Short-term thermal history in transitional lobby spaces

Submitted by

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A Thesis submitted in part fulfilment of the requirements for the degree of

Doctor of Philosophy in Architecture

The University of Sheffield

Faculty of social Sciences

School of Architecture

November 2015

Declaration

I declare that no portion of the work contained in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning. The work has been my own except where indicated. All quotations have been distinguished by quotation marks and the source acknowledged.

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Abstract

Key words: thermal history, transitional spaces, lobby areas

The dramatic concentration of carbon dioxide in the atmosphere is provoking extreme temperatures, where 2°C increase represents a potential risk for humanity. Air conditioning (AC) demands up to 70% of total energy use in buildings, and is extending into moderate climates where it is not necessary. Thermal comfort research has demonstrated that extended exposure to AC environments can significantly modify people's thermal tolerance and thermal preferences, reducing their ability of adaptation. There is limited research exploring people's thermal comfort in short-term and dynamic contexts, which alter people's long-term thermal history.

The aim of this thesis is to evaluate people's short-term thermal history and thermal comfort perception in a real situation in a moderate climate, exploring a dynamic and transient condition repeated in their daily routines. The lobby area where people move from the outdoor to the indoor environment is used as the case study, in order to evaluate how use of the lobby can modify people's thermal perception. One year of fieldwork research (2013-2014) was conducted in three typical lobby units in Higher Educational Institutions in Sheffield, UK. Thermal comfort surveys and simultaneous climatic measurements were used in this study, involving 1,749 international participants.

Findings revealed a seasonal thermal adaptation affecting people's short-term thermal perception and very rapid changes in people's thermal comfort perception and preferences when moving from one space to another. Participants' short-term thermal history was strongly altered by three new identified thermal patterns (flat, sudden and irregular) and a range of temperature differences. The evaluation of 46 thermal patterns revealed a number of considerations that can help to understand people's thermal perception in the short-term, and which can help to improve people's thermal adaptation in the long-term. This research contributes with new parameters that support the implementation of energy related strategies, building design guidelines and international standards.

Acknowledgements

First, I want to thank the ‘Consejo Nacional de Ciencia y Tecnologia’ (CONACYT) in Mexico for fully funding this research, and the ‘Consejo Mexiquense de Ciencia y Tecnologia del Estado de Mexico’ (COMECYT) for complementary economic support. Thank you to my supervisors Professor Fionn Stevenson and Dr Abigail Hathaway for their guidance, support and valuable comments that have allowed me to grow as a researcher. My sincere thanks Dr. Abigail, for facilitating some equipment from the Department of Civil and Structural Engineering during my fieldwork.

I would also like to thank the members of The University of Sheffield who provided help and support to the completion of this project: Keith Lilley and Philip J. Riley from The Estates and Facilities Management, for allowing me to use the seminar rooms of ICOSS, Jessop West and Henry Stephenson buildings, and giving me all the facilities to conduct my surveys. Thank you to the porters Roger, Steve and Mark for their kind help. Thank you to Professor Edward Hanna, from the Geography Department, who provided weather data from the Geography Department weather station. Thank you as well to Alastair McLean for his help with weather data from The Weston Park Museum weather station during my pilot experiments. I am grateful to all the participants that gave me their valuable time to participate in the experiment. Thank you to all the academic staff from different departments of The University of Sheffield for giving me a few minutes of their lecturer to approach students for my fieldwork. Thank you to the DDSS for providing computing equipment and valuable information for my skills development. My immense gratitude to Dr Scott Allen, Dr Sandrine Soubes and Dr Steve Delaney for their mentoring and counselling support during my studies.

Many thanks to all my friends and PhD colleagues who offered me their valuable time to help me during my fieldwork. Thank you to all the enthusiastic students that helped me with the coordination of the surveys: Daniel, Arlina, Elizabeth, Jana, Jing, Geshwin, Zain, Asatu, Jessica, Anastasia, Aida, Simona and Chloe. Thank you to my friends that gave me support, joy, advice and sincere friendship along the way: Vera Hale, Priya Lakshmi, Ruxandra Berinde, Maryam Fazel, Bianca Santini, Elisa Olivares and Sara Mahdizadeh .Thank you to Gianni M. Vesuviano for his love, patience, sense of humour and help with the proofreading of this thesis.

Finally, thank you to my parents Gabriel and Teresa, my siblings Gabriel, Vero, Lore, Roman and Mary for their immense support and love during my journey. I dedicate this thesis to the young generation of my family: little Ivan Antemio, little Verito, Bryan Alexis, Vanessa Saori, Victor Gustavo, Victor Manuel, Alan Jesus and Gabriela Michelle as a way to encourage them to pursue their dreams.

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ΔT	Difference in air temperature change	°C
θ_c	Operative Temperature	°C
θ_{cl}	Surface temperature of clothing	
θ_{ai}	Average air temperature surrounding the body	°C
a	Autumn	
A_1	Group A at the exterior space	
A_2	Group A in the seminar room	
AC	Air conditioning/ Air conditioned building	
ANOVA	Analysis of variance test	
B_1	Group B at the exterior space	
B_2	Group B in the seminar room	
Clo	Clothing value	
CS	Circulation space	
DL	Draught lobby	
EXT	Exterior space	
f_{cl}	Ratio of the area of the clothed human body	
h_c	Convective heat transfer coefficient at the body surface	$W.m^{-2}.K^{-1}$
HEI	Higher Education Institutions	
HS	Sr. Henry Stephenson Building	
I_{cl}	Thermal resistance of clothing	°C
ICS	ICOSS Building	
JW	Jessop West Building	
m	Metres	
m/sec	Metres per second	
M / met	Metabolic rate	
Min	Minimum	
Max	Maximum	
MM	Mixed-mode building	
NV	Natural ventilation / Naturally ventilated building	
PMV	Predicted Mean Vote	
p_s	Partial water vapor pressure in the air surrounding the body	
RH	Relative humidity	%
T_a	Air temperature	°C
TC_1	Temperature change from exterior to draught lobby	
TC_2	Temperature from draught lobby to circulation space	
TC_3	Temperature change from circulation space to seminar room	
TC_4	Temperature change from exterior to seminar room	
T_g	Globe temperature	°C
T_{op}	Operative temperature °C	°C
T_r	Mean radian temperature	°C
s	Spring	°C
SD	Standard deviation	
sm	Summer	
SR	Seminar room	
v	Air velocity	m/sec
w	Winter	
W	External work	$W\text{-}m^{-2}$

Glossary

Adaptive opportunity: An opportunity that elements of the building design offer to the users to make themselves thermally comfortable

Air Conditioned buildings: Buildings in which internal thermal environments are controlled by adjusting the air supply, ventilation, air humidity and air temperature.

ANOVA: Analysis Of Variance test, a statistical test used to compare the variance between more than two groups and the variability within each group.

ASHRAE: American Society of Heating, Refrigerating and Air conditioning Engineers. A global society focused on standards, research and technology in relation to building systems, energy efficiency, indoor air quality and sustainability.

ASHRAE scale: The seven point ASHRAE scale is a set of seven options given to people to tag their thermal comfort perception to a given environment (cold, cool, slightly cool, neutral, slightly warm, warm and hot)

CIBSE: Chartered Institution of Building Services Engineers

Clo: The unit for thermal insulation of clothing, where clo=0.155 mw.K.W^{-1}. For example, 1 clo is equivalent to: underwear, blouse/shirt, trousers, jacket, socks and shoes

Correlation: A statistical analysis used to determine the strength and direction of the linear relationship between two variables.

Dynamic state: Indicates people in an active state such as walking, working, running, etc.

Draught lobby: The delimited space located immediately after the main door, connecting the exterior with the interior environment, it is part of the lobby unit in buildings.

Data-logger: An electronic device used to record physical measurements over time using sensors.

Flat pattern: A thermal pattern that involves a relatively small exterior and interior air temperature range and small temperature changes from one space to another.

Irregular pattern: A thermal pattern that involves variable temperature changes (ΔT) in both directions from cold to hot and from hot to cold.

Lobby unit: A typical 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.

Operative temperature: The joined effect of the air temperature and mean radiant temperature, combined in a single value. It is a weighted average that depends on the heat transfer coefficients by convection and radiation at the clothed surface of individuals.

P value: Determines the significance of statistical results. It is a value between 0 and 1. Large p values (typically larger than or equal to 0.05) indicate strong evidence against the null hypothesis.

Physical measurements: Refers to the measurements of air velocity, air humidity, air temperature and globe temperature.

Mean radiant temperature: The uniform surface temperature of a radiantly black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space.

Metabolic rate: The unit used to express people physical activity, where 1 met=58.2W.m^{-2}

Naturally ventilated buildings: Buildings in which interior spaces are thermally operated without using any heating, ventilation and air conditioning (HVAC) system, but can use other operable building elements such as windows to provide thermal comfort.

Non-uniform environments: Environments in which temperature cycles, transient, drifts and ramps occur.

Post-hoc: A statistical test used with ANOVA test which determined statistical differences between groups through a set of comparisons between group means of all combinations of pair of groups.

Predicted Mean vote (PMV): An example of a steady-state heat balanced model. It combines the influence of air temperature, mean radiant temperature, air movement and humidity with clothing and activity level into a single value on a thermal sensation scale. It is a predicted mean value of the votes on the ASHRAE scale of a large group of people, exposed to the same environment, with the same clothing and activity.

Predicted Percentage Dissatisfied (PPD): The predicted percentage of people uncomfortable in a given environment. It is a function the PMV; it applies to large groups of individuals in the same thermal conditions with the same clothing and activity level.

R squared (r^2): A statistical measure which shows how close the data are to the fitted regression line. It is the percentage (always between 0 and 100%) of the response variation that is expected by a linear model. Higher R square indicates that the model explains more of the variability of the response data around its mean.

Relative humidity: The ratio of water pressure to saturation vapour pressure at the same dry bulb temperature, expressed as a percentage (%RH)

Standard deviation: An estimate of the average variability of a set of data measured in the same units. It shows how spreads out values are. It is the square root of the variance in a set of data.

Steady-state model: A theoretical model of people's thermal comfort responses conducted in the laboratory (climatic chambers) in controlled conditions.

Sudden pattern: A thermal pattern with a much larger exterior and interior air temperature range. It includes sudden temperature changes from one space to another.

Thermal comfort: 'That condition of mind which expresses satisfaction with the thermal environment' (ASHRAE 2004).

Thermal direction: The direction in which people move from one thermal condition to another, for example from cold to hot or from hot to cold.

Thermal history: The previous thermal conditions that influence people's current thermal perception of the environment.

Thermal sequences: A number of spaces thermally connected in a sequence (one after another).

Transient experience: A short-lived or temporary experience

Transition: Indicates change, movement, interruption, redirection, alteration and adjustment in thermal conditions.

Transitional spaces: Those spaces which are located within a building but which are also connected with the exterior environment.

Chapter 1

1. Introduction

1.1. Climate change

Climate change and energy consumption are some of the most important problems in the world and have been the focus of much research. Climate change is the alteration in the mean climate variability which not only shows the resulting adjustments of natural process, but also the effect of direct and indirect human activities (IPCC, 2014). The Intergovernmental Panel on Climate Change (IPCC) 5th Report 2014, confirms the significant influence of human activities in altering the climate system (Pachauri and Meyer, 2015). Current climate change is having a tremendously negative impact on human and natural systems, such as extreme decrease in cold temperatures and dramatic increases in warm temperatures, directly impacting the global economy, energy demand, food production, public health, etc. (UNEP, 2014). From 2000 to 2010, greenhouse gas (GHG) emissions produced by anthropogenic activities were the maximum ever reported in the past (IPCC, 2014) . This is dramatically increasing concentrations of carbon dioxide (CO2) and other gasses driving a warming effect on the earth surface.

Extreme climatic conditions are expected to persist worldwide. According to the IPCC 2014 Report on Urban Areas, the temperatures observed in metropolitan areas increased by more than 1°C from 1910 to 2012 in certain regions in north America, western Africa, south America and central Asia (Revi and Satterthwaite, 2014). With the population predicted by 2025, the temperature change expected for the mid-21st century will be by over 1.5°C in practically all climatic regions. Taking into account a Representative Concentration Pathway 2.6 (RCP 2.6) scenario, which considers a future with strong mitigation of GHG. Considering an RCP 8.5 scenario, that is based on unchanged current GHG emissions trends, people will be facing temperature changes of 2°C minimum by the mid-21st century, without considering the urban heat island effect (UHIE). This scenario is very dramatic, since the mean temperature rise in some cities could be over 5°C including UHIE.

In short, the expectations regarding GHG emissions and temperature changes indicate irremediable negative impacts for humanity. This devastating future has increased awareness and commitment worldwide in different sectors for an extensive reduction in GHG emissions. An urgent response, action, and rapid development of climatic policy, plans, international standards and guidelines are needed from different economic sectors, in all scales, to reduce the negative effects of climate change in the present and near future. Researchers on human health claim that the future climatic scenarios are a latent risk for human physical and mental health. Moreover, that future climatic prediction above 3-4 °C will result in an 'uninhabitable world'. They highlight that air conditioned (AC) environments reduce population acclimatization and increase health risks (Tawatsupa et al., 2012, Liu et al., 2008, Kjellström and McMichael, 2013). The built environment needs to take into account long-term strategies to face energy consumption and temperature changes, taking into account dynamic thermal comfort parameters more than previously.

1.2. GHG emissions and energy consumption in the built environment

Human energy use has raised concern worldwide, not only regarding its contribution to global warming and climate change, but also with the rapid increase in energy demand. According to the United Nations Environment Programme (UNEP) Annual Report 2014 in Climate Change, energy efficiency actions from 2015 to 2030 could possibly reduce emissions by at least 2.5 to 3.3 Gt CO_2 per annum. Urban areas represent more than 70% of global energy demand and cover a wide range of services, including the building sector (UNEP, 2015). According to the Intergovernmental Panel on Climate Change (IPCC) Report 2014, there is clear evidence to suggest that the building sector has a great potential for climate change mitigation. The IPPC 2014 report shows that the main contribution to GHG emissions in 2010 were the energy sector (35%), AFOLU (agriculture, forestry, and other land uses) 24%, industry (21%), transport (14%) and the built sector (6.4%) (**Figure 1.1**). However, in global GHG emissions, the indirect emissions are rapidly increasing, with 19% attributed to the built sector and 31% attributed to the industry sector. Therefore, the building sector could account for approximately 40% of global energy use and up to 30% of GHG emissions (UNEP, 2009).

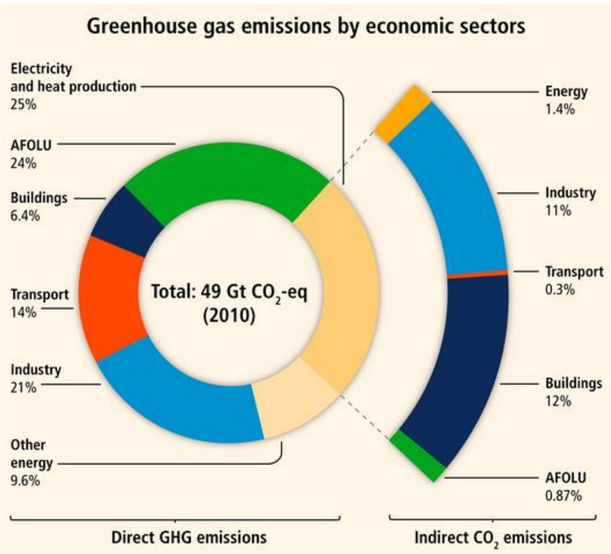


Figure 1.1 Intergovernmental Panel on Climate Change (IPCC) Synthesis Report 2014 website. Total anthropogenic greenhouse gas (GHG) emission by economic sector (http://www.ipcc.ch/report/ar5/syr/)

It has been calculated that around 1 trillion kilowatt hours of electricity are consumed in the operation of air conditioning systems worldwide per year; this is similar to the total energy consumption of Africa. Moreover, energy consumption used for AC is estimated to increase by 4,000TWh by 2050 and pass 10,000TWh by 2100 (Lundgren and Kjellström, 2013). In the USA, AC represents 50% of energy use in buildings and 20% of the total energy consumption in the country (Perez-Lombard et al., 2008). Worldwide, the use of AC in commercial buildings, can consume up to 60% of the total energy that the buildings consume during their operation (Deuble and de Dear, 2012a) equivalent to 50% of all energy in the developed world (Roaf et al., 2010). In Madrid, Spain, a 39°C exterior temperature was registered during one of the hottest summer days in 2008; AC represented around the 30% of the total energy used in this peak day. In Kuwait city, AC can be responsible for up to 70% of daily energy consumption and more than 50% of energy consumption per year. A very similar energy consumption trend is registered in Dubai (UNEP, 2015). Finally, In South and East Asia, AC demand in residential buildings could increase by over 40 times by 2100, compared against the demand in 2000 (Lundgren and Kjellström, 2013). These dramatic numbers point out the important responsibility of the built sector in implementing urgent strategies to reduce energy consumption in buildings, specifically energy used by AC systems.

Currently, there is a common target around the world to reduce energy consumption in AC buildings in a rapidly changing climate, given that even a 1°C increase in AC temperature represents a significant latent risk in increased energy consumption. By 2020 the global energy demand will increase 10% per 1°C increase in temperature on AC configuration (Chua et al., 2013). The rapid rise in AC installation, even in climates where it is arguably not required such as in the UK, could dramatically increase the energy demand; it is expected that by 2050 all UK commercial buildings will be AC (Walker et al., 2014). In fact, this does not look very far ahead, because in the United States around 90% of housing buildings are currently AC. Certainly, with the rapidly increased temperatures, AC will be necessary in tropical and subtropical countries , home to over three billion people, however this will also produce a dramatic increase in energy consumption (Davis and Gertler, 2015). Moreover, the growing demand in AC systems (heating and cooling) provokes additional energy consumption for the implementation of the required technology and infrastructure (UNEP, 2015).

1.2.1. Main problems resulting from air conditioned (AC) buildings

From the literature review (Chapter 2), four main problems can be detected from the increasing use of AC in buildings. First, as described before, that AC can account for up to 70% of energy use in buildings, depending on the climatic region. Another dramatic problem arising from AC systems has been the reduction of the stratospheric damage to the ozone layer caused by harmful Heating Ventilation and Air Conditioning (HVAC) refrigerants containing chlorofluorocarbons (CFCs). Although researchers suggest that 85% of ozone depletion has been replaced (Canan et al., 2015), there is still much work do in order to control GHG emission from energy use. A third problem is the 'sick building syndrome', in which higher levels of CO_2 concentrations are found in AC buildings (up to 2400 ppm) in comparison to Naturally Ventilated (NV) buildings (less than 800ppm) (Honnekeri et al., 2014). Finally, one major problem affecting people in a personal way is that extended exposures to AC environments are modifying people's thermal perception in the long-term. Studies conducted by Candido (2011) and De Vecci (2012) in Brazil show that people using AC are less tolerant to the typical warm temperatures. Interestingly, they also found that the majority of people expose to AC (65.7%) prefer the use of AC systems as a way to cool the environment. This alteration on people's thermal perception has also been observed in single buildings with defined areas operating in different modes (AC and NV) (Honnekeri et al., 2014).

These previous findings are dramatic, since they seem to indicate that the changes not only involve people's physiological system but also an alteration in a psychological way. In short, artificial environments are limiting people's opportunities to adapt themselves and making them less tolerant of the exterior temperature and thermal variability in their everyday lives. There is a big gap in research on how people's everyday thermal experience could affect their long-term thermal experience. This growing problem raises important concerns, first about the ability of populations to adapt to changes in temperature, and second concerning the negative effect of fixed environments on people's thermal history (thermal experiences).

People's thermal history is shaped by previous thermal experiences that they experience in the short or long-term (Nikolopoulou et al., 2001). Recent thinking identifies the importance of providing in buildings a range of thermal variability throughout people's daily experiences. Consequently non-uniform interior environments can have the potential to shape people new habits, behaviours and better thermal adaptation (Parkinson et al., 2012). This could reflect a potential positive effect on people's thermal history in the long-term that could reverse the negative effect of AC exposures. Certainly, the desire to reduce the exposure of people to AC environments has been a concern worldwide and the built environment is the primary sector responsible for reducing the dramatic effects provoked by AC systems. Unfortunately, current predictions are showing a future worldwide built environment fully controlled by AC environments (Walker et al., 2014).

NV buildings are those in which the vast majority of interior spaces are ventilated by natural dynamic forces (without any mechanical system) during most of the time when ventilation is required (CIBSE-GuideA, 2015). Mixed mode (MM) buildings, which combine mechanical systems and NV strategies in the same building, have been widely accepted in the developing world due to the significant energy saving in reduced AC operation (Honnekeri et al., 2014, Deuble and de Dear, 2012b). In temperate climates, the use of mechanical ventilation (MV) during summer can be decreased by up to 90% in operation time by using only NV strategies (Oropeza-Perez and Østergaard, 2013). Moreover, researchers claim that AC can be totally eliminated in summer in moderate climates (Roaf et al., 2010). However, the lack of knowledge on people's thermal perception in real situations, not only is limiting the possibilities of a successful reduction of AC environments, but also limiting an enhanced thermal experience to people using NV buildings.

1.3. Thermal comfort challenges in the built environment

The best strategies to address increasing temperature and energy consumption in the built environment are causing controversy. In particular, the main criticism of building design is increasing use of AC in climatic regions where it is not required (Walker et al., 2014). The debate continues about the consequences of people becoming trapped in AC environments, and losing their connection with the exterior environment in their daily lives (Hitchings, 2009). In the last 20 years, the built sector has increased the use of NV and MM . These two strategies have not only brought benefits in energy saving but also have significantly increased people's thermal comfort satisfaction (Causone, 2015). In many countries, thermal comfort campaigns are promoting the reduction of 2°C in AC set-points mainly in office buildings (Lakeridou et al., 2014). Short-term and long-term strategies, shifts from AC to NV and MM environments, along with gradual 2°C reductions in air temperature, demand more research on people's thermal history and temperature changes. Although thermal comfort research has been conducted for many years, there is a lack of knowledge reflecting how people experience thermal variability in their everyday lives (De Dear et al., 2013). Furthermore, knowledge on this topic needs to be transferred to building operators and estates and facilities managers (EFM) as well as designers and consultants in the built environment.

Perhaps one main problem in thermal comfort research has been to focus too much on people in steady state and fixed environments while overlooking their thermal experiences in real life, in a more natural dynamic state (walking) and more connected with the exterior environment. Reflecting on the literature review, it can be suggested that people's thermal comfort perception in the interior environment is the resulting interaction of repeated interior and exterior thermal experiences in dynamic and steady states. Research related to people's thermal history has revealed that previous thermal experiences can delay or increase people's thermal perception in the following space (Kelly and Parson, 2010, Jin et al., 2011). Therefore, the study of people in dynamic state could reveal unknown variables that could better explain people's thermal perception in steady state. More knowledge in this area could help to better implement design strategies in the short-term that could potentially benefit people in the long-term.

Dynamic thermal comfort study has more complex interactions between people and their environment, reflect more closely the real way that people experience thermal perception in different conditions in real life situations. Psychological studies have also found that people's thermal comfort is influenced by other factors such as thermal expectations (Jitkhajornwanich, 1999), memory(Augustin, 2009), sense of control and notion of time (Nikolopoulou and Steemers, 2003, Knez and Thorsson, 2006) culture (Knez and Thorsson, 2006), and thermal pleasure (Parkinson and De Dear, 2015).

So far, an accurate model or equation to predict people's thermal perception in a dynamic state (people in movement; walking, running, etc.) does not exist (Zhao et al., 2014). This is perhaps due to the isolated study of the different factors, which have not been successfully correlated together. Non-steady-state thermal environments (non-uniform environments) are those where temperature cycles, drifts, ramps and transients (short time) exist (ISO7730:2005, 2005). Previous studies confirm that the study of people in dynamic and non-uniform environments requires different consideration from studies in steady state (Liu et al., 2014, Du et al., 2014). For instance, thermal equilibrium doesn't exist within a time period of 20 to 30 minutes, as it does in steady state (Du et al., 2014). Also, the skin themoreceptors play an important role due to their instantaneous reaction to temperature changes (Romanovsky, 2014). So far, researchers suggest that people's thermal comfort perception in a dynamic state is result of the interaction of dynamic variables, which can drive different conditions where people feel thermally comfortable. Again, this is another reason for more detailed study of the effect of people's thermal history in a dynamic state.

Pitts (2013) points out that transitional spaces (spaces connecting the interior with the exterior environment) are a potential opportunity to explore people's thermal perception and people's limits of thermal tolerance in dynamic state. Between the indoor and outdoor environment, transitional spaces contain a unique and complex range of variables that cannot be found in the interior environment or in steady state. Moreover, transitional spaces can offer the opportunity to reduce energy consumption in buildings, since it has been demonstrated that people can tolerate wider temperature ranges in these spaces (Pitts and Bin Saleh, 2007). Hence, transitional spaces could be wrongly conditioned to the same temperature that exist in other interior spaces that people use for longer periods of time and in a steady state. In some cases, lobby areas could require more energy than other interior areas (Pitts et al., 2008), depending on location, percentage of elements (walls) connected with the exterior and design features (e.g. materials and dimensions). Pitts and Saleh (2007) estimated up to 11% energy saving in the heating system and 2% in the cooling system in transitional spaces in the moderate climate of UK by reducing the AC configuration by 5°C. However, findings from energy simulations in more extreme climates (Hong Kong), suggest that reducing the AC temperature configuration in transitional spaces could reduce energy use by up to 26% (Hui and Jie, 2014). Hence, more research in transitional spaces can contribute to understanding people's perception in dynamic state, which could indirectly increase the understanding of people's thermal perception related with steady state conditions. A number of researchers have pointed out the possible opportunity that transitional spaces offer as an ideal situation to explore people's perception in order to reduce energy consumption (Pitts et al., 2008, Chun et al., 2004, Pitts, 2013, Wu and Mahdavi, 2014).

Most of the studies related with people in dynamic transient states have been conducted in climatic chambers with a limited number of participants. From the limited literature in this topic, it can be seen that the significance of repeated thermal experiences in people's daily lives has been largely overlooked. Furthermore, the multiple variables involved in this topic only allow the study of specific thermal conditions, which do not accurately reflect the wide range of real life situations. Therefore, findings seem limited to specific situations in time, space and thermal conditions. More outcomes from this topic could provide the basis to effectively mirror the way that the population perceives thermal comfort in real life. The study of people's thermal experiences in transitional spaces offers an excellent platform to explore people in a real and dynamic situation. Findings can reveal a better understanding of people's reaction and tolerance to transient climatic conditions. This would further inform strategies to reduce energy consumption in buildings and promote a better long-term adaptation.

1.4. Research questions arising from the gap

One of the significant temperature changes that people experience daily is movement from the exterior to the interior environment (Chun et al., 2004, Pitts, 2013). Through more adaptive environments, perhaps this short-term experience could alter people's long-term thermal history and help to reduce energy consumption at the same time. However, the way that people experience a thermal transition from the exterior to interior environment has not been explored in key transitional areas such as lobby areas. The research gap identified in the literature review leads to a number of new research questions:

- How much thermal variation can be identified in the indoor environments 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?
- How can the use of the transitional lobby unit further modify people's thermal perception during the normal ways that people use connected spaces?
- Does this temporal interaction provide an opportunity to help reduce energy demands by adjusting and influencing people's perception of the thermal state of their final destination?
- How can outcomes from people's thermal perception in real situations influence building design, building operation and thermal comfort policies?

1.5. Aims and Objectives

The overall aim of this thesis, arising from the research questions, is to investigate people's thermal perception in a dynamic state (walking), in a real situation and in a moderate climate, involving the study of people's short-term thermal history. This specific study examines the use of transitional spaces while people are moving from the exterior to interior environment, by using a lobby space as a case study.

Within this aim are the following objectives:

1. To identify thermal variations in transitional spaces; in this case exploring lobby areas as a case study in buildings operating with NV with heated spaces during winter.
2. To quantify possible significant variations in people's thermal perception in an interior space, caused by previous short-term thermal experiences, while using transitional lobby spaces on the way to their final destination. Specifically, to identify a positive pattern that could influence a positive thermal adaptation in the following spaces.
3. To recognise typical alterations (patterns) in people's thermal perception that could modify people's thermal perception in a positive way towards a better adaptation
4. To determine to which extent it is possible to reduce energy consumption in transitional lobby areas, by using outcomes from people's thermal perception and thermal tolerance in dynamic state in a repeated real situation.

5. To evaluate the implication of key findings that can potentially be applied in building design and policies in order to reduce energy demand in buildings while providing thermal comfort.

These objectives will help future work towards understanding how the thermal connections and manipulation of transitional spaces can positively modify people's thermal perception in the long-term.

1.6. Research Approach

The research questions, aims and objectives of this thesis were identified through a careful literature review, identifying research gaps in current studies on adaptive thermal comfort theory, specifically on the study of people's thermal perception in dynamic states. Due to the significant gap in research in transitional spaces, findings from studies related to this subject (non-uniform environments, people's thermal history, transient state studies and health research) were the main source of information that shaped the development of this thesis. At the same time, suitable research methods were identified and evaluated through the literature review.

This research was developed based on a quantitative research methodology. Since the study explores a real situation (people's thermal experience in the lobby area on a daily basis), one year of fieldwork research was the method chosen to reflect data as close to reality as possible under different climatic conditions (seasons). Because of the limited control over a number of variables in non-laboratory situations, a large sample size analysis through quantitative methods was selected. Thermal comfort questionnaires, along with simultaneous measurements of physical variables (air temperature, relative humidity, wind speed and globe temperature), were used to gather people's answers while they used the lobby area to move from the outdoor to the indoor environment. Since the study attempts to provide a large overview of people's thermal perception in the topic gap, no attempt is made to provide qualitative research.

A moderate study climate (Sheffield, UK) was selected for two main reasons: first, to fill a research gap in the exploration of these climatic regions, and second because this climate represents a potential opportunity to reduce AC in buildings and encourage people's thermal adaptation in AC and NV buildings. The exploration of people in NV buildings offers a better environment in which to explore people's limits of comfort and the climatic conditions in which people feel comfortable. First, because interior spaces in NV buildings have more interaction with the exterior climate. Second, because NV buildings have wider thermal variability and more frequent temperature changes than AC buildings. Third because the evaluation of people's limits of comfort and thermal tolerance to temperature change in NV buildings can be transferred to strategies to reduce energy consumption in AC buildings. Finally, the evaluation can be used to adjust or improve thermal connections in NV buildings in order to improve people's thermal experience. Three typical NV lobby layout units were selected for the field study through an extensive quantification on of typical lobby in Higher Educational Institutions in the UK spaces built in recent years (2007 onwards).

1.7. Thesis Structure and Content

This thesis is comprised of seven chapters and six appendices.

Chapter 1 provides a brief background that identifies the problem and justifies the purpose of the research work presented in this thesis in terms of originality, significance and relevance. It also provides the overall research approach and an overview of the content of the thesis.

Chapter 2 provides a literature review situates people's thermal comfort perception in dynamic and transient state, in relation to the wider issues of climate change, energy use and comfort in buildings. People's thermal perception is analysed from different perspectives, including human thermoregulation, physical and psychological factors. The research limitations and gaps within this topic are discussed, referencing examples from previous research.

Chapter 3 provides a methodology for the research and explains the methods that have been used for conducting this research and for the data analysis in this study. It describes a preliminary survey in the UK for the case study selection of buildings in detail. It also shows the development of the survey procedure, the instruments for data collection, the experimental set-up and equipment calibration procedures. Chapter 3 also illustrates preliminary pilot experiments, along with the main modifications to the survey procedure and equipment settings that resulted. Finally, it describes the research design for the data survey and analysis.

Chapter 4 reports the results and illustrates the data organization for analysis. It is focused on findings relating to the physical properties of the case study buildings during the year (air temperature, wind speed, relative humidity and globe temperature). It also provides an overview of people's thermal perception over the year, in order to further understand people's thermal perception in short-term experiences.

Chapter 5 is specifically focused on reporting findings from people's short-term thermal history and related to people's thermal perception in transient state. It presents a meticulous exploration of people's answers in a detailed level of analysis, organized by thermal bins and thermal sequences.

Chapter 6 presents a discussion of the main findings and their implications for potential application in different areas, including architectural practice, building design, building operation, policy development and rating system development. It also gives some insights on the implications of the thesis findings to positively influence people's thermal perception in their daily thermal experiences, for better thermal adaptation in the short and long-term.

Chapter 7 summarises the research findings overall and draws out deeper conclusions from the discussions. The contribution of this research reflects on the aims, objectives and research questions initially presented in this work. Finally, it describes the weaknesses and limitations of this research along with suggestions and recommendations for future research in this topic.

A list of crucial appendices can be found at the end of this thesis, which supports the findings of various chapters.

1.8. Publications

One invited journal submission, three conference proceedings papers and five conference presentations have resulted from the work contained in this research.

Conference paper: **Vargas, G**.(2013) ‘Thermal transition, exploring the comfort of thermal variability’. *The Sustainability +/- Collapse*, East West Research Institute. 9th May 2014, London, UK.

Conference paper: **Vargas, G**. and Stevenson, F. (2014). Thermal Memory in Transitional Lobby Spaces. Energy Procedia 62, 502-511 (http://www.sciencedirect.com/science/article/pii/S1876610214034432)

Journal paper (in review): **Vargas, G**. and Stevenson, F. 2015 (in review), People and climate variability; the impact of everyday transition on people’s thermal comfort. Environmental Sustainability Journal

Conference paper: **Vargas, G.** and Stevenson, F.(2015) ‘Thermal history and sequences in transitional spaces; does order matter?’.*The 7th International Conference on Sustainable Development in Building and Environment (SuDBE)*. 27th-29th July 2015, Reading, UK.
Award for the best paper presentation

Chapter 2

2. Thermal comfort dynamics

2.1. Introduction

This review chapter focuses on the analysis of people's thermal comfort dynamics and is divided into three main sections. The first section, provides an overview of thermal comfort research and people's thermal comfort in dynamic state. The dynamic interaction of people's thermal comfort in relation to the exterior and interior environment is examined from different perspectives; from people's thermoregulatory system, psychological perspective, adaptive thermal comfort theory, health research, thermal quantification and everyday life thermal experiences.

The second section, explores in detail how people experience thermal transition with the exterior and interior environment, and highlights the lack of research on people's thermal perception in transitional spaces (connectors between the indoor and outdoor environments) and transient conditions (short-lived experiences). Related research is evaluated and linked to people's thermal perception in a dynamic state (walking) over short periods of time. A number of concepts and findings from previous work, such as people's thermal history, thermal direction, step change temperatures, thermal alliesthesia and short-term occupancy, shape a bigger picture of people's thermal perception in transient conditions. At the same time a number of research gaps and discrepancies are identified in this section.

The third section explores the concept of transition (implicating change) and transitional spaces, which are then located in a specific case study, the lobby space. The building lobby area is evaluated as a key zone where people experience a number of particular thermal experiences, which are different from those experienced at the exterior or interior environment. The lobby is not only evaluated through its physical functions but also as a multisensory experience involving architectural design, people's behaviour, and perception.

2.2. Background in thermal comfort research

Since ancient times, human beings have interacted with the climate in an active way; they have been able to adapt themselves to the wide range of conditions that they habitually experience (Nicol et al., 2012, Parsons, 2003a). However, from around the 1970s, AC systems (for cooling and heating) gradually introduced fixed temperatures into the indoor environment (Walker et al., 2014). From the 1760s-1850s the study of thermal comfort focused on people's performance, productivity and health (Parsons, 2003a). Many studies on human thermoregulation conducted since that time period have focused on people's productivity (De Dear et al., 2013).

In the 1970s, P.O. Fanger contributed many significant principles and methods to the study of thermal comfort which have dominated the field for many years (Parsons, 2003a), including the Predicted Mean Vote (PMV) equations. They have been used continuously in the research of people in steady-state interior environments. Since the 1970s, Fanger has conducted research with a particular focus on people's health resulting from the unsatisfactory thermal environments that they experience at work (Fanger, 1973). Since then, it has been claimed that thermal perception is different from one individual to another and that it is important to understand the environmental variables, and combinations of them, that affect people's thermal comfort.

The majority of the thermal comfort experiments conducted in this period did not take into account people's thermal experiences in dynamic states and real situations. Most of the work was conducted in climatic chambers with steady state environments. Since then, the study of people in dynamic state has continued to be overlooked, although the topic has been acknowledged.

Studies related with people's perception in different ambient temperatures, transient conditions, temperature fluctuations, temperature changes, and temporal temperature variations were all investigated in the subsequent years (Hensen, 1990). In 1973, Fanger pointed out the importance of studying people in transient state, including fluctuations and sudden temperature changes when people move from the exterior to the interior environment (Fanger, 1973). He also explored thermal comfort variations from one day to another, and found a standard deviation of 0.6°C. He also acknowledged that people can acclimatize themselves to hot or cold surroundings: an example of this is the resulting wide range of thermal comfort conditions in different climatic regions of the planet (Fanger, 1973). Despite the age of this claim, further research has been very limited, not further developed in detail, nor incorporated in international standards. This early gap in research remains to this day.

By the 1900's, the use of AC expanded uncontrollably, even in moderate climates (de Dear, 2004). Since then, due to the over use of AC, people have increasingly lost their flexible interface with their exterior environment and limited their ability for thermal adaptation (Candido et al., 2011). In the same period, more research on thermal comfort became significant for the basis of the Heating Ventilation and Air Conditioned (HVAC) System (de Dear, 2004). However, the majority of this research was also conducted in climatic chambers. Consequently, it was questioned if research using this method accurately reflected peoples' thermal perception in real life. Moreover, there was a concern about the necessity of achieving a fixed 'right temperature', as pointed out by Griffiths (Nicol et al., 2012). Later, the American Society of Heating and Ventilation and AC Engineers (ASHRAE), commissioned field experiments in order to validate earlier experiments conducted in the laboratory (de Dear, 2004). Some researchers agree that there is no convincing evidence to show that AC was a response to human necessity, seeming more like a commercial way to deliver comfort, ignoring people's natural thermal adaptation (Walker et al., 2014).

2.3. People in dynamic state

The study of people in dynamic state requires not only the understanding of different variables, but also the interplay between them. People's thermal comfort is undergoing constant change, driven by different factors, which are also changing over different time periods. Therefore, people's thermal comfort at a specific time is the result of the interaction of multiple variables. This dynamic interplay, plus the additional variability of people in movement, makes the study of thermal comfort very complex. Thermal comfort is dynamic and is related to the way that people perceive, interact with and adapt to the environment (rather than a static condition) to satisfy the majority of the population (Nicol and Stevenson, 2013, Nicol, 2011). (Nicol and Stevenson, 2013, Nicol, 2011). Over the years, researchers have shaped dynamic and flexible concepts of thermal comfort by including variables from different perspectives (Table 2-1). There is considerable research evidence to show that people's thermal comfort perception is never fixed, and that people and their context are in continuous movement, adaptation, and change.

A.P. Gagge and colleagues (1969), explored people's thermal sensations during exercise (pedalling a bicycle) at different ambient temperatures. They reported a range of thermal perception from cool to hot over 30-40 minutes of steady exercise. In the same study, they highlighted the importance of the effect of skin sweating, thermoregulation, metabolic rate, thermal transients, the range of exercise levels and upper and lower limits of comfort (Gagge et al., 1969). Nowadays, the understanding of people's thermal perception in dynamic state is still under research, moving forwards and exploring outside the boundaries of the typical factors that dominated thermal comfort research for decades (Parkinson and De Dear, 2015, Parkinson et al., 2012).

Table 2-1 Thermal comfort concepts over the years

1973: 'People are not alike, thermally or otherwise. If a group of people is exposed to the same room climate it will therefore normally **not be possible**, due to the biological variance, **to satisfy everyone at the same time**' (Fanger, 1973).

1970: It was pointed out by P.O. Fanger the importance of explore **non-thermal climatic variables** affecting people's thermal perception, this includes lighting and acoustics.

1977: 'comfort occurs when the current level of the varying microclimate equals the current level of the varying requirement of the person exposed to it' (**Humphreys, 1977**).

1982: Thermal comfort corresponds to everything contributing to the "**well-being of people's life"** (Pineau, 1982).

1982: Thermal comfort is "a **social constructs"** which reflect the beliefs, values, expectations and aspirations of those who conduct them Cooper (1982)

1990's: Thermal comfort is "**that condition of mind that expresses satisfaction with the thermal environmen**t" (ASHRAE, 2004)

1990: "Yet thermal conditions in buildings are **seldom steady"**, due to the interaction between building, structure, climate, occupancy, and HVAC system (J.L.M. Hensen, 1990)

1994: Thermal comfort is "state of embodiment that is beyond awareness, it is pre-reflective, a way of being that is **beyond physical or mental awareness**, a state of an integrated body" (Morse et al., 1994)

2003: The microclimatic parameters influence 50% of people's thermal sensation. The rest could not be measured by the physical parameters. "**Psychological adaptation seems to become increasingly important"** (Nikolopoulou and Steemers, 2003a)

2005: Thermal comfort is " **a provisional and socio cultural achievement"** with different impacts on energy and environmental issues (Chappells and Shove, 2005)

2005: 'Comfort is the result of the **dynamic interaction** between people and buildings in a particular **social context**, not a steady state fulfilment of physiological conditions' (Nicol and Roaf, 2005)

2010: Neurophysiology, "Thermal comfort is the result of conscious and unconscious **multisensory interactions"** (Candas and Dufour, 2005, Lada H and Atzel, 2010)

2012: Thermal comfort involves different factors; it not only involves the need to maintain a constant body temperature (37 °C) which is crucial for heath and survival, It is a more complex **interplay of variables included in human physiology, psychology, sociology, physics and psychophysics** (Nicol et al., 2012)

2013: "Thermal comfort is one of **the most immediate and direct impacts** exerted by the built environment on its occupants". (De Dear et al., 2013)

2015: "The building industry needs a fundamental paradigm shift in its notion of comfort, to find low-energy ways of creating **more thermally dynamic and non-uniform environments** that bring inhabitants pleasure" (Brager et al., 2015)

2015: Dynamic environments not only offer better thermal comfort opportunities than fixed interior environments, but can also **enhance people's thermal comfort perception** (Parkinson and de Dear, 2015)

The study of people in dynamic state involves a number of active factors not only relating to people's physiological state but also to dynamic interplay with a lively context. First, people's dynamic state refers to individuals performing activities such as standing with active working, walking, running, jogging, etc., in which their metabolic rate is above 1.2 met. Based on the rate of heat production within the body, the metabolic rate (met) shows the level of activity of a person in Watts/m^2 (Nicol et al., 2012). On the contrary, people performing sedentary activities such sitting passive, standing relaxed and sitting have a metabolic rate (met) lower than 1.2 (EN15251, 2007). People walking have metabolic rates over 1.2 met: 0.9 $m.s^{-1}$=2.0 met, 1.3 $m.s^{-1}$=2.6 met and 1.8 $m.s^{-1}$=3.8 met (CIBSE-GuideA, 2015). People can be performing dynamic or sedentary activities in non-uniform or in steady-state environments. In steady-state environments, the climatic conditions are constant in time, while in non-uniform environments people experience temperature changes (Figure 2-1).

Since thermal comfort is in constant change, it also implicates short-time thermal experiences that are denoted as transient conditions. It also takes account thermal transition when people change from one thermal condition to another. Additional factors included in dynamic state are temperature drifts, air movement, and thermal asymmetry. To sum up, people in dynamic states have different configurations depending on metabolic rate, physical context and time.

Thermal comfort dynamics

People	**Non-uniform environments**	**Transient conditions**
People in **dynamic** state perform **activities** above the 1.2 met for sedentary office work. People can vary their metabolic rate out of these boundaries during their daily activities. Even changes over a small duration can significantly alter people's thermal perception (Goto et al., 2002) **People's thermoregulation** **People's psychology** **People's social context**	When people experience temperature changes. **Temperature changes** can be classified into: -Cyclical changes -Ramp or drift changes -Step changes (Hensen, 1990, BS EN ISO, 2005) **Cyclical changes** are repetitive and have a mean value of peak to peak temperature within a period of time and frequency. **Ramps or drifts** are steady changes over time. They are identified by comprising a starting value, amplitude, and rate of change. **Step change** temperatures are experienced from one thermal environment to another (from cold to hot or from hot to cold). They have direction and duration.	Thermal experiences that last only a short period of time, for instance a temporary experience in time and space.

Figure 2-1 People experience different combinations of these variables daily. For instance, when moving from one space to another, from indoor to outdoors, from outdoors to indoors, taking a plane, using a boat (Liu et al., 2014, Nakano et al., 2006, Kotopouleas and Nikolopoulou, 2014, Jitkhajornwanich, 1999)

2.3.1. The Adaptive Thermal Comfort Theory

'If a change in the thermal environment occurs, such as to produce discomfort, people react in ways which tend to restore their comfort'…'Buildings offer an adaptive opportunity when users can interact with the building to adapt themselves'…'The interior comfort temperature is closely correlated with the exterior temperature in NV buildings'…'People take time to perceive and react to thermal changes.. 'The adaptations of people occur over different time scales'
(Nicol and Humphreys, 2002)

The contribution of the 'adaptive thermal comfort theory' by Nicol and Humphreys, from 1973 onwards, in response to the shortfall in understanding of thermal comfort, triggered a vast work of related research. Early work conducted by Nicol and Humphreys, with children in classrooms and with office workers, highlighted the importance of studying the way that people react to the environment (Nicol and Humphreys, 1973). Positive changes such as adjustments of clothing, metabolic rate, and variations in the environment, can trigger a positive effect on people's thermal comfort. They put emphasis on the use of the adaptive principle in building design and the use of survey data (field studies) as a way to explore thermal comfort as a *self-regulated system* where people have opportunity to experience personal adjustments.

Fieldwork evidence revealed that 'the interior comfort temperature is closely correlated with the exterior temperature in naturally ventilated buildings' (Nicol and Humphreys, 2002, McCartney and Nicol, 2002), and significant differences were found in people's thermal perception between NV and AC buildings. From this research, the importance of the dynamic interaction between people and their environment, which was previously overlooked, was recovered again. The fundamental concept of the thermal adaptive thermal comfort theory ('If a change in the thermal environment occurs, such as to produce discomfort, people react in ways which tend to restore their comfort') (Nicol and Humphreys, 2002), formed the basis for further research on people's thermal adaptation, people's thermal behaviour, psychological factors altering people's thermal comfort, and the dynamics of thermal comfort.

Abundant research findings have demonstrated the importance of offering a built environment able to offer adaptive opportunities to people (Brager and de Dear, 2002, Nicol, 2011, Haldi and Robinson, 2008a). Yet, contemporary building design, preferring artificial solutions (air conditioning) has responded slowly, and for decades this type of building has been challenged to offer design solutions able to take into account the dynamic interplay between people and their context.

Nowadays, there is growing concern about people's limits of thermal adaptation. The increasing global temperatures, changing climates and fixed artificial interior environments have generated a complex interaction between people and their environment. In the current context, it is wrongly assumed that people are able to adapt to any kind of climate conditions (Kjellstrom and McMichael, 2013). This problem is questioning people's ability to adapt to temperature changes and to cope with climatic conditions driven by climate change in the short and long-term. Hence, the study of people's thermal perception in more dynamic and challenging contexts has increased in the last decade, growing different research topics around the adaptive comfort theory, such as the adaptive opportunity in buildings, people's behaviour, psychological adaptation and reduction in the use of AC (Table 2-2).

Table 2-2 Research topics around the adaptive comfort theory

Adaptive opportunities	**Behavioural performance gap**	**Psychological adaptation**	**Reduction of AC in buildings**
(Haldi and Robinson, 2008b)	(Brown and Cole 2009	(Nikolopoulou and Steemers, 2003a)	(Candido et al., 2011, Chun et al., 2008)
When people adapt themselves they have reactive and interactive adaptation with personal and building elements	A gap exists between people's knowledge on the operation of building, and building operation and people's behaviour	The major factors comprising psychological adaptation are: perceived control, time of exposure, environmental stimulation, naturalness, expectations and experience.	People in AC buildings have different thermal perception than those in naturally ventilated. People can become addicted to AC environments
Physical adaptation: Options given to occupants to adapt themselves. Interaction with windows, doors, blinds, fans, etc	The building design impacts people's thermal comfort and behaviour through building complexity, simplicity, usability, accessibility and responsiveness		
People have different perceptions of the environment based on expectations, previous experiences, time of	People's behavioural situations, social and psychological factors influence their thermal perception		

exposure, etc.

Physiological acclimatization exists when physiological changes result from repeated thermal experiences.

2.4. Thermal comfort perception; a complex quantification

People's thermal comfort perception is complex to measure; a number of contradictions have been discussed over the years around this topic. For instance, many studies have questioned the accuracy of thermal standards because they are based on experiments conducted in climate-controlled laboratories (Nicol and Humphreys, 2002, Brager and de Dear, 2002). Researchers claim that laboratory experiments do not accurately represent people's real comfort conditions (Nicol and Humphreys, 2009). Investigators suggest the existence of two key problems, first between the assumed and the real perception of people's thermal comfort and second between people's assumed and real behaviour in the same spaces (Brown and Cole, 2009). The existence of a wide range of conditions and variables in which people express comfort at different times adds complexity to the evaluation of these variables (Parkinson and De Dear, 2015). While some researchers have carried out field studies (de Dear, 2004, Nikolopoulou et al., 2001), others have use experimental climate chambers for better control or isolation of some variables (Du et al., 2014, Liu et al., 2014, Parkinson et al., 2012).

2.4.1. The Predicted Mean Vote (PMV) in dynamic state

The majority of studies of people in dynamic states have been conducted in climatic chambers, and only a few of them have been validated through fieldwork. Thermal comfort indices, for example the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD), have been used to a great extent in international standards to predict people's thermal perception in steady state conditions (Humphreys and Nicol, 2002). New adaptive comfort standards have also been included in naturally ventilated buildings (de Dear and Brager, 2002). Furthermore, additional research is in progress, updating international standards in different climates (De Vecchi et al., 2015). However, an accurate prediction of people's thermal perception in dynamic state does not yet exist. International thermal comfort standards have included a limited section referring to non-steady state environments (temperature cycles, drifts or ramps and transients) where the PMV and PPD equations can be used (ISO7730:2005, 2005). Researchers claim that these equations do not accurately reflect people's thermal perception identified in laboratory and fieldwork (Kelly and Parson, 2010, Chun et al., 2004, Wu and Mahdavi, 2014, Du et al., 2014).

Previous studies have addressed this problem in different dynamic conditions. For example, laboratory studies found that the PMV predictions correlate better with thermally adapted participants than those immediately after transition. They have also found that the change in people's thermal perception in transient conditions depends not only on the temperature difference of the two spaces but also on the relationship between people's Thermal Comfort Vote (TCV) and the temperature of the space where people are arriving (Wu and Mahdavi, 2014). Although improvements and modifications to the PMV equation are in progress, a convincing method of calculation is not yet ready. Models have been in constant development to predict people's thermal perception in a dynamic state (Zhang et al., 2004, Zhang et al., 2010, Zhao et al., 2014). However, more research is needed in this area to generate the basis to develop equations that better reflect the variety of factors acting together in dynamic conditions. Furthermore, current thermal comfort indices such as PMV and PPD need to be adjusted to include additional variables for different dynamic scenarios. In short, robust fieldwork research to which this thesis contributes is required to validate the progress of current proposals. Research work with people in dynamic states and in more dynamic environments, such as semi outdoor and transitional spaces, are potential situations to explore people's limits of comfort in transient conditions (Jitkhajornwanich and Pitts, 2002, Steemers, 2003, Chun and Tamura, 2005, Hui and Jie, 2014).

