential thermal discomfort and rewarding thermal comfort in free running buildings. Future developments in EDGE can include ways to report the discomfort hours either for overheating (i.e. above 28^{o}C) or overcooling as a percentage of total occupancy hours.

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Proceedings of 9th Windsor Conference Making Comfort Relevant

Cumberland Lodge, Windsor, UK, 7th-10th April 2016
Network for Comfort and Energy Use in Buildings http://nceub.org.uk
Windsor Conference 2016 www.windsorconference.com

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ISBN 978-0-9928957-3-0

Published by NCEUB 2016
to order go online to www.nceub.org.uk