2.4.2. Thermal comfort parameters

People's thermal comfort depends on the thermal balance of their body. Based on the equations for heat balance in the human body, people's thermal comfort is driven by their clothing (clo) physical activity, metabolic rate (met) and environmental parameters: air temperature (Ta), mean radiant temperature (Tr), wind speed (Va) and relative humidity (RH). With the use of these parameters, the thermal sensation of the body can be predicted by using the Predicted Mean Vote (PMV) calculation. In addition, the Predicted Percentage Dissatisfied (PPD) can also be calculated from these same PMV parameters, (ISO7730:2005, 2005). It is worth noting that people sense the energy loss from the body but cannot feel the spatial temperature of a given space. For this reason, measurement of the thermal comfort parameters is crucial to reflect people's thermal comfort. In addition, the combined effect of each variable is weighted differently during the body's heat loss. Three thermal parameters can each represent the combined effect of several key factors in a single value. The integrating parameters are the Operative Temperature (Top), the Equivalent Temperature (Teq) and the Effective Temperature (ET*). These values are used to describe a given environment (Equation 2-1,Equation 2-2 and Equation 2-3). The description of each variable and thermal index are summarised in Appendix 1.

Equation 2-1: T_{op}= integrated effect of Ta & Tr

Equation 2-2: Teq= integrated effect of Ta & Tr & Va

Equation 2-3: ET*=integrated effect of Ta & Tr & Pa

The basic equation for thermal balance includes:
Metabolic rate (Met), mechanical work done (W), convective heat loss from the clothed body (C), radiative heat loss from the clothed body (R), evaporative heat loss from the clothed body (E), convective heat loss from respiration (C_{res}), evaporative heat loss from respiration (E_{res})and the rate at which heat stored in the body tissues (S) (Nicol et al., 2012).

Equation 2-4: $Met\text{-}W=C+R+E+(C_{res}+E_{res})+S$

These parameters are vital for any thermal comfort study. However, the main limitation of these thermal indices and factors is that they cannot accurately reflect people's thermal perception in non-uniform environments, or in dynamic and transient conditions (Wu and Mahdavi, 2014, Zhao et al., 2014). The key problem is that a thermal balance is not possible in transient conditions, since the human body is in a dynamic state with its environment.

2.5. The comfort of thermal variability

People's sensitivity to thermal variations has been studied since the 1970s. In 1974, Griffiths and McIntryre explored the effect of different temperatures changes on people's thermal perception. They analysed eight groups of people experiencing different temperature changes over 6 hours (0°C, 3°C, 6°C and 9°C, upward and downward, centred around 23°C). They found that thermal variations of 3°C and over had an effect on people's thermal perception detecting the warming and cooling increments over time (Griffiths and McIntyre, 1974). They highlighted the importance of exploring small temperature changes and the discrepancies between the different effects of large and small temperature changes on people's thermal and pleasantness perceptions. This work conducted by Griffiths and McIntryre highlighted the basis and key aspects of the study of variable thermal conditions: direction of change, temperature differences (ΔT) and time of exposure. However, these experiments were focused on linear temperature changes. Related research from different authors followed, exploring people in laboratories and overlooking real situations where temperature change is not linear.

Recent thinking has revealed that active environments can not only offer better thermal comfort opportunities than artificial fixed interior environments (Nicol, 2011, Tuohy et al., 2010) but can also even enhance people's thermal comfort perception (Parkinson et al., 2012). Currently, variable thermal environments are leading research into a new understanding of people's thermal perception, involving the exploration of a number of variables from different perspectives, including factors not considered in steady state conditions. There is clear evidence to suggest that people's thermal perception in dynamic and transient conditions does not reach equilibrium with the surroundings, yet this interaction can also bring a comfortable dynamic relationship (Parkinson et al., 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. Research work shows that people naturally look for temperature variations as a way to reach comfort (Figure 2-2), and that people's thermal comfort is not represented by a single air temperature value. In many studies, people have reported a comfortable thermal desire towards warmer or colder conditions rather than only 'neutral' (Humphreys and Hancock, 2007). This reflects flexibility in ways to feel thermally comfortable. The variability in operative temperature caused by heating, mechanical and AC systems can increase a more flexible use of the interior spaces, since people use these variations as a way to reach personal comfort by moving from one area to another, even in the same space (CIBSE-TM52, 2013).

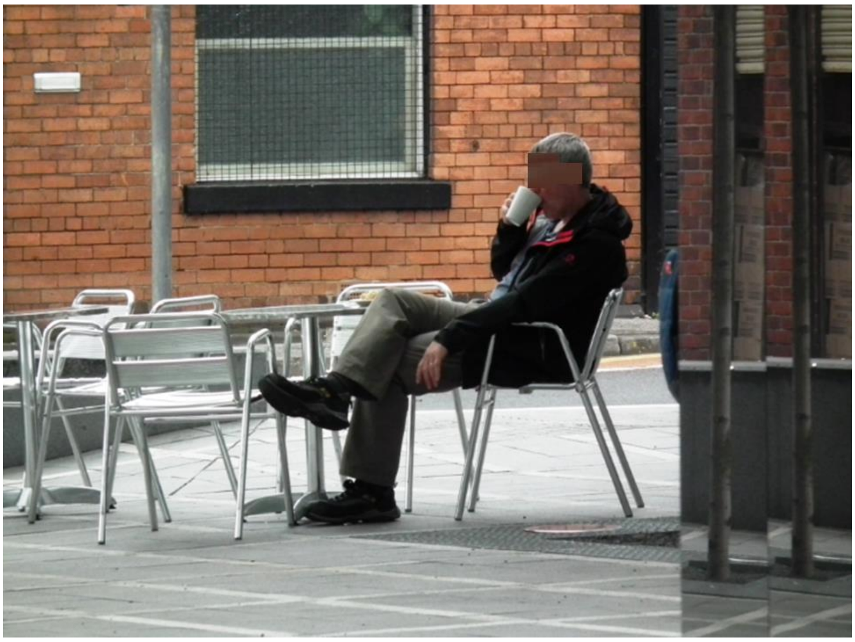


Figure 2-2 People look for thermal variability during the day, for example moving from indoors to outdoors as a break in the day.

So far, although work has explored thermal variability and people's thermal adaptation in the exterior environment (Vasilikou and Nikolopoulou, 2013, Nicol et al., 2006, Potvin, 2000), limited research has been conducted on this in the indoor environment. In the interior environment, the way that spaces are thermally connected has been relatively overlooked and it has been assumed that buildings can offer spatially uniform interior environments. In the interior spaces, temperature changes can be caused by building design features and systems, variations in the outdoor climate, movement and activities that people perform whilst interacting with the building and movement of people from one place to another (De Dear et al., 2013). Based on empirical methods, temperature ranges from 1°C to 13.6°C have been registered within naturally ventilated interior spaces, depending on the season of the year (Pitts, 2010). In AC areas, studies have registered temperature differences from 1.5°C to 6.2°C between spaces (Hensen, 1990, Ghaddar et al., 2011, Kotopouleas and Nikolopoulou, 2014). In both, NV and AC buildings, the larger temperature differences happen in the spaces connecting the exterior with the interior environment (Chun et al., 2004). However, this depends on how much the interior is connected with the exterior environment. Although evidence of thermal variability in the interior environment exists, research work has not explored this topic in detail in relation with people's thermal perception.

Many researchers claim the importance of urgent reincorporation of thermal variability in people's life, before they totally lose their connection with the exterior environment (Hallegatte, 2009). Contrary to a steady temperature, buildings should offer a wide range of experiences by offering different temperatures when people move from place to place (Unwin, 1997). Therefore, building design needs to challenge people and stimulate adaptive reactions, by including thermal variability in people's typical day. People's behaviour has been highlighted as the most powerful unconscious human thermoregulation method to reach thermal adaptation (Nicol et al., 2012), specifically, when people change clothes, change posture, change metabolic rate, move to a different environment or make use of thermal comfort controls (when possible). The study of thermal comfort and people in dynamic states involves the exploration of people's interplay with their environment along with other psychological factors, social context and the understanding of the human thermoregulatory system in action.

2.5.1. The human body in dynamic state

Thermoregulation is the capability of the human system to keep the core temperature stable, balancing the temperature transfer between the body core and the thermal environment (Chen et al., 2011). When people experience a thermal stimulus from the surrounding environment, the thermo-regulatory system works to maintain the body core temperature close to 37°C in thermal balance (homeostasis) (Figure 2-3). In steady state, a person requires 20 to 30 minutes to adjust their thermo-regulatory system to environmental changes to reach thermal equilibrium (Nagano et al., 2005, Du et al., 2014). Hence, it seems that the thermoregulation process can continue for longer than 30 minutes, but more slowly and with less impact on people's thermal perception (Du et al., 2014).

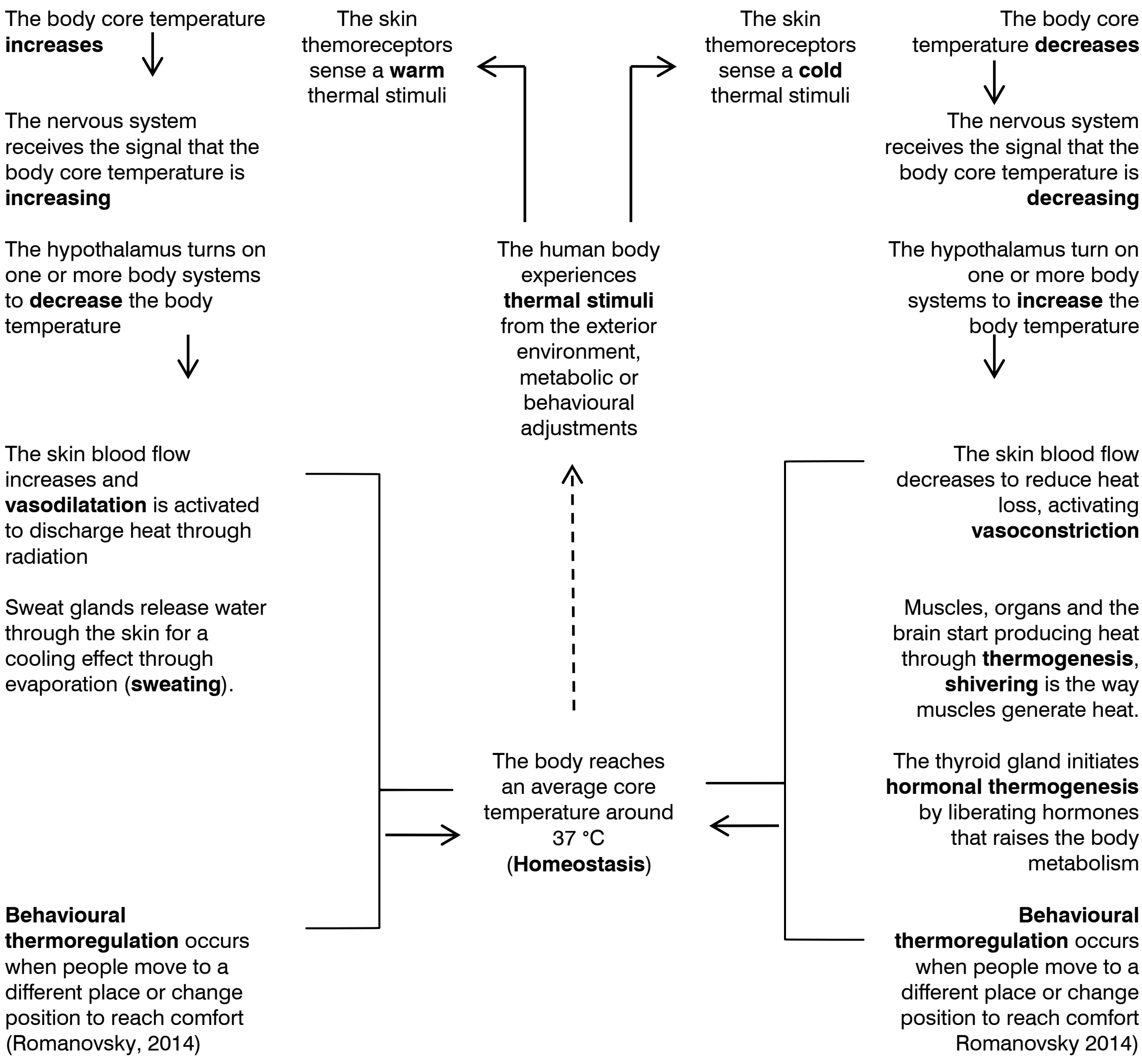


Figure 2-3 Thermoregulation diagram

However, when people are in movement, thermoregulation is constantly changing to find equilibrium with the environment (Hwang et al. 2008). The human body loses its heat to the environment through convection, radiation and evaporation. Heat loss by convection refers to the heat exchange with the air around the body (Parsons, 2003b). Consequently, when the air temperature is lower that the skin temperature the body loses heat. In addition, air circulation around the body will also increase heat loss by convection. When people are in motion, the movement of the body in contact with the air can cause heat loss and a cooling sensation on people's thermal perception. However, when the air temperature exceeds the skin temperature the previous effect works in reverse, heating the body. At this point evaporative cooling starts. Evaporative cooling occurs through sweat released by the human skin. Heat loss by evaporation also occurs during breathing (insensible perspiration) (Parsons, 2003b). Another way in which the body loses heat is through radiation; all objects emit radiation, including the human body. The amount of radiation depends mainly on the surface temperature of the human body and temperature of the surrounding surfaces. Radiation is not visible; it requires infrared imaging to be measured. In the environment that people experience everyday there is a wide variation of surface temperatures in different elements of the urban and built environments (windows, ceilings, floors, etc.). In thermal comfort studies, the way to offer the temperature of a given space is through the operative temperature, which is the combination of the air temperature and the mean radiant temperature. Finally, clothing and metabolic rate are other factors that are key in the heat loss and thermoregulation process.

One of the novel studies of people's physiology and psychology in dynamic state is the exploration of a psychophysiological phenomenon called 'alliesthesia' (de Dear, 2011), which proposes that any thermal stimuli sensed by the skin that diminishes or balances the effect of contrary thermal stimuli will be perceived as pleasant (Parkinson et al., 2012). Alliesthesia can be positive or negative depending on people's current thermo-physiological state and the effect of the thermal stimuli caused by their immediate environment on their thermoregulation. For example, when the core body temperature is raised above the normal value, a cold stimulus will be perceived as pleasant (positive alliesthesia). However, the same cold stimulus will be unpleasant if the core temperature is below the normal value (Parkinson and De Dear, 2015). Therefore, a positive thermal sensation can not be attached to specific situations, it is connected to a dynamic balance between human thermoregulation and the thermal impulse of the thermal environment (de Dear, 2011).

2.6. Transient experiences and transition

The concept of 'transient' and 'transition' are interconnected in thermal comfort studies of people in dynamic state. The word 'transient' refers to a short-lived or temporary experience, while 'transition' is more used to indicate a change. When referring to temperature changes (sudden change or step change) happening in short periods of time researcher use the term transient. The British standard EN ISO 7730-2005 defines 'transients' as a temperature change linked to instantaneous alterations in the environment and people's thermal perception. In brief, 'transient' implicates changes in short periods of time.

'Transition' is a structural category in space and time, which can join or separate phenomena in time and space (Hofmeister and Sabine, 2002). It is a complex process whereby people reinvent themselves in response to life experiences (Kralik et al., 2005). The concept of transition involves change, movement, interruption, redirection, transformation, alteration and adjustment. It involves a stage where people discover how to adapt themselves into new circumstances and it can open and develop new experiences (Kralik et al., 2005). Transition is an intermediate in time and space, marking a starting or change or a wide range of experiences in life. Hence, it can cause a positive or negative effect (Kralik et al., 2005). People experience physical and psychological transition in their daily lives, for example when moving between different spaces as part of their daily routine (Figure 2-4). Even when remaining in the same place, people can experience transition as temperature can naturally vary over short or long periods of time.

In real life, the thermal environments that people experience on a daily basis are frequently dynamic and transient (Liu et al., 2014). These experiences contain information that cannot be found in steady state conditions. Thermal comfort research on people in dynamic state has been conducted in three main areas: performing different dynamic activities (metabolic rates), non-uniform environments, and transient conditions. These topics have been explored individually and combined under different climatic scenarios and people's activities. For instance, research related with people's activities includes the study of the human thermoregulatory system under dynamic state and people's psychology in dynamic and short-term experiences.

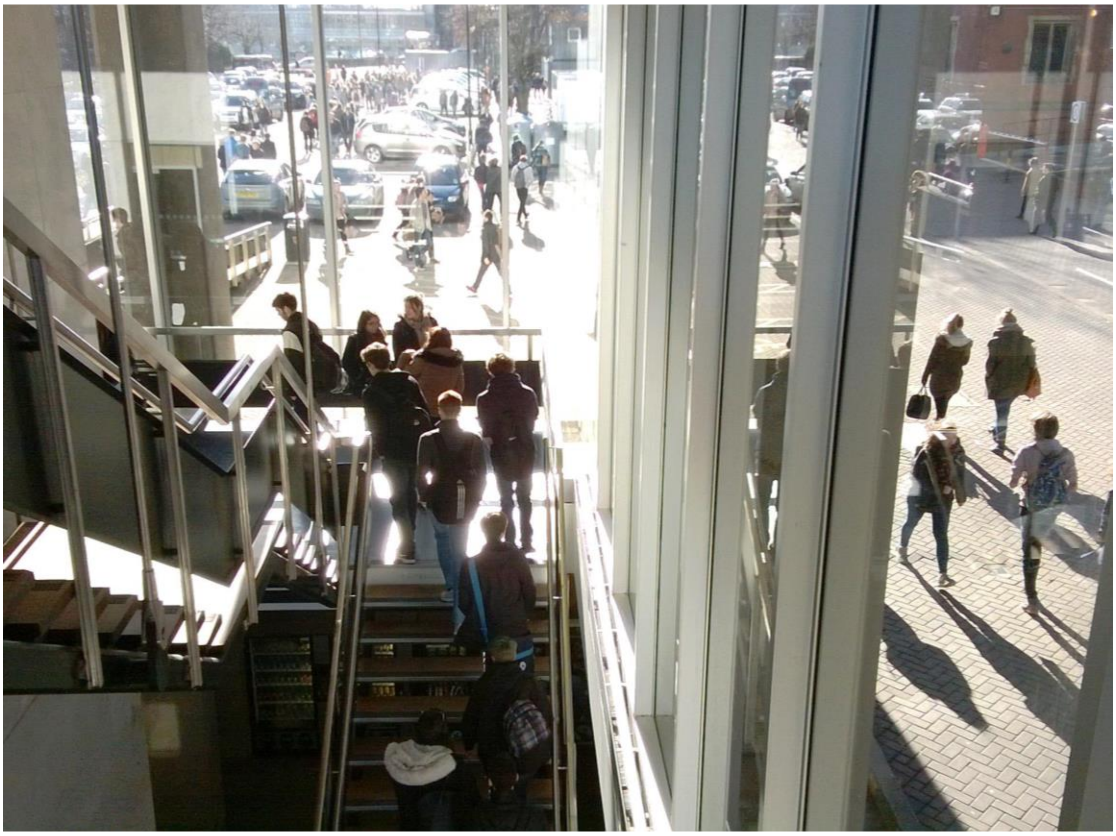


Figure 2-4 People experiencing transition in the indoor and outdoor environment, Arts Tower, University of Sheffield, UK.

2.6.1. People's thermal perception in transient conditions

The study of transient conditions is very challenging due to the rapid change of multiple variables in different temporal and spatial scales. Hence, not much is known about people's thermal perception in short-term experiences. One large limitation of this area is that research work is only able to freeze and capture peoples' thermal experiences in very a short period of time and in a specific space or situation. It seems that previous study of transient conditions has been explored in laboratory conditions in order to better control the rapidly changing variables. However, the disadvantage of this is that findings could be a poor illustration of real thermal experiences. Although, some fieldwork studies have been carried out, more fieldwork studies are necessary to validate results (Jitkhajornwanich, 1999, Pitts et al., 2008, Pitts, 2013, Kelly, 2011).

Conclusions from related studies are also contributing to the understanding of people's thermal perception in transient experiences, in particular, experiments in non-uniform environments, involving people moving from one space to another, people's thermal history and transitional spaces. The combination of some of the variables explored in previous studies has contributed to the understanding of people's thermal behaviour, clothing selection and thermal perception in transient conditions. Key outcomes are discussed in the following section, while a detailed list of related studies can be found in Appendix 2.

2.6.2. People's behaviour in transient conditions

People's behaviour in transient conditions also reveals different factors to take into account. The first factor is the state of people's mind when anticipating a short-term experience. In particular, people are influenced by 'forgiveness' towards uncomfortable temperatures, due to the short duration of the experience. In some cases, an uncomfortable climatic condition does not have a significant effect on people's thermal perception when they know that it will be experienced for a short period of time, that it was their choice to be there or that they do not have control over the natural climatic conditions outdoors (Steemers, 2003)(Figure 2-5).

Other considerations on people's minds are their thermal expectations, referring to the anticipated ideas that people generate before experiencing a thermal situation; these ideas are usually influenced by previous thermal experiences and memories (Knez et al., 2008, Thorsson et al., 2004). For example, fieldwork surveys conducted in Thailand (Jitkhajornwanich, 1999), found that people's thermal perception and expectations in transitional spaces were strongly influenced by the warm environment of Bangkok. Psychologists have found a powerful link between characteristics of a space and people's memory and perception (Augustin, 2009, Steemers, 2003). The impact of transitional experiences has a different impact on people depending on: the meaning that people have about change, their expectations, their level of knowledge and skills about the experience, accessible resources, their capacity to plan for the expected change, and the emotional and well-being state they have in that moment (Kralik et al., 2005). So far, too little attention has been paid to the psychological side of people's thermal perception and little literature has referred to some aspects of the psychological side of thermal comfort in transient conditions (Nikolopoulou and Steemers, 2003b, Knez et al., 2008) .

Figure 2-5 People's adaptation, through clothing, to the exterior climate conditions, over which they do not have control.

Another factor is people's clothing value; people adjust their clothing many times during a day, frequently in response to dynamic environmental conditions or activities. Studies show that clothing behaviour varies from building to building depending on the thermal environments offered to people (Morgan and de Dear, 2003). Fieldwork observation have detected that people's clothing behaviour is different when they are in transient state than in steady-state. For example in airport terminals, passengers 'clo' values are higher than staff's (Kotopouleas and Nikolopoulou, 2014). Furthermore, cultural factors are reflected in clothing habits. Perception of fashion and weather checking are also additional variables to consider for decisions related to dressing (Chun et al., 2008).

2.6.3. Rapid change in thermal perception

Studies of mean skin and core temperature in non-uniform and transient environments have slowly increased in the last decade, exploring people's thermal perception during different temperature changes. One of the main findings linked with transient conditions is that people's thermal sensation can change very fast after air temperature changes, responding to the skin themoreceptors (Wu and Mahdavi, 2014, Chen et al., 2011). However, a difference between skin temperature and core temperature has also been identified. Moreover, a delay in thermal sensation can occur depending on the preceding thermal conditions experienced (Kelly and Parson, 2010). Interestingly, it seems that this delay can not only be found in large temperature changes, but can also be found in small temperature changes or between spaces with the same temperature (Jin et al., 2011). It can be suggested that this is due to the interplay of different thermal history factors.

However, additional research needs to be conducted to better explain the complexity of this phenomenon. The main limitation of these studies is that they have only covered certain temperature ranges (most of them above 24°C), and it is not possible to visualize a general panorama of people's responses in other temperature ranges. This raises the question of to what extent these results reflect people's thermal perception in a number of real situations. There is a lack of fieldwork research to fully validate the growing studies of dynamic thermal comfort.

Another important consideration in transient conditions is that people's thermal perception quickly reacts to the state of the body thermo-receptors immediately surrounding the skin, yet not to the physical environment (Chen et al., 2011). This is an important consideration, since thermal variability exists in the interior environment, and it has been wrongly believed that people's thermal perception at a given time and space point reflects the thermal effect of the entire space or building. This suggests that a more detailed exploration of the interior spaces where surveys are conducted, and more research covering an extensive range of thermal conditions is needed.

2.6.4. Thermal direction

A second main finding is that a significant change occurs in the skin and in people's thermal sensation when subjects move from neutral to cold environments, yet this change is not very significant when moving in the opposite direction (Kelly and Parson, 2010). This trend was also significant in a study comparing people's mean skin temperature after moving from a 22°C environment to one of three different colder environments (12°C, 15°C, 17°C) (Du et al., 2014). A substantial difference was found when participants moved to cooler environments, but not warmer environments. In this experiment, it was determined that a 5°C difference was the limit of acceptable temperature change for people moving towards warm conditions (Jin et al., 2011). Findings from these studies highlight that although the cold and warmth receptors of the skin are active in up and down-step temperature changes, cutaneous cold receptors are closer to the exterior skin layer than warmth receptors. Moreover, it has been found that thermal sensation is perceived differently in different parts of the body (Zhang et al., 2010), and that the body parts that are more sensitive to cold and warm temperatures are the head, chest, back and calf (Liu et al., 2014). A serious weakness in this topic is that the small amount of research carried out has not been able to cover wider temperature ranges that could better explain under which conditions or within which temperature ranges this phenomenon occurs. So far, the relevant studies cover thermal scenarios above 23°, overlooking other climatic conditions.

2.6.5. The influence of relative humidity

In regards to other physical factors in transient conditions, laboratory studies conducted in Kyoto, Japan, explored the skin reaction to different levels of relative humidity. The experiment explored participants moving from one chamber (70%RH) to one of three others (30%, 40% or 50% RH), and significant difference were found in people's responses after moving to the chambers at 30%-40%-50% RH. Participant's skin wetness reduced after moving to a lower relative humidity space. Hence, no differences were found when people moved between 30%, 40% or 50% chambers (Tsutsumi et al., 2007). Researchers from different areas, exploring air temperature, relative humidity and wind speed need to gather common findings in more complex real situations.

2.7. People's thermal history

People's thermal history refers to the previous thermal conditions that influence their current thermal perception of the environment (Nikolopoulou and Steemers, 2003b, De Vecci et al., 2012). The study of thermal history helps to explain people's thermal perception, choices, preferences and expectations. By looking at people's short-term thermal history, previous studies have detected some patterns and preferences that depend on the place and climatic conditions in which they were previously (Roaf et al., 2010). The degree of impact that people's thermal history has on their perception depends on different physical and psychological factors, and people's current thermal state will affect their next thermal experience more or less depending on the time of exposure (Candido et al., 2011, Chun and Tamura, 2005, Song et al., 2011). Findings from studies of people's thermal perception in a dynamic state are not always as expected. From transient condition studies, it has been found that people's thermal perception when experiencing a transition is also strongly influenced by people's previous experiences. Temperature sensing is virtual, for example water feels hot or cold depending on whether the hand has previously been, in hot or cold water (Styles, 2005). Several studies have revealed the importance of people's thermal history in thermal comfort studies including transient situations.

2.7.1. The effect of time on people's thermal comfort perception

Time is an important factor in modifying people's thermal history and people's current thermal perception, because many physical and psychological variables change in the short and long-term (Nicol and Humphreys, 2002, Steemers, 2003, Potvin, 2000, Chun and Tamura, 2005). Many dynamic factors influence people's current thermal comfort; these factors change over different levels of time, hence generating extensive configurations of thermal comfort perception in the short and long-term. Long-term thermal history shows the effect of seasonal temperatures on people's thermal perception, while short-term thermal history is strongly linked with transient conditions and reflects people's thermal experiences during their everyday lives. Studies reveal that the duration of exposure to previous thermal experiences has an effect over different time scales: hours (Song et al., 2011), months (Lin et al., 2011) and in the long-term (Candido et al., 2011, Chun et al., 2008)

There are three ways in which people experience a thermal condition in relation to time and their thermal history, depending on whether they use a place as a resident, visitor or transient user (Kim et al., 2011). Visitor occupants have short-lived experiences in the building. They use spaces for short periods in a random pattern, with few chances to identify adaptive opportunities. Transient users spend some hours in the same space or building on repeated occasions. However, the time they spend in a place only allows them to identify limited adaptive opportunities; an example of a transient occupant is a university students. Finally, resident occupiers are those who spend such a large amount of time in a building (working place or home) that they know the typical operation of the building and what to normally expect from this place (Kim et al., 2011). Visitor occupants of a building seem to be more aware of the exterior environment when moving from one place to another, than when they are in a place performing activities for longer periods of time when they are residents (Morgan and de Dear, 2003).

Studies conducted in airport terminals, shows different thermal perception between transient visitors and airport staff. In this study, employees were 1.6 times more sensitive to temperature changes than visitors (Kotopouleas and Nikolopoulou, 2014). Passengers were more tolerant to cooler conditions and employees were more uncomfortable with the interior temperatures. Similar results were found when comparing guest versus staff responses in a commercial interior. In this case, guests were more tolerant to uncomfortable temperatures than staff (Hwang et al., 2008).

People's thermal history is thus a dynamic state linked with time; every minute people are shaping short and long-term thermal experiences that will influence them in their future thermal expectations and perception. This influence not can only be seen in the long-term, but also in the short-term, in the spatial sequences that people experience in their everyday lives, which this thesis explores.

2.7.2. Thermal history and spatial sequences

People experience a wide range of microclimate exposures daily, constantly changing their physiological thermal dynamics (Parkinson and De Dear, 2015). For instance, the trajectory that people use to go to work involves many different thermal experiences, starting from thermal conditions at home, followed by short-term experiences in the urban environment and transport and in other series of microclimates before reaching their final destination. Once immediately outside the building, people experience a transition from the exterior into the interior space, using transitional spaces such as lobby areas before finally arriving at their work place (Parkinson and De Dear, 2015, Pitts, 2013). This trajectory reflects a complex sequence that people experience daily with different variations in climatic conditions, in some cases involving gradual, delayed and precipitous temperature changes. In some cases, people move through repeated routes in the outdoor and indoor environment, creating spatial sequences. The spatial sequences can also be created by the building layout and way that spaces are connected and conduct people.

There are a number of factors to consider in a short-term experience in a spatial sequence. First, in a basic spatial sequence, with air temperature going from cold to hot or vice versa , the direction in which people experience temperature changes (from cold to hot, or from hot to cold) alters their thermal perception in different way (Chun and Tamura, 2005, Wu and Mahdavi, 2014). The direction of people's thermal comfort vote is consistent with the direction of temperature changes in a sequence of spaces (Wu and Mahdavi, 2014). Second, people's limit of comfort in dynamic states is an additional factor that is just recently being explored as part of the study of thermal alliesthesia (Parkinson and De Dear, 2015).

Figure 2-6 (after Potvin, 2000) illustrates people's thermal comfort perception in a specific dynamic state situation. The vertical lines represent increasing temperature changes from cold to hot in a trajectory. When people are moving continuously from cold to hot, or from hot to cold, thermal comfort is experienced only momentarily, since a positive increase or decrease of air temperature will become uncomfortable at some point. The ± symbols indicate when positive thermal experiences become unpleasant in both directions.

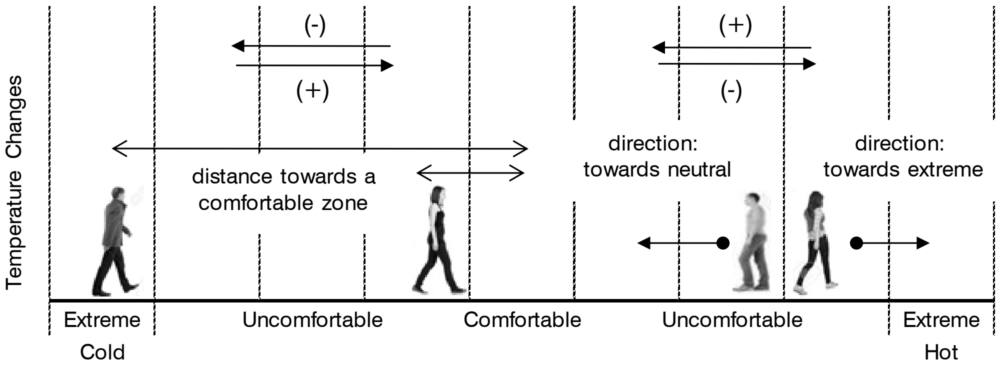


Figure 2-6 The effect of direction on people's current thermal comfort perception, after Potvin (2000)

The third factor refers to people's short-term thermal history. People's thermal perception at a specific point in their journey will be the result of the interaction of the previous temperature changes (Du et al., 2014, Liu et al., 2014). However, this effect can change, depending on the distance to comfortable temperatures. With a large 'effective temperature difference' (thermal distance of the transition) people's thermal perception is negative, and with closer temperature distances people's thermal perception is positive (Wu and Mahdavi, 2014). Finally, the duration of previous and current exposure to specific climate conditions will alter people's perception. In Figure 2-7, people's thermal history is represented by the added effect of previous temperature changes. The vertical lines indicate temperature changes, the separation between lines short and long periods of time. Finally, the thicknesses of the lines specify sudden or gradual temperature changes.

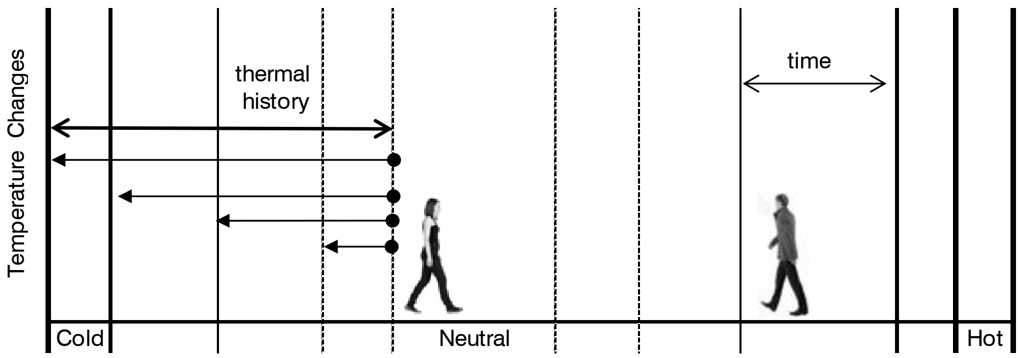


Figure 2-7 The effect of previous thermal conditions (thermal history) on people's current thermal comfort perception

However, in real life, the way people experience temperature changes is more complex than just moving from cold to hot or from hot to cold, involving different temperature changes in different time, periods and sudden and gradual temperature, which also change in direction over different periods of time. Consequentely, people's thermal perception is also moving in a gamut of thermal sensations in continuous change. This short, yet complex experience creates many situations in which people can perceive the same thermal condition in different ways (Liu et al., 2014, Jin et al., 2011). In Figure 2-8, people thermal perception is dynamic, changing based on the effect of sudden or gradual temperature changes, time and thermal direction.

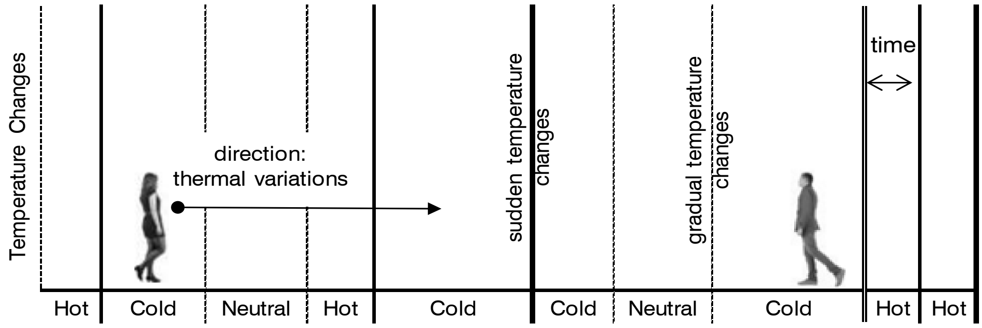


Figure 2-8 Dynamic temperature changes and the effect of time on people's thermal perception

2.7.3. Thermal history and repeated thermal experiences

The buildings that people use for work or study also create repeated experiences in the long-term, for example the use of specific routes inside the buildings becomes habitual. It can be suggested that the design of a building could create new short-term experiences that might influence people's thermal adaptation in the long-term. Individuals adjust themselves in the short-term depending on current situations, and in the long-term by using their 'weather memory'; created from daily experiences (Fuller and Bulkeley, 2013). Furthermore, by changing short-term experiences repeatedly, people may eventually have a different reaction and behaviour that will benefit them in the long-term. For example, since 2011, the Environment Ministry in Japan has been promoting a campaign called 'Cool Biz' during summer time, allowing office workers to adapt themselves by wearing casual clothes of their preference to feel comfortable, but at the same time gradually changing the thermostat set to save energy (Figure 2-9).

Figure 2-9 Cool Biz fashion show, Japan June 2015. Japan Kyodo News 2nd June 2015

An example of a negative effect of repeated thermal experiences in the long-term has been illustrated by a number of researchers. It has been revealed that people exposed to AC environments for long periods of time in their daily lives experience a negative change in their thermal perception and preferences (Candido et al., 2011). In other words, an alteration on people's thermal history can be shaped by daily contact with artificially cold environments. In addition, people with high exposure to AC environments gradually expect to experience a very similar thermal environment in other interior spaces, such as cars, offices, hotels, etc. These finding suggests that the thermal properties of a space can modify people's thermal memory and that a physiological acclimatization is possible when physiological changes result from repeated thermal experiences. People's thermal history in a specific space and time is linked with the effect of multiple dynamic variables (Figure 2-10), which vary on time (Figure 2-11). However, repeated thermal situations could become habitual on people's daily lives.

Researchers point out that in transitional spaces, such as the lobby, stairs and circulation spaces of a building, people experience thermal variability and have a better thermal tolerance (Pitts, 2013, Jitkhajornwanich and Pitts, 2002). First, because people are in a dynamic state and their metabolic rates are higher. Second, because their psychological tolerance is higher in short lived experiences (Evans, 2003, Nikolopoulou et al., 2001).

Figure 2-10 Dynamic factors affecting people's current thermal perception (short –term experience)

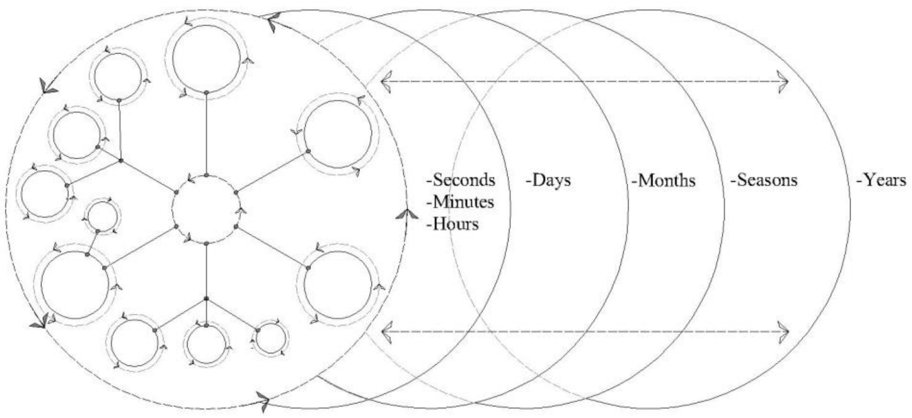


Figure 2-11 People's thermal perception at different timescales

2.8. Transitional spaces

Transitional spaces are often referred to as those spaces which are located within a building but which are also connected with the exterior environment (Kwong and Adam, 2011). Researchers have used many terms when referring to transitional spaces, such as: semi-outdoors buffer zone, buffer spaces, in-between, physical links, semi-enclosed or half-opened (Chen et al., 2011, Hwang et al., 2008, Saleh, 2007, Pitts and Bin Saleh, 2007). While many definitions of the term transitional spaces have been suggested, this thesis utilises the definition given by Chun, Kwok and Tamura (2004) who state that transitional spaces are 'locations where the physical environment bridges between the interior and exterior environments'. They divide transitional spaces into three types (Figure 2-12). Type 1 spaces are those contained within the building such as lobbies or atriums. Type 2 spaces are those transitional spaces attached or connected to the building, in which the exterior environment is dominant over the interior environment. Some examples of these spaces are balconies, arcades and external corridors. Type 3 transitional spaces are exterior spaces with a defined design and structure that is independent from the building, for example pergolas or pavilions.

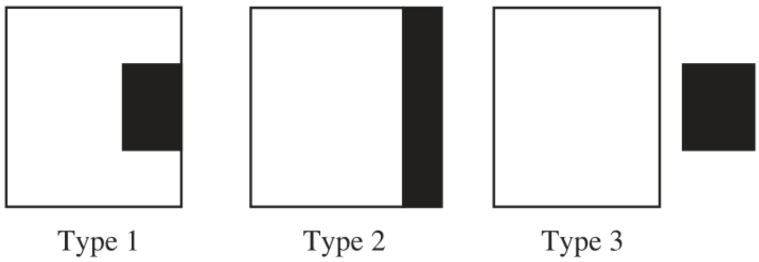


Figure 2-12 Classification of transitional spaces proposed by Chun and Kwok (2004)

Pitts and Saleh (2007) classified the transitional spaces into four types depending on their location in the building layout (Figure 2-13). Type A includes linear transitional spaces located in the short side of buildings with a rectangular layout plan and connected with the facade. Type B includes transitional spaces located in the central area of buildings and connected with the exterior, such as lobby spaces. Type C includes linear transitional spaces typically located in the central area of buildings and in parallel with one of the axis of the building. Finally, type D includes linear transitional spaces located in the perimeter of the building connected with the facades. This classification attempts to show the impact they have in terms of energy use in the whole building. Having a larger effect on energy saving the linear transitional spaces located in the perimeter of the façade (Type A and D) than those located in the centre of the building (Type B and C). Although transitional spaces type A and D could reduce energy in buildings (from 11.4 to 32.7% used for heating and from 2.2 to 6.6% used for cooling), more research is needed to quantify which transitional spaces are the most typical in buildings or use the major percentage of area. Although, type B and C seem to had less impact on energy reduce (from 4.2 to 6.6% of energy used for heating and from 0.7 to 0.9 used for cooling) they could be more typical or could be using the largest percentage in buildings. In this thesis, Type 1 transitional spaces located in the centre of the buildings (type B) and connecting the exterior with the interior environment is explored further in detail (Figure 2-14).

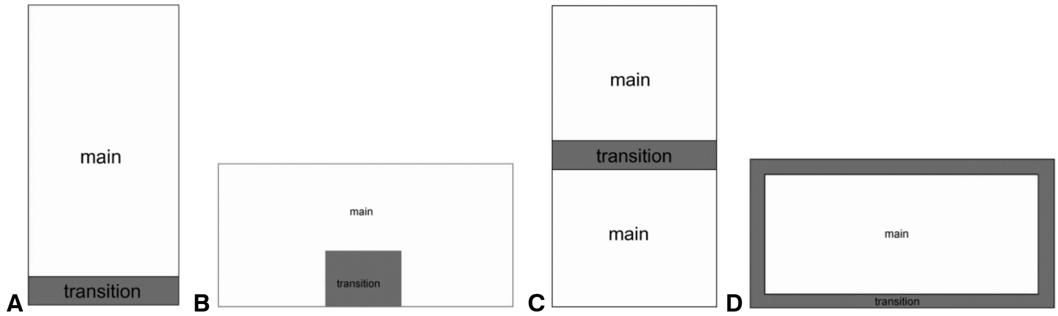


Figure 2-13 Classification of transitional spaces based on their location in the interior space proposed by Pitts and Saleh (2007)

Figure 2-14 Transitional space Type 1, lobby area connecting the exterior and interior environment. Sr Henry Stephenson Building, The University of Sheffield, UK.

Transitional spaces and transient conditions have been studied in building entrances (Jitkhajornwanich, 1999), trains (Kelly, 2011, Nakano et al., 2006), airports (Kotopouleas and Nikolopoulou, 2014), streets in urban areas (Vasilikou and Nikolopoulou, 2013, Chun et al., 2004), arcades (Potvin, 2000), commercial interiors (Hwang et al., 2008), atriums (Pitts, 2010, Yokoe et al., 2007), passageways (Chun and Tamura, 2005) and in laboratory work focused on the human thermoregulatory system (Zhang et al., 2010). However, still little is known about people's experiences in transient conditions. In short, researchers claim that there is a lack of research in this topic, a lack of fieldwork research to validate the laboratory work and stress the importance of exploring this area further and more deeply. Researchers have suggested the potential opportunity to save energy in transitional spaces by reducing the AC set-point -5°C (Saleh, 2007). This decrease could be reflected in around 2% energy saving in cooling systems and up to 11% in heating system. However, more research is needed in order bring the significance of this topic to light. Apart from the physical characteristics of transitional spaces, little has been discussed in previous work about people's behaviour and perception in transitional spaces and transient conditions. Hence, a number of factors have been identified in the exploration of short-term experiences.

2.9. The lobby space as a case study

In this thesis, the lobby space was selected as a transitional space case study for a number of reasons. First, because very limited research has explored the spaces comprising the lobby area in buildings (Pitts, 2013). Second, because of its location and function, the lobby is an independent space with more complex thermal connections to other interior areas, such as office space, where people are in a sedentary state. In contrast to interior spaces however, the lobby is designed for dynamic activity. In the lobby, people have short-term experiences and experience changes in the physical conditions from exterior to interior and from interior to exterior. Therefore, there is a key alteration to people's short-term thermal history when moving from the outdoor to the indoor environments. Finally, since the lobby is one of the spaces that people use every day; it can be a potential opportunity to help people to have a better thermal adaptation to the indoor environment in the long-term. Overall, the lobby space offers interesting settings to study different variables related with people's thermal comfort perception.

2.9.1. People's experience in the lobby space

The lobby area is a key setting to study people's thermal comfort in transient conditions because, from other interior transitional spaces such as circulation spaces, stairs and lifts, the lobby space is the first and last contact with the indoor environment. It is also the area where people can experience a significant change of physical conditions when moving from the outdoor to the indoor environment, and vice versa. The lobby area is the first visual and spatial contact that people have with the inside of a building. It can include foyers, entrances and delimited areas close to the entryways (Channell, 2012). However, it has diverse definitions from different perspectives; it has also been referred to as a spatial connector, multifunctional area, key interior design area, psychological transition and buffer space.

As a connector, people use the lobby to guide them to other interior spaces, vertically or horizontally, through stairs, lifts, corridors or other transitional spaces such as atriums or courtyards. The lobby also connects people with public or private spaces, service areas or spaces with different uses. As a multifunctional area, people in the lobby experience short-term events such as meeting others and socializing. In addition, it is used as orientation point, reception area, resting area, waiting space, conversation area, information point, presentation venue or meeting place (daab, 2006). Overall, lobby spaces are designed to accommodate many people moving and interacting at the same time and in some cases operate nonstop (Channell, 2012) (Figure 2-15). However, lobby spaces are also in some cases referred to as a place for moving from the individual to the collective environment, where people have the opportunity to meet and socialize with others (Kilpatrick, 2010). Therefore, the building use and the physical aspects of the lobby can influence how people socialize, engage and feel in the building (Ogden et al., 2010) (Figure 2-16).

Figure 2-15 Lobby area and transitional spaces in the Student Union, The University of Sheffield, UK.

Figure 2-16 Lobby area and transitional spaces in the Jessop West Building, The University of Sheffield, UK.

In terms of design, the lobby has become an important space for architects, clients and interior designers, since it aims to reflect the building's functions and the internal spaces that people cannot yet see in a positive way. In addition, it is a key visual connection with people. Therefore, contemporary lobbies are designed to induce the curiosity to know more about the building and its interior spaces. Lobby design has been in continuous innovation in a wide range of building typologies such as offices, hotels, airports, educational institutions, research centres, retail, etc. (daab, 2006, Santos 2008). In the lobby, people also experience a psychological transition. Their responses and behaviour in this space are valuable because they involve renewal and the start of a new stage. The lobby can produce a mental emotional shift into new experiences, for example, to allow an emotional preparation before going to the next space and to serve as a transitional preparatory space (Kilpatrick, 2010). The lobby transmits a sense of anticipation, a relief opportunity, a break in the journey, a meaning of welcome, a sense of arrival, a sense of departure, memories, a first and a last experience (Rutkin, 2005).

Finally, the lobby functions as a buffer space between and connecting the indoor with the outdoor environment (Chun et al., 2004). It is a filter for wind, rain, pollutants, sound, climate and even people (staff, visitors, maintenance, etc.). As a filter, it can be designed to control the level of interaction between elements of the exterior with the interior. For example, it can be the buffer zone for large temperature differences during summer and winter in some climatic areas. To sum up, the lobby is a complex transitional space that people experience differently from the exterior and interior spaces. The first consideration is that people use the lobby spaces for short periods of time. However, depending on the building use and design, people can extend their stay in the areas comprising the lobby. For example, a hotel lobby works differently from a museum, office or university building lobby.

So far, one of the most cited works involving the lobby area is the fieldwork carried out in Thailand by Jitkhajornwanich and Pitts (2002), who studied people's thermal perception immediately after moving from the exterior to the interior environment and vice versa. People's thermal comfort votes were collected immediately after they crossed the main entrance in both directions (indoor-outdoor, outdoor-indoor). Their thermal expectations were also collected before they moved indoors or outdoors. The study was conducted in both NV buildings and AC buildings. One limitation of this approach is that it does not take into account the effect of the lobby on people's short-term thermal history in following spaces. In fact, it seems to focus more on the effect of the exterior environment immediately after moving to the indoor space. Although people's thermal comfort vote was collected immediately after entering the main door, the effect of the thermal conditions of the lobby on other spaces was missing. It is very important to highlight this issue, since the objective of this work is to evaluate the effect of the lobby space on people's perception of the short-term thermal experience in a sequence of spaces as experienced in real life conditions.

2.9.2. Lobby Spaces in Higher Educational Institutions (HEI)

Lobby spaces in Higher Educational Institutions (HEI) offer a good opportunity to explore people's thermal perception in a dynamic state. Firstly, because students are transient users of university building and they move between buildings many times during the day, experiencing indoor-outdoor thermal transitions repeatedly. Secondly, typically large groups of students use the university lobby area at the same time in. For example, during peak hours, the lobby area becomes a very busy space, transferring students in both directions from both the exterior to the interior and from the interior to the exterior (Figure 2-17). This makes the lobby an area mainly used for transition, although based on its design, it could also be connected with other social areas. A more detailed analysis of the lobby areas in HEI is found in section 3.2.

Figure 2-17 Students using the lobby are during peak hours in The Arts Tower, The University of Sheffield, UK.

2.10. Conclusions

This chapter evaluated previous research in relation to people's thermal perception in dynamic state in short periods of time and transient conditions. Currently, there is still not enough understanding regarding people's thermal perception in dynamic state. Moreover, the thermal tolerance of people in transient conditions has not been deeply studied and few researchers have explored this area. However, work regarding people in dynamic state seems to have been rapidly growing over the last decade. The dynamic interactions of thermal comfort variables make people's thermal comfort perception difficult to accurate quantify. Consequently, researchers have approached this topic through laboratory studies in order to control the majority of variables at one time. Hence, fieldwork studies are still required to validate previous findings in different contexts.

A number of findings from related areas confirm that people's thermal perception in transient state results from the influence of interconnected factors with different configurations in addition to the widely explored physical and physiological variables. Although different research areas have conducted work with people in dynamic state, findings and discussion have generally not been linked together to shape a general concept of people's thermal perception in dynamic state. Perhaps this is due to the large research gaps that exist in this area, which make the prospect daunting. Apart from the few studies exploring transitional spaces, outcomes from people's thermal history and non-uniform environments (step change temperatures) are the most substantial references that can be interconnected with results from transient conditions. Time of exposure, thermal direction, order of temperature and temperature difference seem to be the most significant factors explored so far. However, there is a lack of information related to people's thermal history in a series of linked spaces connecting the indoor with the outdoor in moderate climates.

To conclude, most thermal comfort studies have been conducted in climatic chambers, and not much has been explored regarding the wide range of thermal experiences that people face in their everyday lives. Although laboratory work can help to isolate many confounding variables, studies have not yet covered the wide range of real life thermal conditions. The majority of studies have been focused on extreme climatic conditions, overlooking the potential opportunity to explore people's thermal perception in moderate climates where AC is not required, and therefore to present a more feasible opportunity to explore thermal adaptation and potential energy savings. Lobby areas in HEI are a potential case study to explore, due to the main use of the lobby as a transitional space.

Finally, robust fieldwork research is essential to compare the outcomes from controlled studies against real life behaviour. This approach could also reveal under which real situations research results are valid and applicable in real architectural practice. Fieldwork research is the approach chosen for this thesis. The following chapter sets out the development of the methodology.

Chapter 3

3. Methodology

3.1. Introduction

In this chapter, the research methodology for this study is presented. It is divided into three main sections. The first section refers to the selection of the case study: the transitional lobby areas in Higher Educational Institutions (HEI) in the UK. A typical lobby layout was identified based on a preliminary survey from 50 faculty buildings in 25 Higher Educational Institutions in the UK, and different physical variables were identified in order to determine a typical lobby layout unit for this study. Findings from this survey determined the selection of the three case study lobby areas included in this research.

The second section describes the methodology used in this study. Quantitative research and thermal comfort surveys were the main techniques used for the fieldwork. This decision was based on the analysis of research techniques used in previous studies connected with the topic of this study. Some of the factors analysed were the climate of study environment, number of participants, statistical analysis, equipment, experiment duration, procedures, subjective measurement scales and type of thermal comfort questionnaires. This process involved two pilot experiments, the first was conducted in an early stage of the survey design and the second was carried out one week before starting the main survey. The final survey procedure, questionnaires, equipment setup, preliminary work, data analysis plan and filed work coordination are all described in detail here.

The third section illustrates the two pilot experiments. In an early stage of the study, the first pilot experiment was conducted in July 2012 in one case study building (Jessop West Building) involving 20 participants. It and was used to shape the final survey procedure and identify previous considerations related with the equipment, questionnaires, number of participants, building preparation and filed work coordination. Because the purpose of the first pilot study was to take a decision regarding the survey process and equipment selection, the number of physical measurements was limited by the equipment available at that stage. The second pilot was upgraded based on the lessons learned in the first study and the procedure was made less complicated procedure. The second pilot experiment was carried out in April 2013, one week before starting the main experiment. The aim of the second pilot experiment was to test the final survey procedure with a complete set of equipment. It was conducted in Sir. Henry Stephenson Building with 40 participants. In short, these three stages support the decisions making in the methodology design process of this research.

3.2. The Lobby Spaces in Higher Educational Institutions (HEI) in the United Kingdom

This study focused on the lobby space in Higher Educational Institutions (HEI) in the United Kingdom (UK). First because in the UK, buildings accounts for almost half (45%) of total energy consumption (CIBSE-TM36 2005), and HEI in the UK account for over a quarter (27%) of the total office buildings existing in the UK (Barbhuiya and Barbhuiya 2013). This means that they contribute a large part of the 17% of total energy consumed by the office sector in the UK, which is second place in energy demand in the UK out of all non-domestic sectors. Second, because the moderate climate in the UK brings a potential opportunity to eliminate the use of AC during summer and promote an adaptive design. Finally, the Higher Education sector, in the UK, needs to reduce CO2 emissions by 80% against the 1990 baseline by 2050. The HEFCE (Higher Education Funding Council for England) promotes strategies for carbon reduction which include: sustainable development performance, building monitoring, sustainable design, behavioural change and improvement of performance of existing buildings (HEFCE 2010).

3.2.1. Higher Education Institutions (HEI) Survey in the UK

The case study methodology involved a preliminary survey in order to identify the most typical lobby typologies in Higher Education Institutions (HEI) in the UK. This study helps to identify a typical lobby layout unit suitable for study which could represent a predominant spatial configuration in HEI buildings. The sample consisted of a random selection of 50 new HEI faculty buildings in the UK, which were built from 2007 to 2012. The cases were limited to faculty buildings, since they represent the majority of the HEI buildings; libraries, residential and administrative buildings were excluded. The survey was conducted from September to December 2012, and the goal was to have buildings that reflect lobby designs from the last 5 years, in order to reflect contemporary trends and possibly the direction of lobby design in the current and following years. In the UK, in 2012, there were a total of 129 HEI registered at the Higher Education Founding Council for England (HEFCE). Most of the universities, and in some cases architectural design firms, were contacted via internet, and asked to give a brief description of the building operation and provide the drawing plans of the lobby area with dimension annotations.

3.2.1.1. Results

From the 100 contacted universities, only 25 declared to have built new faculty buildings from 2007 to 2012. The survey collected information from different projects located in different regions of the UK to ensure a good graphical spread (Figure 3-1). A total of 50 lobby areas in faculty buildings were analysed. As data was collected under a confidential agreement, specific building drawings cannot be illustrated in this thesis. However, diagrams are used to represent key results. The analysis involved a classification of lobby layouts and a spatial analysis of dimensions, connections and lobby features as a comparative background to inform the final case study selection. The analysis of the lobby areas included building use, building operation, and lobby typologies such as shape, dimensions, connections, and use.

Figure 3-1 Map illustrating locations of the universities participating in the HEI survey, in some cases more than one university from the same region participated in the survey.

3.2.1.2. Building uses

In terms of building use, two major groups were identified: mixed-use faculty buildings and specific use faculty buildings. Buildings in the first group host different faculties and facilities in the same place, along with other study and teaching facilities such as lecture theatres, conference facilities, auditoriums and IT areas. In this group, 20% of the buildings hosted science faculties such as physics, engineering, chemistry, biosciences and aerospace, and 32% total social science faculties such as business, law and humanities. In the second group, 20% had specific use for health sciences only. Some of the faculties included were: clinical education, nursing, health research, medical sciences and mental health. 38% hosted only one faculty, such as business, engineering, creative disciplines, education, art and psychology. Results from the surveys show a number of services (lectures, laboratories, cafes, social areas) in new buildings are located in the same faculty building. Moreover, if mixed-use faculty building increase in number, the number of people moving through transitional spaces is likely to be massive. Therefore, transitional lobby areas, depending on the building type, certainly would be hosting different activities in the same place, with large number of people. The trend of building lobby design needs to take into account a flexible design strategy that includes thermal comfort.

3.2.1.3. Building operation

Findings reveal that HEI in the UK are moving towards a Naturally Ventilated (NV) and Mixed Mode (MM) operation in buildings. The majority operate fully with NV in summer and with heated spaces in winter with some AC spaces. During summer, 86% of the buildings operate in NV and mixed mode and only 14% are fully AC. NV was usually provided in all the interior spaces located in the perimeter of the buildings, and supplementary mechanical ventilation or AC was used in some specific areas such as IT rooms and a few spaces where the NV is more difficult to effectively achieve. During winter, all of the buildings use different heating systems connected to floor heating trenches and wall radiators. The majority of the building entrances (90%) did not have an AC curtain on the main door. The remaining 10% are cases in which it was not possible to get an answer due to the limitation of time from the university services to get the precise information. In short, the findings reflect the effort of HEI to save energy by reducing the use of AC in summer. These results suggest that case study buildings operating with NV are optimal to study; therefore the study will focus on similar buildings to ensure the findings from this thesis benefit a wider community

3.2.1.4. Lobby typology and variations

In terms of design, the lobby areas showed contemporary proposals. Elements such as stairs, foyers and double or triple height ceiling were common. In this analysis, the lobby area was defined by the space which connects the interior of the building with the exterior environment. This includes the main entrance, foyers and part of well-defined circulation areas connected with the entry doors. Regarding the building entrances, 54% had a double door entryway with a space between two parallel door systems, and 46% had a single entry door. From the total cases with single entry doors, revolving doors (60%) were more common than swing doors (40%), Figure 3-2. It seems that the trend in HEI is towards the use of double door entry door (draught lobby), possibly due to the benefits of a buffer space during the winter period when building are operating with AC. From these results, it was clear that a typical case study should have a double door building entrance. Future research exploring single elements in the lobby area could study in detail the effect of using different variations (dimensions, shape and style) of doors in the main entrance.

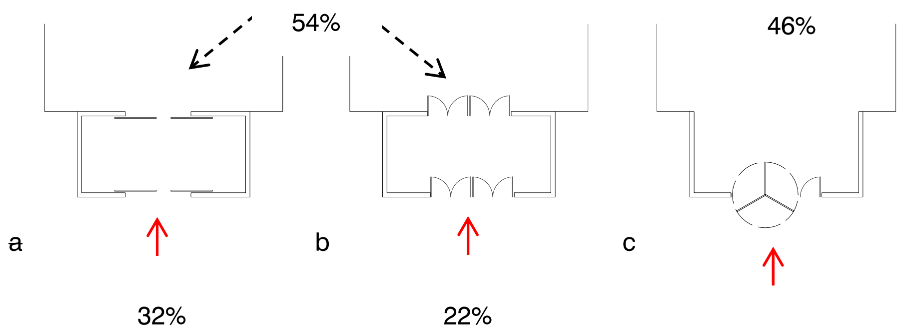


Figure 3-2 Building entrance typologies: a) double sliding doors, b) double swing doors, c) single door

Entry doors ranged from 2.5 to 3.0 metres in width, from 2.5 to 3.5 metres in height, and the distance between the two parallel doors ranged from 2.5 to 3.5 metres. The lobby shape were rectangular (54%), square (20%) and irregular (26%); the irregular shape involved curves and rectangular and square deformations (Figure 3-3). 70% of the lobby areas had an average height of 3.2 metres (min=2.5m, max=5m, N=35), while the other 30% had double or triple height with an average height of 11.6 metres (min=6.3m, max=18.02m, n=15). So, a lobby area with rectangular shape and within the identified mean dimension ranges described above was considered for the selection of the case study. It was identified that large lobby areas tend to have double or triple height; this was also linked sometimes with the use of social areas (lounge furniture).

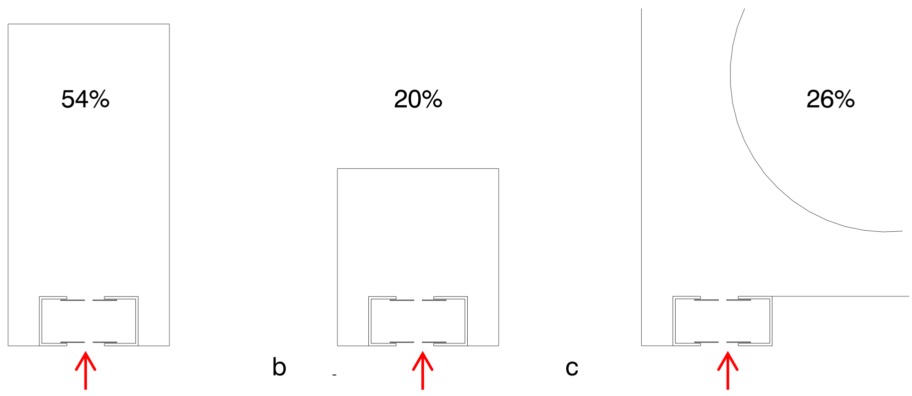


Figure 3-3 lobby shape typology: a) rectangular shape, b) square shape, c) irregular shape

Reflecting on the lobby layouts, large lobby areas had a more complex layout design because of the large number of horizontal (circulations) and vertical connections (double or triple height, stairs and lifts) with other spaces, including links to other main entrances. In some cases in this study, a single entrance was sometimes multiplied at different key points connecting the exterior with large circulation areas. This adds additional points of connections between the exterior and interior in the same area, which need to be considered in terms of physical variables (e.g. air temperature and wind speed) altering the interior environment. Also, it was difficult to determine the lobby boundaries because in some cases they merged with large circulation areas, which were very variable in design and dimensions. The maximum dimensions for circulation areas identified were 16 metres width, 21 metres length and 18 metres height. The typical average dimension was 5.6 metres width, 6.2 metres length and 5.7 metres height. From the total sample, 4% of the lobby spaces had an immediate connection with the interior spaces, 46% connected with well-delimited corridors and 50% merged with large circulation areas (Figure 3-4).

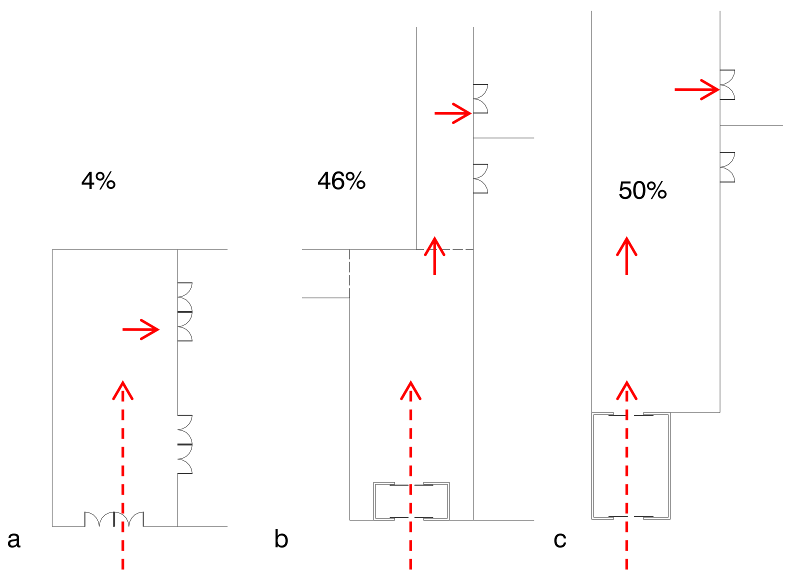


Figure 3-4 Lobby connection: a) immediate connection with interior spaces, b) connected with other transitional spaces, c) merged with large spaces.

Finally, 76% of the lobby areas were designed to function as transitional spaces, and 24% were designed as large circulation areas, which can have other uses such as exhibition spaces, social spaces and atria spaces (Figure 3-5). It was identified that those building hosting different faculties and with up to four large lecture theatres were those where large circulation areas merged with the main entrance. This would seem to indicate that the peak student Full Time Equivalent (FTE) moving in the building is one of the key factors in the design decisions and connections of transitional spaces.

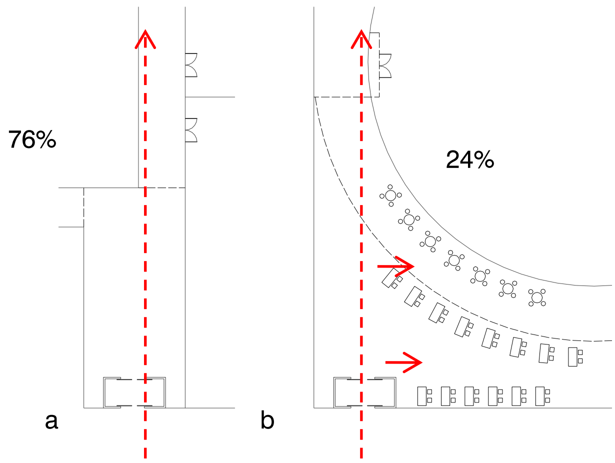


Figure 3-5 Lobby use: a) circulation and b) circulation and social area

3.2.1.5. The defined typical lobby unit

Results revealed that the majority of the new buildings in HEI in the UK gather different faculties within the same building (Arts and Humanities, Social Sciences, Engineering, Medicine, dentistry and health, and Sciences), which suggests this can be taken as typical. From analysing the drawing layouts, it was found that there is a wide variety of design solutions (shape, and dimensions), and also that a number of design typologies were the same in terms of use and connections. A typical lobby 'layout unit' was thus identified, comprising a double door entry door entrance and connected to other transitional spaces (circulation or social areas), which are then linked with interior space such as seminar rooms or lecture theatres (Figure 3-6).

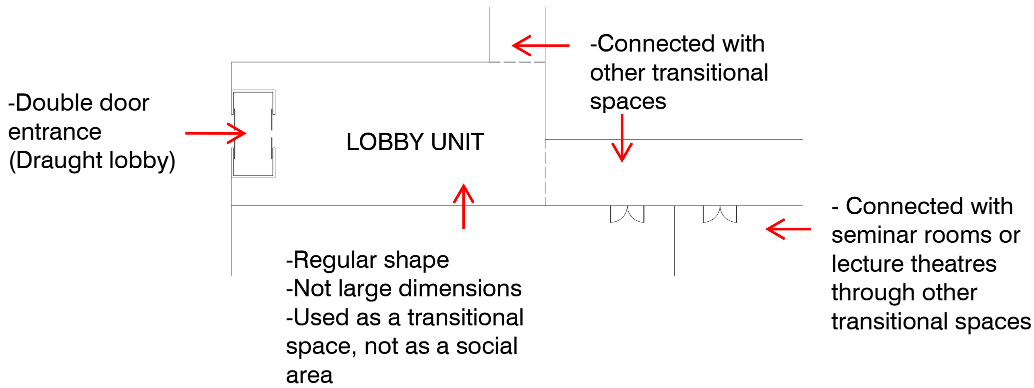


Figure 3-6 Typical lobby unit layout and spatial sequences

In short, a typical 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. Based on the findings, a typical lobby unit characteristic was proposed as follows:

- Double door entry doors (draught lobby) with parallel sliding doors (from 2.5 to 3.0 metres in width and from 2.5 to 3.5 metres height)
- Distance between the two parallel doors (draught lobby) from 2.5 to 3.5
- Average height around 3.2 metres (min=2.5m, max=5m)
- Typical average dimension of the immediate 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)
- Rectangular shape
- NV building operation with heated spaces in winter

3.2.2. Demographic population of the study

The HESA (Higher Education Statistics Agency) annual report (2013-2014) illustrates that in 2013-2014 there were 2,299,355 students in HEI in the UK. From the total population, 1,759,915 were undergraduate students (76.6%) and 539,440 (23.4%) were postgraduate students. Of the total, 435,495 (19%) were international students (no UK domicile). From the first year UK domiciled first degree students, 82% were 18 to 24 years old, and 18% were 25 years old and over. 63.4% of the total undergraduate students were female and 36.6% male. Finally, 13.1% were Non-UK domicile undergraduate students (HESA 2015). It was therefore determined that at least 80% of the same population in this study will be undergraduate students from 18 to 24 years old, including both UK and international students.

3.2.3. Location of case study

Sheffield was selected for the case study since its moderate climate brings the potential opportunity to eliminate the use of AC and promote adaptive design. Sheffield is a city located in the South Yorkshire in England, 53.3836° N, 1.4669° W (Figure 3-7). Sheffield 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, based on climate average records from 1981 to 2010 (UK Met Office, 2014). It rains in Sheffield 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 relative humidity in Sheffield fluctuates around 80% and sometimes peaks at 90% during spring (Met Office UK, 2012).

Figure 3-7 Location of Sheffield in the United Kingdom

3.3. The Case Study Buildings

Based on results from the study of lobby typologies in HEI in the UK, three faculty buildings from the University of Sheffield were selected for this study, Sir. Henry Stephenson building, Jessop West building and ICOSS (Interdisciplinary Centre of the Social Sciences) building. The buildings were selected for three reasons. First, because their layouts very closely reflect a basic lobby unit design as defined in the preliminary study. Second, because the connections between the spaces were similar, allowing a replication of similar spatial sequences in different buildings. In addition, the three seminar rooms had a fire door that connects the space directly with the exterior, which is necessary for the survey procedure described in section 3.7. Finally, the three buildings operate in the same way, NV during summer and with heated spaces during winter. The location of the case study buildings are illustrated in Figure 3-8.

Figure 3-8 Location of the case study buildings

3.3.1. *Sir. Henry Stephenson (HS) building*

Sir. Henry Stephenson building lecture theatre 2 was used as the first case study; it is located on the ground floor of the building with a west orientation (Figure 3-9). This lecture theatre operates with NV; it has some windows that can be opened manually. In addition, the space has an Air Handling Unit (AHU) above the ceiling that provides mechanical ventilation when it is necessary. The AHU is not part of a cooling or heating system; it only provides fresh air intake with a constant wind speed. The lecture room has three square louvres in the ceiling for air supply and three more for air return to the AHU. This system is turned on and off manually by the porter of the building at peak hours or when it is requested by the users. During the surveys, this system was never used; the space was always working with NV. For heating, there are two radiators inside the lecture theatre which supply hot air during winter in order to maintain a temperature around 21°C.

The Sir. Henry Stephenson building lobby is NV; therefore the internal temperature can vary from day to day during this period of the year. The heating system is controlled by the University BMS (Building Management System); it is turned on in late October and turned off in early March. During winter, the lobby unit is heated with four radiators distributed in this area. There are two sensors connected to the BMS that provide information about the interior air temperature. During winter the lobby unit is kept at 21°C. The lobby unit does not have any hot air supply curtain in the main entrance. The lobby unit faces west, so solar radiation can penetrate the interior of the lobby and entry doors during summer afternoons.

Figure 3-9 Sir. Henry Stephenson Building:1) exterior, 2) entry doors (draught lobby), 3) circulation space, 4) seminar room

3.3.2. *ICOSS (ICS) building*

The seminar room selected for this study room is located in the ground floor of ICS building (Figure 3-10). It is a NV seminar room with integrated windows that can be opened manually. It has a north orientation, for this reason, the temperature inside is generally cooler than outside. There is one air temperature sensor in the room, connected to the BMS. During winter, the room is heated by radiators located in one of the lateral walls that keep the room at 21°C. The ICS lobby unit is NV; it has some windows at the top of the facade that take hot air out of the lobby unit. During winter, the lobby unit is warmed by the under floor heating system that is controlled by the BMS. There is one sensor located in the reception that reports the interior air temperature of this space to the BMS.

Figure 3-10 ICOSS Building:1) exterior, 2) entry doors (draught lobby), 3) circulation space, 4) seminar room

3.3.1. *Jessop West (JW) building*

The Jessop West building hosts the faculty of Arts and Humanities. The seminar room for this study is located on the ground floor of Jessop West building (Figure 3-11). It is NV; there are windows that can be opened manually by the occupants. The meeting room has windows in the east and west facades of the building. The seminar room can operate in two modes during summer, NV or using mechanical ventilation (MV), which can be controlled manually by the users. There are two air diffusers in the ceiling, for air supply and return respectively. During winter, the building operates with a trench heating system, which provides warm air from floor grilles located in the perimeter of the facades. The JW lobby unit comprises the entry doors space and the exhibition area, which are NV. During winter, the trench heating system in the exhibition area and seminar room are kept at 21°C. The heating system is generally turned on at the end of September. The draught lobby space does not have a heating system and operates with NV for the whole year.

Figure 3-11 Jessop West Building:1) exterior, 2) entry doors (draught lobby), 3) circulation space, 4) seminar room

3.4. The quantitative approach

The quantitative methodology was shaped by the analysis of previous thermal comfort methodologies involving people in dynamic state. The methodologies examined included previous work related to transitional spaces, non-uniform environments, temperature changes, thermal history and short-term occupancy. The methodologies used in previous experiments, equipment setup, experiment procedure, data analysis, number of participants, experiment location, period of the year, building type and main variables of study were all explored through the literature (Appendix 3).

Fieldwork was selected because, although climatic chambers provide controlled climate environments with fewer confounding variables, evidence from many experiments has demonstrated the importance of fieldwork on the study of the adaptive thermal comfort model (de Dear and Brager 1998; McCartney and Nicol 2002; Nicol 2004; Nicol et al. 2012; Nicol and Humphreys 2009; Rijal et al. 2007). Empirical work ('real-word-research') provides robust results, predicts effects and solves problems, contrary to just gaining knowledge or finding causes (Leaman et al. 2010). Finally, results from controlled experiments are more reliable, yet with less validity in existent contexts.

A quantitative approach was determined since in fieldwork there is no control of the exterior environment and other personal factors altering people's thermal perception, so a larger number of people is required. The analysed laboratory work involves a smaller number of participants (from 9 to 48) (Appendix 3), in comparison with fieldwork research that involved from 314 to 3,087 people. In addition, a larger number of participants is required to conduct valid statistical analysis.

3.5. Preliminary Work

The preparation of surveys involved a number of previous considerations. Authorization from the University Estates and Facilities Management to use the building spaces, and approval of the survey proceedings from the University Health and Safety advisor, was required because of the use of the fire doors in the seminar rooms. Before starting the surveys, the building spaces were visited many times to conduct preliminary measurements and coordinate access to the spaces with the building porters. Also, it was necessary to submit a calendar to the person responsible for the Building Managements System (BMS) in order to deactivate the fire alarms, in the doors of the selected seminar rooms during survey times. Finally, the seminar rooms were booked two months in advance in each season with the room booking service of the university. Other preliminary activities involved equipment preparation, calls for volunteers, portable equipment arrangements, preliminary measurements with equipment, training for other team members and finally two pilot experiments.

3.5.1. Ethical Clearance

This study required ethical approval from the University of Sheffield Research Ethics Committee, via an ethics form (Appendix 4) prior to the start of the fieldwork. Therefore, all the participants in this study signed a consent form before starting the survey and after reading the information form.

3.5.2. Pilot Experiment 1

Before the final procedure was established for the thermal comfort survey, two pilot experiments were conducted. The main goal of the pilot experiments was to test the proposed methodology at an early stage, in order to improve the survey procedure and decision making. They were also conducted to check that the questionnaires were comprehensive, to detect unanticipated problems during the process, review team coordination, test the equipment requirements and setup, and carry out preliminary statistical analysis.

The first pilot experiment was conducted at The University of Sheffield's Jessop West Building on the 3rd of July 2012 with 20 university students. The study was designed to explore participant's thermal perception in two different thermal sequences when walking from the exterior to the interior environment using the lobby area in opposite directions. One of the objectives was to determine which spaces or spatial changes were key for the topic of study. It is important to note that the survey procedure of the first pilot experiment does not match with the final methodology reported in this thesis, since developing the survey was part of the decision making process. This pilot experiment was very useful for the development of the final questionnaires, equipment selection and coordination of the survey procedure.

During the preparation process of the first pilot experiment, a number of preliminary tests were conducted using different versions of the questionnaires. The different options were used to test the overall length of the forms, question statements, number and order of sections, number of questions, key useful definitions for international participants, visual instructions matching with on-site signs and test options of graphical representation of the 7 point ASHRAE scale in a clear way for participants to provide their thermal perception. Finally, sample questionnaires were used to determine the time people spent answering the questionnaire in relation to the time people spend moving in real life from the exterior through interior in the lobby unit. The different formats of the pilot questionnaires can be seen in Appendix 5. Regarding the equipment, the first pilot experiment tested the selection of the instruments required to cover all the physical measurements.

Findings from the first pilot experiment and the survey procedure determined a number of considerations to take into account for the main survey. One consideration was to study people in different thermal settings in the same spaces, in order to be able to generalize results identified in the pilot experiment. It was decided not to include 30 minutes of thermal stability, primarily because people's thermal perception quickly changed after moving from one place to another (in this case from the starting point to the exterior of the doors) in the pilot study, and also because this would alter the normal way that people arrive to the place. Therefore, it was decided to avoid this step and study people in a more natural way that better reflected reality.

It was decided instead to focus on the study of people's thermal perception with different thermal conditions and different ranges of temperature changes in the same place. This was to help understand different responses to temperature variation. The study was reduced to only one direction (outside-inside) because of the large sample size required and the limited amount of time to conduct the surveys. By understanding the effect of different temperature changes, the study of different thermal settings could be better understood in different contexts covering different thermal directions. Outcomes from the pilot experiment confirmed that the key temperature change to focus on the one when people move from the outside to the inside or vice versa. It was also seen that the physical variables changed along the route. This helped to determine the best location for the equipment in order to detect the temperature differences in the final survey procedure

The pilot experiment revealed significant results. It showed that people change their thermal perception in a very short period of time. It also illustrated how people's responses corresponded with the physical factors of each space (relative humidity and air temperature). In the first experiment, responses from two groups (A and B) walking in opposite directions were compared. Group A walked from the main entrance through the lobby unit and then out using the fire door located in the seminar room. Group B walked in the opposite direction, from the exterior to the seminar room, then through the lobby unit and out to the exterior using the main entrance. Surprisingly, it was seen how each group of people perceived the same room in different way with the same thermal conditions. Again, although the procedure revealed interesting results, due to the limited time, budget and coordination, it was not possible to go further with this procedure. However, the outcomes helped to focus attention on specific trends which could be analysed in depth in the final survey. Also, results suggested that people's thermal preferences were more positive in group A than B; however this was a point that was studied later with a larger sample size.

The pilot study enabled general visualization of the range of thermal differences between spaces and the way people perceived these changes. Finally, it was helpful for improving the questionnaire in the sections or questions where people were more confused. At this point it was not possible to run the entire statistical test because of the small sample size. However, it was useful to think about the process for entering the data from questionnaires and equipment in the most efficient way, and to adjust a few details in the questionnaires coding for future data analysis.

3.5.3. Pilot Experiment 2

The second pilot experiment was conducted two weeks before the main experiment, in May 2013 in the Sir. Henry Stephenson Building. The main goal of this experiment was to test the final version of the questionnaires and final equipment setup over an experimental time of 35 minutes. Due to the limited time available to book the seminar rooms for this experiment, and following the idea of reflecting a real situation, it was important to rehearse the survey in a short period of time with a large number of participants. The main feedback from the second pilot experiment was the procedural adjustments needed when managing a large number of participants one after another. The major adjustment from this pilot was to make it easier for people to follow the instructions from questionnaires and have a better coordination with the speed of the surveys. Therefore, additional printed signs (arrows illustrating the routes) with different colours for group A and B were integrated at the points where the equipment was located. In addition, the number of question for each space was printed in separate sheet in the questionnaire to avoid confusion. The time when participants started and ended the questionnaires was written in the questionnaires. A detailed description of the two pilot experiments can be seen in Appendix 6.

After the second pilot study, it was decided to guide people through the routes and create circuits with the people supporting the researcher. In the seminar room, one person was receiving the questionnaires and answering any questions that participants had regarding the last section of the questionnaire. Another decision was made regarding the time references when people were answering the different sections of the questionnaires: it was better controlled by the researcher assistants adding the time to the questionnaires with synchronized clocks. Data from the second pilot experiment was not analysed since there was still not good control on the way people answered the questionnaires. In the real situation, participants were not as careful reading the instructions as was expected. Therefore, people didn't fill some sections of the questionnaires or answered some sections in the wrong place. The main lessons learned from this second pilot experiment were how to guide a large group of people, without stopping, in the most efficient and controlled way.

3.6. The thermal comfort survey setup

3.6.1. Questionnaires

After the preliminary pilots, two types of very short 'right here, right now' thermal comfort questionnaires were designed for the survey purposes (Type A and Type B), depending on the route that participants used to arrive to the seminar rooms. Both questionnaires included a cover letter with the instructions, an ethics form and a section at the end to collect people's demographics, their current clothing description and previous location and activities. Questionnaire A was designed for participants walking to the seminar room using the lobby area (entry door space and circulation space). It had four sections corresponding to the four spaces in which they were walking (Appendix 7). Questionnaire B was designed to be used by participants entering directly from the exterior to the seminar room, and included only two sections, one for each space (Appendix 8). A seven point ASHRAE scale was used to measure people's thermal perception. A 3 point McIntyre scale was used for thermal preferences. Temperature change perception was measured with a 3 point McIntryre scale (Jitkhajornwanich and Pitts 2002), wind speed and relative humidity perception with a seven point scale, as used by Jitkhajornwanich and Pitts (2002), and relative humidity with a seven point scale (Tsutsumi et al. 2007). Some recommendations for future work, regarding the use of these scales, are described in Section 7.9. Questionnaire A was proposed to be answered in 10 minutes maximum and questionnaire B in 7 minutes maximum.

From the literature review, a number of categorical variables were included on the last section of the questionnaire, as part of participant's thermal history section. The selected variables were those that have shown a significant influence on people's thermal perception in previous studies exploring people in steady state. Hence, it was important to determine if these factors were altering people's thermal perception in dynamic state. The selected variables were: (1) Gender, (2) Nationality, (3) Age, (4) Weight, (5) Height, (6) Time of residence in Sheffield, (7) Clothing, (8) Previous activities (indoor or outdoor thermal exposure), (9) Previous activities (active work and passive work), (10) Previous activities (eating: yes/no), (11) Previous time of exposure to indoor or outdoor climatic conditions, (12) Previous AC exposure.

3.6.2. Volunteer elicitation

Since the focus of the study was undergraduate students, a call for volunteers was conducted to the whole undergraduate community by using the university volunteers e-mail delivery system with an invitation letter. In addition, people were selected randomly when attending their lectures in the case study buildings and other nearby university buildings. Therefore a mixture of methods was used to get participants: e-mail, snowball and random selection as they approached to the case study buildings.

Finally, short invitation talks of 3 minutes were presented in large lecture theatres of different faculties. The call for volunteers was conducted in every season of the year a few weeks before the surveys and during the survey period in order to maintain a volunteer snowball effect. Since one of the aims of this study was to study people in a real situation, people were not asked to wear any particular garment or do any other preparation that could change their normal routine.

3.6.3. Equipment

A total of four sets of equipment, one for each space (exterior, entry doors space, circulation space and seminar rooms) were mounted in tripods (Figure 3-12), four small digital clocks were attached to each tripod. Air temperature (T_a), wind speed (A_v), relative humidity (rh) and globe temperature (T_g) were measured simultaneously while people were answering the questionnaires. Air temperature and relative humidity were measured using data-loggers (HOBO-U12-012). In addition, back up measurements were conducted outside using a hygrometer i-button (Thermochron) inside a waterproof capsule.

Outside, wind speed was measured with a cup anemometer OMEGA (OM-CP-Wind 101A Kit series). Inside, wind speed was measured with two rotating vane anemometers (TSI Airflow LCA 501) located in the entry doors space and circulation spaces, and three OMEGA hot-wired data logging anemometer, located in the seminar rooms, entry doors space and circulation space. In addition a BSRIA portable manual hot wire anemometer TA-410 was used to measure the wind speed manually at specific times, and for preliminary measurements. The globe temperature was measured using a small data logging device (Thermochron i-button) inside a black painted 40mm table tennis ball.

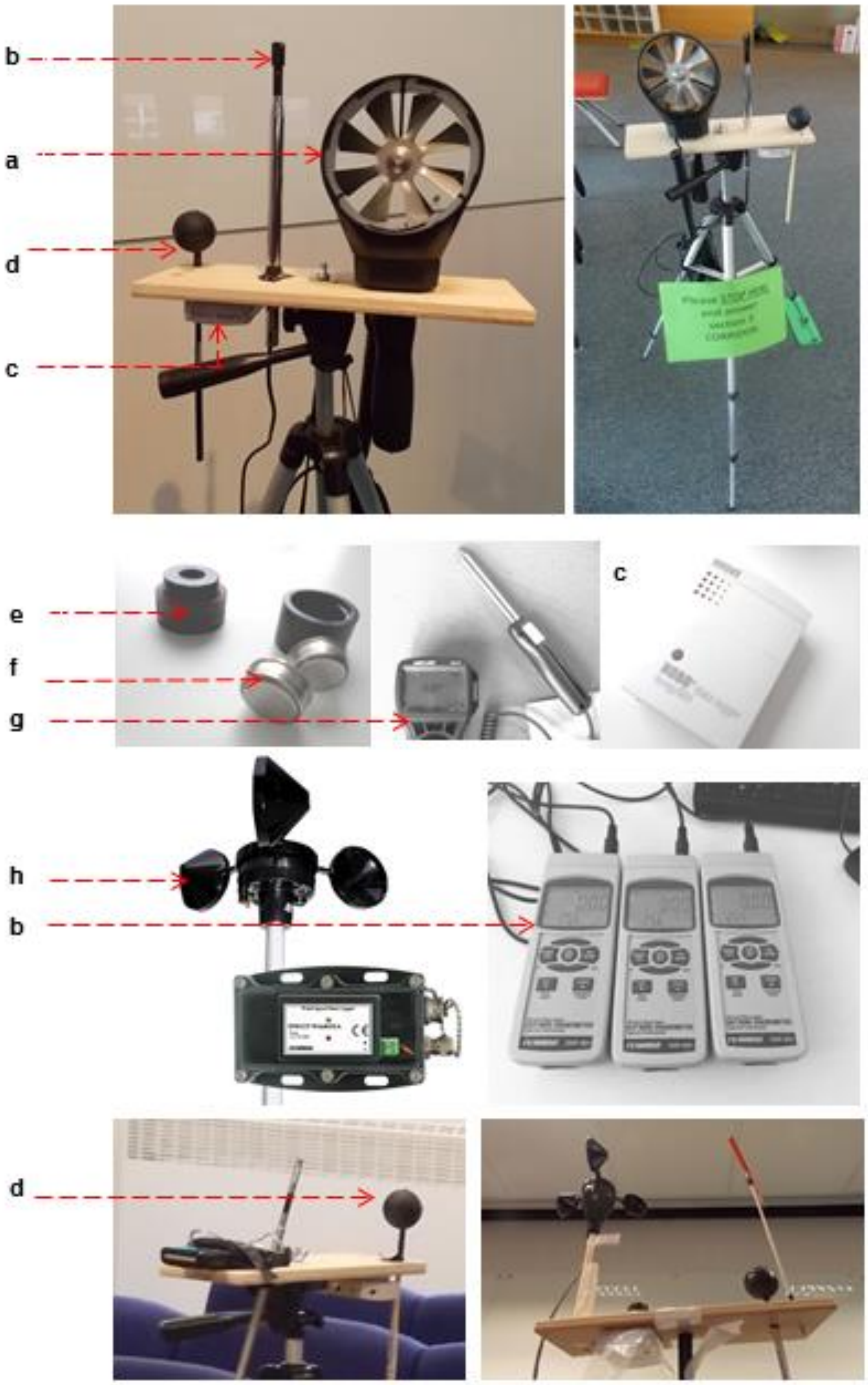


Figure 3-12 Equipment: a) vane anemometres (TSI Airflow LCA 501), b) OMEGA hot-wired anemometer, c) data-loggers (HOBO-U12-012), d) globe thermometer using a Thermochron i-button inside a black painted 40mm table tennis ball, e) water proof capsule for i-button, f) Thermochron i-button, g) portable manual hot wire anemometer (BSRIA TA-410), cup anemometer (OMEGA OM-CP-Wind 101A).

3.6.3.1. Equipment setting

The equipment was attached to four demountable tripods with a flat piece of wood on top. Black waterproof fabric bags were used to hold the data-logging devices, and hung on the tripods (Figure 3-13). At the exterior of the lobby, the equipment was located at 1.70 metres and 1.10 metres height above the floor (ASHRAE 2004); the 'L' shaped wooden supports protected the equipment (air temperature data loggers) from direct solar radiation. Inside, the equipment was located at 1.10 m height. In the seminar rooms and circulation spaces, the equipment was located in the centre of the space. In the entry doors, the equipment was locates in the centre of the space between the two entry doors 1.0 metre from the main entrance in HS and ICS buildings and 3.0 metres from the main entrance in JW building. Outside, the tripod was located in the middle point of the trajectory between the main entrance and the door connected to the seminar rooms. All the equipment was programmed with the corresponding software to start measuring automatically at the same time, 30 minutes before the survey started. All the tripods were located in their place 40 minutes earlier. This gave enough time for the instruments to adjust to their surrounding conditions and provide accurate measurements as specified in previous fieldwork studies (CIBSE-GuideA 2015; Nicol et al. 2012).

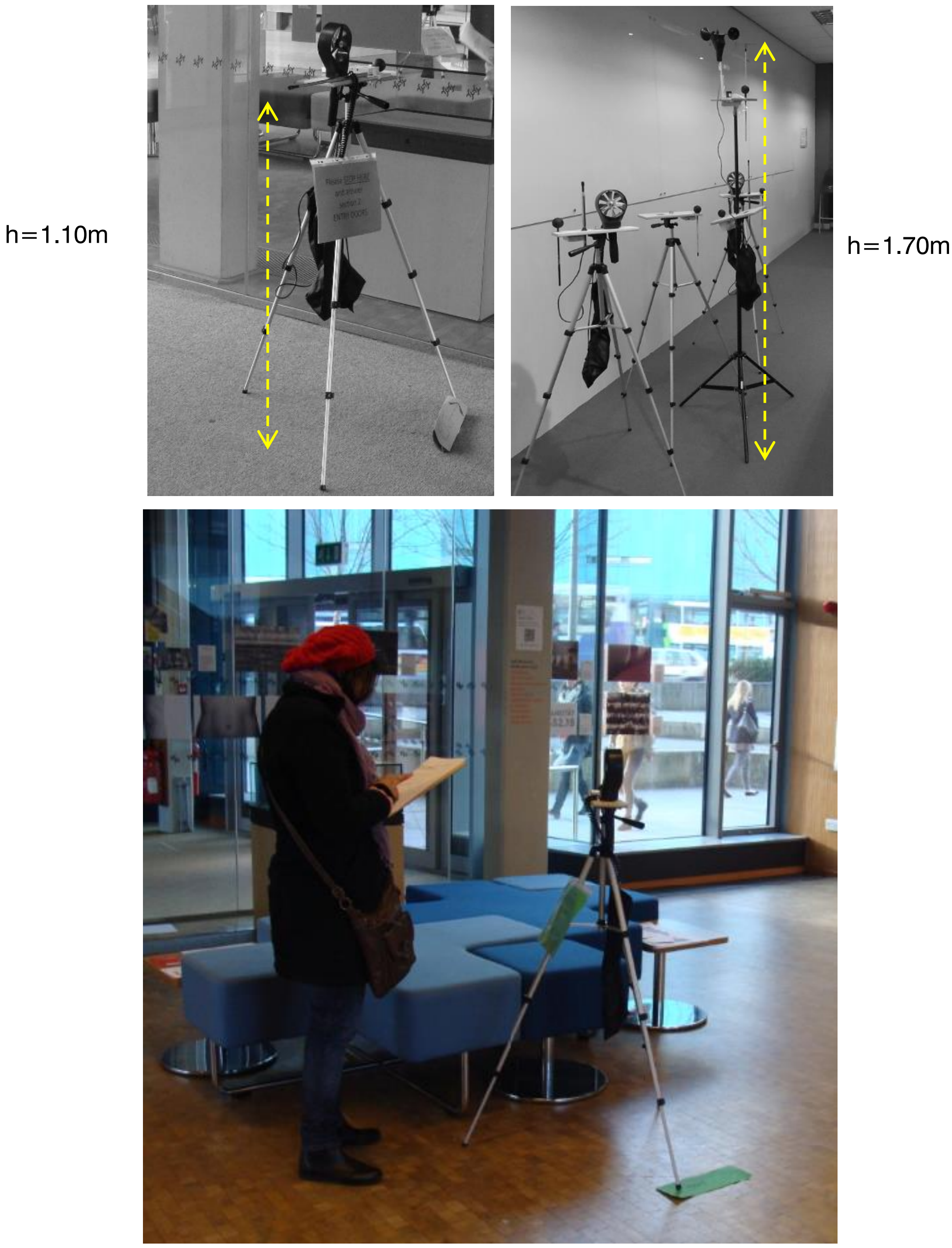


Figure 3-13 Equipment setting mounted in portable tripods

Measurements were conducted in the case study buildings one month before the main surveys, in order to evaluate how similar or different the temperatures of the three buildings were. The measurements included different equipment sampling-time setups, in order to determine how frequently the climatic conditions changed in the four spaces. Measurements were first taken every 5 seconds, and then every minute. The preliminary measurements revealed that the air temperature change in the exterior 1°C in periods of time from 15 minutes up to 1hr. It was also seen that the air temperature in the seminar rooms was the same for longer periods of time (perhaps more than 3 hours) when the rooms were empty. As the surveys involved very short periods of time, it was key to record the physical measurements corresponding to the precise moment that people were moving through the spaces. Therefore, a previous rehearsal with a few volunteers was conducted to determine the time that people spent walking from one space to another. In this way, the sample-time setup was also defined. It was found that the physical conditions of the seminar room and circulation areas stayed the same for periods of time up to 1 hour. However, the conditions were more variable in the entry doors and at the exterior. Outside, air temperature changes occurred after 15, 30 and up to 1 hour (e.g. 12°C changed to 13°C). Small temperature changes were variable over one minute (e.g. 12.1°C -12.3°C-12.9°C-12.5°C). Wind speed was the most variable factor over short time periods in comparison with air temperature and relative humidity. It was found that the physical conditions in the entry doors changed only during the periods that the doors were in use. After a number of tests, 5 seconds was determined as the sampling time.

3.6.3.2. Equipment calibration

All the equipment was obtained by the researcher, except from the vane anemometers (TSI Airflow LCA 501) and the portable manual hot wire anemometer (BSRIA TA-410) which were from the Department of Civil and Structural Engineering of The University of Sheffield. The new equipment was calibrated by the manufacturer and the used anemometers had a calibration certificate covering the period that was used in the experiment. The certificate was requested by the department of Civil and Structural Engineering of the University of Sheffield and issued by the manufacturer BSRIA. In addition, all 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 the instruments were programmed with exactly the same date and time, and same measurements units (°C.) The instruments were located as far as possible from the window. The space remained closed, with closed windows and dampers avoiding solar radiation and direct sunlight (Figure 3-14). The same measurement values where shown in all the devices as in the calibrated equipment. Because of the limited budget, it was not possible to calibrate or compare the globe temperature measurements with a calibrated device. However, based on the literature review, under non-variable interior conditions and very limited solar radiation, the globe temperature measurements are very close to the air temperature. Therefore, the data was compared during night periods.

Figure 3-14 Equipment setup for calibration

3.6.4. Subjective measurements

In order to be able to compare results with previous work exploring similar factors connected with this thesis, the thermal comfort scales used by previous studies were used in this research. The 7 point ASHRAE scale was used to measure people's thermal perception and three point Nicol's scale 'warmer', 'no change' and 'cooler' (CIBSE-GuideA 2015) was used for thermal preferences (Figure 3-15). For temperature change perception, the three-point scale used by Jitkhajornwanich and Pitts (2002) was used.

Thermal comfort perception

cold	cool	slightly cool	neutral	slightly warm	warm	hot
-3	-2	-1	0	1	2	3

uncomfortable cold band	comfortable band	uncomfortable warm band

Thermal preference

cooler	no change	warmer
1	2	3

Temperature change perception

sudden	gradual	little/no change
1	2	3

Figure 3-15 Scales used to evaluate people's thermal comfort perception.

3.6.4.1. In Equipment limitations

Due to the limited budget and availability of equipment, there were some limitations in the equipment selection which need to be taken into account in future related research. The instruments used to measure wind speed and globe temperature have the following limitations:

Outdoor wind speed was measured with a cup anemometer (OMEGA OM-CP-Wind 101A Kit series). This did not register low speed winds below the starting threshold of 1.75 mph (approximately 0.8 m/s – see Appendix 9, section 1.1). However, it was decided to use this equipment because although a hot-sphere anemometer can measure low wind speed, it has an upper wind speed limit. Therefore, based on preliminary measurements and equipment availability, it was decided to use a cup anemometer to register wind speeds above 1.75mph, since in the pilot experiment, participants found it difficult to state their perception of low speed wind values. A three dimensional measurement (horizontal and vertical) 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, in this case, it was not possible to combine instruments.

The equipment used to measure wind speed inside (TSI Airflow LCA 501, OMEGA hot-wired data logging anemometer and BSRIA portable manual hot wire anemometer TA-410) has problems related to directionality. A unidirectional instrument is not the best recommendation 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 and Lykoudis 2006) and considering the equipment specifications described in the ISO 7726 standard. In this work however, devices were used in the transitional areas; based on preliminary evaluation and measurements, the equipment was carefully positioned to measure the wind speed through the narrow draught lobby and corridor caused by the main entrance doors. 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). Different instruments to measure wind speed have different advantages and disadvantages, and need to be selected very carefully, based on the space that is being measured and the budget available (Nicol et al. 2012).

In relation to the globe thermometers used in this work, there is a limitation in accuracy. A 38 mm sphere has been the most recommended size for indoor measurements since 1977 (Humphreys, 1977) and onwards (Nikolopoulou et al. 1999). Also, small data loggers have also been recommended to measure globe temperature (Nicol et al. 2012). When the budget is small, it is better to use thermocouples or a resistance probe with black painted spheres (EN ISO 7726:2001). In this study, a globe thermometer with an i-button inside a 40mm sphere was used (illustrated in Appendix 9-1.8). This assembly needs further testing to be approved as an alternative option to measure globe temperature, since the dimension of the i-button and the sphere could have an effect on the accuracy of data. Finally, it is also recommended to use a grey sphere for measurements at the exterior and a black for interior (Nikolopoulou and Lykoudis 2006).

The globe thermometer was designed to be placed elevated above other equipment and without any obstacles around it (refer to figure 3.12). However, during these surveys, the globe thermometers should have been more elevated from the wooden base attached to the tripod. Therefore, it is recommended to take this into account and set the globe thermometer far away enough from any other devices, structures, etc.

For decades, different variations in physical measurements of the physical variables in thermal comfort studies have created some discrepancies. Therefore, it is worth being aware of key factors to consider in the instrumentation of thermal comfort experiments (Johansson et al. 2014).

3.7. Survey Procedure

The experiment started immediately after participants arrived at the meeting point outside of the case study buildings. First, they were asked to sign the ethics consent form followed by precise instructions. Participants arrived in smalls groups or individually, and they were assessed one after another, and in small groups of maximum three people, without stopping, over periods lasting from 5 to 10 minutes. The spaces were typically available for the survey for 35 to 45 minutes, and in few cases up to 4 continuous hours. As the survey required a large sample size, it was important to capture a large number of participants under the same climatic conditions. Therefore, six students assisted the researcher during fieldwork. Participants were asked to use trajectory A or B through the building randomly (Figure 3-16) and to answer each section of the questionnaire at specific points. Signs were located in the line of sight of the trajectory, to guide participants along the sequence of spaces. The experiment lasted from 5 (Group B) to 7(Group A) minutes on average per participant, with about 30 seconds in each space (exterior, entry doors, circulation and seminar room). Data-logging equipment was set in each space to measure thermal conditions at the time that volunteers were answering the questionnaires. Participants answered each section of the questionnaire in each space next to the equipment. Two types of questionnaires were used to test two routes of arrival to the interior space. Group A were asked to walk to the seminar room using the lobby area, and group B were asked to move directly from the exterior to the seminar rooms.

The trajectories diagrams and equipment location in each building are illustrated in Figure 3-17, Figure 3-18 and Figure 3-19. Volunteers participated only once in the survey, using only one route, for two reasons. First, in order to avoid bias by repeating the dame task, and due to the large sample size, it was not possible to ask participants to spend more than 10 minutes in the survey and conduct the protocols to avoid bias in their next participation (e.g. a stabilization period). Second, since the aim of this study is to analyse people's short-term thermal history in a real situation, the first trial could also alter participants' short-term thermal history. A participant control sheet was filled by the researcher during the surveys in order to balance the number of participants in each group, and balance the males and females.

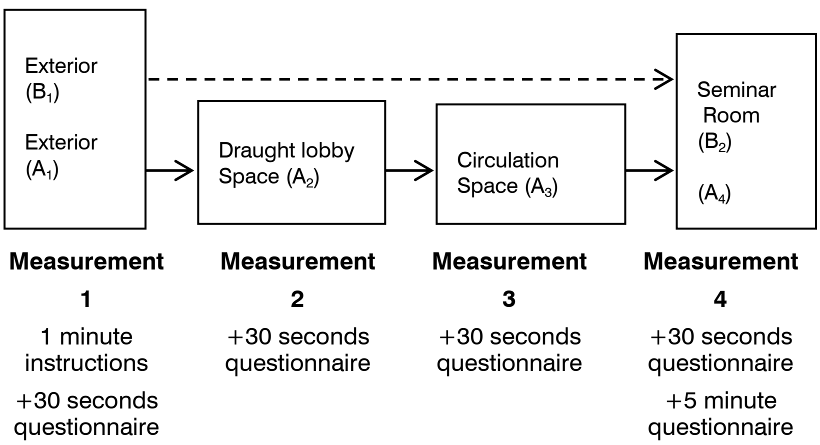
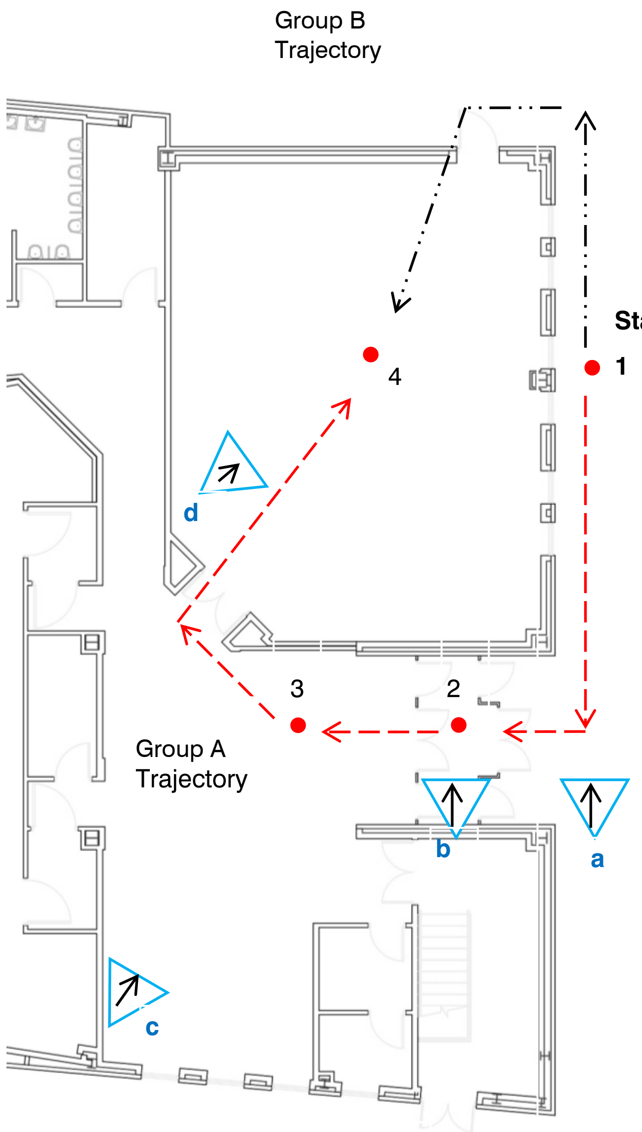


Figure 3-16 Survey procedure diagram



a Exterior

b Entry door space

1 Exterior
2 Entry doors space
3 Circulation space
4 Seminar room

Location of the equipment

Group A route

Group B route

Picture view

Figure 3-17 Sir. Henry Stephenson Building: Plan layout Equipment location and Group A and B trajectories

c Circulation space

d Seminar room

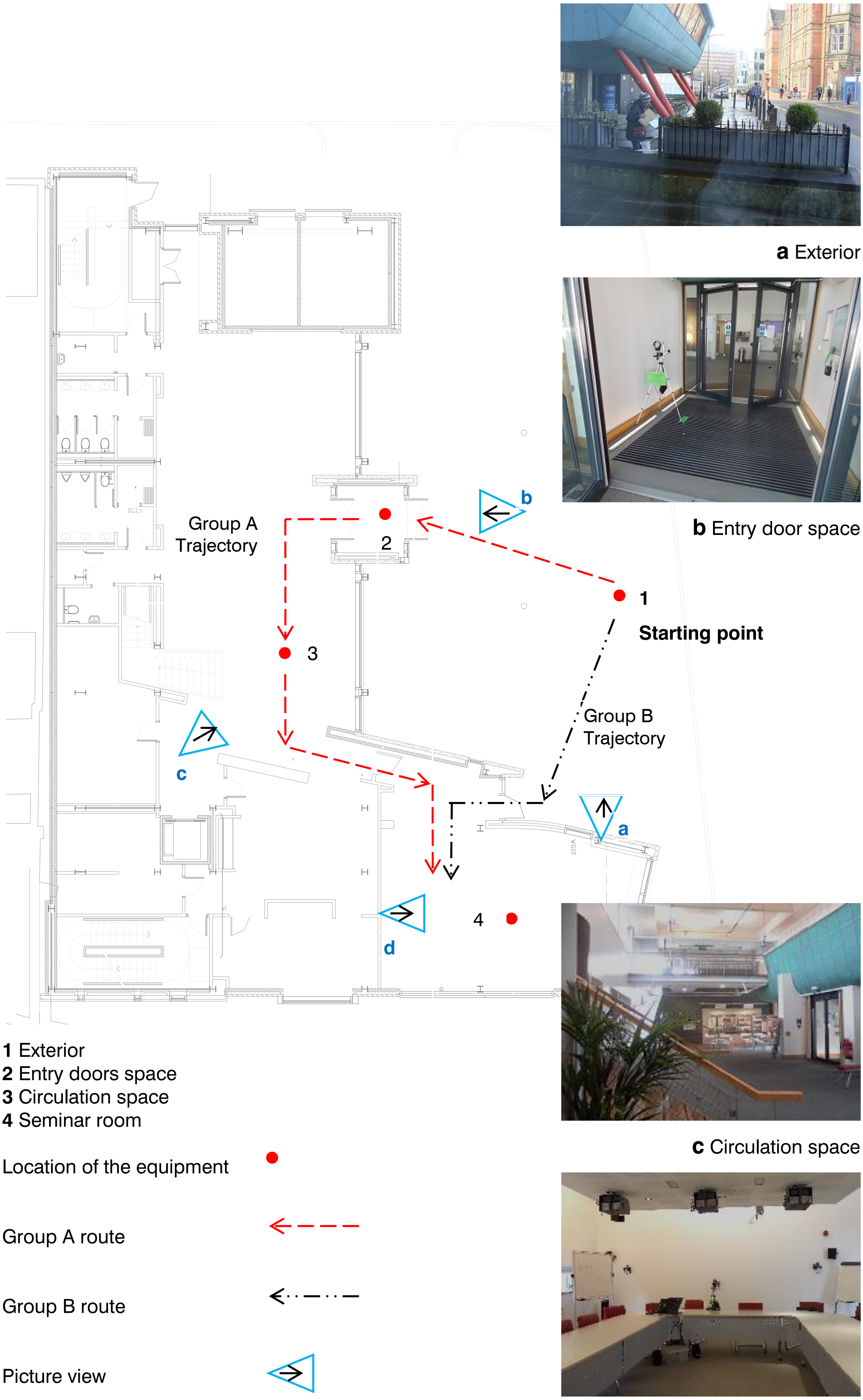
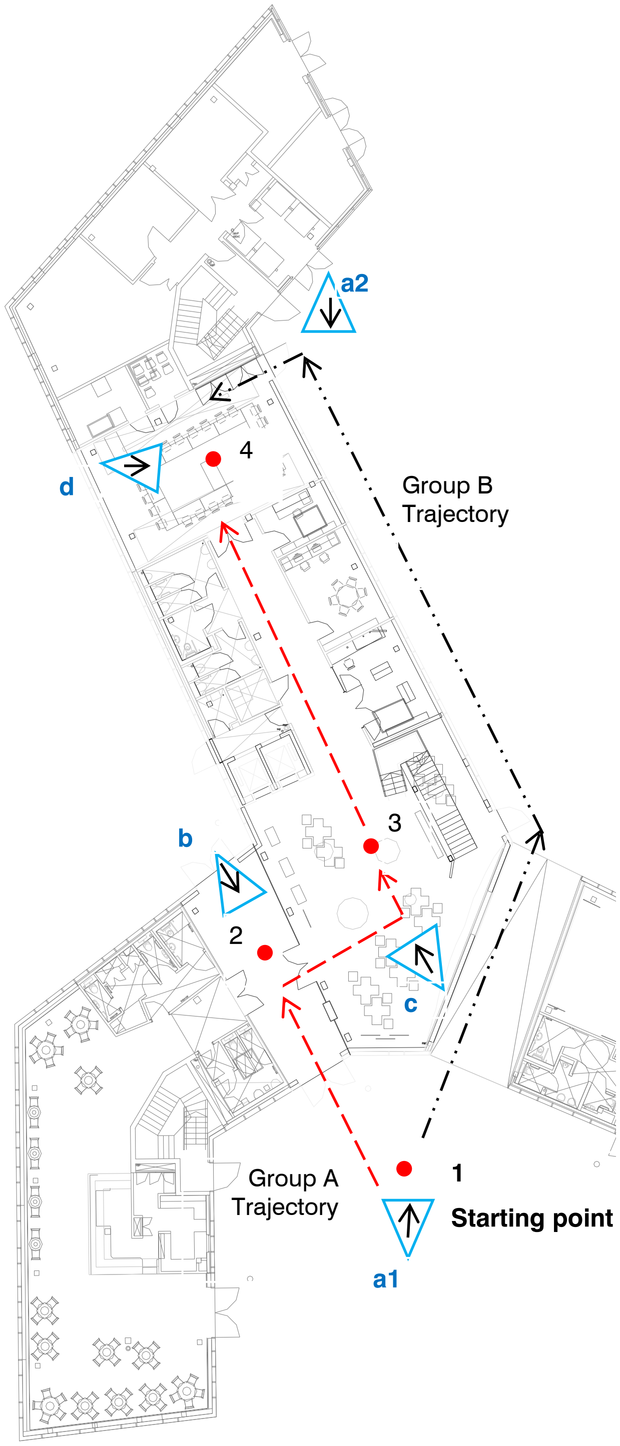


Figure 3-18 ICOSS Building: Plan layout
Equipment location and Group A and B trajectories



1a Exterior
1b Exterior 2 (fire door)
2 Entry doors space
3 Circulation space
4 Seminar room

Location of the equipment
Group A route
Group B route
Picture view

Figure 3-19 Jessop West Building: Plan layout
Equipment location and Group A and B trajectories

a1 Exterior

a2 Exterior

b Entry door space

c Circulation space and social area

d Seminar room

3.8. Analysis plan

Based on previous studies, it was determined that the strategy for data analysis would include different parametric and non-parametric statistical tests. Parametric statistical tests are designed to work with numerical and normally distributed data (Field 2013). In this study, numerical data was collected from the physical measurements (air temperature, relative humidity and wind speed), and was analysed with parametric tests. On the other hand, categorical (ordinal type) data was collected from people's responses using the 7 point ASHRAE scale and from other questions included in the questionnaire, such as demographic and thermal history variables. People's thermal comfort perception was planned to be analysed with non-parametric tests, since they are designed to work with ordinal (ranked) scales. However, since this study involved a large sample size, and people's answers showed a normal distribution, results were also planned to be compared with parametric tests as a reference. Authors mention that parametric tests are more powerful but designed for numerical data; in contrast, non-parametric tests are sometimes less sensitive, but designed to analyse categorical data (Field 2013; Pallant 2010). For this reason, it was decided to compare results from both tests to confirm significant results. Therefore, one test can cover aspects that the other fails to detect because of the nature of the data (numerical or categorical) (Pallant 2010).

3.8.1.1. Thermal bins

As part of the analysis, people were divided into thermal bins. Thermal bins referred to the way that people were grouped in order to have similar short-term thermal history. Each thermal bin can have different thermal sequences, depending on if people were in group A or B. Sequence A is comprised of four spaces (exterior, entry doors space, circulation space and interior) and three temperature changes from one space to another. Sequence B is comprised of two spaces (exterior and interior) and one temperature change. The total number of participants were divided in groups based on the same date, range of time and exterior temperature when people took part in the survey. Each 'thermal bin' corresponded to people who participated under the same range of climatic conditions in each space.

3.8.2. Statistical tests

3.8.2.1. Pearson's and Spearman's correlation coefficients

General descriptions of the statistical tests to are described along with a diagram of the analysis plan. Parametric (Pearson's) and non-parametric (Spearman's) correlations are used to identify the strength and direction of a linear relationship between two numerical variables (Pallant 2010). In this study, correlations are used to compare results from physical variables measured in the different spaces and in the different case study buildings.

3.8.2.2. Simple Linear regressions

A regression is based on correlations and permits a more advanced exploration among a set of independent variables. It is used to determine the degree of association existing between multiple independent variables and the dependent variables (Pallant 2010). Many studies in thermal comfort use simple linear regressions to predict the value of a variable based on the value of another variable, for example in the work conducted in building entrances by Jitkhajornwanich (1999).

3.8.2.3. Paired T-test and Wilcoxon signed rank test

In this research, results from people's responses are divided in two groups: A (using the lobby area) and B (entering directly from the exterior). The paired sample T-test (parametric) and Wilkinson Signed Rank test (non-parametric) are used to compare if two mean responses from the same sample population are significantly different from one to another (Brace 2012). Therefore, this test is used to compare people's responses before and after entering to the seminar room (A1 Vs A2 and B1 Vs B2) (Figure 3-20). For example, non-parametric test have been previously used by (Tsutsumi 2007) to measure the effect of different levels of humidity on people's thermal comfort and by Song (2011) to compare people's thermal comfort perception.

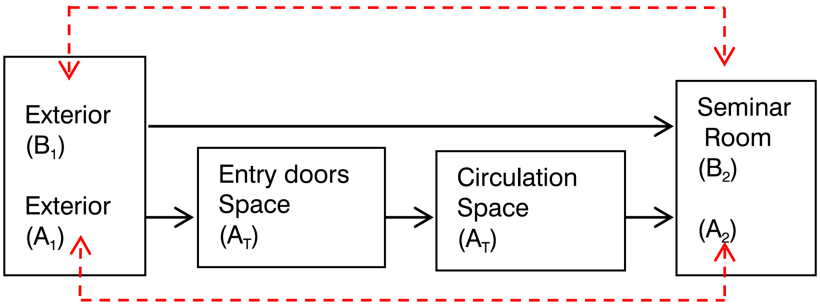


Figure 3-20 Data analysis diagram: groups A and B paired sample comparison.

3.8.2.4. Independent T-test and Mann-Whitney test

These tests were used to compare group A_2 and B_2 responses in the seminar rooms, in order to determining a significant difference in people's mean responses between the two independent groups (Figure 3-21). These tests have been used to determine differences in people's thermal responses in NV and AC buildings (De Vecchi 2011).

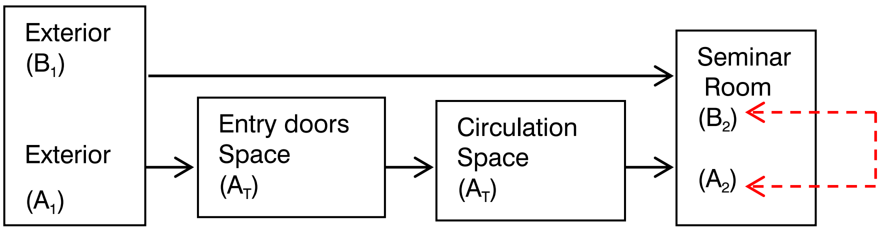


Figure 3-21 Data analysis diagram: comparison of people's thermal comfort responses

3.8.2.5. One way ANOVA and Kruskal-Wallis test

ANOVA (parametric) and Kruskal-Wallis (nonparametric) tests are used to measure the variance or variability in people's answers between three or more groups. A post-hoc test is used to identify in which groups people's responses were significantly different. In this study, these tests were used to compare people's responses in the four seasons of the year. Previous studies have used these tests when comparing people's thermal responses under different thermal conditions, for example in research exploring people's long-term thermal history (De Vecci et al. 2012)

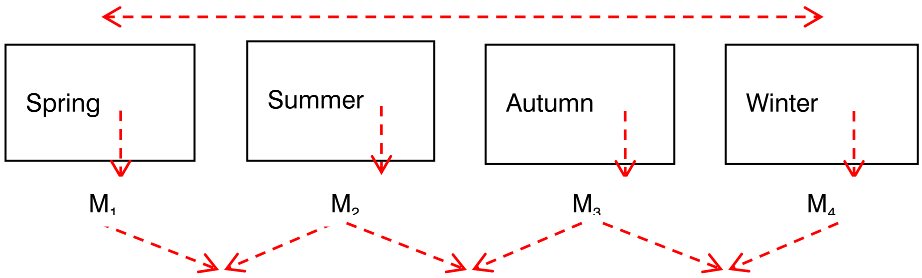


Figure 3-22 Data analysis diagram: Comparison between more than three groups of people under different thermal conditions.

3.8.2.6. One way repeated measures ANOVA with post-hoc and Friedman test

In this research, repeated measures ANOVA (parametric) and Friedman Test (non-parametric) were used to measure group A thermal responses in in the four different thermal conditions when moving from one space to another. A post-hoc test (parametric) or Wilcoxon signed rank test (non-parametric) is used to determine in which specific spaces people significantly changed their thermal perception (Figure 3-23). Kelly and Parson (2010) used these tests to analyse people's thermal comfort in train journals and Nagano (2005) and Tsutsumi (2007), Du (2014) to compare people's thermal comfort vote in relation to their mean skin temperature.

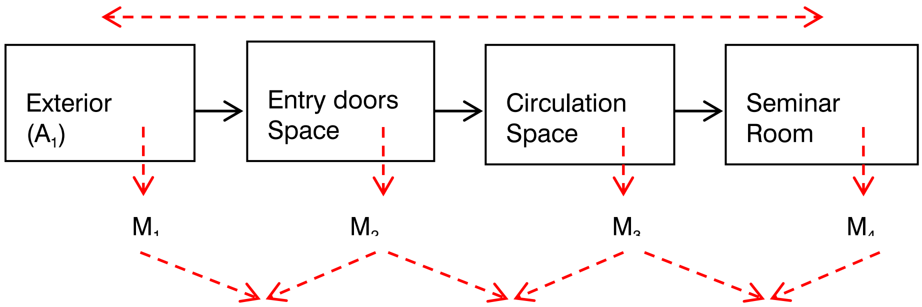


Figure 3-23 Data analysis diagram: Group A comparison after moving from one space to another using repeated measurements ANOVA and Friedman test (M=media).

3.9. Conclusions

In this chapter, the final methodology and methods to answer the research questions were defined using a combination of a preliminary survey and two pilot studies in order to successfully coordinate the final procedure. The preliminary survey of HEI in the UK, revealed a wide variety of contemporary lobby layouts in terms of design. Results illustrated bigger and more complex lobby areas hosting large number of people using lecture theatres and other services. A 'typical lobby unit', which was representative of the sample, was identified. The most recurrent spatial connection was a main entrance with double door entry doors (draught lobby) and immediate connections with other transitional spaces. The identification of this typical lobby unit was important, in order to select case study buildings with the same characteristics. Regarding the participant sampling procedure, it was identified that HEI in the UK are distinguished by hosting an international student body. Therefore, it was decided to include international students in the sample.

The pilot experiments guided towards a less complicated survey procedure in order to allow better control, guidance and understanding of a large sample size in the process. The pilot experiments also determined the final survey procedure, equipment setup and questionnaires design. Due to the number of participants required to provide an overview of a real situation, it was decided to follow a quantitative approach. Since most of the previous studies were conducted in laboratories, it was proposed to change this tendency and conduct fieldwork research. This could result in a difference in the outcomes, since fieldwork could reveal some hidden factors that a controlled experiment cannot expose.

Chapter 4

4. Primary results

4.1. Introduction

This chapter deals with the results related to the physical conditions of lobby units and the way that people perceive the thermal environment in these spaces under transient conditions when moving from the exterior to an interior seminar room. The chapter covers the objectives established in Chapter 2 regarding the identification of thermal variations in transitional spaces. The chapter illustrates primary findings in two main sections: first, the spatial physical variables and second participants' thermal perception (Figure 4-1) Parametric (One way ANOVA, pairwise and independent sample T-test) and non-parametric (Mann-Whitney, Kruskal-Wallis and Friedman test) statistical tests were used to identify significant differences in physical conditions and participants' thermal comfort between seasons, buildings and spaces.

The first section reports the results of physical climatic measurements (air temperature, relative humidity, wind speed and globe temperature) collected from data logging equipment during surveys. These results were explored at four different levels: over a typical year, in the seasons of the year (from spring 2013 to winter 2013-2014), in the three case study buildings (Sir. Henry Stephenson, Jessop West and ICOSS Buildings) and in the specific spaces of study (exterior, entry doors space, circulation space and seminar rooms). A preliminary detailed analysis of the physical variables was crucial in order to visualize the climatic conditions at the time when the surveys were conducted. Results illustrate detailed exterior and interior climatic conditions and thermal variability between spaces in each season of the year.

The second section introduces findings relating to participants' thermal comfort perception from the 1,749 volunteers who participated in the study. In the same way that the results were organized in the first section, outcomes from participants' thermal perception are ordered by season, case study building and groups A or B (Figure 4-2). Results from statistical analyses compare participants' thermal perception (using the seven point ASHRAE scale) in relation with the measured physical conditions. The analysis focuses on participants' current Thermal Sensation Vote (TSV) in relation to different thermal variations presented in the four spaces of study. A number of indicators influencing participants' thermal perception are discussed, as well as a number of considerations to take into account for the data interpretation. Due to the seasonal thermal adaptation that people experience in a year, the way that people use the 7 point ASHRAE scale in each season is explored in detail. Equally importantly, the significance of the interpretation of numerical values used in physical measurements is evaluated. Results from this first stage set the basis for data organization for the detailed analysis conducted in the following chapter (Chapter 5 'Thermal history'), which focuses in detail on participants' short-term thermal perception in relation to previous thermal experiences.

Thermal connections results

Spatial physical variables

1 Exterior climatic conditions, comparison with a typical year climatic conditions in Sheffield 2013-2014 during the surveyed period

2 Exterior climatic conditions
Interior climatic conditions

- Air temperature
- Air velocity
- Air humidity
- Globe temperature

3 Climate analysis by case study
Exterior-Interior seasonal comparison between buildings

- Henry Stephenson (HS)
- Jessop West (JW)
- ICOSS Building (ICS)

4 Thermal variability in the four measurement points

- Exterior
- Draught lobby
- Circualtion space
- Seminar rooms

Participant's thermal comfort perception

1 Participants' demographics

2 Indicators of people's thermal adaptation
Participants' clothing adjustments across the four seasons
The seasonal variations on the use of 7 point ASHRAE scale

- Spring
- Summer
- Autumn
- Winter

3 Participants' thermal perception of the exterior environment
Participants' thermal perception of the interior environment

- Exterior
- Entry doors sapace
- Circulation space
- Interior space

4 Moving from the outdoors to the indoor environment
Participants' thermal preferences

5 Conclusions

Figure 4-1 Organization of result

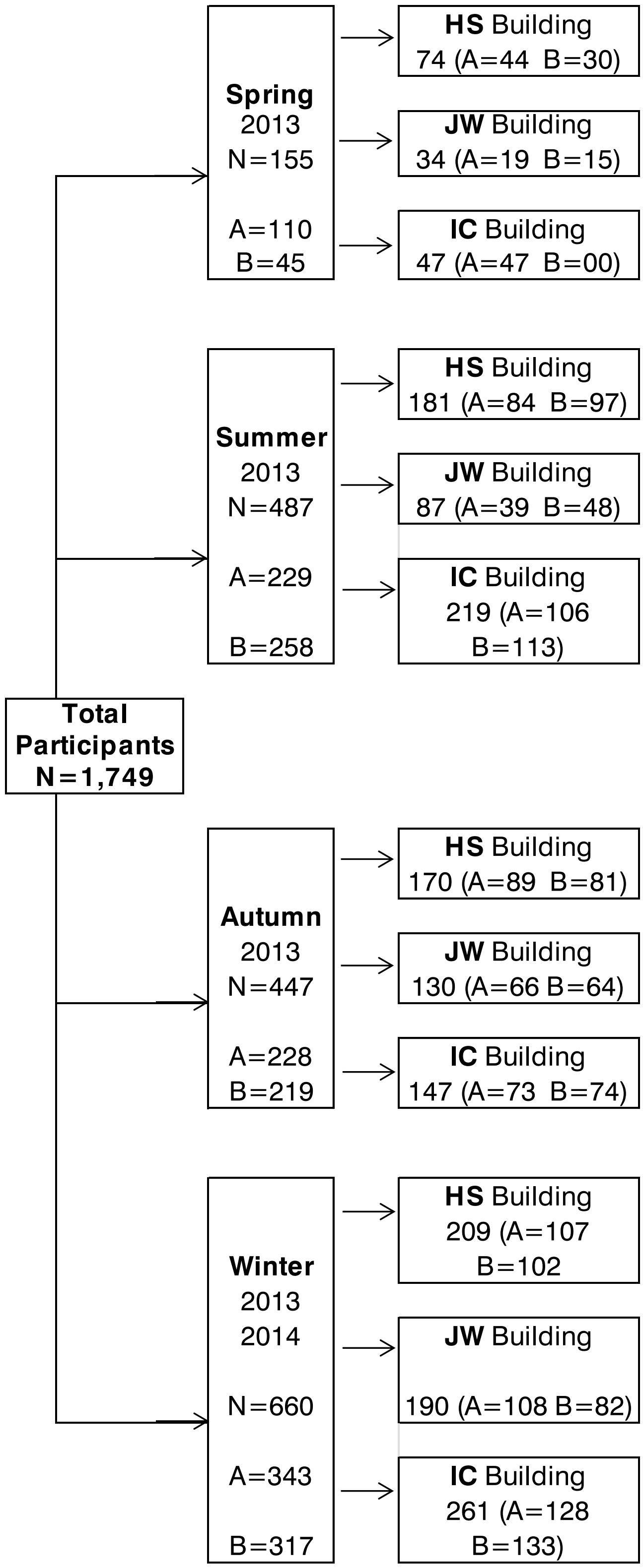


Figure 4-2 Summary of data collection showing the number of participants for each season, building and group

4.2. Results and validation of physical variables

4.2.1. Previous considerations

Before exploring the results, a number of considerations are described in order to define the context in which the fieldwork was carried out.

4.2.1.1. Scope of physical measurements

The surveys were conducted during the four seasons of the year. One limitation of this study is that March, April, September, December 2013 and January 2014 were not included because the required spaces in the buildings were not available during university holidays and exam periods. However, the months when the surveys were conducted were the representative hottest (summer) and coldest (winter) months based on information from the UK Met Office. The transitional months between cold and hot periods were May, October and November. Therefore, although not all the months were included, the selected periods substantially reflect climatic conditions over the year. Due to equipment limitations, the physical variables were recorded only during the hours that the surveys were carried out, having exterior daily readings from the UK Meteorological Office and from Sheffield University weather station located in the Geography Department as references.

4.2.1.2. Operative temperature (T_{op})

In this study, a 40mm globe thermometer was used to calculate the operative temperature of the four spaces. It is not possible to measure the operative temperature (T_{op}) directly since it is a theoretical index that combines the effect of the air temperature (T_a) and the mean radiant temperature (T_r) in a single value (CIBSE-GuideA, 2015; Nicol, Humphreys & Roaf, 2012). In practice, the globe temperature is very close to the temperature at the centre of a black painted 40mm globe thermometer (CIBSE-TM52, 2013; Humphreys & M.A., 1977). This because the globe thermometer reacts to the environment very similarly to the human body (Nicol *et al.*, 2012). In interior spaces with good insulation, and without direct solar radiation or other strong sources of radiation, air temperature, mean radiant temperature (T_r) and operative temperature are very similar (CIBSE-GuideA, 2015). The radiant temperature (T_r) was calculated using the globe temperature (T_g) , wind speed (v) and air temperature (T_a) using Equation 4-1 (Nicol *et al.*, 2012). The operative temperature (T_{op}) was calculated using the air temperature (T_a), wind speed (v) and radiant temperature (T_r) using Equation 4-2 (Nicol et al. 2012) and Equation 4-3 (CIBSE-GuideA, 2015). Equation 4-2 was used to calculate the operative temperature of the circulation space and the seminar rooms, since these spaces registered air velocities below $0.1m^{s-1}$. Equation 4-3 was used to calculate the operative temperature of the spaces where the wind speed was above $0.1m^{s-1}$.

$$T_r = T_g + 4.02 \sqrt{v}\, (T_g - T_a)$$

Equation 4-1 Calculation of the radiant temperature for a 40mm diameter globe thermometer (CIBSE-GuideA, 2015)

$T_{op}=1/2T_a+1/2T_r$

Equation 4-2: Calculation of the operative temperature when indoor air velocity is below 0.1m^{s-1} (CIBSE-GuideA, 2015)

$T_{op}= (T_a\sqrt{10v}+T_r) / (1 +\sqrt{10v})$

Equation 4-3: Calculation of the operative temperature when indoor air velocity is above 0.1m^{s-1} (CIBSE-GuideA, 2015)

In this study, the operative temperature and the air temperature were strongly correlated in all the spaces: exterior (r^2=0.7616, p=0.001<.05), draught lobby (r^2=0.7875, p=0.001<.05), circulation space (r^2=0.9925, p=0.001<.05) and seminar room (r^2=0.9290, p=0.001<.05), see Appendix 10. One limitation in the measurement of globe temperature variable is that it was not possible to calibrate the globe thermometers readings with the accurate values of a manufactured and calibrated globe thermometer. Also in some cases there was an equipment malfunction, resulting in empty information with the globe thermometer. Therefore, most of the results refer to the air temperature values and the operative temperature values are illustrated as a second reference.

4.2.1.3. Building operation

The three buildings operate with NV all year round with heated spaces in winter. During winter, the draught lobby of HS and JW are not heated, while the draught lobby of ICS is heated through the floor. The University's Estates and Facilities Management (EFM) control the heating system in the interior spaces; which is usually switched on in late October and switched off in late March. During winter, the air temperature in the interior spaces is kept around 22 °C. The operation at the buildings was not changed for the purposes of the survey, since the idea was to measure the spaces during their normal operation. Due to the climatic conditions of Sheffield, the building occupants and exterior climatic conditions shape the thermal connections and temperature in each space during summer naturally. In contrast, during winter, the resulting temperature connections between spaces are modified by the heated spaces. Therefore, in the cold season larger temperature differences are expected between the exterior and interior environment.

4.2.1.4. Participants' density

In this study, the surveys were conducted during available hours when the seminar rooms were not in teaching use, in order to allow the participants to move freely from one space to another and keep the room temperature relatively stable. Consequently, the interior temperature during this period was indeed mostly stable since only the participants used the spaces. During the manual inspections around the spaces during the surveys, it was detected that with large groups of participants in the seminar room (from around 12 upwards) the temperature increased by up to 1°C, although the measuring equipment was located 1.5 meters away from the participants. Also, high interior temperatures were measured after entering the seminar rooms, just after the lectures finished. This also brings to light the importance of considering people's heat generation and the density of space occupation during the thermal design of lobby units in these kinds of buildings.

This needs attention in future research, in particular in transitional spaces in which a large number of people move (train stations, airports, etc.). Transitional spaces in university buildings are also included, specifically during peak hours when students move in and out of lecture theatres and move to other buildings.

4.3. Exterior climatic conditions, comparison with a typical year

An understanding of the climatic conditions of the year of study in comparison to a typical year is necessary in order to assess if the collected data reflects representative thermal conditions. In some cases, other studies have reported extreme and unexpected events such as heat waves or very hot or cold years out of the average trend that illustrate a very particular case study. Based on data from the UK Meteorological Office, the typical exterior winter air temperature in Sheffield ranges from 1.7 °C to 2.3 °C, the coldest month is February; peak rainfall also occurs during winter. Spring is a mild season with an average air temperature around 10°C. In summer, July is the warmest month of the year, with an average temperature of 21.1°C. Air temperature gradually reduces from late August, reaching an average temperature of about 13 °C by October (Met-Office-UK, 2015). The air temperature from this study was compared against the average typical seasonal variations registered by the UK meteorological office in previous years.

The study surveys, conducted from May 2013 to February 2014, were compared with the 1981-2010 average climatic record from the UK Met Office in order to reference the temperature ranges that occurred during this study. Since the data logging equipment was used to record the climatic conditions only during surveys, the measurements of 2013-2014 were provided by the Sheffield University weather station located in the Geography Department. This weather station is a few hundred metres away from the case study buildings: 700 metres from HS building, 500 metres from ICS building and 400 metres from JW building). A comparison between Sheffield historic climate records (1981-2010) and average temperature during the survey period (2013-2014) shows surveys climatic conditions within the average minimum and maximum temperature ranges. On the whole, 2013-2014 follows the same 1981-2010 trend when comparing the survey information against Sheffield weather stations (Figure 4-3). The average wind speed registered during 2013-2014 was 7.5m/sec. with a minimum of 4.3m/sec and maximum of 12.74 m/sec (www.sheffieldweather.co.uk). The registered values from the data-logging equipment (1.70m above ground level) were less than 1m/sec for the whole time that participants were outside; however values up to 3m/sec were registered during the survey days.

In conclusion, the physical measurements of the year of study illustrate typical climatic conditions in Sheffield, UK. This also supports the climatic context of further analysis presented in this chapter involving spatial thermal connections and participants' thermal perception. Finally, this comparison not only helps to validate fieldwork measurements, but also provides valid data that can be used as a reference in future studies.

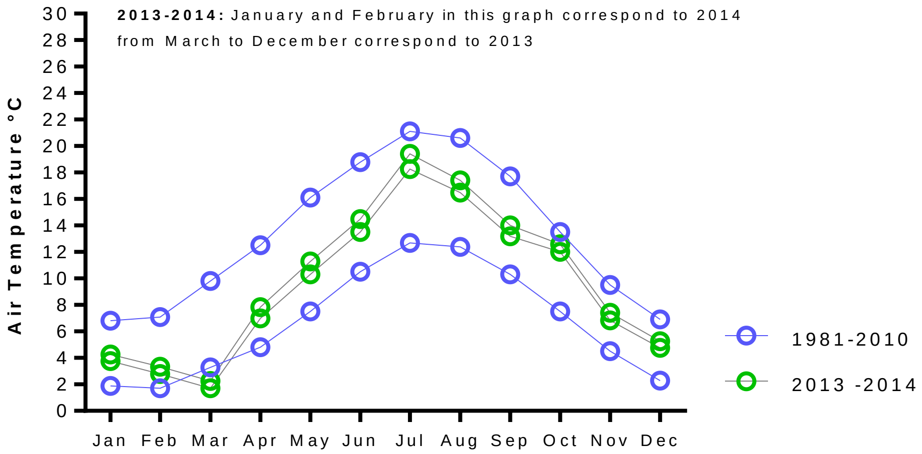


Figure 4-3 Monthly average maximum and minimum air temperature in Sheffield over 1981-2010, from data records from http://www.metoffice.gov.uk, and over 2013-2014, from The University of Sheffield Geography department weather station.

4.4. Seasonal exterior and interior climatic conditions

The seasonal exterior and interior climatic conditions are analysed, first in order to evaluate the indoor and outdoor climatic conditions during the fieldwork period and to identify any significant variations between seasons. This first assessment helps to frame preliminary expectations and develop a better understanding of the results presented in chapters 4 and 5 regarding participants' thermal perception.

4.4.1. Exterior climatic conditions

As would be expected, results illustrate that there was a clear seasonal air temperature variation at the exterior with some overlapping temperature ranges (Figure 4-4). Summer was the warmest season (23°C), followed by spring (19°C), autumn (14°C), and winter (9°C). Spring and summer show similar relative humidity measurements, likewise autumn and winter. Wind speed was extremely variable, changing quickly over just a few seconds, and records from the exterior data logging equipment reported small time periods with high air velocities up to 3m/sec. Mostly, low air velocities (around 1m/sec) were recorded at the exact moment that people were answering the questionnaires. Using the ANOVA statistical test, significant difference in climatic conditions between summer and winter were found ($p<.05$) and not significant difference between spring with summer and autumn with winter ($p>.05$). Although some differences were not statistically different, the physical values in each season were clearly different from each other. Finally, in order to verify the collected physical measurements in more detail, results were compared with outcomes from other studies conducted in Sheffield, UK.

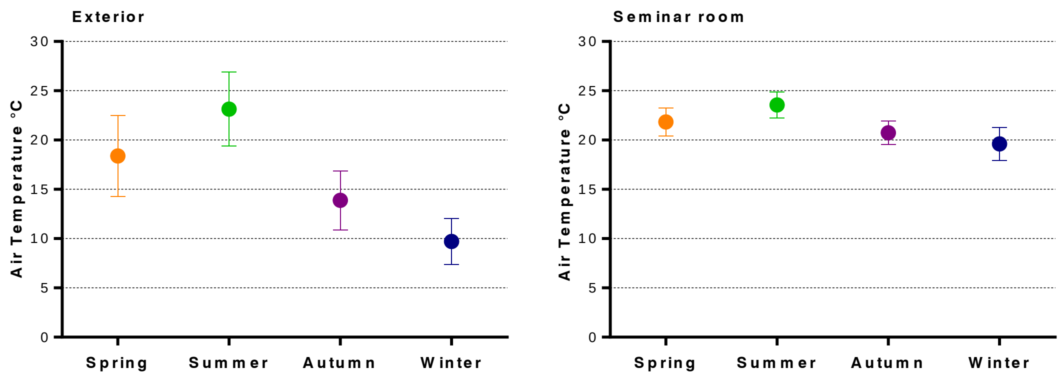


Figure 4-4 Difference between seasonal exterior and interior climatic conditions: a) seasonal exterior air temperature, b) seasonal air temperature in the seminar rooms. The graph illustrates the mean air temperature and standard deviation.

The average exterior climatic conditions during the fieldwork match with the findings of a previous field survey conducted by Nikolopoulou and Lykoudis (2005) in Sheffield in 2001-2002 as part of the Europe project RUROS (Rediscovering the Urban Realm and Open Spaces). The findings from the on-site measurements conducted in the RUROS project show very similar climatic conditions to this study (Table 4-1). The different values in the wind velocity could be because the current study involved only measurements over short periods of time, which do not accurately represent the seasonal average conditions as in the RUROS project. In short, the exterior climatic variations per season are similar to the patterns illustrated in previous studies conducted in Sheffield. Moreover, illustrates similar seasonal patterns to those from studies conducted in Manchester (Nicol, Wilson, Ueberjahn, Nanayakkara & Kessler, 2006) and Cambridge (Nikolopoulou & Lykoudis, 2005).

Table 4-1 Exterior climatic conditions during the surveys in 2013-2014 and results from the RUROS project conducted in Sheffield, UK in 2001-2002 (Nikolopoulou & Lykoudis, 2005).

	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
	Relative humidity	Mean= 50%	Mean= 51%	Mean= 70%	Mean= 61.7%
	Wind speed	Mean= 0.14m/s	Mean=0.10m/s	Mean=0.04 m/s	Mean=0.9m/s
Sheffield 2001-2002 RUROS	Air Temperature	Mean= 13.1°C	Mean= 21.3°C	Mean= 16.7°C	Mean= 9.5°C
	Air humidity	Mean= 60%	Mean= 69%	Mean= 63%	Mean= 49%
	Wind speed	Mean= 0.5m/s	Mean=1.0m/s	Mean=0.9 m/s	Mean=0.5m/s

4.4.2. Interior climatic conditions

As expected, rooms the mean air temperature in the seminar was higher in summer (23°C) than in spring (21°C), autumn (21°C) and winter (20°C) (Figure 4-4).The minimum air temperature in the seminar rooms (16°C) was registered during autumn and winter at morning times, whereas the maximum seminar room air temperature (25°C) was identified during summer. The mean relative humidity in the seminar rooms was slightly higher in summer and autumn (50%) than spring and winter (40%). The wind speed in the interior spaces was nearly uniform during the year under 0.1 m/sec (Table 4-2).

From these results, it can be seen that there were not as large variations in air temperature in the seminar room during winter as during summer. In addition, that some of the lowest temperatures in the seminar room were registered in autumn and early spring, presumably outside the time that the building operated with space heating. This is one of the reasons to highlight the importance of studying the thermal conditions of buildings for at least one year in order to detect key temperature changes during operation. During the surveys, it was noted that increasing the number of people inside the room increased the air temperature values.

Table 4-2 Interior climatic conditions in the seminar rooms during the surveys in the four seasons of the year

	Seminar rooms	Spring	Summer	Autumn	Winter
Sheffield	Air Temperature	Mean= 21.9°C	Mean= 23.5°C	Mean= 21.1°C	Mean= 20.0°C
2013-2014	Relative humidity	Mean= 41%	Mean= 49%	Mean= 50%	Mean= 40%
	Wind speed	Mean= 0.05m/s	Mean=0.05m/s	Mean=0.05 m/s	Mean=0.05m/s

4.5. Climate analysis by case study

The methodology chapter described the aim of selecting the three case study buildings with very similar 'lobby unit' layouts. The comparisons between results from the three case study buildings are to validate and determine the boundaries, in order to be able to generalize results. Moreover, this is done in order to confirm at which level findings from this study are not simply concidential for a specific case study building. Although it is expected that each building has its own specific thermal conditions, it is also expected to find similar thermal patterns in the thermal connections from one space to another (exterior-interior) and therefore in participants' thermal perception. Therefore, three levels of analyses were carried out in order to present, compare and validate physical variables between buildings:

1. A comparison of the exterior and interior (seminar room) air temperature between the three buildings.
2. An exterior-interior seasonal (air temperature) comparison between buildings
3. A comparison of the thermal variability at the four measurement points (exterior, entry doors space, circulation space and seminar room) between the three buildings.

4.5.1.1. Comparison of exterior and interior air temperature between the three buildings

A one-way ANOVA test was used in order to identify significant differences in exterior air temperatures between the case study buildings. It was found that the ICS and JW buildings had similar exterior air temperatures during the year ($p=.619>.05$). However, HS building had a significantly higher exterior air temperature than both ICS and JW ($p<.05$). When comparing interior temperatures during the year, it was found that JW Building had a slightly higher temperature in the seminar room than HS and ICS buildings. Also, it was found that the interior air temperature range (from 16°C to 25°C) in the three buildings was very similar and narrower than their exterior air temperature ranges (Table 4-3, Figure 4-5). It is important to note that the physical measurements in each building were conducted in the same period but with a few days of difference. Therefore, this test helps to evaluate how different the physical conditions were in each building. However, the analysis is not accurately comparing the three buildings under the same climatic conditions, because they were not measured at the same day and time. Consequently, the measured differences do not necessarily illustrate differences in local microclimates.

Table 4-3 Exterior and interior air temperature for each building during the survey

Exterior Air Temperature °C			**Seminar Room Air Temperature °C**		
HS N=324	ICS N=354	JW N=232	HS N=324	ICS N=354	JW N=232
min=8.0°C max=30.9°C	min=8.0°C max=29.0°C	min=6.0°C max=27.0°C	min=16°C max=25°C	min=16°C max=25°C	min=17°C max=25°C
mean=16.1°C SD=6.61	**mean=14.1°C** SD=5.67	**mean=14.6** SD=6.32	**mean=21°C** SD=1.77	**mean=21°C** SD=2.23	**mean=21.4°C** SD=2.39

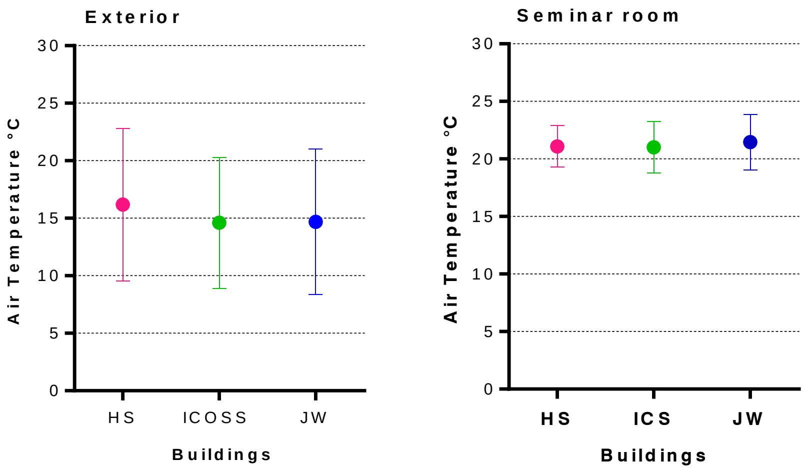


Figure 4-5 Climatic conditions during the surveys in each building: Exterior air temperature and interior air temperature. The points and lines in the graphs illustrate the mean air temperature and standard deviation.

Although the three buildings have similar layouts, they have different orientations, exterior contexts, façade designs and materials that give each of them particular thermal conditions. However, only a few differences were found between them, and in general the ranges of values of the physical variables were similar for the three buildings. Specifically, a higher temperature was expected at the exterior measuring point of the HS building, since it has a west orientation and more exposure to solar radiation during the survey hours. On the other hand, the reason why the ICS and the JW buildings had very similar exterior temperatures, at the exterior measuring point, could be because they are located in the same street 30 metres away from each other. Although they have different orientation (JW south and ICS north) the data logging equipment was protected from direct solar radiation (under shade) in both cases and this could help to cause similar observed exterior temperatures. In addition, the JW and ICS building designs (building shape and pedestrian area) allow more wind speed and shade at the exterior than the HS building, particularly in the area where the measurement equipment was located. Because of the north orientation of the ICS building, air temperatures at the exterior were always lower than at the other buildings.

In short, at this level of analysis, although a few significant differences were found between physical variables (as would be expected), the climatic configurations (exterior and interior temperature differences and temperature ranges) were very similar in all three cases. Therefore, it can be suggested that findings can be generalized only to a certain extent, assuming that local external temperatures vary between the three buildings, yet expecting similar temperature ranges and thermal connections (exterior-interior) for all of them. It is worth mentioning that the three buildings have similar lobby unit layouts and all are NV with heated spaces in winter. Therefore, results cannot be generalized to other climatic regions or more complex lobby unit design layouts. These need to be explored further in order to determine the threshold of the results presented in this thesis.

4.6. Exterior-Interior seasonal comparison between buildings

Seasonal comparison between buildings was conducted using one way ANOVA and post-hoc tests, It was found that the exterior and interior (seminar room) air temperatures in the three buildings were significantly different ($p<.05$) in each season of the year (Figure 4-6). This result was expected during the cold seasons, when the buildings were operating with heated spaces and the temperature differences (exterior–interior) were large. During the warm seasons, when the buildings were operating with NV, the significant temperature differences are explained by the distance between the exterior measurement point and seminar room measurement point (around 20 meters). Therefore, a close temperature correlation between the exterior and interior as reported in other studies cannot be expected. In addition, the windows in the seminar rooms were closed during the survey, and due to the brief time that participants were in the seminar rooms, they did not have an active interaction opening windows to connect with the exterior.

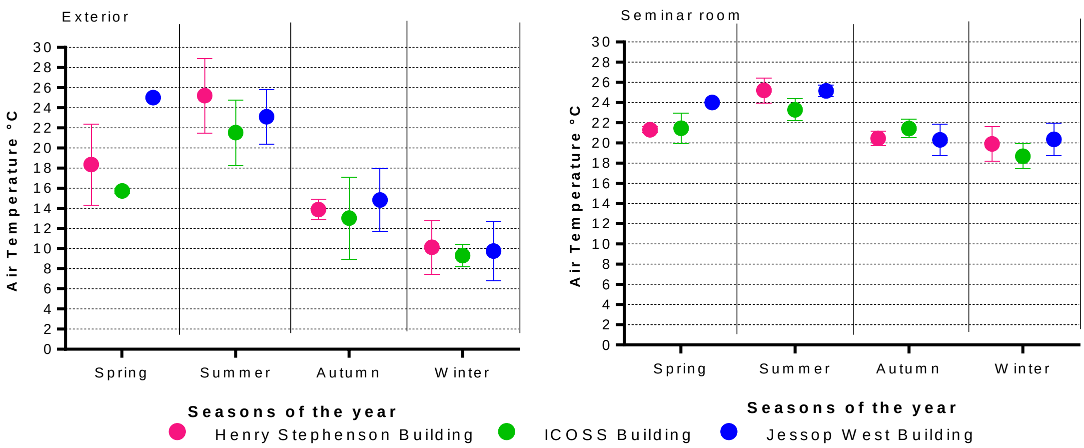


Figure 4-6 Seasonal comparisons between the three case study buildings, exterior and interior (seminar room) air temperature during surveys in each building. Points and lines in the graphs illustrate mean air temperature and standard deviation in the four seasons of the year.

At the exterior, significant differences in temperature ranges were found between buildings. For example, ICS building registered the lowest exterior temperatures in all the seasons. Using a one way ANOVA test, it was found that during summer, HS building registered significantly higher exterior temperatures than JW and ICS buildings ($p=.000<0.05$). During spring, the exterior temperature of JW building was significant higher than ICS and JW ($p=.000<.05$). In winter, the three buildings had closer mean exterior temperatures than in other seasons. In the interior spaces, significant temperature variations by season were found in the seminar rooms of the three buildings. Again, a number of significant thermal differences can be noted between buildings. However, it can be seen that the registered seasonal temperatures varied within similar temperature ranges in each season. Not consistent clear pattern of the hottest and coldest building exterior was identified when conducting a seasonal comparison between the exterior temperatures between buildings. However, ICS building had the coldest exterior environment of the three buildings throughout the year due its north orientation. At this level of analysis, results can be generalized within a temperature range by season due to some significant differences between buildings.

4.7. Thermal variability of the four measurement points

One of the main contributions in this analysis is a demonstration of the thermal variability of the interior spaces. It was found that the exterior environment strongly influenced the way that interior spaces are thermally connected. There were wider temperature variations at the exterior than in the interior spaces. In general, temperature ranges gradually narrowed from exterior to interior spaces (Figure 4-7).

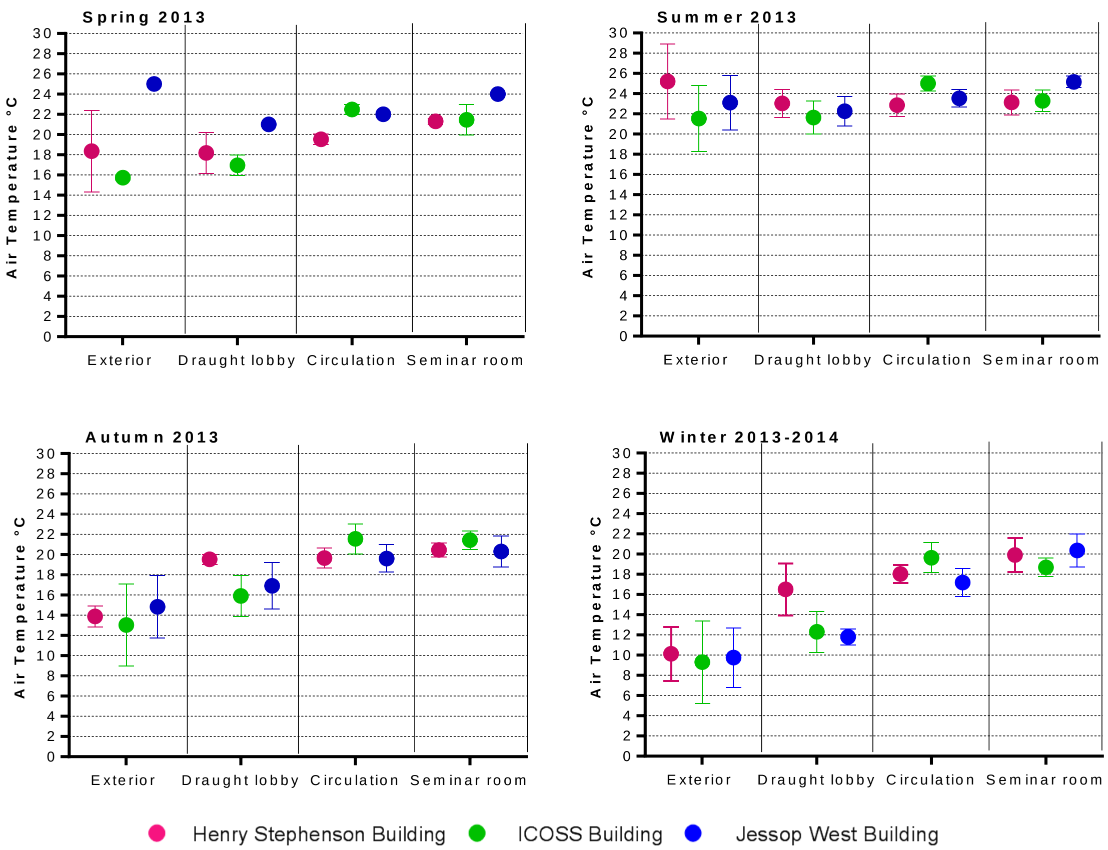


Figure 4-7 Air temperature during the surveys in each building space in the four seasons of the year, points and lines in the graphs illustrate the mean air temperature and standard deviation.

The air temperatures between the connected interior spaces of the buildings varied all four seasons. The air temperature of the entry door spaces, circulation spaces and seminar rooms were compared. It was found that the seasonal exterior climatic variations had a similar effect on the temperature changes from one space to another in the three case study buildings. Notable temperature changes from one space to another can be seen in autumn and winter due to larger temperature differences existing between the exterior and interior, due to the use of heated spaces. In contrast, temperature changes between spaces were less in spring and summer. During summer, temperature changes from one space to another (exterior to interior) were from warmer to cooler. In contrast, temperature changes were from cooler to warmer in autumn and winter, and were more irregular in springClear thermal patterns were identified in each season of the year, which are significant for practical applications, as discussed in section 6.2.

The average temperatures in the lobby units and seminar rooms in the three buildings were closer to the exterior thermal conditions in spring and summer than in autumn and winter. One explanation for this result is that the buildings operate with NV; consequently, no abrupt temperature differences among the spaces were registered as they were in autumn and winter when the spaces were heated. In this thesis, the air temperature differences between the exterior and seminar rooms were larger in autumn and winter, followed by spring and summer (Table 4-4). It can be seen that there are small temperature changes between the four spaces in summer and a closer thermal connection with the exterior environment. So, in moderate climates, the thermal connection between the spaces seems to need more attention during autumn and winter due to larger exterior-interior air temperature differences than in spring and summer. The largest temperature differences between spaces were registered between the exterior and draught lobby, and draught lobby and seminar room. It is very interesting to see wide range of thermal variability that occurs in only a few metres between the interior spaces comprising the lobby unit. Individual results for each case study building are illustrated in Table 4-5 for Sr. Henry Stephenson building, Table 4-6 for ICOSS building and Table 4-7 for Jessop West building.

Finally, when analysing the mean air temperature from the three buildings; correlations between the exterior and interior spaces the strongest correlation was found between the exterior and draught lobby space ($r^2=0.74$, $p=0.0001<.05$), followed by exterior and circulation space ($r^2=0.60$, $p=0.0001<.05$), and exterior and interior space ($r^2=0.54$, $p=0.0001<.05$). It can be noted that the correlation between the exterior temperature and interior temperature decreases for the interior spaces that are further from the exterior (Figure 4-8: a-b-c). 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 4-8: d-e). These results show how, in NV buildings, the exterior temperature shapes the way that the lobby unit spaces are thermally connected, highlighting the importance of exploring thermal patterns in the immediate exterior climatic conditions of buildings. In both correlations (exterior to interior spaces, and between connected spaces), it was confirmed that the lobby unit plays an important role in connecting the exterior with the interior environment. It can be suggested that the draught lobby in AC buildings should have an air temperature closer to the exterior air temperature than the interior air temperature, in order to reduce the effect of sudden temperature changes in winter.

Table 4-4 Temperature difference (ΔT) between spaces in the four seasons of the year. Average temperatures resulting from the three buildings

Season	Air Temp. °C	Exterior (EXT)	Draught Lobby (DL)	Circulation Space (CS)	Seminar Room (SR)	(ΔT) EXT-DL	(ΔT) DL-CS	(ΔT) CS-SR	(ΔT) EXT-SR
Spring	**mean**	19.1	18.4	20.9	21.9	-0.7	+2.5	+1.0	**+2.8**
2013	min	14.0	16.0	19.0	20.0	+2.0	+3.0	+1.0	+6.0
	max	25.0	18.4	23.0	24.0	-6.6	+4.6	+1.0	-1.0
	SD	4.3	2.0	1.4	1.3				
Summer	**mean**	23.1	22.2	23.8	23.5	-0.9	+1.6	-0.3	**+0.4**
2013	min	17.0	19.0	21.0	21.0	+2.0	+2.0	0.0	+4.0
	max	30.0	26.0	26.0	26.0	-4.0	+1.0	-1.0	-4.0
	SD	3.5	1.5	1.3	1.3.0				
Autumn	**mean**	14.2	17.6	20.2	21.1	+3.4	+2.6	+0.9	**+6.9**
2013	min	8.0	12.0	18.0	18.0	+4.0	+6.0	0.0	+10.0
	max	20.0	20.0	23.0	24.0	0.0	+3.0	+1.0	+4.0
	SD	2.9	2.2	1.5	1.2				
Winter	**mean**	9.5	13.4	18.4	20.0	+3.9	+5.0	+1.6	**+10.5**
2014	min	6.0	10.6	16.0	16.0	+4.6	+5.4	0.0	+10.0
	max	17.0	21.0	21.0	25.0	+4.0	0.0	+4	+8.0
	SD	1.8	2.6	1.4	1.6				

Table 4-5 Sr. Henry Stephenson Building: average temperature difference (ΔT) between spaces in the four seasons of the year.

Season	Air Temp. °C	Exterior (EXT)	Draught Lobby (DL)	Circulation Space (CS)	Seminar Room (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				
Summer	**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				

Table 4-6 ICOSS building: average temperature difference (ΔT) between spaces in the four seasons of the year.

Season	Air Temp. °C	Exterior (EXT)	Draught Lobby (DL)	Circulation Space (CS)	Seminar Room (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				
Summer	**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				

Table 4-7 Jessop West building: average temperature difference (ΔT) between spaces in the four seasons of the year.

Season	Air Temp. °C	Exterior (EXT)	Draught Lobby (DL)	Circulation Space (CS)	Seminar Room (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				
Summer	**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				

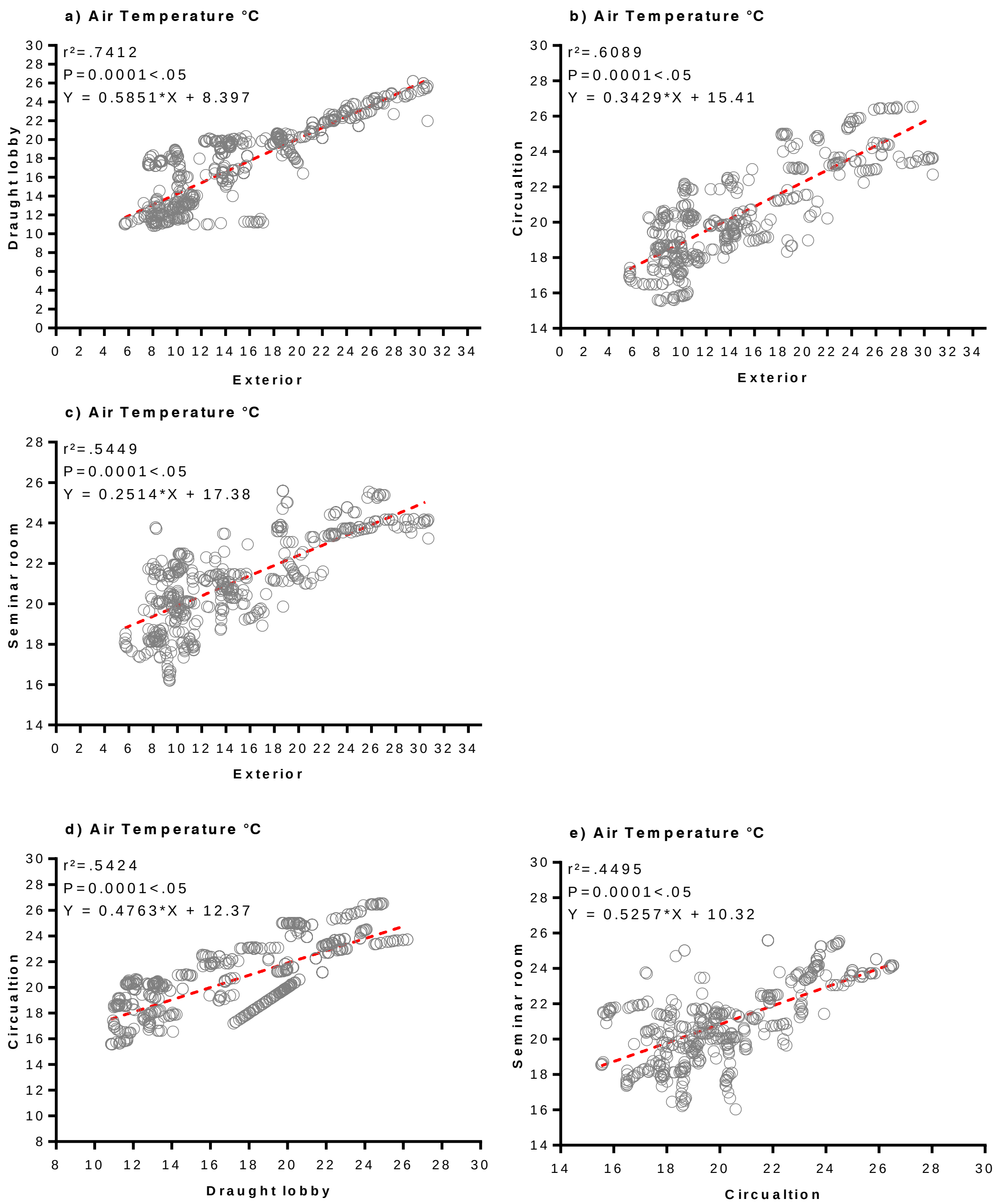


Figure 4-8 Air temperature correlations between spaces: a) exterior and draught lobby, b) exterior and circulation space, c) exterior and seminar room, d) draught lobby and circulation space and e) circulation space and seminar room.

Previous measurements conducted in spaces around atria, also within a university building located in Sheffield (Pitts, 2010), showed a similar pattern; larger temperature differences (ΔT) from exterior to the entrance (ΔT=10°C) in winter and smaller temperature differences towards the interior areas of the building (ΔT=5°C) in summer. The temperature range is slightly different between this study and Pitts' study, due to the design features and context of each case study. However, this comparison with Pitts' work (2010) adds validity to the findings presented in this thesis and strengthens understanding in this topic. However, it is important to consider that the thermal connection between spaces can vary depending on the climatic region of study and the building operation (NV, AC or MM). For example, in another study conducted in the hot climate of Bangkok (Jitkhajornwanich & Pitts, 2002), the exterior air temperatures in winter and summer (from 25.0 to 30.9°C) are warmer than the winter climate in Sheffield, UK. Also, the use of AC in hot regions generates larger thermal differences between the exterior and interior environments over the year. Another example is the work conducted by Kwong & Adam (2011) in Malaysia, who registered air temperatures in the lobby unit during summer and autumn from 23 to 32 °C and 72.6%RH, and maximum exterior air temperatures from 30 to 36°C, which are out of the range found in Sheffield, UK. In climatic regions like this, relative humidity (around 70%) plays a more important role in transitional spaces than it does in moderate climates. In short, it can be seen how the lobby unit is a key connector of the exterior thermal conditions to the interior spaces in different climatic regions. Results, in terms of thermal variability in lobby units, can vary depending on the climatic region, building design, building operation and the interaction of the spaces with the exterior environment.

4.7.1. Comparison with international standards

The average air temperature in the seminar rooms (20°C in winter, 23°C in summer) from the three buildings is within the recommended ranges specified by different international standards (Table 4-8). For educational buildings, the CIBSE Guide-A (2015) recommends for AC buildings an operative temperature from 19 to 21 °C in winter, in corridors, lecture halls and seminar rooms. In summer, the recommended operative temperature is from 21 to 25 °C in the same spaces. For NV buildings, CIBSE Guide A 2006 shows a 25°C operative temperature as acceptable. Also, the international standard BS EN 15251:2007 recommends indoor operative temperature values from 20 to 26°C for AC conference rooms or auditoriums, assuming 50% RH, and an operative temperature of 25°C for summer is recommended for NV buildings. ASHRAE 55-2004 recommends a supply temperature of 20.3-24°C in winter for AC buildings in education facilities and 23-26°C in summer for conference rooms. For auditoriums, assuming 40-50% RH, the values are 20-23.9°C in winter and 23.1-26 °C in summer, and for corridors, 20°C is recommended.

There is a lack of information on transitional spaces in international building policies. International standards do not take into account design temperatures for the existing wide range of transitional spaces. In addition, the limited recommended temperature ranges for corridors and halls are the same as for interior spaces. Finally, they only consider two seasons of the year, summer and winter.

Firstly, international standards need to acknowledge the lobby unit and other transitional spaces as important thermal connectors, which need to be independent and dynamic, considering that their main function is to balance temperature differences from one space to another. Results from this chapter illustrate the range of thermal variability existing in the lobby unit, requiring different considerations for different climatic regions and building operation modes (AC and NV buildings). Moreover, results from this thesis revealed the importance of considering different thermal parameters for spring and autumn, since the thermal conditions in the lobby unit are variable are strongly connected with the exterior environment. Results from this chapter cannot be compared with the values published in international standards, since this chapter illustrates clear differences in thermal patterns in transitional spaces that located between the exterior and interior environments. This is discussed further in section 6.4.

Table 4-8 Comparison of lobby unit air temperatures in relation to international standards

Season	Air Temp. °C	Draught Lobby (DL)	Circulation Space (CS)	Seminar Room (SR)	ASHRAE 55 (2011)	CIBSE Guide A (2015)	BS-EN 15251 (2007)	NV Buildings
Spring 2013	**mean**	18.4	20.9	**21.9**	---	----	---	---
	min	16.0	19.0	20.0				
	max	18.4	23.0	24.0				
Summer 2013	**mean**	22.2	23.8	**23.5**	23-26	21-25	23-26	25-26
	min	19.0	21.0	21.0				
	max	26.0	26.0	26.0				
Autumn 2013	**mean**	17.6	20.2	**21.1**	---	----	---	---
	min	12.0	18.0	18.0				
	max	20.0	23.0	24.0				
Winter 2014	**mean**	13.4	18.4	**20.0**	20.3-24	19-21	20-24	---
	min	10.6	16.0	16.0				
	max	21.0	21.0	25.0				

4.8. Participants' thermal comfort perception in the lobby unit

4.9. Participants' demographics

A total of 1,749 participants from 84 different counties took part in the fieldwork of this thesis. The sample population in this study reflects the international student environment typically found in an HEI in the UK based on HESA's annual report 2013-2014 discussed (see section 3.2.2). In this thesis, the majority of the participants were undergraduate students from 18 to 24 years old (81%), the rest were postgraduate students (14%), and staff members and visitors (5%). 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 (Table 4-9).

Table 4-9 Participants' demographics

	Gender	Weight (Kilograms)	Height (metres)
Participants N= 1,749	Male= 1,062 Female=687	Minimum=42 Maximum=118 Mean=67 SD=13.29	Minimum=1.42 Maximum=2.20 Mean=1.71 SD=0.10
	Age (years)	**Age group**	**Nationality group**
	Minimum=18 Maximum=72 Mean=22 SD=4.3	18-24 =81% 25-30=15% 31-35=3% Over 35=1%	UK= 45% International=55% (from 83 different countries)

Since one of the objectives in this study is to understand people's thermal perception in dynamic state, it was also important to take into account the previous activities and thermal context of the participants. 90% of the survey population claimed to be performing sedentary activities during the 30 minute period before walking to the case study buildings. 85% of the population spent from 1 up to 15 minutes 'walking relaxed', 0.9 $m.s^{-1}$=2.0 met (CIBSE-GuideA, 2015), from a previous interior space to the exterior of the case study buildings were the study was conducted. In this study, 84% of the population claimed to be exposed to AC environments during autumn and winter, and 50% claimed to be exposed to AC environments during summer. Due to the international population, AC exposures referred in some cases to their home countries before arriving in Sheffield and in some cases to student accommodation and university buildings in Sheffield. Finally, 56% of the survey population claimed to be living in Sheffield from 1 day up to 1 year before the survey.

Participants' clothing and behaviour were not controlled; this was because the aim of the fieldwork was to mirror participants' behaviour in their everyday lives. Therefore, no instructions were given in relation to the way that subjects used or adjusted their clothes during the survey, and in each season, participants were free to wear the outfits they typically use in that season. The clothing value was registered individually as what people were wearing during the survey. Participants wore the same clothes that they were wearing outside for the whole duration of the survey (Figure 4-9). No behavioural adaptation that involved clothing was observed during any survey. This was presumably for three reasons. First, because the participants knew that the survey would only take a short period of time. Second, because the short time participants were inside the seminar room was not enough to modify their thermal perception in a way to trigger an adaptive action, and finally because the temperature change was not large enough to reach participants' limit of comfort to trigger an adaptive action.

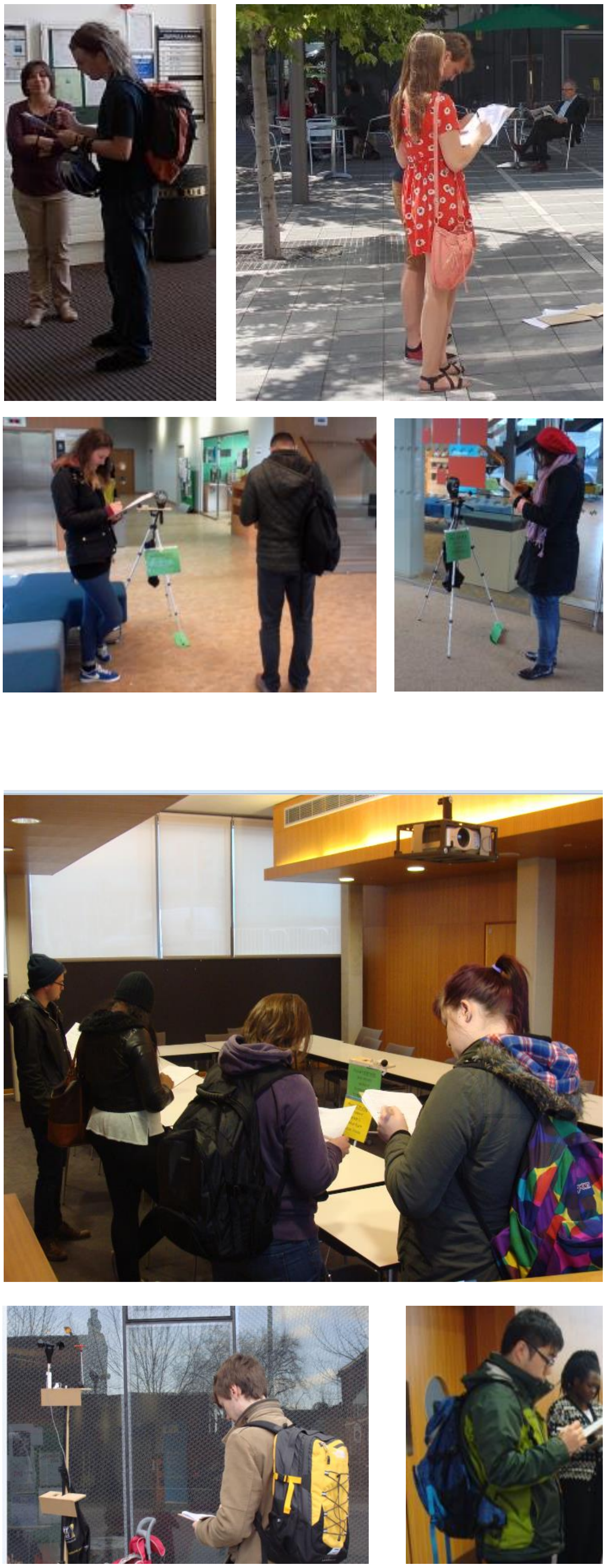


Figure 4-9 Top four images: differences in participants' clothing during the surveys in the four seasons of the year, Bottom image: additional elements that people carried during the survey.

It was identified that 84% of the population were carrying a backpack during the survey, and in many cases additional bags. This is an issue that has not been addressed in this field of study and it would be valid to study in future whether these additional items add stress or discomfort to participants' thermal perception. Due to the nature of the fieldwork and incidental external factors, the number of participants per group was slightly different in many cases for a number of reasons: first, because the physical variables were controlled only in the seminar rooms and second because of some restrictions related to the building facility management, the academic calendar and weather. This is not a limitation, since other large fieldwork studies have also varied the sample size. However, the number of males and females per group was controlled to a certain extent. Although there was a larger number of male participants than females participants throughout the study, each groups had the same proportion of males and females per group in the majority of the cases. Previous studies have controlled the number of participants; however, they have been conducted in climatic chamber and the sample size is usually small. However, it is worth mentioning the organization of the sample population as a recommendation for future research work.

4.10. Evidence of people's thermal adaptation

Participants' thermal perception of the exterior and interior spaces was different in the four seasons of the year. Results demonstrate that people adapted to the seasonal exterior climatic variations. This adaptation process can be seen when comparing findings from different seasons. In addition it was found that the exterior environment influences participants' thermal perception in the indoor environment in different ways in each season of the year. The first important finding is the effect of time and the different seasonal climatic conditions on participants' thermal adaptation. In this study, there were three indicators of participants' thermal adaptation: first, the different clothing people were wearing across the four seasons. Second, the "adjustment" of their thermal sensation votess when using the 7 point ASHRAE scale to label their responses. A final factor, strongly linked with the second one, is the flexibility of participants' thermal perception in relation with a given temperature value.

4.10.1. Participants' clothing adjustments across the four seasons

At the exterior of the buildings, findings revealed clear evidence of participants' 'reactive thermal adaptation' to the seasonal temperature changes. This evidence was more noticeable at the exterior than in the interior spaces. Since thermal comfort perception is a dynamic state, it was not surprising that participants' thermal perception changed over the four seasons of the year. In this thesis, results match with previous findings, highlighting clothing as the main reactive means of participants' adaptation at the exterior between the seasons of the year (Nicol *et al.*, 2006; Nikolopoulou & Lykoudis, 2005). The findings in this thesis show a strong correlation between participants' thermal sensation vote and both the exterior air temperature ($r^2=0.885$ $p<0.05$) and globe temperature ($r^2=0.797, p<0.05$). Participants' clothing values were significantly different in the four seasons of the year ($p<.05$). A large seasonal difference in participants' clothing can be seen when comparing spring and summer with autumn and winter (Figure 4-10). Although, the survey involved volunteers from 84 different nationalities, their clothing behaviour were very similar in terms of number of layers and type of footwear. A difference in clothing style was, however, observed which reflected the culture and other personal preferences of each participant.

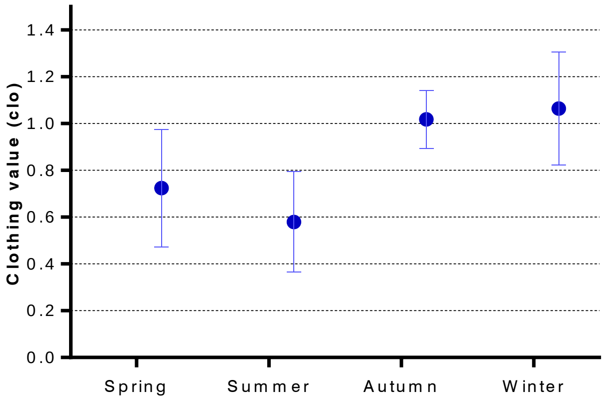


Figure 4-10 Participants' clothing value in the four seasons of the year, pints and lines in the graphs indicate the mean values and standard deviation

It can be seen that, in transitional spaces, people are less involved with interacting with physical building elements (e.g. windows or doors) to adapt themselves. When people are in movement, clothing seems to be the main option of personal adaptation; however participants' decision to perform a change could depend on the time of exposure or perception of uncomfortable temperatures that surpass their limits of thermal tolerance. This raises some questions about whether building elements such as windows or shadings could be used by people on their way through transitional spaces as adaptive opportunities through the building design. Moreover, whether exterior elements attached to the building or exterior landscape features could contribute to enhance people's thermal perception in the lobby unit. This issue is discussed further in section 6.2.

Finally, it is worth mentioning considerations from a number of additional observations conducted during this study, which were outside the hours of the surveys. It was observed that the majority of students arrived at the buildings around ten minutes before the lecture started, in many cases when the seminar room was still in use by other students. It was noted that students waited until they were inside to perform adaptation with their clothing and modifications with the additional items that they carried with them. This could also be related with the short time they were waiting in the lobby before their lecture. In contrast, it was detected that the minority of students who arrived from 10 to 15 minutes before the lecture had enough time to perform some changes, and took off their backpack and some layers of clothing. Finally, it was observed that a number of students arriving less than 5 minutes before the lecture were in a rush, suggesting a total disconnection with the interior environment. This also brings other factors to take into account for understanding thermal comfort behaviour in this type of space. Given the mental state of people when they are in movement, perhaps in some cases their thoughts disconnect them from the environment that they are walking through.

4.11. Variations in the use of the 7 point ASHRAE scale in each season of the year

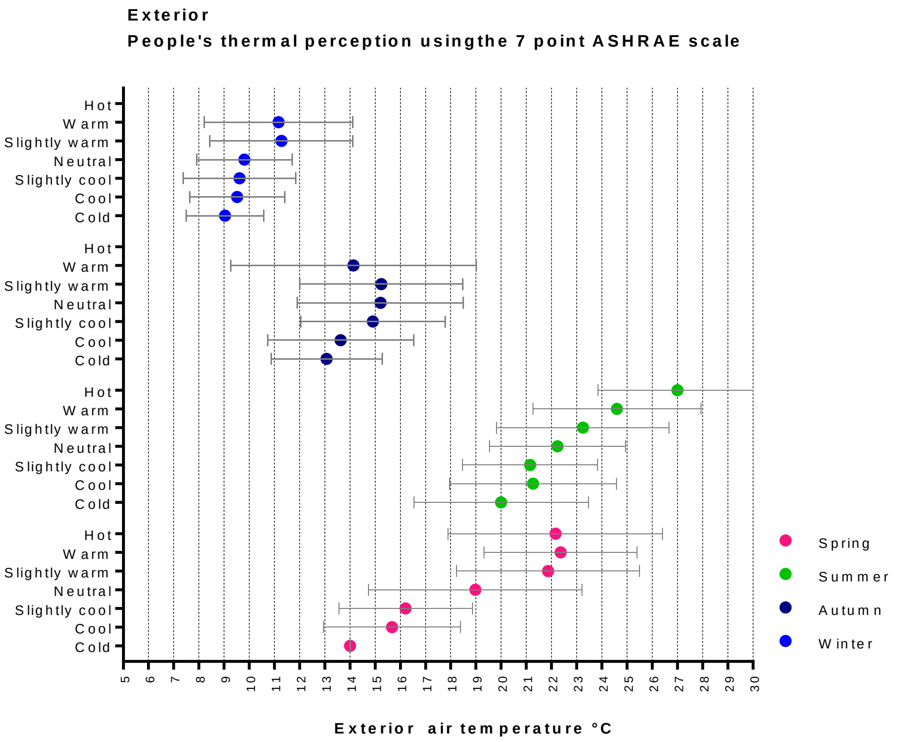
4.11.1.1. Air Temperature

An interesting process of thermal adaptation was found when analysing participants' current thermal sensation vote (TSV) at the exterior. The values of TSV at the outside and inside show the different temperature ranges in which people preferred 'no change'. The seasonal variation in the climatic modified the subjects' TSV and thermal preferences. When analysing the way they used the 7 point ASHRAE scale while tagging their responses, it was found that participants' changed the use of the same ASHRAE scale value to label their thermal perceptions between season (Figure 4-11). They labelled a 'cold' sensation to very different temperatures depending on the season of the year. For example, some people used the 'cold' label for 9°C in winter, 13°C in autumn, 14°C in spring and 20°C in summer. The same difference can be seen in the way that people labelled a 'warm' exterior air temperature in summer (from 22 to 28°C) and winter (from 8 to 14°C). Likewise, although the interior space had narrower seasonal temperature variations, a difference in participants' responses in relation with the associated temperature can be noted. A clear difference can be seen between summer and winter: the 7 point ASHRAE scale was used to tag temperatures around 20°C as 'hot' in winter and temperatures around 24°C as 'hot' in summer.

It is very interesting to note the range of air temperature differences that people refer to when tagging their thermal comfort perception. This range is larger at the exterior than in the seminar rooms (Table 4-10). In addition, the way that participants tag their answers is different between the exterior and the interior in the same season. For example, in winter participants tagged 'slightly cool' to 9°C at the exterior and a few minutes later used the same tag for 19.5°C in the seminar room. This shows how variable participants' thermal perception can be when evaluating their thermal responses in the short-term. This is a significant factor to take into account in building design and policy, discussed further in section 6.3.

Table 4-10 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	*



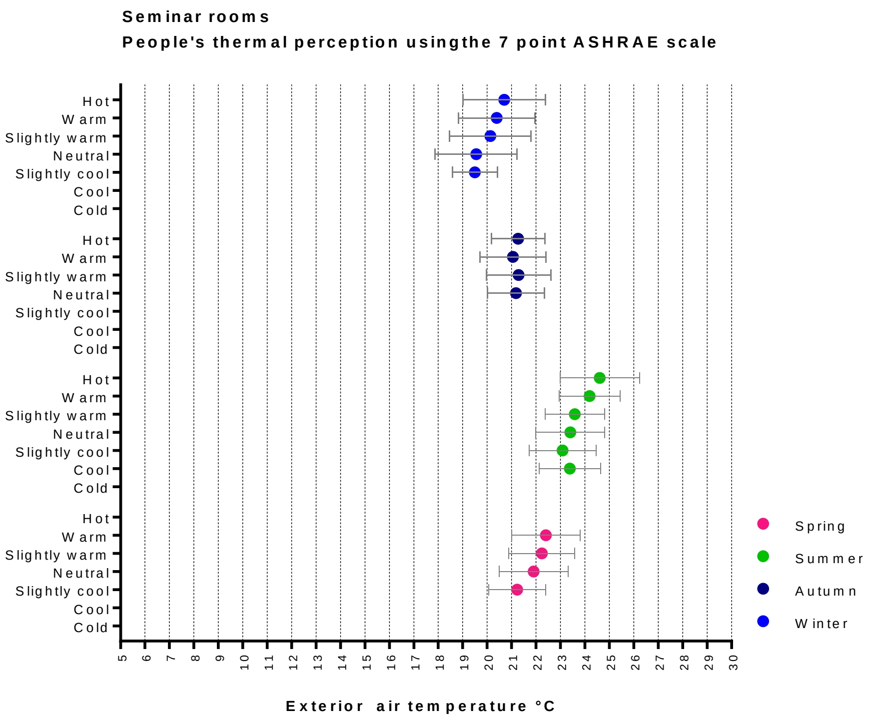


Figure 4-11 Participants' thermal comfort perception in the exterior space and seminar room in relation to temperature ranges per season.

4.11.1.2. Relative humidity and wind speed

A similar adaptation was observed in participants' perception of relative humidity and wind speed as presented in the previous section. Although seasonal variations were recorded in both variables, participants' perception of both variables was always within the comfortable band. Even at the exterior there were differences in perception which were larger than in the interior spaces. Relative humidity perception was tagged 'just right' for exterior and interior environments in the four seasons. Wind speed perception was slightly different from the exterior to the interior, at the exterior it was perceived just right and slightly breezy. It was observed that it was not easy for people to provide their current perception of humidity, probably because humidity was always within a comfortable range, around 50%. Similarly, it was observed that when people had to provide their vote for wind speed perception they had to wait and focus on how they perceived the air. This behaviour was more frequent in low air velocities (less than 1 m/sec).

Since previous studies have demonstrated that people feel comfortable with different levels of relative humidity and wind speed depending on the climatic region (Indraganti, Ooka, Rijal & Brager, 2014; Modeste, Tchinda & Ricciardi, 2014), it was assumed that these variables did not significantly impact on participants' thermal perception and preferences in the different sequences. Previous studies (Tsutsumi, Tanabe, Harigaya, Iguchi & Nakamura, 2007) found differences in participants' thermal perception when moving from 70%HR to 30,40 and 50% RH, but not when moving from 30% to 50% and 40% to 50% RH. In this thesis, although relative humidity was within a range from 30 to 70%, and there were differences in final relative humidity per sequence, participants' humidity perception was always within the comfortable band. In hot humid climates, relative humidity from 55% to 70% has a significant impact on peoples thermal perception (Nagano, Takaki, Hirakawa & Tochihara, 2005). In summary, it seems that people were not aware that their answers reflected an "adapted thermal sensation vote" corresponding to the climatic conditions of each season. In addition, the majority of participants were comfortable with the exterior environment (air temperature, relative humidity and wind speed) throughout the year. This also confirms participants' thermal adaptation, expectations and acceptability reported in previous work (Nicol *et al.*, 2006; Nikolopoulou & Lykoudis, 2005). An important implication from these findings is that a given value in air temperature alone cannot be associated with the way that people perceive an environment.

Consequently, findings need to be interpreted very carefully taking this phenomenon into account and exploring at least one year of thermal history in order to give an appropriate meaning to the findings. In this way, seasonal adjustments in the way that people reflect their 'thermally adapted' answers, using the 7 point ASHRAE scale or any other method, can be detected. A one-year study can better provide a more solid context of study that can better validate the findings and evaluate participants' thermal history under the four seasons, including the transitional months. Finally, it is interesting to see participants' responses in the seasons that connecting the coldest and hottest periods (spring and autumn connecting summer and winter), and note the importance of evaluating at least a one year period in order to understand participants' thermal adaptation in the outdoor environment.

4.12. The interpretation of numerical values in physical measurements

Not much previous work has reported the thermal variations of interior spaces in detail, which is a gap that this study aims to fill. Exploring further the 'adapted thermal sensation vote', it was also found that a given air temperature value can be perceived differently by participants in different spaces and seasons of the year. In this study, participants' perception in relation with wind speed and humidity was within the comfortable band in both the interior and exterior environments across the four seasons of the year. Taking this into account, a further analysis was conducted with the most repeated air temperature values in the experiment (20°C, 22°C and 24°C). When organizing the distribution of participants' thermal sensation vote for each air temperature value, it was found that their thermal comfort perception was different for each20°C, 22°C and 24°C depending on which of the four spaces the participants were in (Figure 4-12).

For example, it can be seen that 20°C can be perceived 'slightly cool', 'neutral' or 'slightly warm', depending on which transitional space people were in. Likewise, 22°C and 24°C were perceived differently. Therefore, it is necessary to give an appropriate meaning to participants' thermal perception by studying the influence of other physical and psychological thermal experiences along with their short and long-term thermal history.

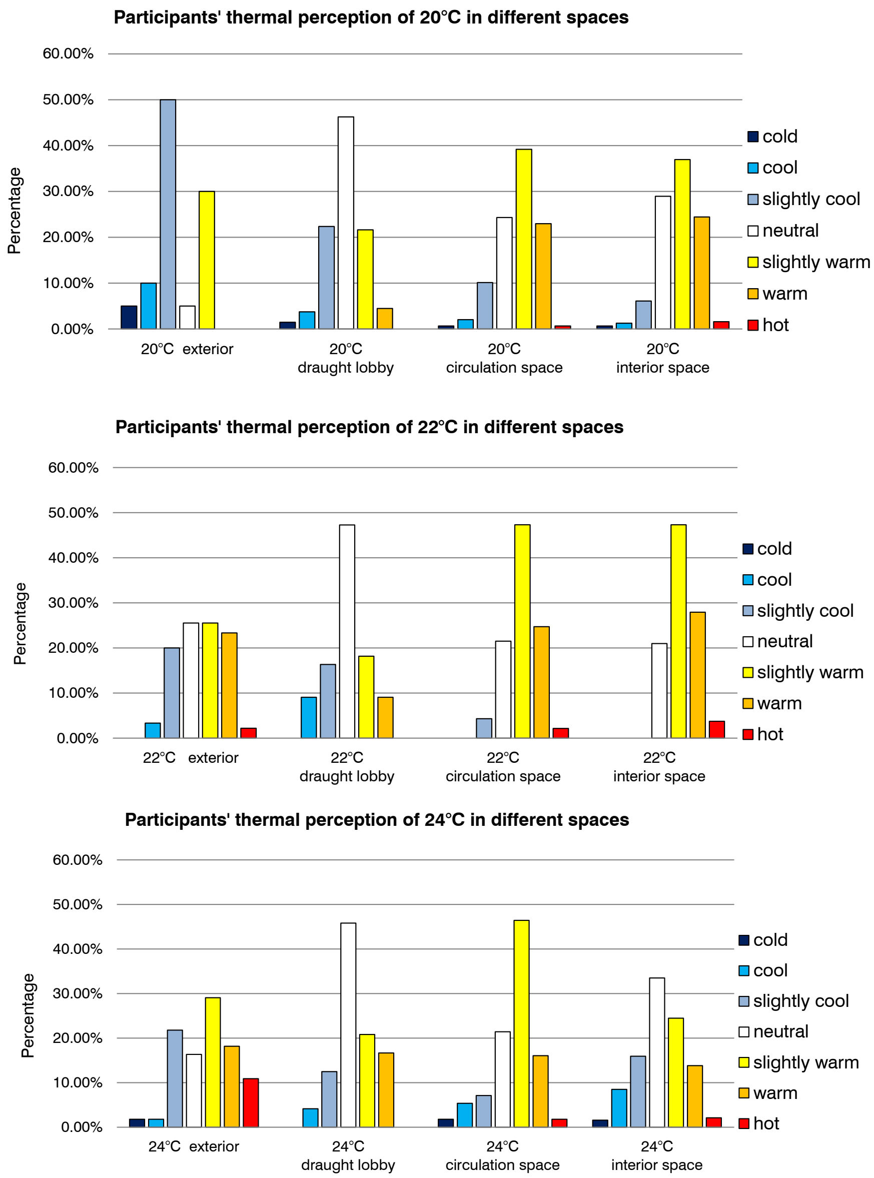


Figure 4-12 Participants' thermal perception at a given temperature value, in different spaces when the wind speed and humidity were tagged comfortable

4.13. Participants' thermal perception of the exterior environment

As would be expected, participants' thermal comfort perception of the exterior air temperature was variable across all the seasons of the year (Figure 4-13). People gave their thermal sensation votes within the comfortable band: 'slightly cool, 'neutral' and slightly warm'. Surprisingly, despite the seasonal differences in climatic conditions, at the exterior the majority of people (50-67%) were comfortable with the climatic conditions in every season (air temperature, relative humidity and wind speed). Except in winter, where only 43% of people were comfortable.

Spring (mean air temperature =19°C), was perceived by people as a neutral environment and participants' responses were more equally distributed between comfortable and uncomfortable answers. Almost half of the study population (54%) felt 'comfortable' (slightly cold, neutral and slightly warm) and almost equal percentages of the remaining 46% felt either 'uncomfortable cold' (cool and cold) or 'uncomfortable warm' (warm and hot). Summer was the warmest season during the year (mean air temperature=23°C) and participants' mean exterior thermal comfort was between 'slightly warm' and 'neutral'. In this season, people felt comfortable in the exterior environment (68%), and only a minority of the population felt uncomfortably cold or warm. Autumn and winter were the coldest seasons of the year (mean air temperature= 14°C and 9°C respectively). A notable difference in participants' thermal perception can be seen in these seasons, where up to 84% of the population answered within the cold band ('cool',' slightly cold' and 'cold'). However, in autumn more people felt comfortable (50%) than in winter (43%). A one-way between groups analysis of variance (ANOVA) was conducted to explore differences in participants' thermal perception in each season of the year. There was a statistically significant difference in participants' thermal comfort perception in the exterior environment in each of the four seasons of the year ($p<.05$). Post-hoc comparisons indicated that the mean scores were significantly different between seasons, except autumn and winter.

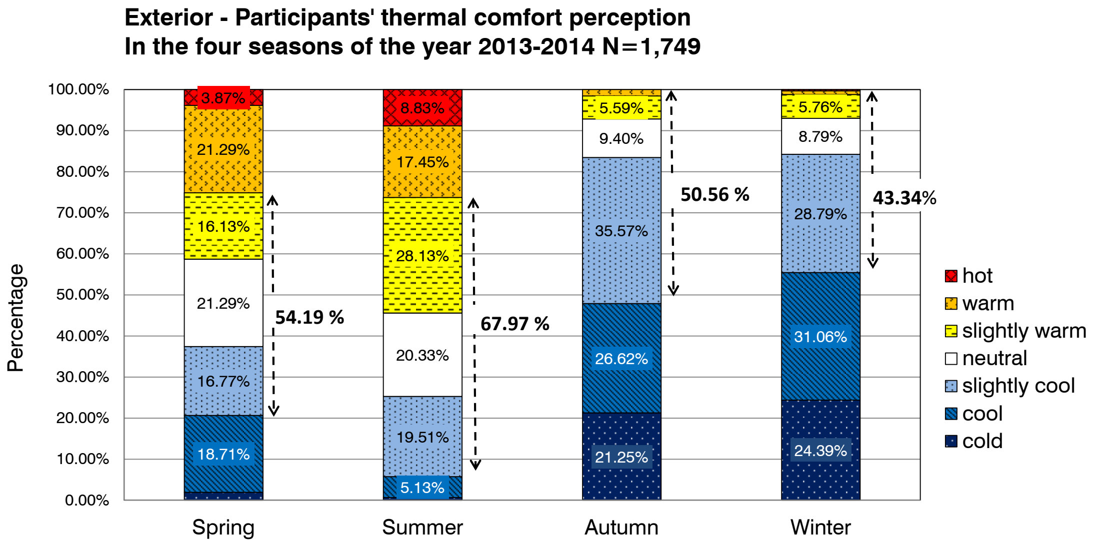


Figure 4-13 Participants' seasonal thermal perception at the exterior

4.14. Temperature ranges per season of the year and participants' perception

Participants experienced different exterior air temperature ranges per season. The air temperature ranges in which people preferred 'no change' were lower in autumn (from 8 to 20°C, ΔT=12°C wide) and winter (from 6 to 17°C,ΔT=11°C wide) than in spring (from 14 to 25°C,ΔT=11°C wide), summer (from 17 to 30°C, ΔT=13°C wide). In each season, the width of the "no change" thermal band is around 12°C between different maximum and minimum points. The mean 'no change' exterior temperature was 19.8°C in spring, 22.6°C in summer, 15°C in autumn and 9.8 °C in winter. These results showed similar temperature ranges to the findings illustrated in previous studies conducted in Manchester, UK (Nicol *et al.*, 2006), in which people were uncomfortably cold in temperatures lower than 10°C and uncomfortably warm in temperatures above 20-25°C. Overall, the majority of people in this thesis were comfortable with the exterior environment, in cold and warm seasons. These findings also support previous studies conducted in Sheffield, UK (Nikolopoulou & Lykoudis, 2005) in which it was demonstrated that around 80% of the people were comfortable with the climatic conditions of each season, all of which were very similar to the seasons that occurred in this study. A detailed breakdown of temperature ranges per season is illustrated in Table 4-11.

Table 4-11 Air temperature ranges from the three buildings and participants' thermal perception

	Exterior	**Spring**	**Summer**	**Autumn**	**Winter**
				Air Temperature range	
Uncomfortable Band	1=Cold	14°C	17°C-24°C	8°C-15°C	6°C-11°C
	2=Cool	13°C-19°C	18°C-25°C	11°C-16°C	7°C-11°C
Comfortable band	3=Slightly cool	14°C-19.5°C	18°C-24°C	12°C-18°C	6°C-12°C
	4=Neutral	15°C-23°C	20°C-25°C	12°C-19°C	8°C-12°C
	5=Slightly warm	18°C-25°C	20°C-27°C	12°C-19°C	9°C-14°C
Uncomfortable band	6=Warm	19°C-24.8°C	22°C-28°C	10°C-20°C	9°C-14°C
	7=Hot	18°C-25.5°C	24°C-30°C	No cases	No cases
	Interior	**Spring**	**Summer**	**Autumn**	**Winter**
		Air Temperature range			
Uncomfortable Band	1=Cold	No cases	No cases	No cases	No cases
	2=Cool	No cases	22°C-24.5°C	No cases	No cases
Comfortable band	3=Slightly cool	20°C-22.5°C	21.5°C-24.5°C	No cases	18.5°C-20.5°C
	4=Neutral	20.5°C-23.5°C	22°C-24.5°C	20°C-22.5°C	18°C-21.5°C
	5=Slightly warm	21°C-23.5°C	22.5°C-24.5°C	20°C-22.8°C	18.5°C-22°C
Uncomfortable band	6=Warm	21°C-24°C	23°C-25.5°C	19.5°C-22.5°C	19°C-22.5°C
	7=Hot	No cases	23°C-26°C	20.2°C-22.5°C	No cases

The relative humidity at the exterior had similar values in spring and summer (50%) and higher values in autumn (70%) and winter (61%). Despite these differences, the mean humidity responses were 'just right' in the four seasons of the year. Regarding the exterior wind speed, people felt comfortable in spring and summer with a mean response of 'just right'. In autumn and winter people perceived the wind speed as 'slightly breezy'. The mean wind speed value in all seasons was around 1m/sec, although there were brief periods with wind speed values greater than 3m/sec.

Finally, participants' clothing value also changed by season, from a minimum of 0.30 clo value in both spring and summer up to a maximum of 2.0 clo value in both autumn and winter (Table 4-12).

Table 4-12 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

4.15. Exterior factors provoking discomfort

At the first measurement point (exterior), the thermal comfort questionnaires also collected a number of different physical factors provoking discomfort (air temperature, relative humidity, wind velocity, solar radiation, dryness and rain). The given answers reflect participants' general opinion of the season in which they participated in the study, but not the exact moment and place where they answering the questionnaire (see the recommendations addressed in section 7.9). Results illustrate that air temperature was one of the main physical factors that people perceived uncomfortable: during summer 'uncomfortable warm' and during autumn and winter 'uncomfortable cold'. Wind was the second factor marked by people as uncomfortable followed by solar radiation, rain, relative humidity and dryness. A significant difference in participants' responses can be seen between cold and warm seasons (Figure 4-14).

During autumn and winter; the majority of participants (65%-74%) gave wind and air temperature as the main factors provoking discomfort, exceeding by far the values of the other factors. These responses reflected participants' judgment of the season rather than any particular moment. Therefore, it was difficult to match these responses with measurements conducted in the precise time that people were participating in the study. In addition, people found it more difficult to give their opinion about relative humidity, wind speed and dryness perception.

In spring and summer, the distribution of uncomfortable factors was more variable. In summer, temperature, solar radiation and wind were the most indicated factors provoking discomfort. Interestingly, in spring, solar radiation, rain and wind (17%, 20% and 25% respectively) were indicated more than air temperature (8%). Results from this data correlate with participants' thermal sensation votess, as the majority of people felt more comfortable in spring than in other seasons. In the same way, the factor provoking discomfort in summer is linked with participants' thermal perception (slightly warm, warm and hot) and thermal preferences (wanted to be cooler). In short, in Sheffield weather, relative humidity and dryness seem to have not a large impact on participants' thermal comfort, Finally, in autumn and winter participants' thermal perception was clearly towards the cold band, and their answers match with uncomfortable cold temperatures.

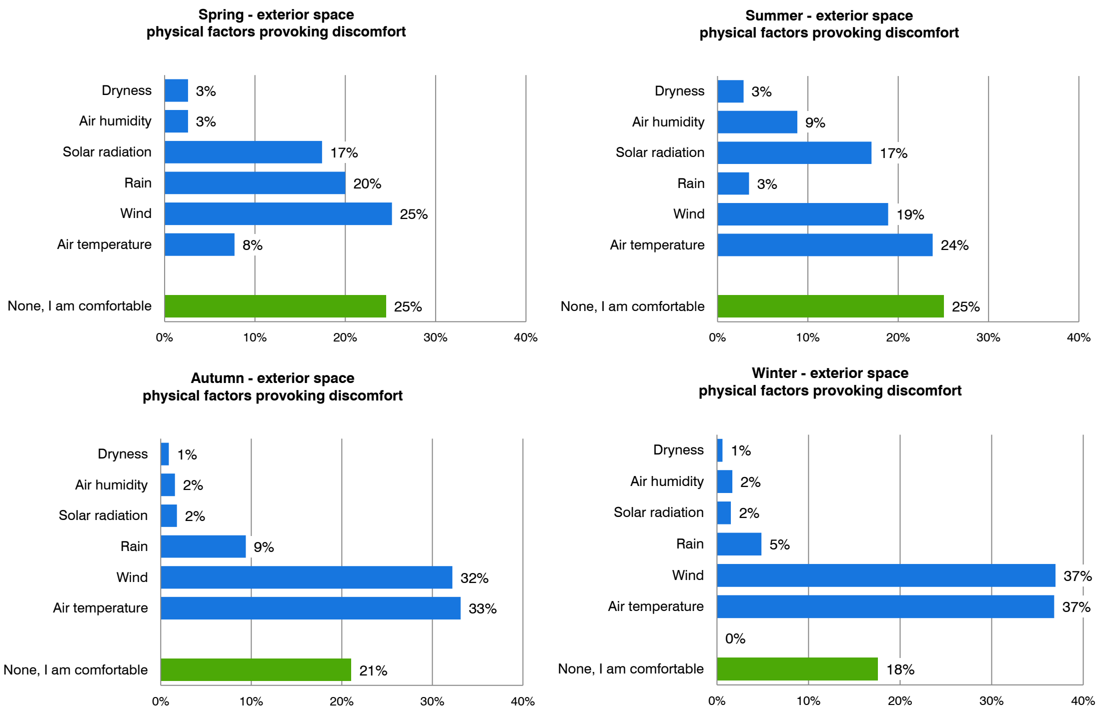


Figure 4-14 Exterior factors provoking participants' discomfort per season of the year

4.16. Participants' thermal perception of the interior environment

Inside in the seminar rooms, participants' thermal comfort perception was variable in the four seasons of the year (Figure 4-15) The minimum air temperature recorded was 16°C in winter (with heated spaces) and the maximum was 25°C in summer (NV). In the seminar rooms, people felt more comfortable in spring (85%) than summer (78%), autumn (66%) and winter (70%). In autumn and winter, people gave a larger number of answers (30%) towards the uncomfortable warm band (feeling 'warm' and 'hot') than spring and summer (10%). In general, participants' responses in the seminar rooms were opposite to their thermal perception outside. In spring and summer, people gave very similar responses, likewise in autumn and winter. In spring and summer, the mean response was 'neutral', and in autumn and winter the mean thermal response was 'slightly warm'.

Using one-way between groups analysis of variance (ANOVA), no significant differences in participants' thermal sensation votess were found when comparing spring($M=4.35$, $SD=1.0$) with summer ($M=4.17$, $SD=1.17$), and autumn ($M=5.03$, $SD=0.915$) with winter ($M=4.94$, $SD=0.994$). However, post-hoc comparisons indicated significant difference between spring with autumn and winter ($p<.05$) likewise summer with autumn and winter ($p<.05$). Participants' perception of air temperature was wider in the exterior than in the interior spaces and the main difference was found between the exterior and the entry door spaces (Figure 4-15).

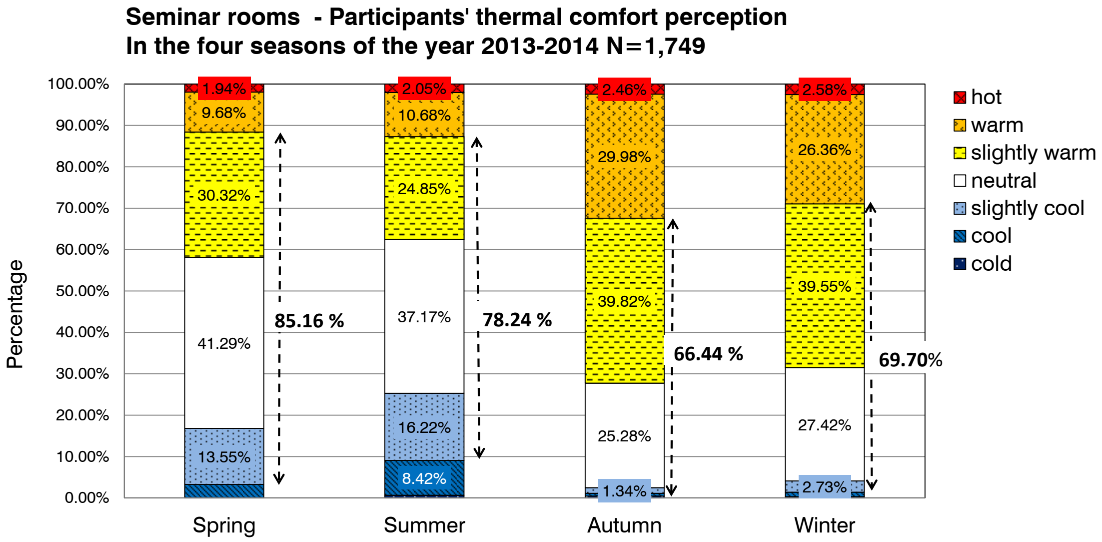


Figure 4-15 Participants' seasonal thermal perception at the interior

The air temperature ranges at which people preferred 'no change' in the seminar rooms varied in each season. In autumn and winter the range was colder than in spring and summer. In spring the range was from 20°C to 24°C, in summer from 22°C to 26°C, in autumn from 20°C to 22°C and in winter from 18.5°C to 22.5°C. The mean temperature at which people preferred 'no change' was in spring 21.5°C, summer 23.4°C, autumn 20.5°C and winter 19.5°C. A detailed breakdown of participants' thermal perception (in both groups A and B) at the exterior and in the seminar rooms is illustrated in Table 4-13. The information in the table is supported by the regressions illustrated in Figure 4-16, Figure 4-17 and Figure 4-18

Table 4-13 Seasonal temperature ranges in relation to people's preferences 'no change'

	Spring	**Summer**	**Autumn**	**Winter**
Exterior	Min=14°C Max=25°C **Mean= 19.8°C** SD= 4.197	Min=17°C Max=30°C **Mean= 22.6°C** SD= 3.17	Min=8°C Max=20°C **Mean= 15.0°C** SD= 3.21	Min=6°C Max=17°C **Mean= 9.8°C** SD= 2.11
Interior Group **A**	Min=20°C Max=24°C **Mean= 21.5°C** SD= 1.34	Min=21°C Max=26°C **Mean= 23.4°C** SD= 1.32	Min=18°C Max=23°C **Mean= 20.5°C** SD= 1.20	Min=16°C Max=25°C **Mean= 19.5°C** SD= 1.65
Interior Group **B**	Min=21°C Max=24°C **Mean= 22.12°C** SD= 1.21	Min=21°C Max=26°C **Mean= 23.3°C** SD= 1.45	Min=20°C Max=24°C **Mean= 21.57°C** SD= 1.27	Min=18°C Max=24°C **Mean= 20.48°C** SD= 1.55

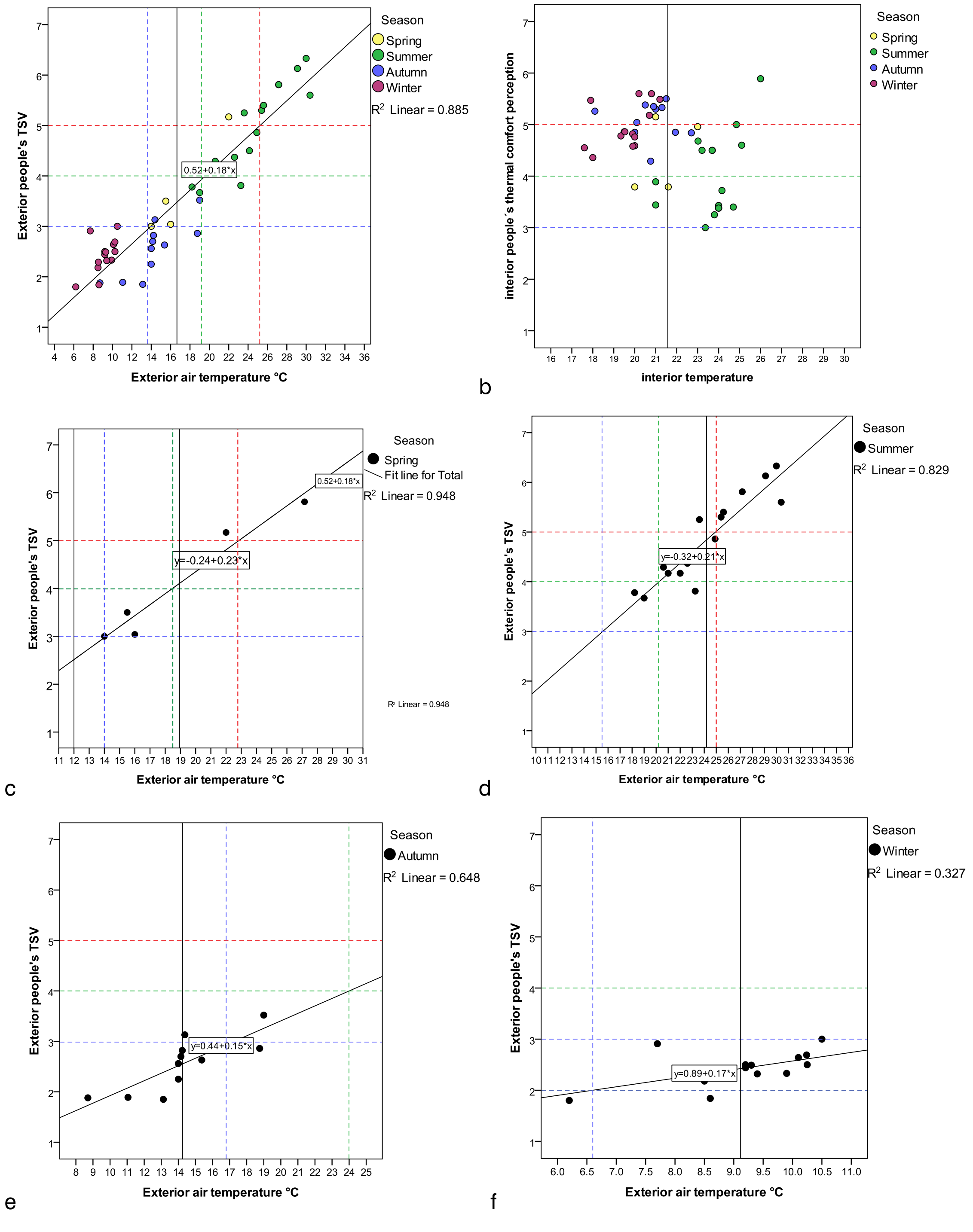


Figure 4-16 Linear regressions (grouping participants in thermal bins) comparing the exterior temperature and people's thermal comfort perception in the four seasons of the year (Group A and B together). The black continuous line indicates the mean temperature. The dotted lines indicate the comfortable thermal comfort band: green= neutral, red: slightly warm and blue=slightly cool.

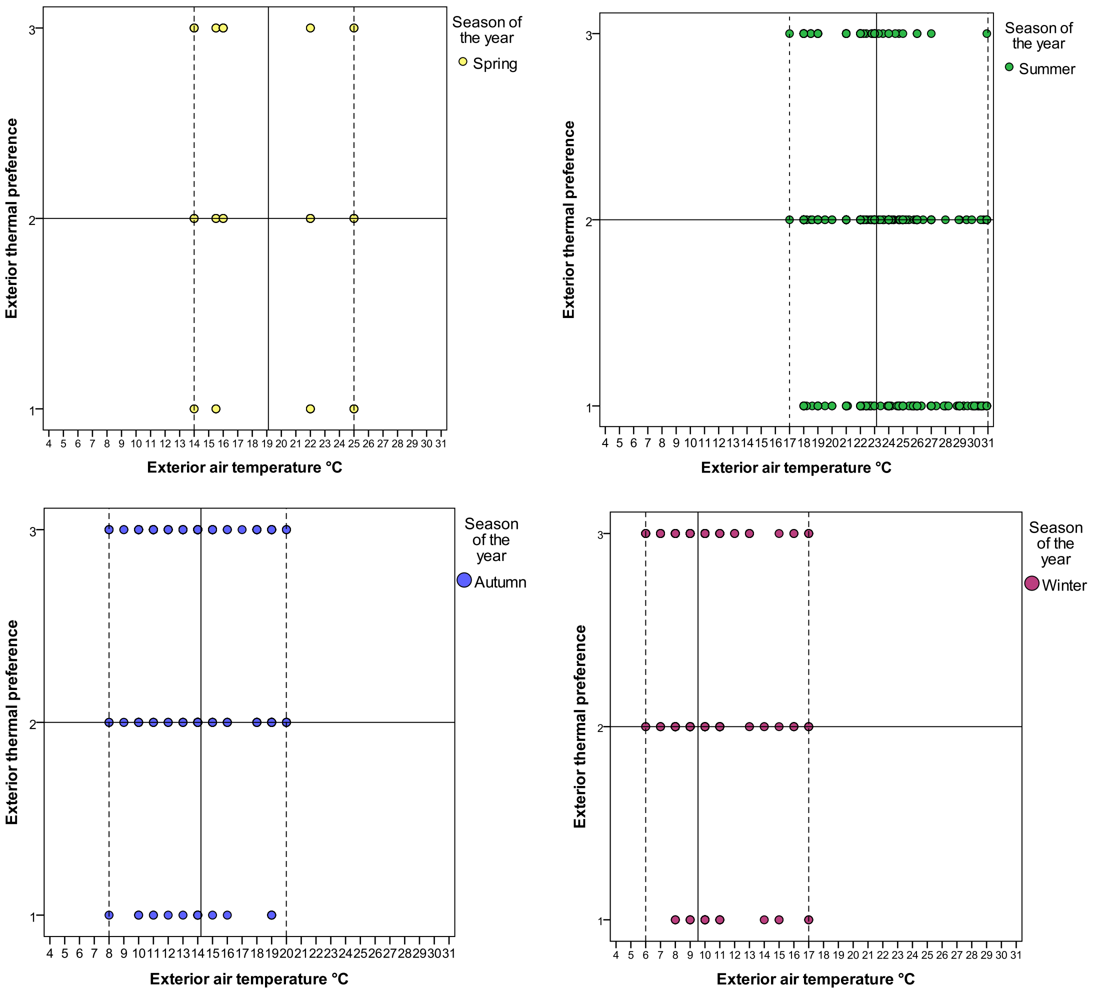


Figure 4-17 Graphs illustrate the exterior air temperature and participants’ thermal preferences (group A and B) in the four seasons of the year. The dotted lines indicate minimum and maximum values; the continuous line indicates the mean value.

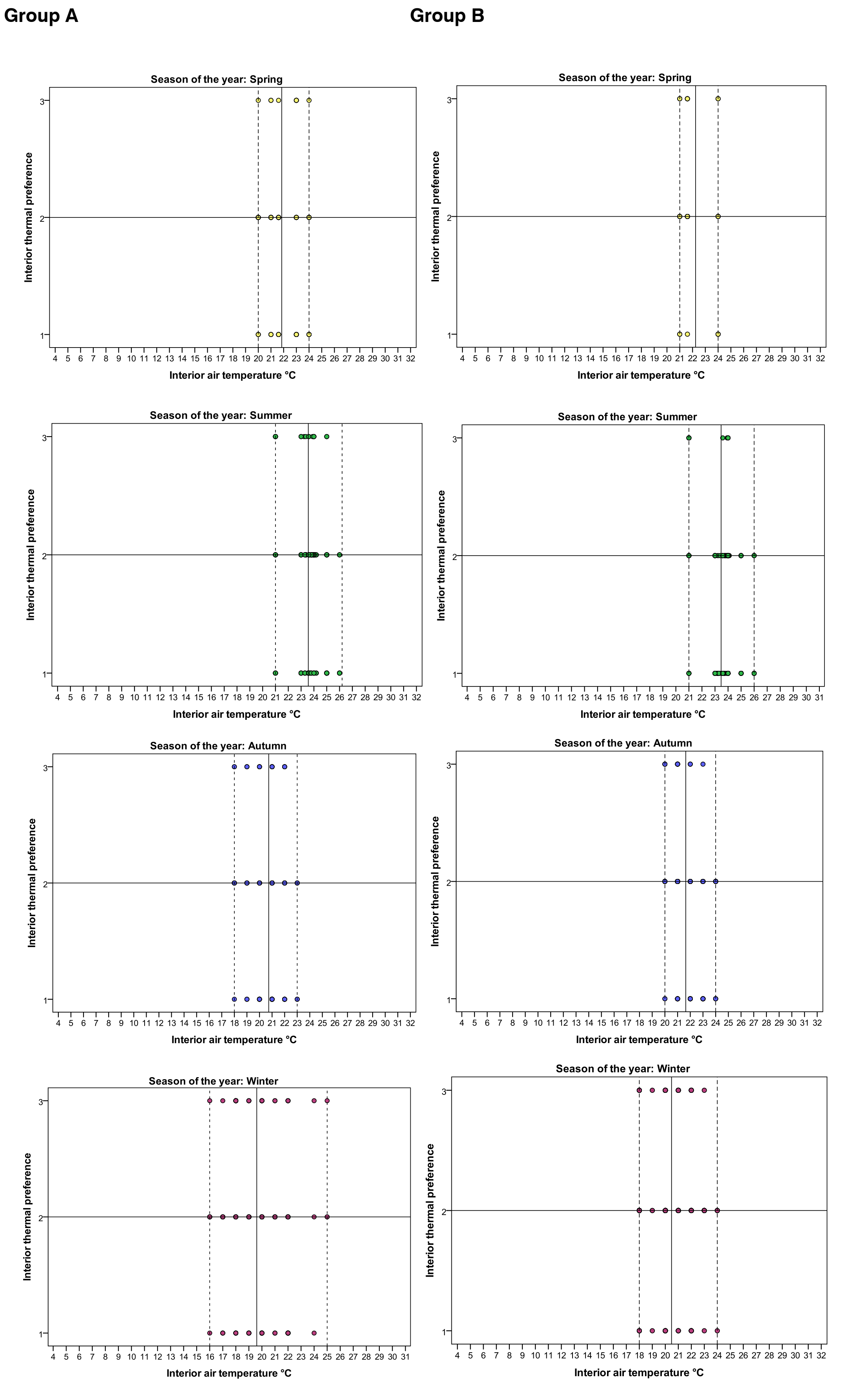


Figure 4-18 Graphs illustrate a comparison of thermal preferences between group A and B in the seminar rooms in the four seasons of the year. The dotted line indicates minimum and maximum values and the continuous line indicates the mean value.

Participants' thermal perception of the air temperature in the four spaces was more variable in autumn and winter than spring and summer Figure 4-19. Regarding the relative humidity, in the seminar rooms, it was a comfortable factor across the year (40% to 50% RH). In the four seasons, the mean responses were 'just right' (Figure 4-20). Regarding wind speed, the interior spaces show less variation than the exterior. In the seminar rooms, the mean wind speed velocity was less than 0.1 m/sec. The existing windows were kept closed during the surveys; however, the entry door spaces registered wind speed values closer to the exterior during the periods that participants used the doors. During the survey, it was noticed that the movement of people rather than other external factors generated wind speed values around 0.5m/sec. In general, the people perceived the wind speed in the interior spaces as 'slightly still' and 'just right' (Figure 4-21). Hence, wind speed was not an uncomfortable factor during the surveys.

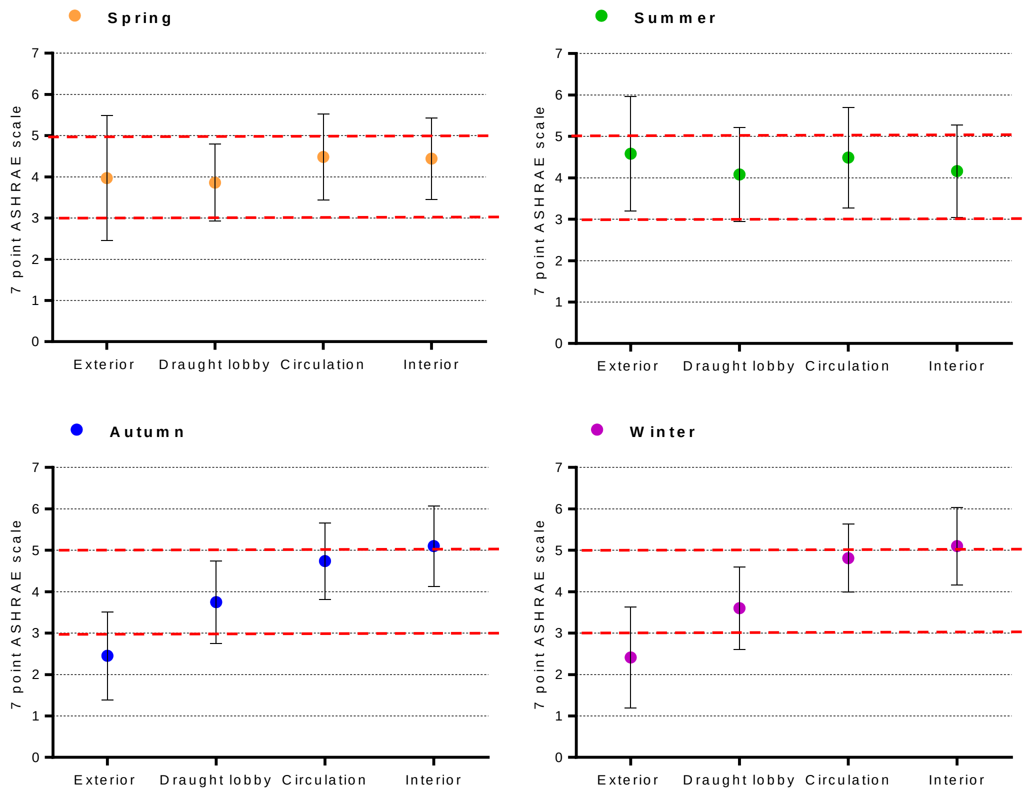


Figure 4-19 Participants' air temperature perception during the four seasons of the year using a 7 point ASHRAE scale: 1=cold, 2=cold, 3=slightly cool, 4=neutral, 5=slightly warm, 6=warm and 7=hot

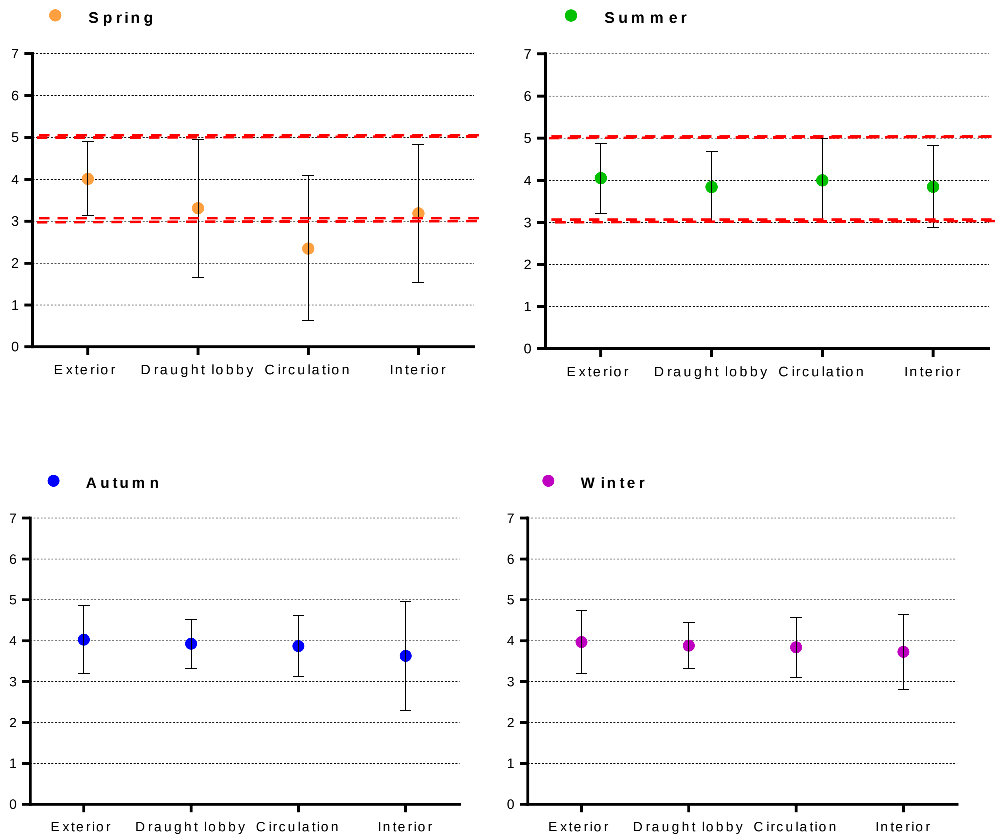


Figure 4-20 Participants' relative humidity perception during the year: 1=much too dry, 2= too dry, 3= slightly dry, 4=just right, 5=slightly humid, 6= too humid, 7= much too humid.

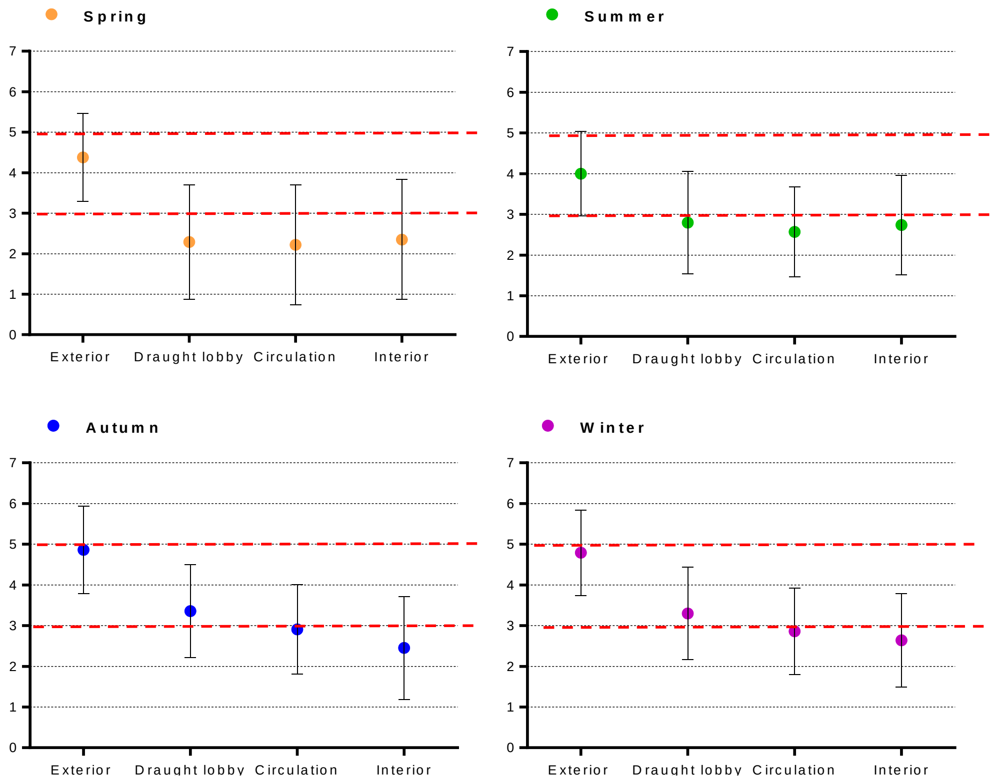


Figure 4-21 Participants' wind speed perception during the year: 1= much too still, 2=still, 3=slightly still, 4=just right, 5=slightly breezy, 6=too breezy, 7=much too breezy.

4.17. Moving from the outdoor to the indoor environment

The seasonal thermal adaptation that people experience during a year also affected the way that people perceived the interior spaces. In general, participants' thermal response in the seminar rooms was opposite to their thermal perception of the exterior space. For example, when participants' thermal perception at the exterior was in the cold band ('slightly cool, 'cool' and 'cold'), their thermal perception in the interior was towards the warm band ('slightly warm', 'warm' and 'hot'). This pattern was more noticeable in autumn and winter than spring and summer (Figure 4-22), since these were the seasons with major temperature differences between the outdoor and indoor environments. In autumn and winter, people responded towards the cold band at the exterior and dramatically changed towards the hot band when they moved to the interior space. In contrast, during spring and summer their change in thermal perception was less dramatic.

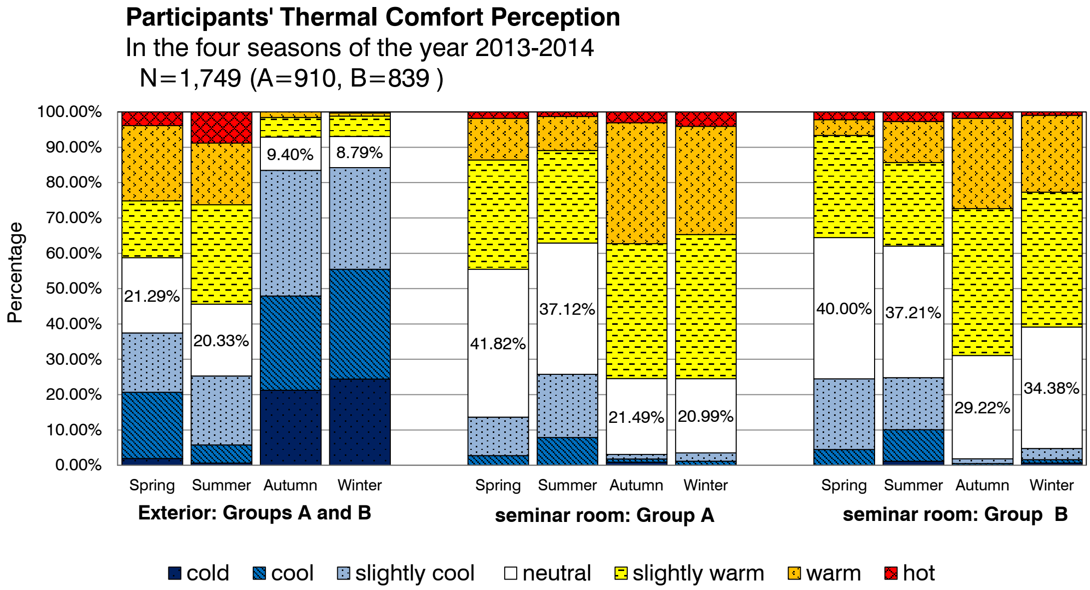


Figure 4-22 Participants' seasonal thermal perception at the exterior and seminar room, with and without using the transitional lobby unit. Comfortable band= slightly warm, neutral and slightly cold

Results from a Wilcoxon Signed Rank Test showed that (in autumn and winter) there was a statistically significant difference in participants' thermal perception between the exterior and interior ($p<.05$). Presumably because the temperature at the exterior (autumn mean=14°C and winter mean=9°C) and in the interior (autumn mean= 21°C and winter mean= 20°C) were very different. Likewise, in summer there was a significant difference ($p<.05$) between participants' thermal perception at the exterior and interior, although the temperature changes between inside and outside were moderate. In contrast, differences were not very significant in spring ($p=0.08>.05$), since outside and inside temperature were similar, so the differences in participants' thermal perception were not very significant ($p=0.10>.05$).

In order to identify if the use of the lobby unit can modify participants' thermal perception when they move inside the building, a comparison between people using the lobby unit (Group A) and by passing it (Group B) was conducted in each of the three buildings. When comparing participants' responses from both groups in the seminar rooms, no large differences between spring and summer were found. However, during autumn and winter, group B had larger number of responses within the comfortable band than group A (around 10% more). However, group A presented more answers towards the hot band, ‘slightly warm’, ‘warm’ and ‘hot’, (75%) than group B (60%). In spring, participants’ thermal responses at the exterior and interior were very similar, in contrast to autumn and winter. In spring and summer, the use of the lobby unit did not significantly alter participants’ thermal perception in the seminar room.

4.18. Participants’ thermal preferences

Participants’ thermal preferences in the seminar rooms (‘warmer’, ‘colder’ and ‘no change’) were altered by the exterior seasonal temperature variations and participants’ thermal adaptation to the climatic conditions of each season. Similar to results from participants’ thermal sensation votes (section 4.11), people tag their thermal perception within a temperature range which differs by season. In spring and summer, when comparing participants’ thermal sensation votes and the thermal preference for ‘no change’, a wide range of thermal perception from ‘cool’ to ‘warm were included, except extreme uncomfortable answers ‘hot’ and ‘cold’. In contrast, an interesting result was that in autumn and winter, although around 70% of participants’ thermal sensation votes were within the cold side (slightly cool, cool and cold); their interior thermal preferences were ‘no change’ (Figure 4-23).

In the cold season, such a large percentage of ‘no change’ answers was unexpected. In fact, it seems that overall people positively accepted the different thermal variations of each season, adapted to them and preferred ‘no’ or ‘little’ temperature change. It can also be suggested that the results reflect that their process of adaptation also had an impact on their thermal preferences, which were eventually also adjusted by the natural temperature variation of the next season.

From these results, it can be seen that participants’ seasonal thermal adaptation had a stronger influence on their thermal preferences in autumn and winter than in spring and summer. Interestingly, in autumn and winter the majority of people (67%) simultaneously felt comfortable but also ‘cold’, ‘cool’ or ‘slightly cool’; this also could be explained by the ‘naturalness’. Perhaps people know that the weather is cold in winter and are prepared for this; moreover, they could even be enjoying the cold temperature. However, when they moved to the seminar rooms, their thermal preferences dramatically changed towards warmer thermal sensations, even when at the exterior the majority of participants did not want to be warmer.

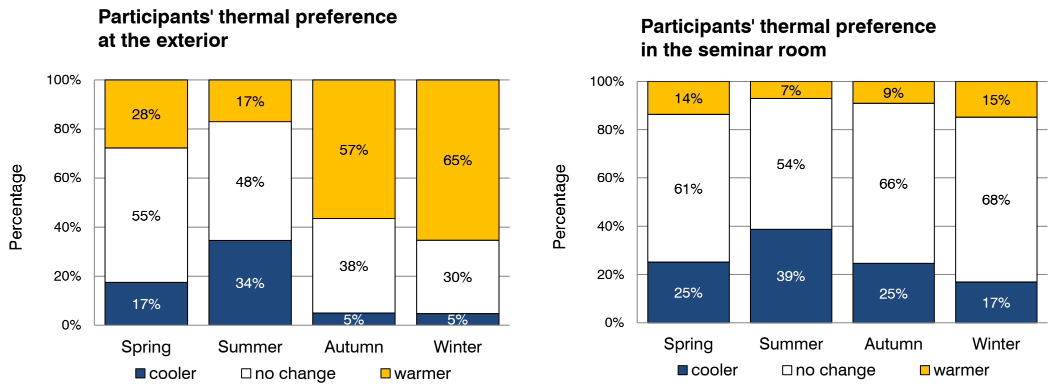


Figure 4-23 Participants' thermal preferences at the exterior and in the seminar room

When people arrived at the seminar rooms, their thermal preferences significantly changed (Figure 4-24). In spring and summer, a larger percentage of people preferring 'no change' answered within the comfortable band votes (slightly cold neutral and slightly warm) when moving from exterior to interior, increasing by 23% in spring and 10% in summer. In autumn and winter the difference in participants' thermal preferences from exterior to interior were by far larger than in spring and summer, people preferred 'no change' in thermal conditions, even when about 70% were feeling 'slightly warm' and 'warm' in the seminar room. In the warm seasons, no statistically significant differences in participants' thermal preferences were found in the seminar rooms when comparing group A and B. However, in autumn and winter people in group A, using the lobby, seemed to tolerate lower temperatures in the seminar room than people in group B. In conclusion, the use of the lobby unit seems to have a more significant impact on participants' thermal preferences in the colder seasons.

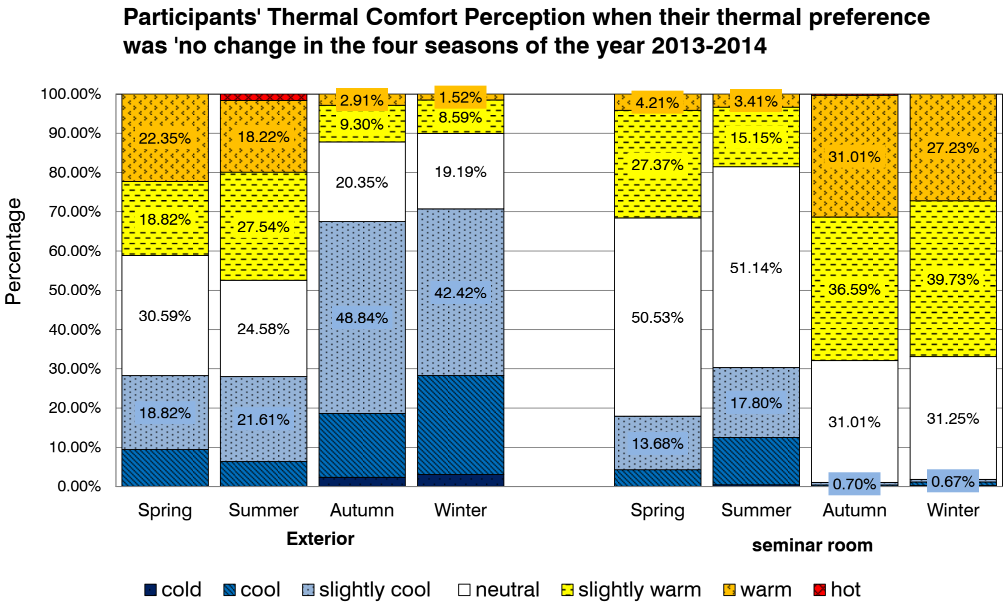


Figure 4-24 Participants' thermal preferences at the exterior and interior spaces

From these findings, it seems that participants' thermal preferences in the seminar rooms were more linked with their exterior thermal perception answers (e.g. feeling cold) than with their preferences (e.g. no change). This also means that participants' thermal preferences at the exterior are not always a good basis to predict or assume how they would prefer to be in the indoor environment. This topic, along with the implications of participants' thermal preferences in the four seasons in terms of temperature set up and energy savings will be discussed in further detail in section 6.3.

4.19. Conclusions

This chapter identified thermal variations in the lobby unit in the three case study buildings. It covered two of the objectives of this thesis, relating to the quantification of thermal variability in transitional spaces and to understanding participants' thermal perception in relation to temperature changes. A very important finding was the quantification of the seasonal thermal variability in the lobby unit of the three buildings. It was found that the seasonal exterior climatic conditions significantly altered the thermal variability in the lobby units. A strong correlation was found between the air temperature values in immediately adjacent spaces (exterior and draught lobby, draught lobby and circulation space, and circulation and seminar rooms). However, the connection of the exterior with the interior climate conditions decreased towards the further interior spaces.

Another key finding was revealed when people moved to the interior spaces and it was identified that their thermal perception changed very quickly, even in only a few seconds. This can also explain why people changed their thermal preference very quickly, from preferring to be warmer to preferring to be colder after just 60 seconds. Finally, the use of the lobby unit seems to have a larger effect on participants' thermal perception during autumn and winter than during spring and summer, due to the large temperature differences between the outdoors and indoors in the cold seasons. In addition, there was strong evidence of participants' thermal adaptation to the seasonal climatic conditions during the year, which also influenced the way that they perceived the transitional lobby unit.

Finally, it is important to note that the thermal connection between spaces can vary depending on the climatic region of study, the building design, the exterior context and the building operation (NV, MM, MV or AC). Knowledge on the way that the lobby unit is thermally connected with other spaces and on the seasonal thermal adaptation that people experience provides valuable information to better understand people's thermal perception in the short-term.

Chapter 5

5. Thermal History Analysis and results

5.1. Introduction

In this chapter, the results related to participants' short-term thermal history are presented. Previous findings in Chapter 4 provided primary results associated with the climatic conditions and participants' thermal perception in the case study buildings during the four seasons of the year. These results provided the basis to better understand one year of participants' long-term thermal history and their seasonal thermal adaptation. In this chapter, key factors that can alter people's perception over short periods of time are examined in detail. Preliminary considerations in the analyses are described first, in order to put into context the conditions from which these results arose.

In this chapter, participants are organized into thermal bins (as described in the analysis plan in Chapter 3) in order to compare their responses under the same ranges of physical conditions. A number of key demographic categorical variables (gender, nationality and years of residence in Sheffield) and different types of thermal sequences (flat, sudden from cold to hot, sudden from hot to cold, and irregular) are compared with participants' short-term thermal perception and thermal preferences. The most significant findings that explain the alterations in people's short-term thermal history are analysed and discussed in this chapter. Differences in temperature changes, temperature order and change of thermal direction along with personal variables are analysed in detail. Participants' thermal interaction in the transitional lobby unit space is described in detail, along with the combinations of different variables that alter their short-term thermal history. Finally, the thermal indices PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied) are analysed by thermal sequence type. Key themes raised from the main findings presented in this chapter are discussed further in Chapter 6, which presents the implication of the outcomes of this thesis, in relation to lobby unit design, people's thermal history and building design policy. The organization of this chapter is illustrated in Figure 5-1.

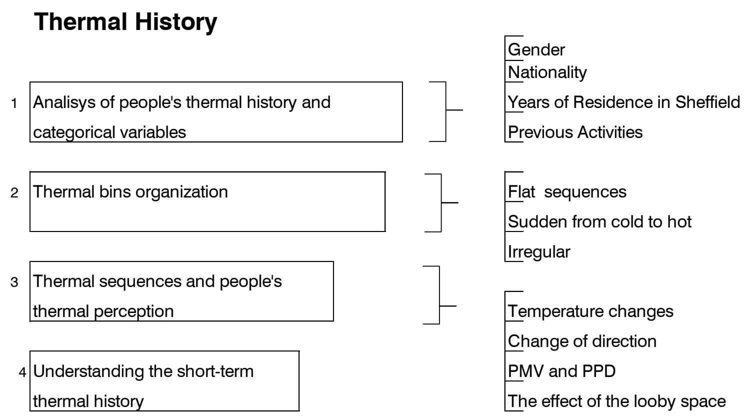


Figure 5-1 Organization of themes in Chapter 5

5.2. Previous considerations
Participants' thermal history and categorical variables

In Chapter 3, crucial demographic variables along with other long-term and short-term thermal history variables were identified from the literature review. In steady state thermal comfort studies, some of these variables show significant influence in participants' thermal comfort perception. However, in dynamic state the effect of these variables in people's thermal perception is not yet clear. One of the first considerations in this chapter is to determine to what extent these factors could influence people's answers in dynamic state (walking). The twelve selected variables were analysed in order to determine key factors altering participants' thermal perception in the short-term. The variables were clothing, gender, nationality, time of residence in Sheffield, age, weight, height, previous activities, previous exposure to indoor and outdoor environments, previous activities before the survey, metabolic rate altered by eating, previous time of exposure to indoor or outdoor climatic conditions and previous exposure to AC environments.

In this study, it was found that in dynamic conditions (walking) there is only a significant correlation between participants' thermal comfort perception and participants' clothing, gender, nationality and years of residence in Sheffield. Interestingly, the significant results in gender, nationality and years of residence in Sheffield come into view only in the cold seasons (autumn and winter) and in the exterior measurement point.

5.2.1. Clothing

In Chapter 4, a large seasonal difference in participants' clothing was identified. At the exterior measurement point (outside of the building), there is a strong positive correlation between participants' thermal perception and their clothing value. Interestingly, however this does not happen in the interior spaces. In the seminar room for example, participants' clothing had less effect on their thermal perception.

5.2.2. Gender

A medium strength correlation was found between participants' gender and their thermal perception. Mann-Whitney non-parametric t-tests revealed larger differences between male and female thermal perception at the exterior than in the interior space (seminar rooms). Differences at the exterior were larger in autumn and winter ($p<.05$). Although statistically significant differences were not found in spring and summer, it can be noted that females gave a larger number of votes in the direction of the cold band than males (Figure 5-2). Perhaps this could be because the range of temperatures in cold seasons generates larger temperature differences between the exterior and interior environments, and because this exceeds the temperature range that people from different nationalities are able to tolerate in their countries.

In each of the four seasons of the year, males were more comfortable (spring=59%, summer= 70%, autumn=56%, winter=45%) than females: spring (spring=52%, summer=63%, autumn=42%, winter=40%). These results agree with previous studies, which have demonstrated that females have a cooler mean skin temperature than men (Kelly and Parson 2010), and that females are more sensitive to temperature changes than males (Yokoe et al. 2007). Previous studies have reported similar results.

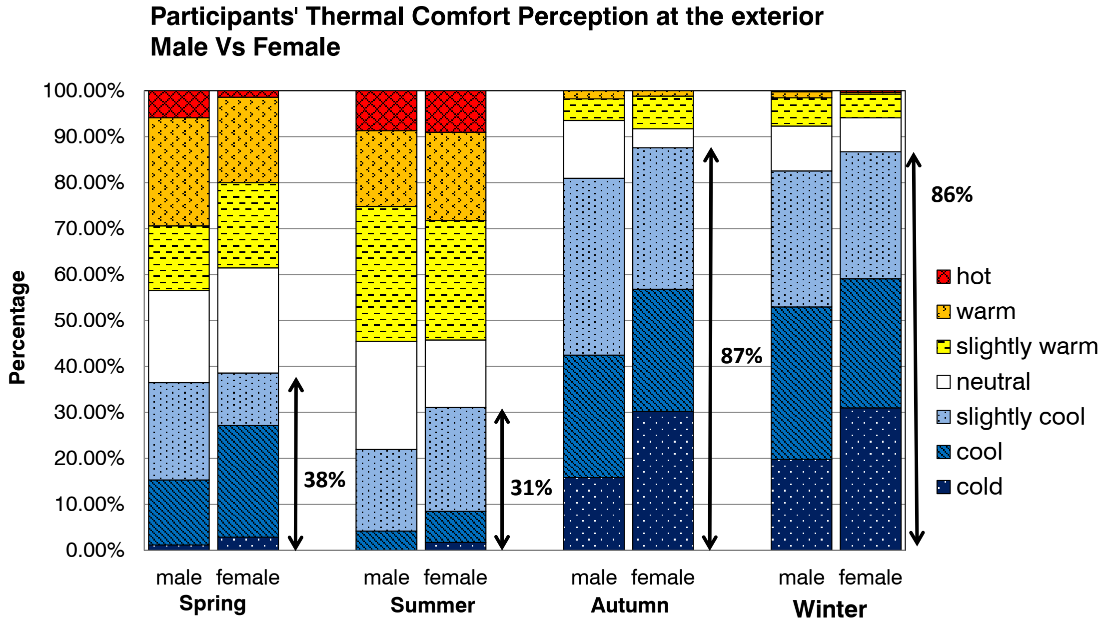


Figure 5-2 Participants' thermal perception at the exterior by gender

5.2.3. Nationality

When examining participants' nationality, differences were identified between two large groups (UK and International participants) when conducting a Mann-Whitney non-parametric t-test. A medium strength correlation was found between participants' thermal perception and their nationality group (UK or International). No additional research was conducted exploring people from different nationalities in the same place; however, this finding could add understanding to the study of participants' thermal history in relation with time and thermal adaptation. As the main objective of this study was not focus on nationality in detail, the collected sample size was not to subdivided further into specific groups due to the imbalance in the sample (number of participants per non-UK nationality). Hence, it is interesting to provide an overview of international students thermal perception. Again, as in the gender variable, differences were noted when people were at the exterior. People from the UK gave more responses within the comfortable band and towards the hot side than international participants (Figure 5-3). This is also strongly linked with the years of residence in Sheffield, since UK students have been in the UK for longer periods than international students.

5.2.4. Years of residence in Sheffield

At the exterior, a similar trend was found in people who have lived in Sheffield for less than one year towards the cold side of thermal perception (Figure 5-4). Larger differences between the mean responses were found in summer, autumn and winter ($p<.05$) than spring ($p=.866>.05$). In the interior spaces, the differences were not significant in any season. On the whole, the effect of gender, nationality and years of residence in Sheffield, in relation to participants' seasonal thermal history, had a clear impact at the outside but not inside. Further discussion explaining this phenomenon is discussed in section 6.3.

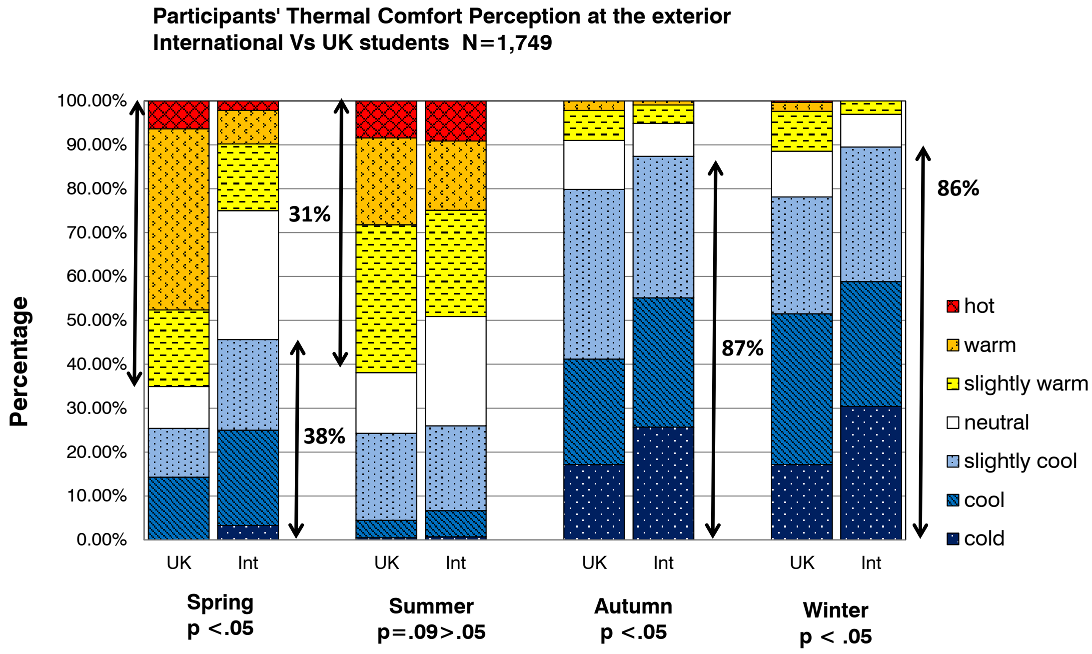


Figure 5-3 Participants' thermal perception at the exterior by nationality group

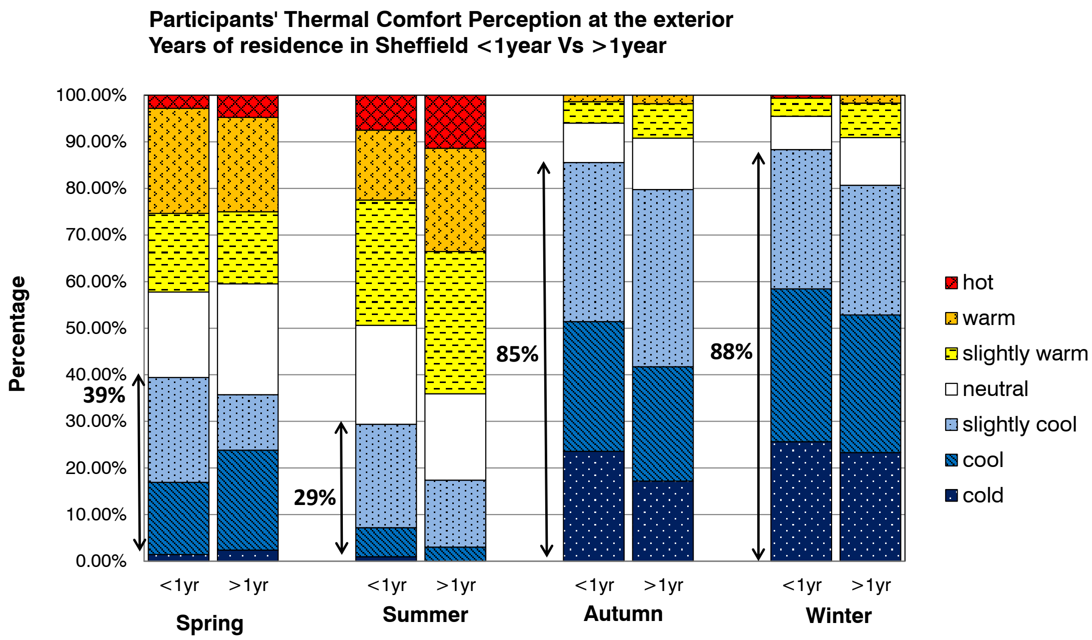


Figure 5-4 Participants' thermal perception at the exterior by years of residence in Sheffield, UK

5.2.5. Previous exposure to Air Conditioned (AC) environments

Since a number of studies have recently explored this topic, it is worth mentioning that in this case, previous exposures of participants to AC environments did not show a significant effect in participants' thermal perception using Spearman rho and Friedman correlations, in contrast with other studies involving people performing sedentary activities. Presumably, this was because the dynamic state (walking) that people were experiencing in transient conditions was strong enough to reduce the effect of other variables significantly. The non-significant results in this study could also be due to participants in Sheffield being less exposed to AC environments at home and within the University buildings than in other studies. The participants probably had to change venues (AC, NV, MM, etc.) during the day and they had more interaction with the exterior environment when moving from one building to another, all factors which reduce the effect of the short exposure to AC conditions. In addition, other studies have only analysed a single nationality, which could have resulted in very similar thermal histories within the sample population. For example, studies in hot humid climates with a single nationality sample conducted by Jitkhajornwanich (2002) in Bangkog (Thailand), Candido (2011) in Maceio (Brazil) and De Vechi (2012) in Florianopolis, (Brazil)reported strong correlations between participants' thermal perception and preferences in relation to long-term exposures to AC environments. In this thesis, the sample population is comprised of students from different nationalities where the effect of previous AC exposures is not clearly reflected. However, this does not mean that it does not exist.

5.3. Thermal patterns

Although previous studies exploring transitional spaces have measured physical conditions in different points of a transitional space, as in the work conducted by Pitts (2010) and Jitkhajornwanich (2002), additional information is needed that provides findings related with thermal connections of entire journeys or sequences of spaces in real situations. This requires the analysis of a sample size experiencing the same journey and climatic conditions. Chapter 3 described the importance of grouping the sample size into thermal bins in order to conduct further statistical analysis in which each thermal bin represents a group of people under the same climatic conditions. From the data collected, the exterior air temperature was the main variable that was taken into account when grouping participants in thermal bins, because this should remain almost constant without abrupt changes. The maximum time range where the climatic conditions were constant was from 30 up to 40 minutes. From the total 1,749 participants, only 1,679 were organized into a total of 46 thermal bins (Figure 5-5); very small groups (around 5 participants) each were excluded, since they not comply with the statistical requirements (size) to carry out tests. Each of the 46 thermal bins had different thermal sequences, which refer to the order in which air temperature changes from one space to another. Four patterns were identified in this study, before this research, previous experiments had not clearly included a classification of thermal sequences or patterns. The patterns refer to the change in air temperature between the spaces comprising the lobby unit, the identified patterns in group A are:

1. 'flat pattern ' : The flat pattern was identified as primarily occurring during spring and summer in the three buildings. This pattern involves a relatively small exterior and interior air temperature range, from 20°C to 23°C in the four spaces and only up to 2°C difference in temperature from one space to another.

2. 'sudden pattern' (from cold to hot): The sudden pattern (from cold to hot) corresponded primarily to autumn and winter. This pattern contains much larger exterior and interior air temperature range from 6.2°C to 26°C and with up to 13°C temperature difference between spaces. As might be expected, the largest sudden temperature difference occurred between the exterior and the draught lobby space in all sudden patterns from cold to hot.

3. 'sudden pattern' (from hot to cold): Only two thermal bins were identified with sudden patterns from hot to cold, corresponding largely to summer. The exterior air temperature range in this case was from 30°C to 23°C. However, because of the very small sample size, it was not possible to include this pattern in the statistical analysis.

4. 'irregular pattern': The irregular pattern contains temperature changes from cold to hot or from hot to cold without any consistent order. The majority of these thermal bins (irregular) were identified in summer and in a few cases in autumn and winter. The exterior and interior air temperature ranges in the irregular patterns 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).

The majority of cases correspond to sudden cold-hot patterns (18 bins) followed by irregular (15 bins), flat patterns (4 bins) and sudden patterns from hot to cold (2 bins). Results reveal that participants' thermal comfort responses were very similar in each pattern, in other words they followed the same trend (Figure 5-6). Also, it was identified that each thermal pattern corresponded to different exterior and interior air temperature ranges, which also generate different air temperature differences between the spaces.

Throughout, findings revealed that different seasons create different thermal patterns in a given spatial sequence connecting the exterior environment with the interior. Frequently, research only takes into account isolated seasons, or just summer and winter. However, data from this experiment highlight the importance of spring and autumn as transitional periods for participants' thermal adaptation from cold to hot and from hot to cold seasons. It can be suggested that, apart from the different seasonal climatic conditions that people experience, the temperature patterns that these seasons created in the transitional spaces played an important role in participants' thermal perception and preference. Most of the laboratory studies created controlled thermal variation between spaces; in this study, the findings illustrated the thermal variations that typically occurred in the transitional spaces of the fieldwork case studies in reality. These findings can also help to focus on the key temperature changes that need to be reproduced in a climatic chamber for more detailed future studies needed in moderate climates. By identifying thermal patterns, this can help to provide strategies to reduce dramatic temperature changes between spaces in each season of the year. Transitional spaces should work as dynamic thermal connectors able to change their properties to create a better balance between the exterior and interior climatic conditions.

Total Participants N=1,679

Spring 2013 N=155	**HS Building** 74 (A=44 B=30)	1	(17.0 - 20.0 - 20.0 - 20.0 ºC) N=32	A (20)	B(12)
		2	(14.0 - 16.0 - 19.0 - 21.0 ºC) N=42	A (24)	B(18)
	JW Building 34 (A=19 B=15)	35	(25.0 - 21.0 - 22.0 - 24.0 ºC) N=34	A (19)	B(15)
	IC Building 47 (A=47 B=00)	17	(15.0 - 16.0 - 22.0 - 20.0ºC) N=24	A (24)	B(00)
		18	(16.0 - 18.0 - 23.0 - 23.0ºC) N=23	A (23)	B(00)
Summer 2013 N=478	**HS Building** 178 (A=84 B=94)	3	(21.0 - 22.0 - 21.0 - 21.0 ºC) N=38	A (18)	B(20)
		4	(25.0 - 22.8 - 22.9 - 23.6 ºC) N=27	A (10)	B(17)
		5	(29.2 - 25.1 - 23.5 - 23.0 ºC) N=13	A (08)	B(05)
		6	(30.3 - 25.1 - 23.5 - 24.0 ºC) N=14	A (08)	B(06)
		7	(22.9 - 22.0 - 22.7 - 23.2 ºC) N=14	A (04)	B(10)
		8	(22.5 - 22.1 - 23.0 - 23.0 ºC) N=33	A (19)	B(14)
		9	(24.7 - 22.0 - 23.0 - 24.0 ºC) N=19	A (07)	B(12)
		10	(33.7 - 24-1 - 24.4 - 24.4 ºC) N=20	A (10)	B(10)
	JW Building 87 (A=39 B=48)	36	(19.0 - 20.0 - 22.0 - 26.0 ºC) N=18	A (09)	B(09)
		37	(23.8 - 22.9 - 23.9 - 25.0 ºC) N=43	A (20)	B(23)
		38	(26.4 - 23.8 - 24.0 - 25.1 ºC) N=26	A (10)	B(16)
	IC Building 213 (A=106	19	(22.0 - 21.0 - 24.0 - 21.0 ºC) N=48	A (18)	B(30)
		20	(20.2 - 20.8 - 24.4 - 23.1 ºC) N=31	A (14)	B(17)
		21	(23.9 - 22.9 - 25.4 - 24.0 ºC) N=44	A (18)	B(26)
		22	(27.1 - 24.6 - 26.1 - 24.0 ºC) N=16	A (16)	B(00)
		23	(18.1 - 20.2 - 24.8 - 23.7 ºC) N=74	A (40)	B(34)
Autumn 2013 N=433	**HS Building** 157 (A=81 B=76)	11	(15.0 - 16.0 - 22.0 - 20.0ºC) N=33	A (20)	B(13)
		12	(16.0 - 18.0 - 23.0 - 23.0ºC) N=66	A (28)	B(38)
		13	(16.0 - 18.0 - 23.0 - 23.0ºC) N=58	A (33)	B(25)
	JW Building 130 (A=66 B=64)	39	(11.0 - 14.0 - 18.0 - 19.3 ºC) N=37	A (19)	B(18)
		40	(15.3 - 17.0 - 20.9 - 21.7 ºC) N=21	A (08)	B(13)
		41	(14.0 - 16.5 - 19.0 - 22.0 ºC) N=29	A (18)	B(11)
		42	(18.5 - 19.8 - 21.0 - 22.6 ºC) N=43	A (21)	B(22)
	IC Building 146 (A=73 B=73)	24	(14.7 - 17.3 - 22.4 - 21.9 ºC) N=49	A (39)	B(10)
		25	(19.0 - 18.9 - 23.0 - 22.7 ºC) N=25	A (00)	B(25)
		26	(14.1 - 16.0 - 22.2 - 20.7 ºC) N=38	A (17)	B(21)
		27	(9.10 - 12.8 - 19.0 - 21.4 ºC) N=34	A (17)	B(17)
Winter 2013 2014 N=613	**HS Building** 191 (A=99 B=92	14	(8.67 - 17.6 - 17.6 - 20.9 ºC) N=85	A (43)	B(42)
		15	(10.1 - 18.6 - 18.6 - 19.9 ºC) N=39	A (21)	B(18)
		16	(10.0 - 12.9 - 17.6 - 20.1 ºC) N=67	A (35)	B(32)
	JW Building 162 (A=90 B=72)	43	(6.2 - 11.2 - 16.8 - 19.5 ºC) N=25	A (15)	B(10)
		44	(9.4 - 12.7 - 16.8 - 21.1 ºC) N=35	A (25)	B(10)
		45	(9.2 - 11.4 - 16.0 - 21.4 ºC) N=71	A (39)	B(32)
		46	(7.6 - 12.5 - 20.0 - 22.0 ºC) N=31	A (11)	B(20)
	IC Building B=132)	28	(9.28 - 12.5 - 20.1 - 19.3 ºC) N=32	A (32)	B(00)
		29	(10.5 - 13.1 - 20.0 - 19.5 ºC) N=29	A (28)	B(01)
		30	(8.55 - 11.2 - 18.9 - 17.6 ºC) N=56	A (56)	B(00)
		31	(9.20 - 12.2 - 20.1 - 20.0 ºC) N=34	A (00)	B(34)
		32	(10.2 - 13.2 - 20.0 - 20.0 ºC) N=29	A (00)	B(29)
		33	(8.54 - 11.3 - 18.9 - 18.0 ºC) N=55	A (00)	B(55)
		34	(10.1 - 14.7 - 21.0 - 20.4 ºC) N=25	A (12)	B(13)

Figure 5-5 Data organization by thermal bins by seasons, case study building, number of sequence, air temperature changes and number of participants.

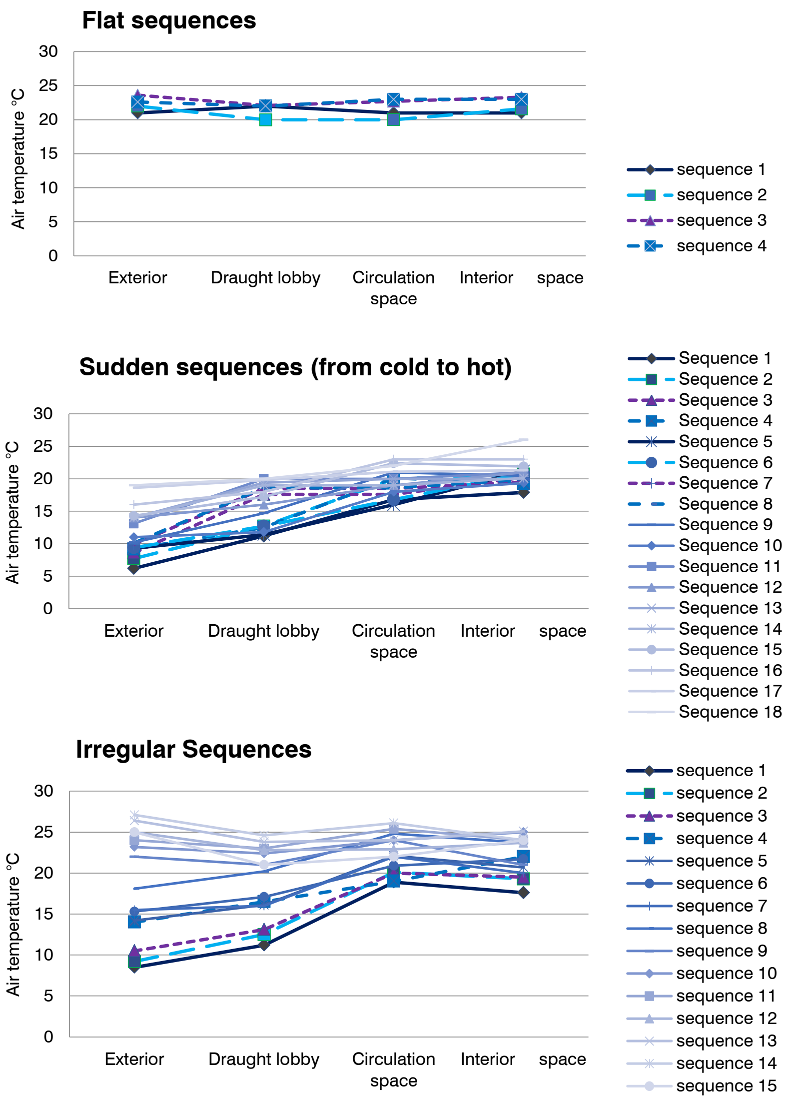


Figure 5-6 Thermal sequences: flat, sudden (from cold to hot) and irregular

Table 5-1 Thermal sequence patterns

	Flat sequence	Sudden sequence	Irregular sequence
Air temperature °C	Min= 20°C (exterior) Max= 23°C (interior) Mean= 21.9 °C	Min= 6.2°C (exterior) Max= 26°C (interior) Mean= 17.07 °C	Min= 8.5°C (exterior) Max= 27°C (interior) Mean= 20.44 °C
Range of temperature Changes (ΔT) between spaces	From 0°C to 2 °C	From 0 °C to 13 °C	From 0°C to 10 °C

In this research, study of the thermal connection between the seasonal exterior climatic conditions and the thermal patterns in the interior environment was extended by reporting findings from small spaces connected with each other within a lobby area boundary. This could help to provide a wider point of view in which thermal comfort findings can be better interpreted. In this study, linear regressions show that there was a strong correlation between participants' thermal perception and the exterior temperature ($p<.05$) by thermal bin. However, the relationship between participants' thermal perception in the environment around them decreased gradually as they moved towards the interior space (Figure 5-7). In the interior, there was no clear link between temperature and participants' thermal perception. Interestingly, something happened in participants' thermal perception after moving to the interior space that alters the way that they then perceived the seminar room. In order to understand this phenomenon, participants' responses in the interior spaces (draught lobby, circulation space and seminar room) are explored in a different way, by dividing the data into thermal patterns (flat, sudden and irregular). In this way, participants' thermal history seems to be more organized following more narrowed criteria.

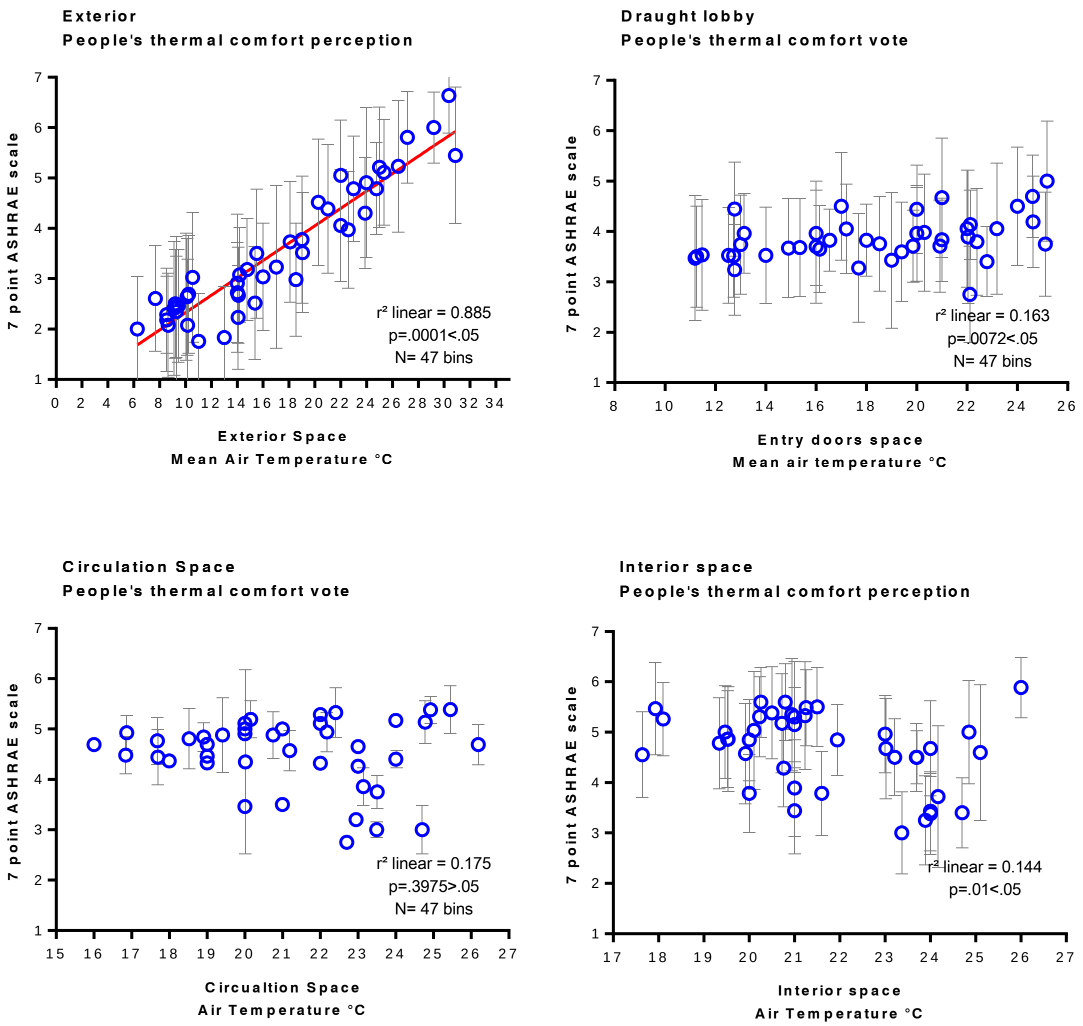


Figure 5-7 Participants' thermal perception by thermal bin in the four spaces

5.4. Thermal sequences analysis

Based on the literature review, three main factors associated with the alterations in participants' thermal perception were analysed in each sequence pattern in order to understand the effect of previous thermal conditions (thermal history) on participants' current thermal perception:

1. First, an overview of the way people experienced thermal perception in each space by sequence pattern. This analysis explored participants' thermal comfort responses, participants' thermal comfort preferences, humidity perception, wind speed perception and perception of temperature changes from one space to another in the four spaces.

2. Second, to what extent small and large temperature changes between spaces affected participants' thermal perception along the spaces in the sequences. Participants in group A experienced a different number of temperature changes than group B, due to going through a different number of spaces which are described in Chapter 3.

Participants in Group A moved through three temperature changes:

- Temperature change TC_1 (from exterior to the draught lobby space)
- Temperature change TC_2 (from draught lobby to circulation space)
- Temperature change TC_3 (from circulation space to seminar room)

Participants in group B experienced only one temperature change:

- Temperature change TC_4 (from exterior directly to seminar room)

In order to identify participants thermal state before and after arriving at the seminar room, both groups were labelled as B_1 (people at the exterior) and B_2 (people in the seminar room), and A_1 (people at the exterior) and A_2 (people in the seminar room). The analyses included paired and independent sample tests. Paired analysis: group A_1 (before) and A_2 (after), group B_1 (before) and B_2 (after) were conducted using paired sample T-test and Wilcoxon signed rank test. Independent samples comparisons (group A_2 vs group B_2 in the seminar room) were conducted using Mann-Whitney test and Independent sample T-test.

3. Finally, to see if the use of the lobby unit had a significant effect in participants' thermal perception when arriving at the interior space.

5.5. 'Flat pattern' thermal sequences

In the four flat patterns It can be seen that the majority of participants' responses were always within the comfortable band (3=slightly cold, 4=neutral and 5=slightly warm) in the four spaces (Figure 5-8). While people were moving towards the interior areas, they were feeling more comfortable that in the previous spaces. At the exterior, 66% of the answers were in the comfortable band, increasing to 79% in the draught lobby space and 86% in both the circulation and interior spaces. When analysing participants' thermal preferences, the majority of participants preferred 'no change' in temperature in the four spaces (55% at the exterior, 66% in the draught lobby, 73% in the circulation space and 67% in the interior space). These results are consistent with their thermal comfort responses; since the majority felt comfortable, they did not prefer a change in temperature. Regarding the humidity perception, people perceived the four spaces as comfortable and labelled them as 'slightly dry' and 'just right'. In the same way, wind speed was perceived comfortable; at the exterior, it was 'just right' and in the entire interior spaces 'still' (Figure 5-9). Overall, people felt comfortable in terms of temperature, humidity and wind speed, and they perceived a gradual temperature change from one space to another. Since flat sequences correspond to spring and summer thermal bands, it can be suggested that these months and the NV operation of the buildings, generate a good range of thermal connection between the spaces within a comfortable band. This confirms that in the UK, buildings with this type of thermal connection can eliminate the use of AC.

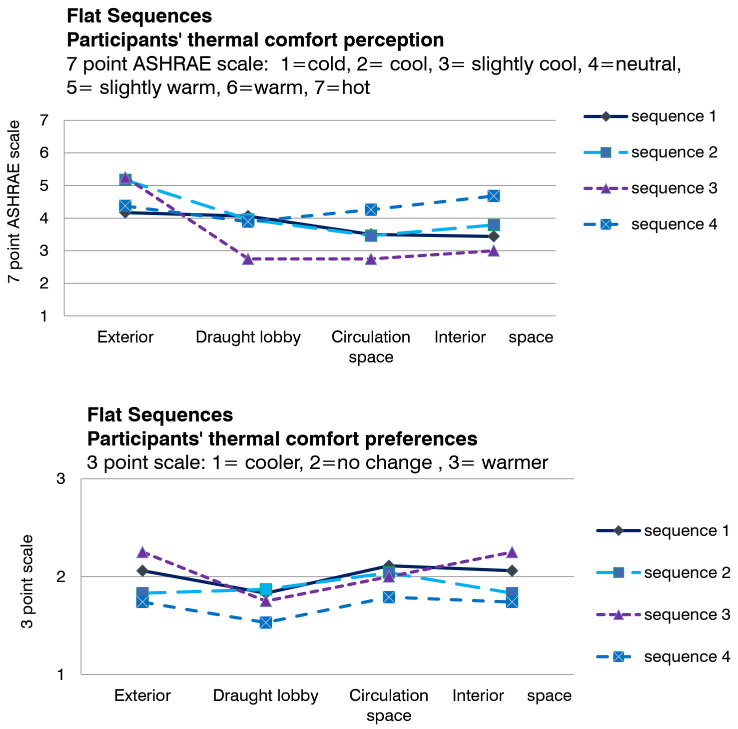


Figure 5-8 Flat sequences: A) participants' thermal comfort perception, B) Participants' thermal comfort preferences

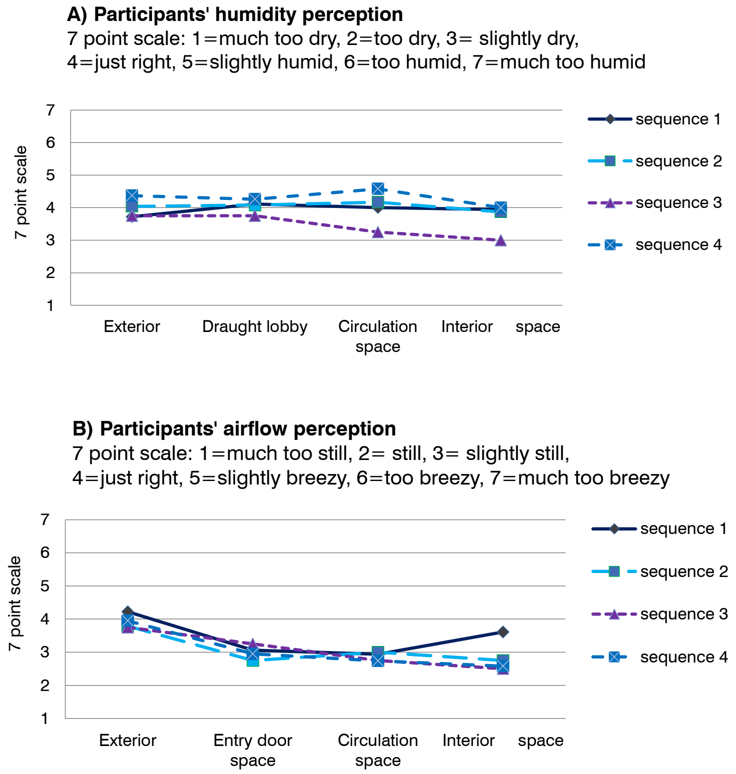


Figure 5-9 Flat sequences: A) participants' humidity perception, B) Participants' wind speed perception.

5.5.1. Temperature changes in flat patterns

In the flat patterns, the majority of people felt gradual, little and no temperature changes from one space to another from exterior to draught lobby 81%, from draught lobby to circulation space 74% and from draught lobby space to seminar room 88% (Figure 5-10). Repeated measures ANOVA and Friedman tests were conducted in order to compare participants' thermal comfort perception in each space and identify when a temperature change had a significant effect in participants' thermal perception. In both parametric and non-parametric tests it was found that small temperature changes (less than 2°C) did not have a significant effect in participants' thermal perception ($p>.05$) when they moved from one space to another. In the four groups, Friedman test showed no significant difference ($p>.05$) in participants' thermal perception of temperature changes. This could be explained by two reasons; first, because temperature changes in flat sequences were small, and second because the temperature ranges in the sequences involved moderate temperatures (from 20°C to 23°C). In addition, results illustrate that people felt comfortable with humidity and wind speed. Therefore, there were no additional factors provoking discomfort in this study.

In short, the impact of the use of the lobby unit, in participants' thermal perception in the seminar rooms, was not significant in flat sequences with small temperature differences between the spaces. In addition, the range of exterior and interior temperatures was within a moderate comfortable band (from 20°C to 23°C). However, it is probable that flat sequences with extreme temperature ranges (higher than 24°C or lower than 14°C) could provoke more uncomfortable results. This is a topic that needs to be explored further in order to determine the limits of a flat sequence in different climatic regions

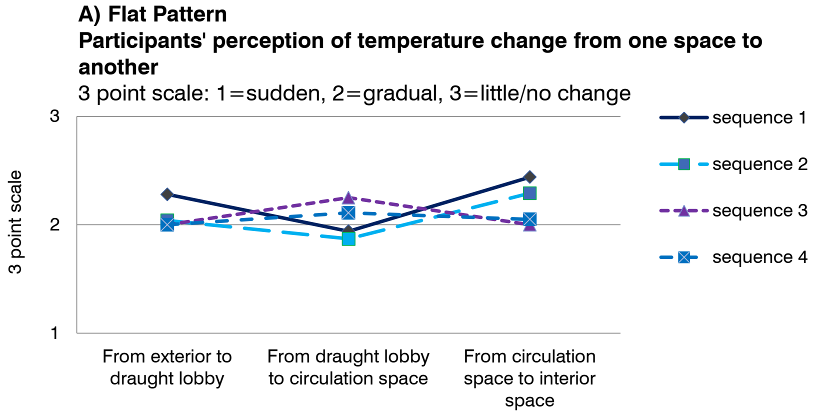
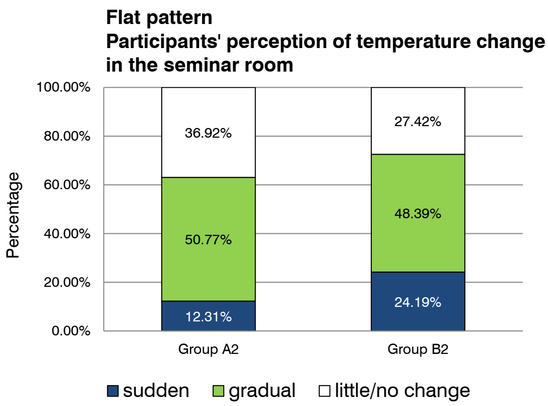


Figure 5-10 Participants' perception of temperature changes from one space to another

5.5.1.1. Comparison of temperature change perception between groups A and B In flat patterns

In the flat sequences, there was no significant difference in the way people from group A_2 and B_2 perceived temperature change from the exterior to the seminar room ($p>.05$), with around 80% perceiving 'gradual', 'little' or 'no change in temperature from exterior to interior in both groups (Figure 5-11). However, a narrower standard deviation in participants' responses was found in group A in sequence 1 (SD A_2=0.85, B_2=1.05), sequence 2 (SD A_2=0.83, B_2=0.85), sequence 3 (SD

A_2=0.81, B_2=1.41) and 4 (SD A_2=0.82, B_2=1.00). This result suggests that people in group A experienced a gradual thermal adaptation, but not one strong enough to alter their perception significantly. In addition, pairwise comparisons showed no significant difference in the way people from group A_1-A_2 and B_1-B_2 perceived temperature changes from exterior to interior ($p>.05$). Consequently, the use of the lobby unit was not significant in this context.



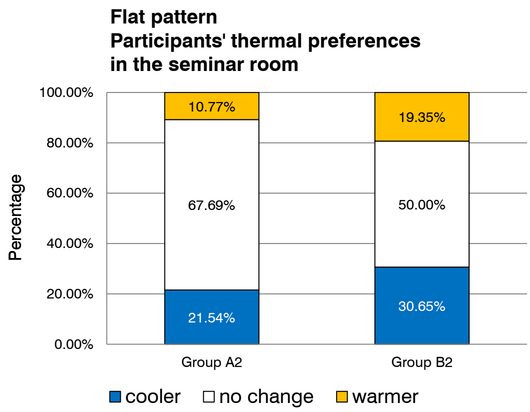


Figure 5-11 Flat sequences: participants' perception of temperature change and participants' thermal preferences

5.5.2. Short-term thermal history in the lobby unit In flat patterns

5.5.2.1. Example of flat sequence (1)

In the first flat sequence, it can be seen how different participants' thermal perception was after moving from one space to another (Figure 5-12). Participants' Thermal sensation vote (TSV) was statistically significant only in TC_1 and TC_4 ($p<.05$) in Friedman and ANOVA tests. This is because in the air temperature difference was 2°C in TC_1. Although, the temperature difference was small in TC_4, it involved a change towards a cooler environment, and this could explain the significant difference, since the body system is more sensitive to temperature changes towards the cold side (Jin et al. 2011). An interesting result was found in TC_2, where the same air temperature (20°C) was perceived differently in two spaces. Although 90% of participants' answers were within the comfortable band in both spaces (slightly cool, neutral and slightly warm), a larger number of 'slightly cool' answers were found in the circulation space. It seems that people did not perceive the 2°C decrease in air temperature until they arrived in the circulation space, this could be caused by a 'delay' in thermal sensation. As the changes from one space to another were quick (around 30 seconds), people in the draught lobby were still influenced by the exterior thermal conditions and were still in the process of adjusting to a cooler environment. This process did not seem to be complete until they were in the circulation space integrated in the lobby unit. These results are linked with a delay in participants' thermal sensations in relation with their actual thermal experiences (Jin et al. 2011).

Studies conducted in Liaoning, China, found 'hysteresis' (delay) in participants' thermal perception after moving from an interior space to the exterior and turning back again. This means that people perceive the same interior space cooler than originally, after going outside to a different temperature. They found a small delay with small temperature changes and in warm environments, but larger hysteresis occurred when people moved from warm to cold environments. When the PMV was calculated in the interior spaces (draught lobby, circulation space and seminar room) of this sequence, it was found that participants' current TSV matched better with the air temperature changes illustrated in the graphs than with results from PMV ('neutral' in all the spaces). These results are consistent with other previous studies in which the PMV and current peoples' TSV is different. This topic is extended in section 5.9, in which is compared the PMV in relation to the three thermal patterns (flat, sudden and irregular).

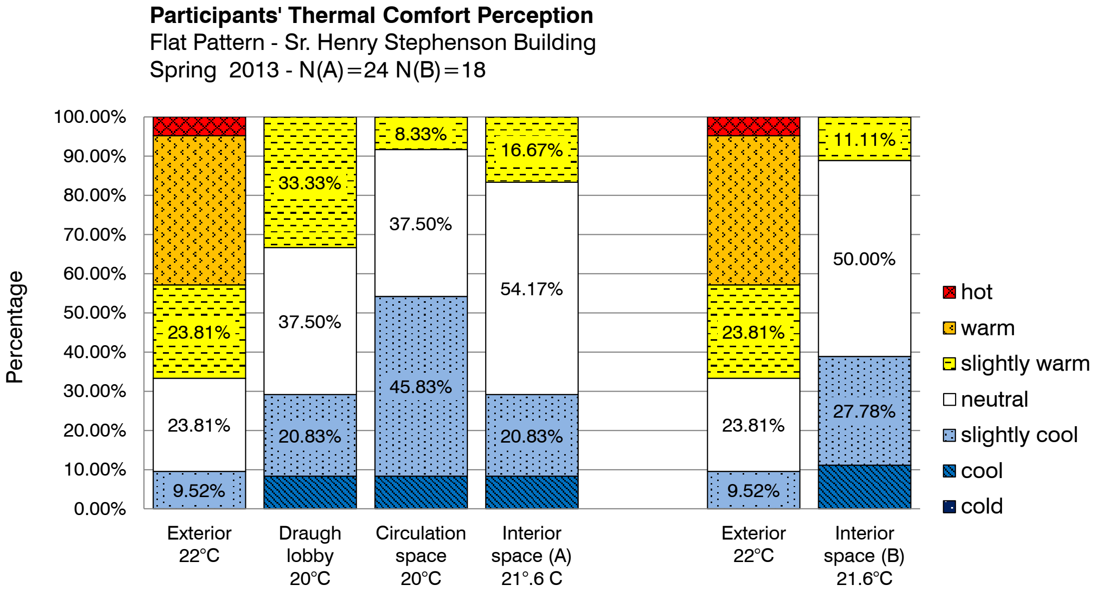


Figure 5-12 Participants' thermal perception in an example of a flat sequence (1)

In TC_3, there was an increase of 1.6 °C in air temperature; in this case, the difference in participants' thermal perception was not statistically significant ($p>.05$). However, it can be seen that the number of 'neutral' answers increased by 16.6% and the number of 'slightly cool' answers reduced by 25%. When comparing TC_3 with TC_4, responses were similar in both cases (90% comfortable). However, in TC_3 the resulting thermal perception came from the combination of previous temperature changes, while in TC_4 answers were more connected with the previous thermal experience at the exterior. Therefore, the results need to be carefully interpreted, since the combination of temperatures in the transitional spaces (group A) could trigger similar responses in people (group A and B) when they arrive in the seminar room. These findings show that it is important to be aware of participants' thermal history when conducting a thermal comfort survey in specific spaces. The PMV for transitional spaces, such as lobby units, should also take into account a range of physical, personal and psychological data from long and short previous thermal experiences (thermal history).

Finally, in TC_4, the air temperature difference was very small (0.4°C). However, participants' responses were significantly different ($p<0.5$). Perhaps, as the mean thermal preference in the exterior was 'no change' (feeling warm, slightly warm and neutral), people feeling warm and slightly warm moved their answer to slightly cool in the seminar room. In this case, as the change was immediately from exterior to interior (final destination), additional psychological factors and expectations could have more influence in participants' responses. In addition, in transitional spaces people were still in movement (met = 2.0), but in TC_4 people moved only once from the exterior to the interior, consequently their metabolic rate did not increase much .

5.5.2.2. Example of flat sequence (2)

In the next example of a flat sequence, air temperatures were the same (21°C) in all spaces, except the draught lobby space (22°C). Therefore, changes in participants' thermal comfort perception were not statistically significant between spaces ($p>.05$). However, from the graphs (Figure 5-13) it can be seen that 21°C was perceived slightly differently at the exterior and in the interior (circulation and seminar rooms). Other studies have found a similar pattern, reporting that people perceived the same temperature differently (even in controlled climatic conditions) after moving to the exterior and coming back to the same place (Jin et al. 2011). Studies have also found that the mean skin temperature has a different reaction moving away and coming back to the same place after (Liu et al. 2014). These differences were larger when moving towards a cooler environment. In this sequence, the largest difference was in TC_1 and participants' responses moved slightly from 'slightly cool' to 'neutral' and 'slightly warm'.

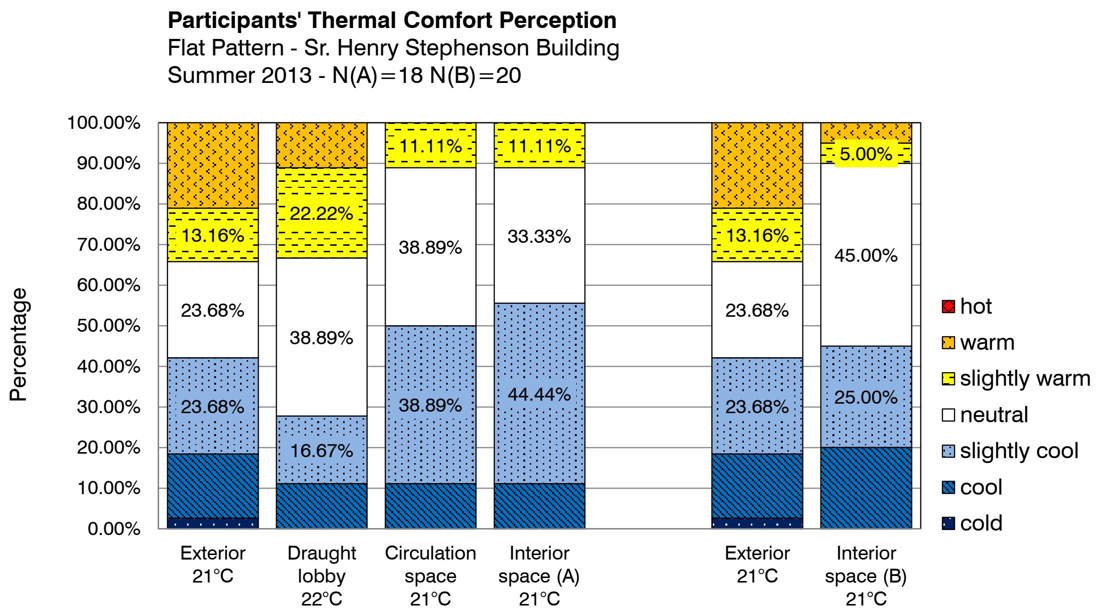


Figure 5-13 Participants' thermal perception in an example of a flat sequence (2)

Again, it seems that results in TC_4 could be explained more by psychological factors such as participants' expectations (Jitkhajornwanich 1999) and the psychological change from an exterior to an interior environment. In this sequence, the resulting PMV was 'neutral' and 'slightly warm' thermal perception (from 0.5 to 0.71), however in reality people were feeling 'slightly cold' in the interior spaces and 'slightly warm' at the exterior. Also, people preferred 'no change' and 'warmer' temperatures at the exterior; this could also be a key factor that made people assume or expect that the interior was colder than the exterior and therefore give different responses in the interior. Additional graphs illustrating flat sequences are found in Appendix 12.

5.6. Sudden patterns (from cold to hot) in thermal sequences

With respect to the sudden patterns, in the exterior 85% of participants' answers were towards the cold band (1=cold, 2=cool and 3=slightly cold), in the draught lobby space 85% felt within the comfortable band (3=slightly cold, 4=neutral and 5=slightly warm), in the circulation space 79% felt within the comfortable band and in the interior space 81% of participants' answers were towards the warm band (5=slightly warm, 6=warm and 7=hot) (Figure 5-14). In general, participants' thermal perception was more comfortable when walking towards the seminar rooms. However, participants' thermal preferences moved opposite to their thermal perception (Figure 5-15).

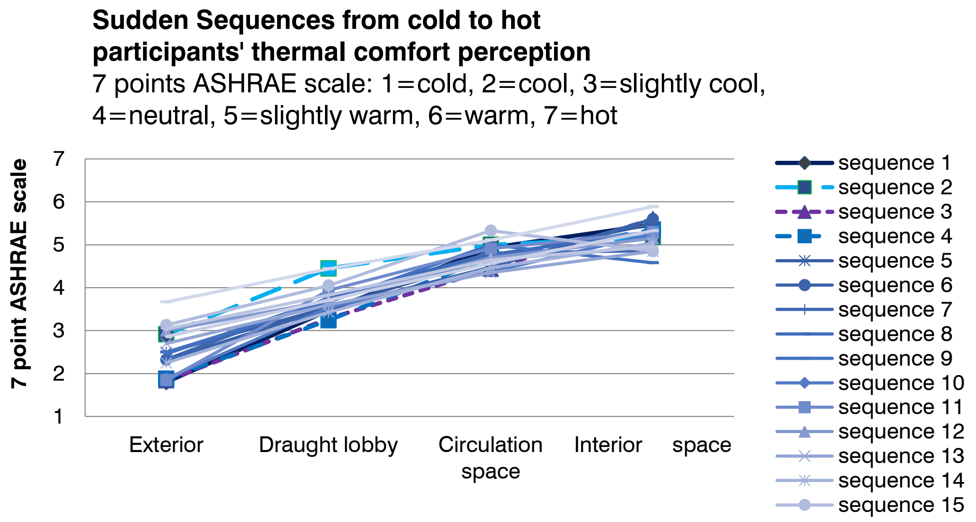


Figure 5-14 Sudden sequences from cold to hot: A) participants' thermal comfort perception

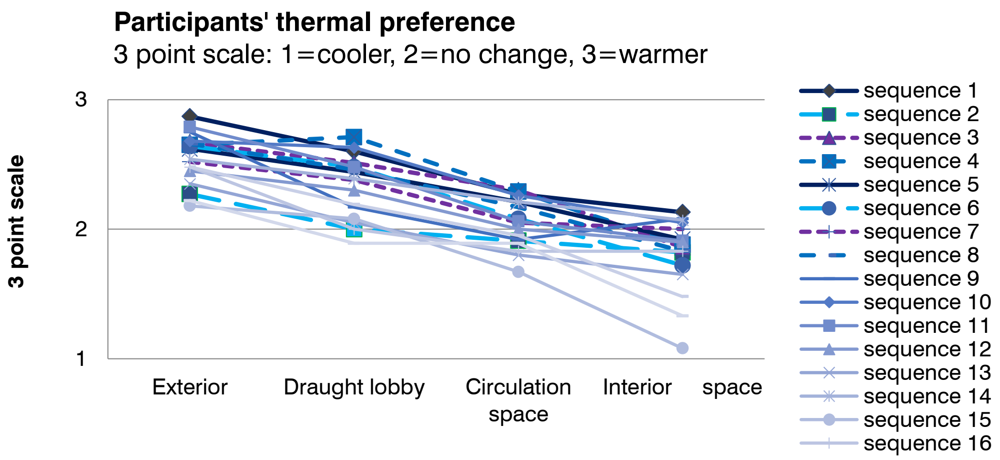
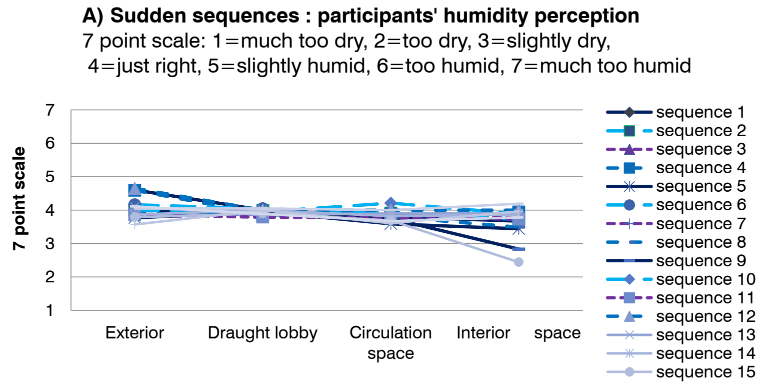


Figure 5-15 Sudden sequences from cold to hot: participants' thermal preference.

Finally, the relative humidity was perceived as 'just right' by more than 80% in all of the spaces. Wind speed was perceived 'slightly breezy' and 'too breezy' at the exterior and gradually perceived 'just right', 'slightly still' and 'still' in the interior space (Figure 5-16). Therefore, it can be concluded that participants were comfortable with relative humidity and wind speed. This helps in the interpretation of the results, since it can be seen that these two variables do not have a significant impact in participants' thermal perception. Again, as illustrated in Chapter 4 and reported in previous work, participants could also experience a seasonal adaptation to the changing relative humidity throughout the year. This gradual adaptation could explain their comfortable answers. In addition, the differences in relative humidity values between the spaces were not large enough to trigger a significant negative impact.



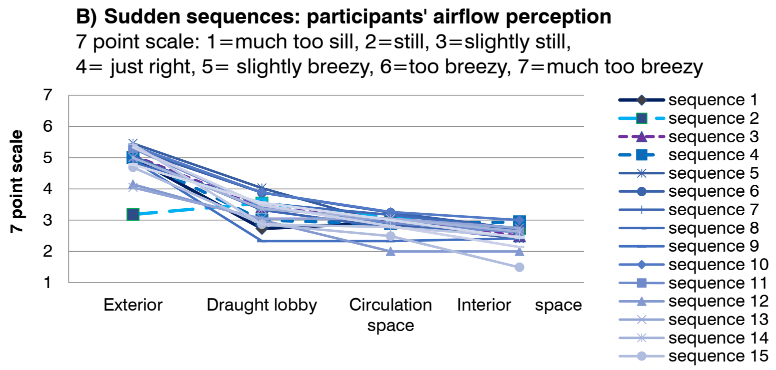


Figure 5-16 Sudden sequences from cold to hot: A) participants' humidity perception, B) Participants' wind speed perception.

5.6.1. Temperature changes in sudden patterns

Regarding the sudden sequences from cold to hot, temperature changes from one space to another were between 0°C and 13°C. The 18 groups of participants experienced larger temperature changes between the spaces than the four groups from flat patterns. The largest temperature change was identified from exterior to draught lobby (up to 9 °C), followed by draught lobby to circulation space (up to 7.6 °C) and circulation space and seminar room (up to 5.2 °C). The maximum temperature difference from exterior to seminar room was 13°C. Repeated measures ANOVA and Friedman tests revealed significant differences ($p<.05$) in participants' thermal perception from one space to another in all the sudden sequences. A post-hoc test in each sequence revealed that results were not significant in consecutive spaces with equal temperatures or with a variation of ±1°C, when the majority of the sample population felt a 'gradual', 'little' or 'no change' in temperature from one space to another (Figure 5-17). People perceived the relative humidity as comfortable in all the spaces. However, people perceived the wind speed as 'slightly breezy' at the exterior and comfortable in the following spaces. Overall, both variables did not significantly impact participants' thermal perception.

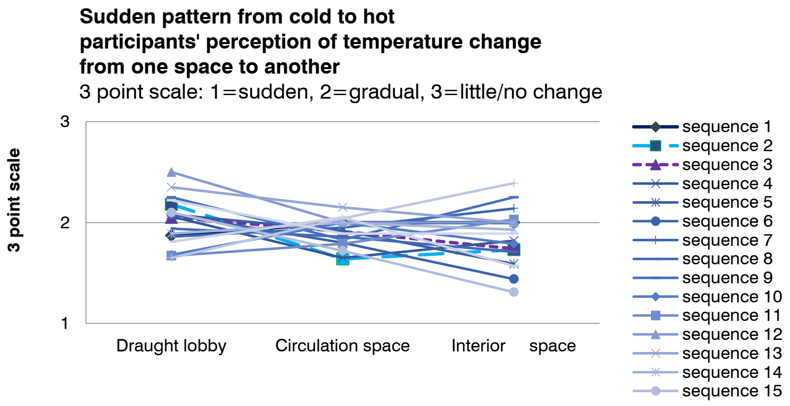
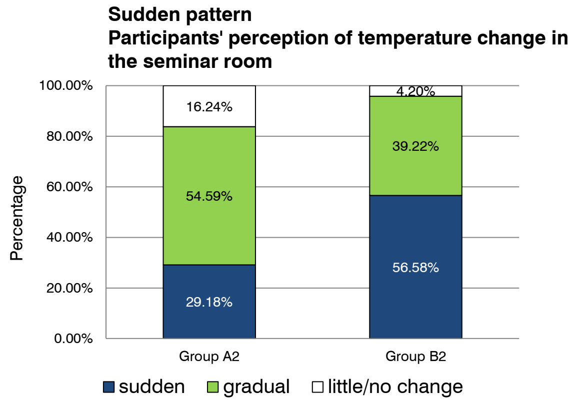


Figure 5-17 participant's thermal perception in sudden patterns

It is worth noting that although the sudden sequences involved large temperature changes from the exterior to interior environment; a logical temperature order was identified going from cold to hot. Hence, participants' responses followed the same pattern going from the cold band towards the hot band. Sudden patterns with a clear thermal direction altered participants' thermal perception more effectively when they arrived at the seminar room. It can be expected that gradual temperature changes in the same direction have a better influence for guiding people towards a desired comfortable thermal perception. This is an important finding of this research that can inform better thermal connections between spaces in building design.

5.6.1.1. Comparison of temperature change perception in groups A and B In sudden patterns

In contrast to flat patterns, in sudden patterns, the use of the lobby unit had a significant effect ($p<.05$, $N(A)=441$, $N(B)=361$) in participants' perception in the seminar room. Moreover, 56% of people in group B perceived a 'sudden' change in temperature compared with 29% in group A. The use of the lobby unit triggered more 'gradual', 'little' and 'no change' thermal preference responses in group A_2 in the seminar room (71%) than in group B_2 (43%). Interestingly, when comparing thermal perception results with participants' thermal preferences in the seminar room, group B_2 preferred 'no change' (Figure 5-18). This can be explained because at the outside, a large number of participants (A_1 and B_1) wanted to be warmer, consequently group B_2 immediately experienced a warmer temperature directly satisfying their thermal preference. Accordingly, the use of lobby the unit had more influence in participants' thermal perception. However, a strong or weak influence depended on two additional factors: the way people perceived temperature changes (gradual, sudden, little or no change) and participants' thermal preferences before moving to the interior space. The later might be connected with people's thermal expectations as in results conducted by Jitkhajornwanich and Pitts (2002).



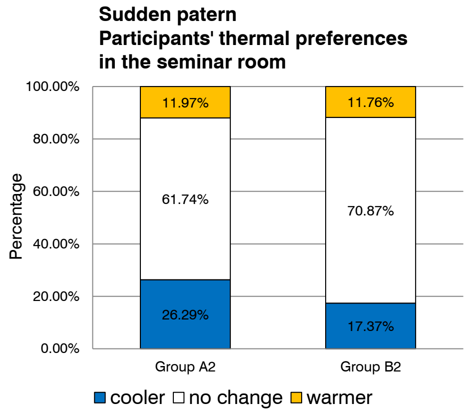


Figure 5-18 Sudden sequences: participants' perception of temperature change and participants' thermal preferences

5.6.2. Short-term thermal history in the lobby unit in sudden patterns

5.6.2.1. Example of sudden sequence(1)

This first example of a sudden sequence was from a survey conducted in winter in HS building (Figure 5-19). First of all, by knowing the period of time, it can be expected that large temperature differences between the exterior and interior spaces occurred, and people wanted to be warmer. Since the exterior temperature is lower than 14°C, temperature changes (A_1-A_2 and B_1-B_2) towards the warm side can be expected to be significant. From the graph it can be observed that participants' thermal perception before and after entering the seminar room was significant in both groups (A_1-A_2, B_1-B_2 $p<.001$). However, when comparing participants' responses from group A_2 and B_2, results were not significant ($p=.763>.05$). This could be because of the effect of the large temperature difference (exterior-seminar room=9.6°C ΔT) in both groups. It could be also due to the majority of people at the exterior wanting to be 'warmer', provoking answers towards the warm band in both groups.

An interesting effect was found in this sequence, as in many others. It seems that people experienced a psychological 'sense of arrival' when arriving at the seminar room (final destination), which had an effect in their thermal perception. In other words, when people arrived at their final destination and stopped walking, they seemed to perceive the interior environment in a different way (more aware) than in the transitional spaces. This could also be caused by the sudden change of their metabolic rate from an active to a passive state. For example, in this example, people experienced the largest temperature change in TC_1 and TC_4. However, by the time that group B experienced this change, arriving at the seminar room (19.5°C), group A was in the draught lobby space (18.5°C). From this point, group A experienced very small temperature changes in TC_2 and TC_3, and their answers were completely towards the warm band until they arrived at the seminar room.

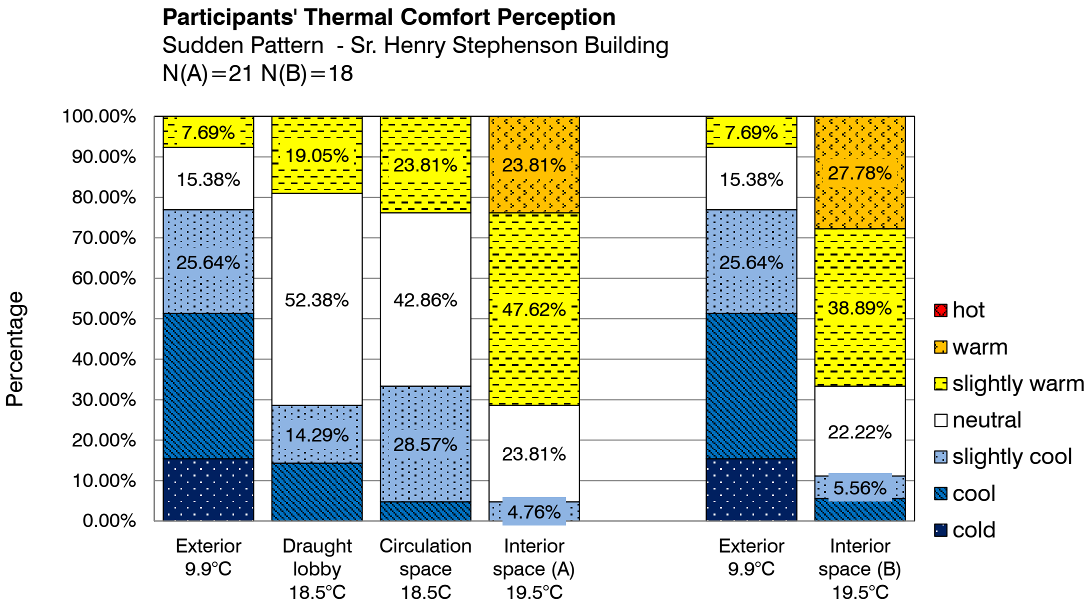


Figure 5-19 Example of participants' thermal perception from one space to another in a sudden sequence (1)

5.6.2.2. Example of sudden sequence (2)

In the second sudden sequence, also conducted in winter, 90% of participants gave answers within the cold band (slightly cool, cool and cold) at the exterior and the majority preferred to be 'warmer' (Figure 5-20). The total air temperature difference from exterior to interior was 7.9°C. Therefore, participants' responses in TC_1 and TC_4 changed immediately towards the comfortable band (slightly cool, neutral and slightly warm), and a significant difference was found in participants' thermal perception ($p<.01$) from Wilcoxon and T-tests. Significant differences were also found between TC_2 and TC_3 ($p<.05$), although the before and after temperatures were either the same (TC_2) or 1 °C different (TC_3). The thermal comfort perception in group A increased towards the warm side as they moved towards the seminar room. In TC_1, as in previous sequences, it can be suggested that people in the draught lobby space (20.0°C) were still influenced by the effect of the colder exterior temperature (13.1°C). However, in TC_2, since participants' previous perception (in the draught lobby space) was neutral, their thermal perception in the circulation space (20.0°C) was influenced this time by that previous neutral thermal perception. Hence, their thermal sensation votes were different in two different spaces with the same air temperature.

Since the larger temperature differences were experienced previously, TC_3 showed no significant differences, since people were already feeling warm and comfortable in the circulation space. Moreover, at this point (the circulation space of the lobby unit) they preferred to be 'colder'. An interesting finding related to participants' perception in this sequence was that, before arriving at the seminar room, people in group A wanted to be 'colder' while people in group B wanted to be 'warmer'. Therefore, their thermal perception in the seminar room was also influenced by their thermal preferences. It can be seen that people in group A perceived a warmer temperature in the seminar room than people in group B. Another possible explanation is that people in group A walked a longer trajectory to the seminar room than group B; this could have kept their metabolic rate (met =2.0) higher than that of people in group B. Participants' TSV was calculated in the four spaces, the resulting PMV did not comply with either the steady state requirements or with the adaptive method. The PPD was larger than 5% in all cases. Additional graphs illustrating sudden sequences are found in Appendix 12.

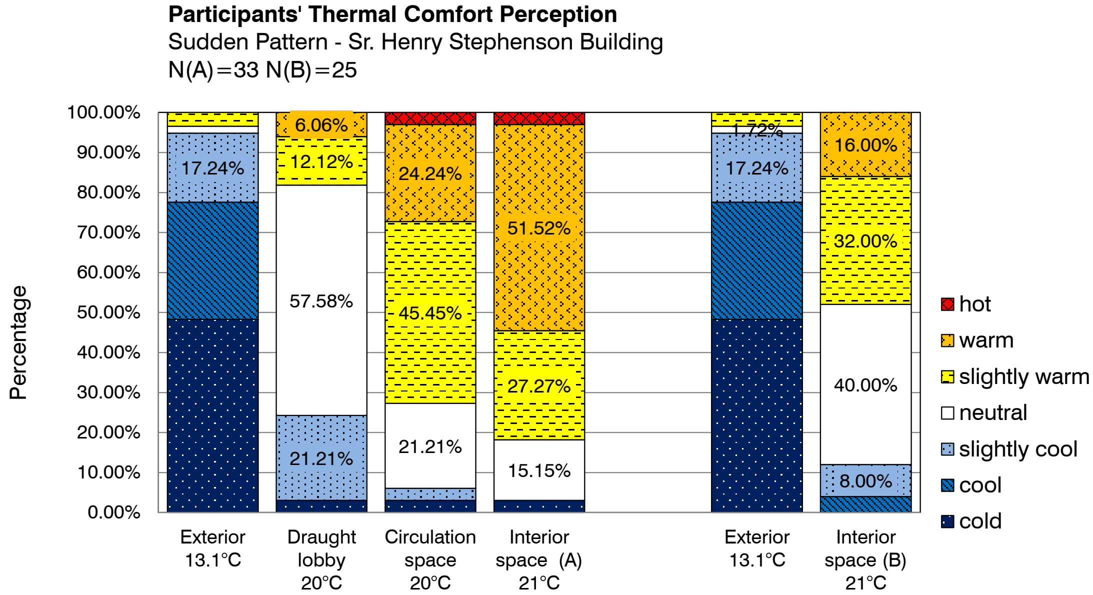
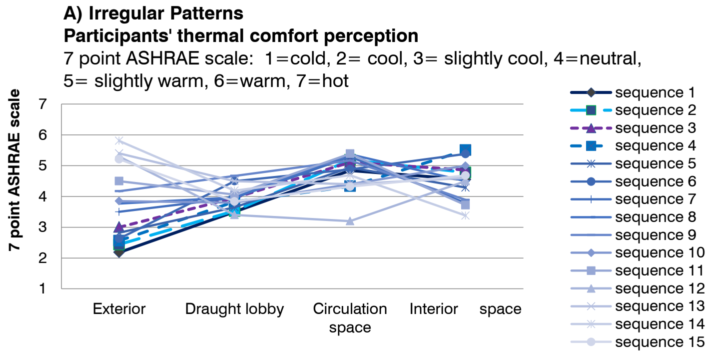


Figure 5-20 Example of participants' thermal perception from one space to another in a sudden sequence (2)

5.7. Irregular patterns in thermal sequences

In the irregular patterns, 60% of participants were comfortable at the exterior, 27% were uncomfortable cold and 13% were uncomfortable warm. When moving to the draught lobby, the number of people feeling comfortable increased to 84.5%. In the circulation space, the number of people feeling comfortable reduced again to 74%, at this point 24% felt uncomfortable warm. In the seminar room, 78% felt comfortable and the majority of the people feeling uncomfortable were feeling warm and hot 17% (Figure 5-21). In the same way, participants' thermal preferences were variable in each space. At the exterior 45% of the participants wanted 'no change' in the temperature, and 26% wanted to be 'warmer'. In the draught lobby 56% wanted 'no change' and still 26% wanted to be 'warmer'. In the circulation space 56% wanted 'no change', however 33% wanted to be 'cooler'. Finally in the seminar room, 61% wanted 'no change' and 26 % wanted to be 'cooler'. Results were similar to the sudden sequences, in which participants' thermal preferences wanted to be 'warmer' when they were at the exterior, but 'cooler' when they moved to the circulation space. Regarding relative humidity, people were comfortable in all the spaces and their perception was that it was 'just right'. Wind speed perception was variable at the exterior, but it was perceived as 'just right', 'slightly still' and 'still' in the interior spaces.



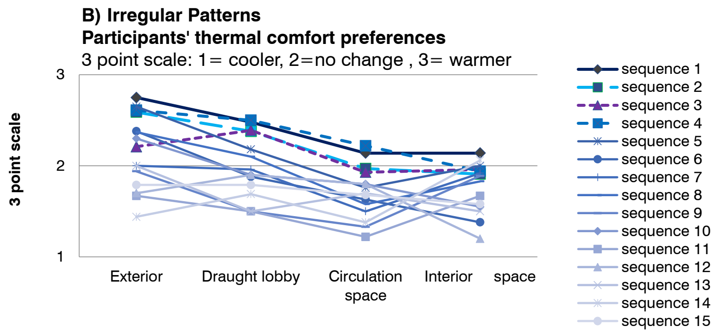
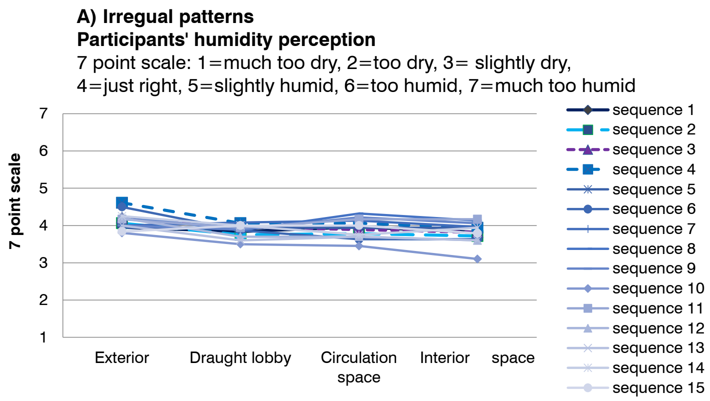


Figure 5-21 Irregular patterns: A) participants' thermal comfort perception, B) Participants' thermal preferences



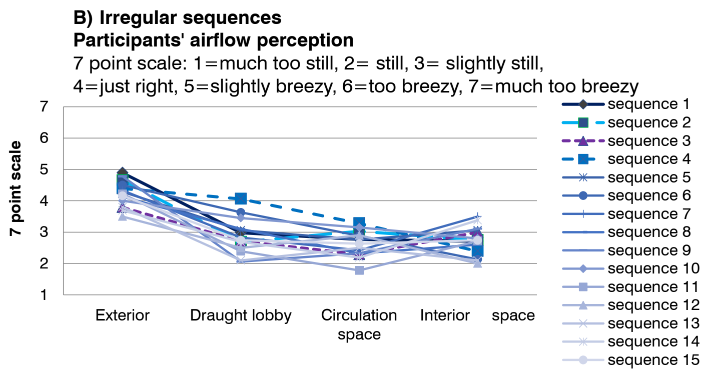


Figure 5-22 Irregular sequences: A) participants' humidity perception, B) Participants' wind speed perception.

5.7.1. Temperature changes in irregular patterns

In the irregular patterns, the 15 groups of participants experienced large temperature changes between the spaces. The largest temperature differences was from draught lobby to circulation space (up to 7.6°C), followed by exterior-draught lobby (up to 4.0 °C) and circulation-seminar rooms (up to 2.1 °C). The largest temperature difference from exterior to seminar room was 9.1 °C. Repeated measures in ANOVA and Friedman tests revealed significant differences ($p<.05$) in participants' thermal perception between the spaces in all the sequences. A post-hoc test in each sequence 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. Therefore it could be suggested that a ± 1°C difference can make a significant difference when people experience the temperature change in an extreme hot or cold temperature range. Finally, temperature differences larger than 3°C from the draught lobby to the circulation area revealed significant differences. Similar to the other patterns, wind speed and air temperature were perceived within the comfortable band (Figure 5-23).

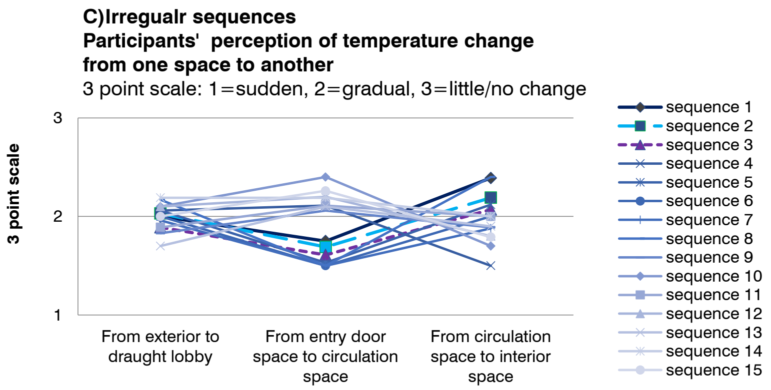


Figure 5-23 Participants' thermal perception for temperature changes from one space to another in irregular sequences

5.7.1.1. Comparison of temperature change perception in groups A and B in irregular patterns

Results from independent sample tests in the irregular patterns (A_2 vs B_2), revealed no significant differences in participants' thermal perception in the seminar room ($p=.320>.05$, $N(A)=334$, $N(B)=207$), illustrating variable answers due to changing thermal conditions. However, paired comparisons showed significant differences in both groups (A_1-A_2 and B_1-B_2) after moving to the seminar room: A_1-A_2 ($p=.01<.05$ $N=344$) and B_1-B_2 ($p=.006<.05$ $N=207$). In other words, people in each group independently experienced significant temperature changes ($A_1 \neq A_2$ and $B_1 \neq B_2$) but gave very similar responses when they arrived at the seminar room ($A_2=B_2$). In the seminar room 44% of group B perceived sudden temperature changes compared with in 20% group A (Figure 5-24). Also, more participants' in group B seems to preferred to be cooler than in group A. However, these responses were possibly triggered by other factors, since these patterns involved variable temperature changes. One particular interesting factor that could explain these results was the change of thermal direction that people experienced in some of the irregular sequences. This means that people changed their thermal sensation vote when moving from cold to hot, then from hot to cold and finally from cold to hot spaces again. This change of direction could also be altering participants' thermal perception before arriving in the seminar rooms. It was identified that in the irregular patterns, a case-by-case analysis could bring to light more specific results that could better explain the influence of the lobby unit in participants' thermal perception.

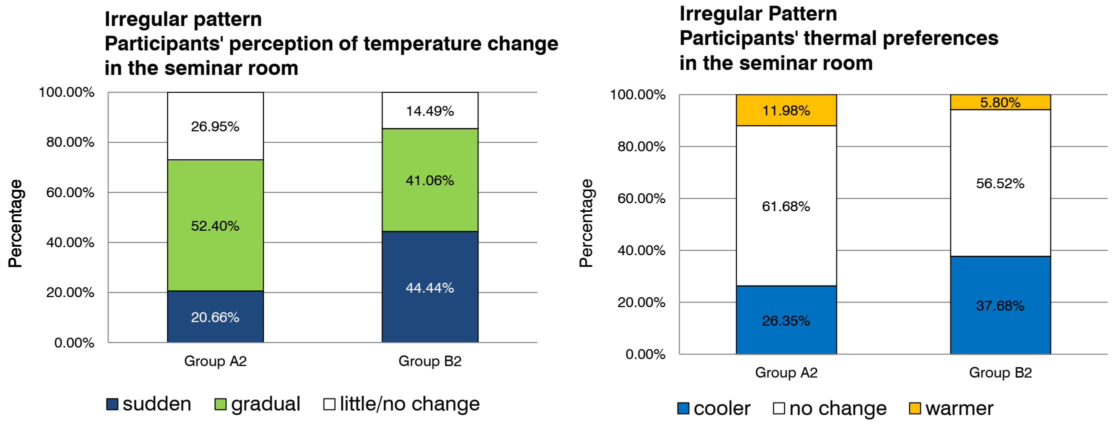


Figure 5-24 Irregular sequences: participants' perception of temperature change and thermal preference.

5.7.1.2. Change of thermal direction in irregular patterns

In flat and sudden sequences, it was shown that when people moved in one thermal direction, from cold to hot or from hot to cold, there was a major effect of the use of the lobby unit in participants' thermal perception. Since people are moving in the same thermal direction, the added thermal effect of the previous spaces contributes to alter participants' perception towards a cold or hot band. Conversely, in some irregular sequences, when there is no logical order in temperature changes, previous thermal experiences in participants' short-term thermal history can override them quickly, effectively cancelling them out. In this study, 'change of temperature direction' was one of the identified variations in the irregular patterns. It was noted that this factor had a significant effect in participants' thermal perception in a sequence of spaces. Two key patterns of thermal direction were identified. The first one involved only one change at the end of the sequences, after moving from cold to hot. This indicates a sequence of 'warmer-warmer-colder'. The second one included two changes of direction, 'colder-warmer-colder' (Figure 5-25).

Sequences with one change in thermal direction were analysed using Friedman and Wilcoxon signed rank tests. Results illustrated no significant differences in participants' thermal comfort perception after a change of temperature of less than 2°C ($p>.05$ $N= 197$). Therefore, this temperature difference was not large enough to alter participants' thermal perception in a different direction. Interestingly, however, a temperature change larger than 2°C had a significant effect in participants' responses in one of the sequences ($p<.001$ $N=24$). On the other hand, different results were found when analysing sequences with two alterations in thermal direction. Sequences with more than one thermal direction were found during summer, with temperature changes in the range 21°C to 27°C. It can be seen that a double change of direction with from 1 °C to 4°C difference can significantly alter participants' thermal perception, very quickly (p<.05). It can therefore be suggested that the alteration of thermal direction in transitional spaces could also reduce the positive thermal effect at the final destination (Figure 5-26) .More complex interaction and alterations occurred in participants' perception when moving in different thermal directions.

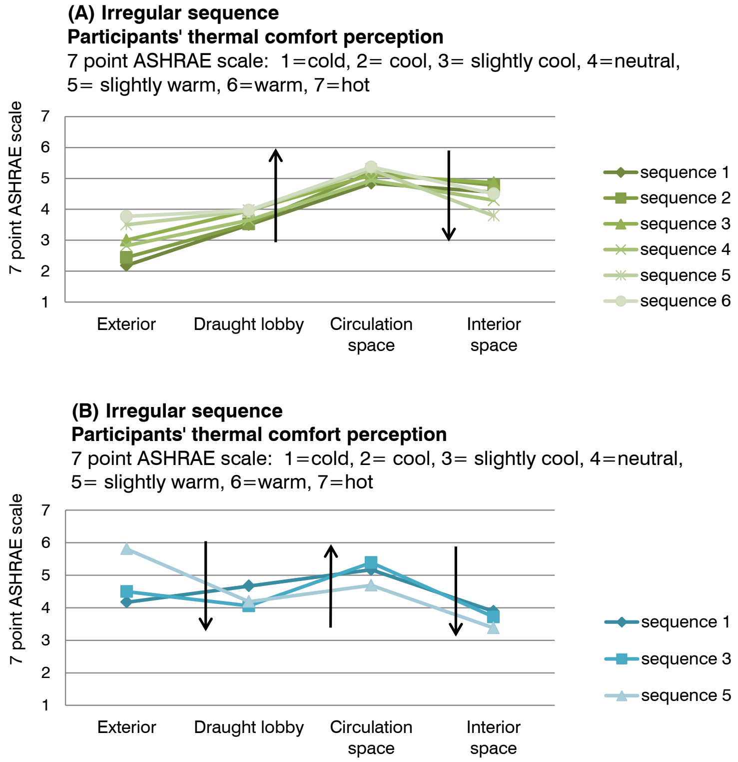


Figure 5-25 Irregular sequences: A) one change of thermal direction, B) two changes of thermal direction.

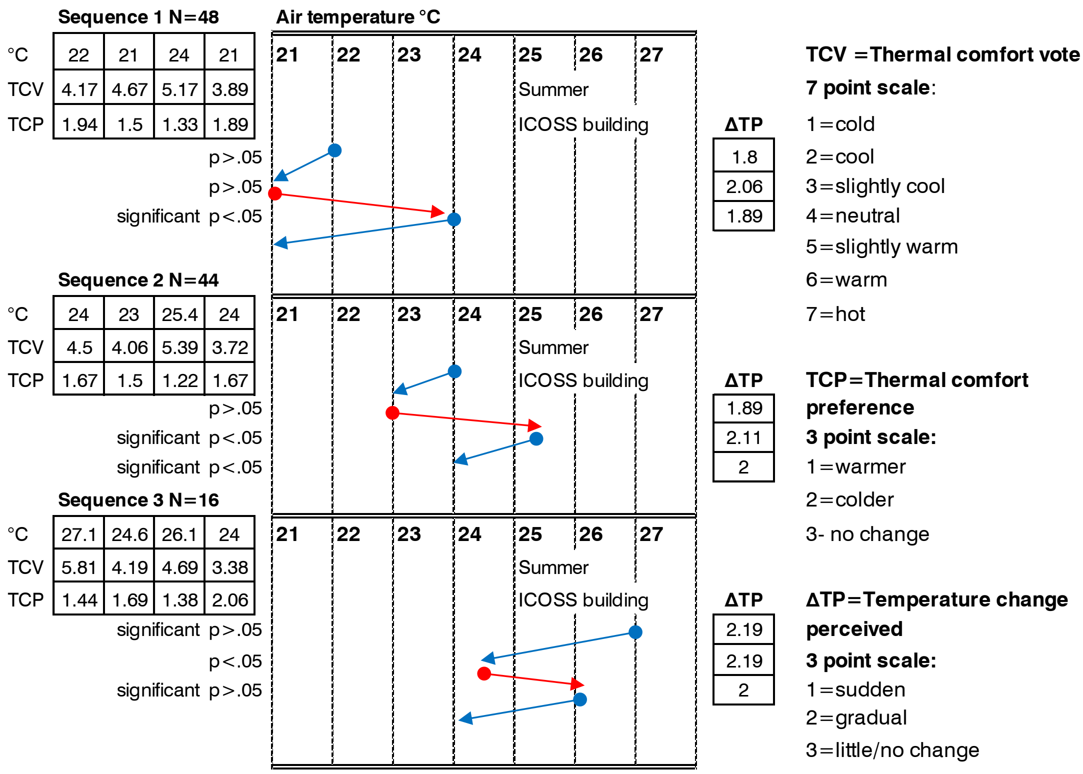


Figure 5-26 Examples of participants' thermal perception with change of direction in irregular sequences

Results from this study extend the overview of previous laboratory work conducted by Chun and Tamura (2004) in Yokohama, Japan. They named it 'relative placement of temperature' to refer to the effect of a fixed temperature in participants' thermal perception, depending on its position in the sequence (first place, middle or final). Results from this research illustrated many additional combinations of temperature order and temperature differences (ΔT), extending the range studied by Chun and Tamura (from 18 to 30°C /ΔT =2,4 and 6°C).

5.7.2. Short-term thermal history in the lobby unit in irregular patterns

5.7.2.1. Example of irregular pattern(1)

In the irregular sequences, participants' thermal perception in the seminar room was significantly different between group A_2 and group B_2 (Figure 5-27). The resulting participants' thermal perception in the seminar room in group A was the outcome of the interaction of a sequence of different temperature changes before arriving at the seminar room. In the first example, people in group A experienced a sudden temperature change in TC_2, triggering a significant difference in thermal perception ($p<.01$) between the two spaces. Consequently, people in the circulation space preferred to be 'cooler' before entering the seminar room. In contrast, the majority of people in group B wanted to be 'warmer'. This could have provoked more people in group A to perceive the seminar room 'warmer and neutral' than in group B, since group A still had the previous effect of the uncomfortable 24.8 °C in temperature in the circulation space.

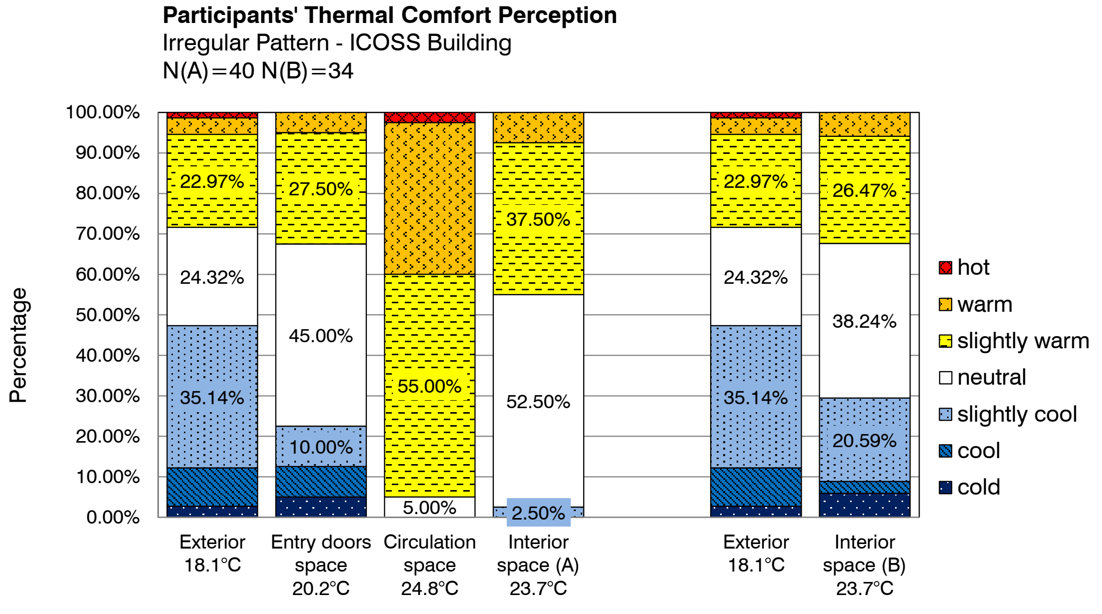


Figure 5-27 Participants' thermal comfort perception in an example of irregular pattern (1)

In contrast, since people were comfortable with the exterior environment (82%), no significant difference in thermal comfort was found in group B before (B_1) and after (B_2) moving to the seminar room (85%). However, people in group A had significant differences in their responses in TC_2 and TC_3 ($p<.01$) when using Wilcoxon and paired T-Tests. In group A, in TC_3 the delay in participants' thermal perception plus the added effect of their metabolic rate (walking, met=2.0) provoked warmer thermal perception in the final destination. Again the calculated PPD was far larger than 5% in the seminar room (11-29%), even in spaces where 82% of people reported feeling comfortable (e.g. draught lobby). Finally, the use of PMV was not suitable for dynamic conditions, since the predicted sensation did not match participants' current thermal sensation vote in any of the four spaces.

5.7.2.2. Example of irregular pattern (2)

In another example of an irregular sequence (Figure 5-28), participants experienced a 'change of thermal direction' in air temperature while walking towards the interior space. At the start of the sequence, around 80% of answers were towards the warm band and preferring a cooler temperature. Group A experienced a larger initial temperature change (TC_1=25°C - 21°C) than group B (TC_4= 25°C - 24°C) and therefore their thermal responses changed significantly ($p<0.01$) since TC_1 decreased 4 °C. In the following temperature change for group A (TC_2) the temperature increased 1°C, however in TC_3 the air temperature increased again 2°C toward a warmer uncomfortable temperature (24°C). A change in temperature altered the positive thermal direction in participants' thermal perception (warm+warm = warmer but warm+cool = variable thermal perception).

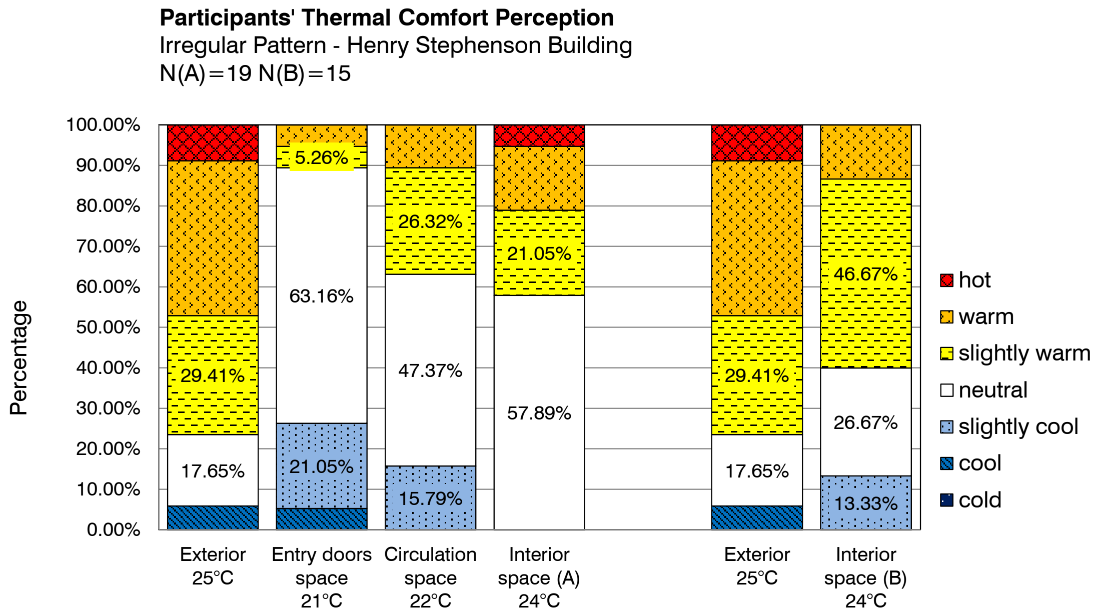


Figure 5-28 Participants' thermal comfort perception in an example of irregular pattern (2)

In summary, the use of the lobby unit in this study did not have a significant impact in participants' thermal perception when the difference in temperature between spaces did not follow an order (increasing or decreasing). In the irregular patterns, participants' thermal perception in the seminar rooms was the resulting value of different combinations of temperature changes. Moreover, in some cases, people experienced one or two changes of thermal direction, which could have altered their perception twice before entering the seminar room. Therefore, these findings could be the reason why in some cases, the final comparisons between groups A_2 and B_2 revealed no significant difference. This study also confirms that people can perceive the same temperature differently in two sequential places, in the same way that Jin (2011) and Liu (2014) found that people perceived the same space differently after going out and coming back. It is important to note that in this thesis people experienced temperature changes very quick compared to previous studies where people remained in the chamber for at least 10 minutes before moving to the next chamber. Additional graphs illustrating irregular sequences are found in Appendix 13.

5.8. Summary of ranges of temperature changes

Findings from this work related with temperature changes have expanded the range of temperature changes that can be considered in the literature, starting from a different set of temperatures. From Figure 5-29, it can be seen that the majority of previous studies were conducted in extreme warm temperatures where AC is mostly required. However, outcomes from this thesis cover a wide range of information that can benefit temperature ranges predominantly found in moderate climates where AC can be totally eliminated. The graphical representation of these temperature changes also helps to understand under which initial and final air temperature values people experienced a significant change in their thermal perception. Not many findings from this thesis can be directly compared with previous experiments, since this thesis covers a new range of temperature changes. In addition, the majority of these studies were conducted in laboratories and include time for people to reach thermal equilibrium before the experiment. However, the comparison with earlier work help to expand the understanding of the effect of different temperature ranges in participants' thermal perception. The results summarize the findings presented in the previous sections. Additional discussions on the implications of these findings are set out in section 6.2 and 6.5.

Perhaps one reason why the majority of previous work has examined hot temperature ranges towards cold environment is because the use of AC is more common in these climatic regions and there are larger temperature differences. From the summary of previous results, it can be seen that temperature changes in the warm band were always significant. In the transition band, results from previous work show significant results in all the larger temperature differences (above 4°C) which were not covered in this study (up to 4°C).

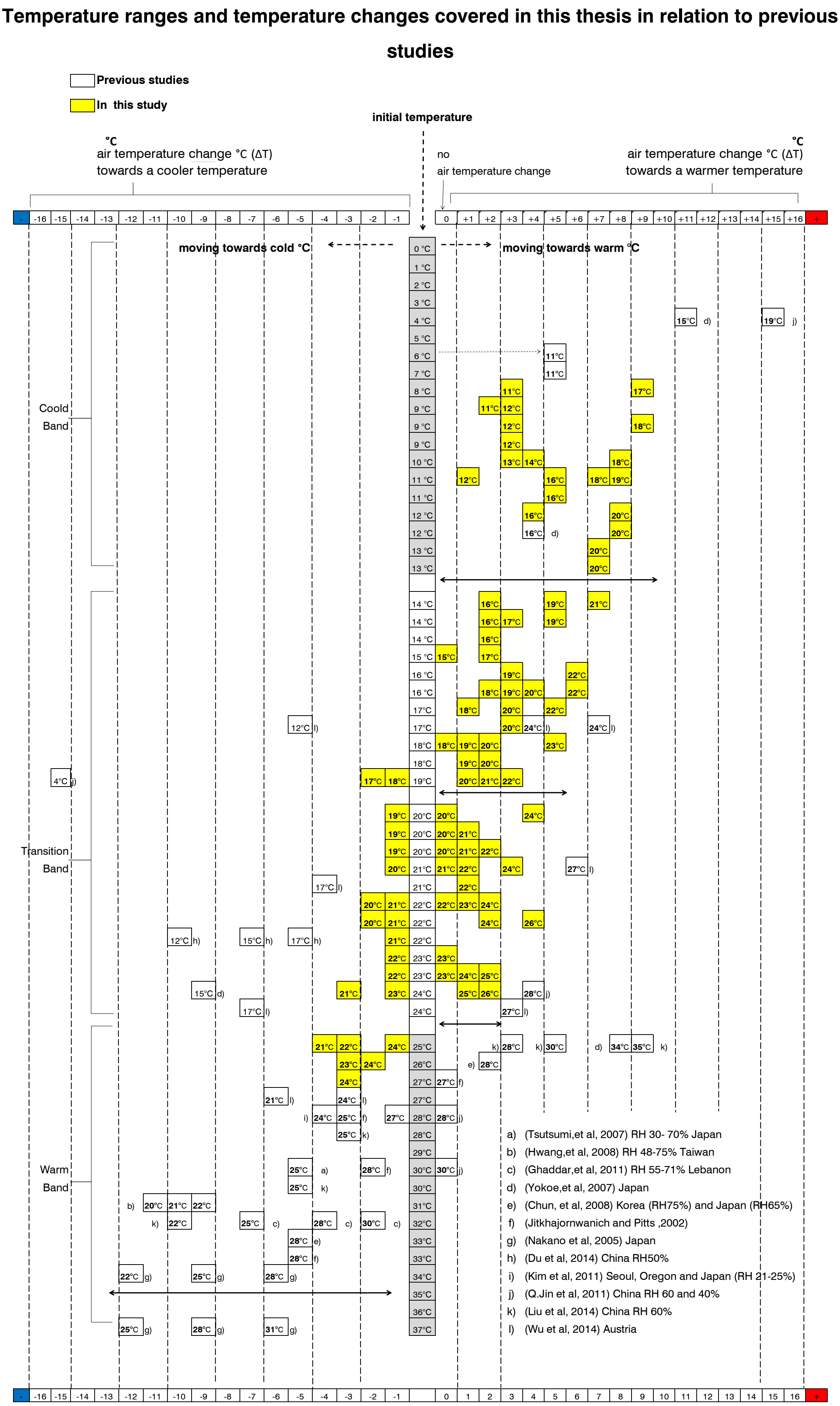


Figure 5-29 Comparison of air temperature changes in this study with previous studies

In this thesis, temperature changes from space to space were analysed in relation to the 46 thermal bins. Parametric (repeated measures ANOVA, post-hoc test, and paired T-test) and non-parametric (Friedman and Wilcoxon signed rank) statistical test were used in each sequence in order to identify significant differences in participants' thermal responses between the four spaces, in group A: (exterior-draught lobby space, draught lobby-circulation space and circulation space-seminar room), and in group B (exterior-seminar room). A total of 133 temperature changes were analysed, taking into account that some of the bins did not include participants in either group A or group B. The temperature changes started from an initial outdoor temperature between 6°C and 27°C (21°C range). The maximum temperature difference between spaces was 9°C and the minimum was 0°C.

Surprisingly, in this study, the thermal pattern classification shows that some temperature changes can have a different effect, depending not only on the temperature difference value (ΔT), but also on the location of the initial and final temperature within a temperature range. Significant and non-significant results in participants' thermal perception after a temperature change are illustrated in different graphs for each of the three types of sequences: flat (Figure 5-30), sudden (Figure 5-31) and irregular (Figure 5-32). Based on the significant results from participants' responses, three temperature ranges were identified and were named 'cold band', 'transition band' and 'warm band'. In the cold band (from 6 to 13°C) temperature changes always had a significant effect in participants' thermal perception ($p<.05$). In this range, temperature changes were always towards the warm side (cold to hot). In contrast, in the transition band, participants' thermal perception is more variable with a combination of significant and non-significant results. Also, temperature changes were towards both cool and warm bands. In this temperature range, temperature changes of ± 1°C were always not significant in the three patterns. In the same way, when the temperature difference between two spaces was 0°, results were not significant either. Finally, in the warm band (above 24°C) temperature changes were always significant and temperature changes were always towards the cool side (from hot to cold).

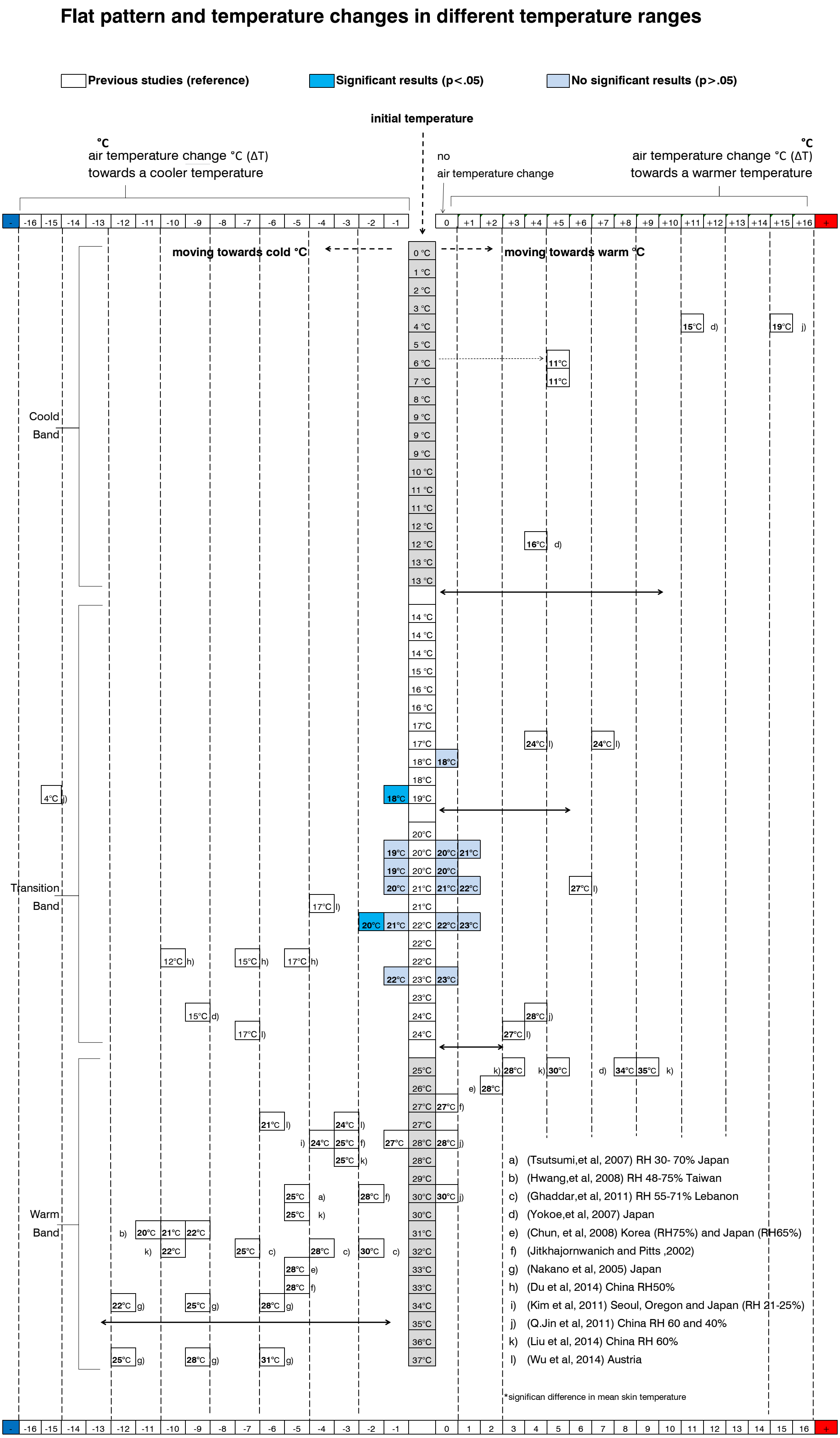


Figure 5-30 Flat pattern and air temperature changes in different temperature ranges

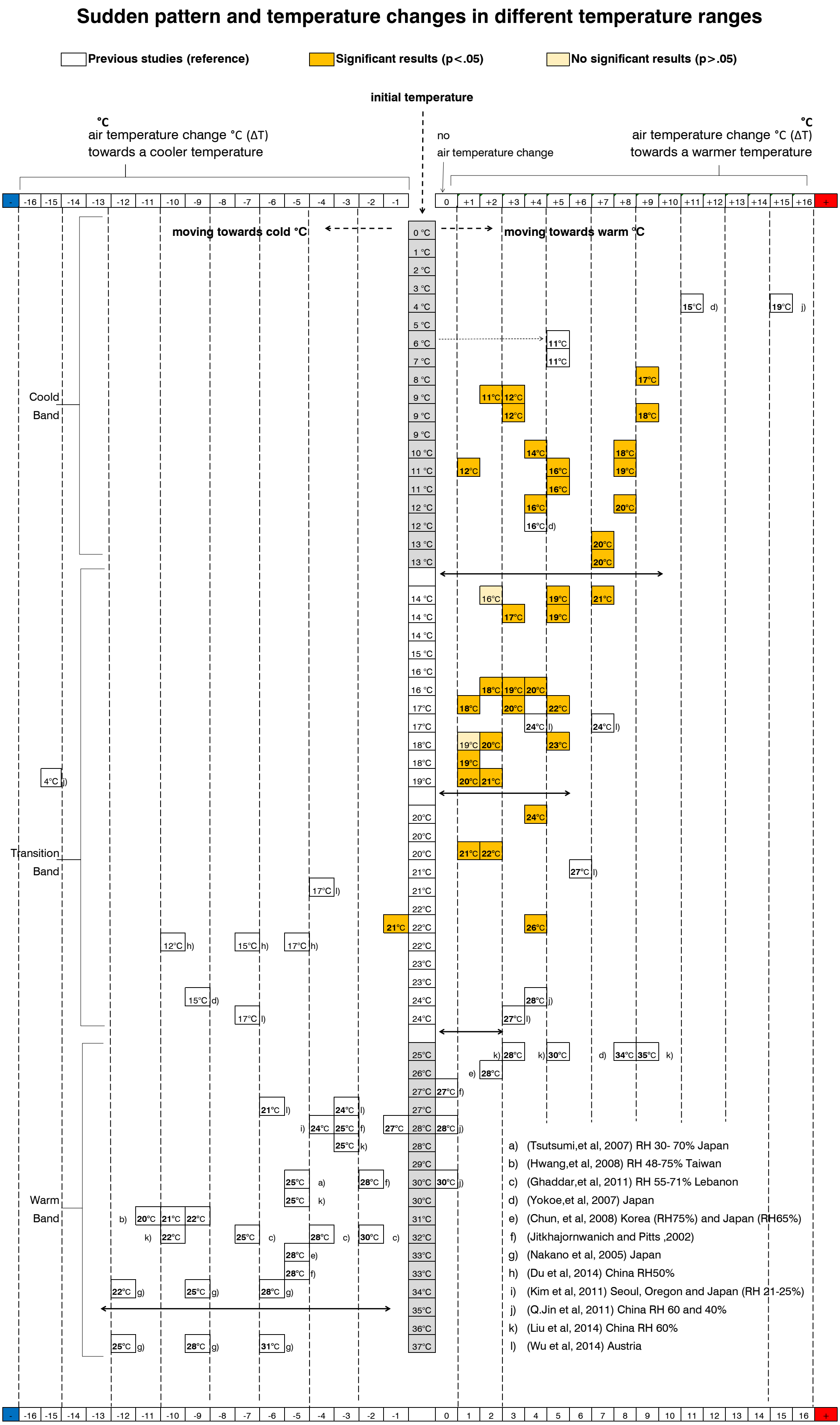


Figure 5-31 Sudden pattern and air temperature changes in different temperature ranges

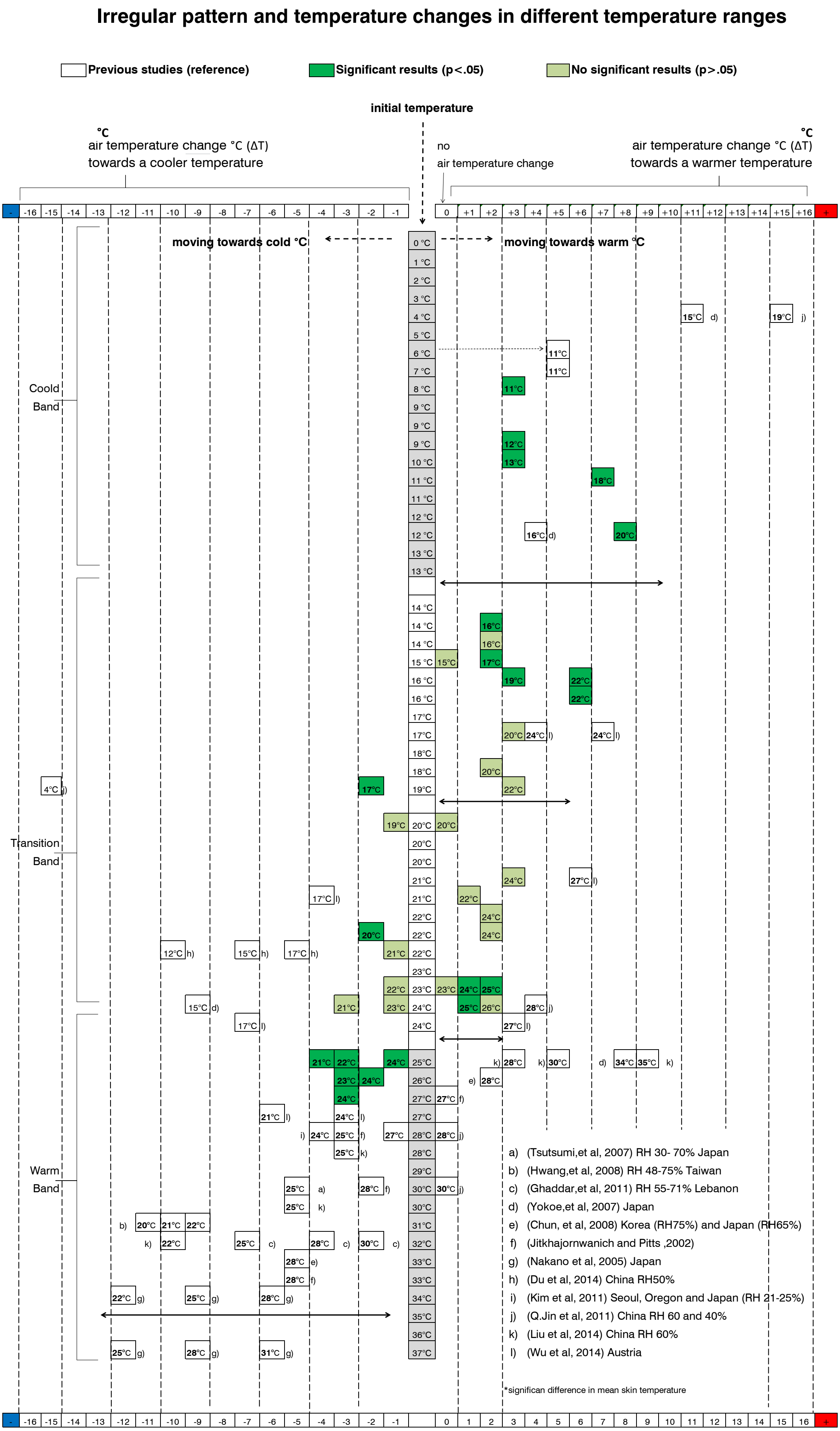


Figure 5-32 Irregular pattern and air temperature changes in different temperature range

5.9. Prediction of participants' thermal comfort in dynamic conditions

In this study, the Predicted Mean Vote and (PMV) and Predicted Percentage Dissatisfied (PPD) were calculated for group A in the seminar room in order to evaluate the effect of temperature changes when moving through the lobby unit on participants' thermal perception at their final destination. Therefore, only thermal responses from group A (using the lobby unit) were evaluated. The calculations were conducted using Equation 5-1, from CIBSE Guide-A (2015).

$$\mathbf{PMV}=(0.303e^{-0.036M}+0.028)\{(M-W)$$

$$-0.00305[5733-6.99\ (M-V)p_s]$$

$$-0.42[M-W-58.15]$$

$$-(1.7x10^{-5})\ M\ (5867-p_s)$$

$$-0.0014\ M\ (34-\theta_{ai})$$

$$-(3.96x10^{-8})f_{cl}[(\theta_{cl}-\theta_{ai})^4$$

$$-(\theta_c+273)^4]-[f_{cl}h_c(\theta_{cl}-\theta_{ai})]\}$$

Where the surface temperature of clothing (θcl) is given by:

$$\theta_{cl}=35.7-0.028(M-W)-I_{cl}\{(3.96x10^{-8})$$

$$xf_{cl}[(\theta_{cl}+273)^4-(\theta_c+273)^4]$$

$$+f_{cl}h_c(\theta_{cl}-\theta_{ai})\}$$

Where: I_{cl} = thermal resistance of clothing ($m^2.K.W^{-1}$)

For $\{2.38(\theta_{cl}-\theta_{ai})^{0.25}>12.1\sqrt{v_r}$:

$$h_c=2.38(\theta_{cl}-\theta_{ai})^{0.25}$$

For $\{2.38(\theta_{cl}-\theta_{ai})^{0.25}<12.1\sqrt{v_r}$:

$$h_c=12.1\sqrt{v_r}$$

For $I_{cl}<0.078m^2.K.W^{-1}$:

$$f_{cl}=1+1.29I_{cl}$$

For $I_{cl}>0.078m^2.K.W^{-1}$:

$$f_{cl}=1.05+0.645I_{cl}$$

Equation 5-1 Equations to determine the Predicted Mean Vote PMV (CIBSE-GuideA 2015).

Where: PMV= Predicted Mean Vote, M=metabolic rate ($W.m^{-2}$ of body surface), W=external work ($W\text{-}m^{-2}$ of body surface, 0 for most activities), f_{cl}=ratio of the area of the clothed human body to that of the unclothed human body ,θ_{ai}= average air temperature surrounding the body (°C), θ_c=operative temperature (°C), p_s=partial water vapour pressure in the air surrounding the body (Pa), h_c=convective heat transfer coefficient at the body surface ($W.m^{-2}.K^{-1}$), θ_{cl}=surface temperature of clothing, I_{cl}=thermal resistance of clothing (°C).

$$PPD= 100-95\ \exp[-(0.03353\ PMV^4+\ 0.2179\ PMV^2)]$$

Equation 5-2 Equations to determine the Predicted Percentage Dissatisfied PPD (CIBSE-GuideA 2015).

Results show that PMV calculations are not suitable for transitional spaces; participants' current TSV was different from the PMV for the majority of the irregular patterns, the PMV was opposite to participants' responses: while PMV showed 'neutral' and 'slightly warm' values (from 0 to+1), participants' current TSV showed neutral and cool thermal perception (from 0 to -2.0) (Figure 5-33). This is not surprising, since previous results presented in section 5.7 illustrated that, in irregular patterns, participants experienced one or more changes of thermal direction, resulting in very variable thermal responses not correlated with the current interior thermal conditions. In some irregular and flat sequences, PMV and current TSV were within the same range of thermal responses, from neutral to slightly warm (0 to +1). However, the PMV was always slightly higher than the current TSV. In the flat sequences, this could be explained due to the gradual air temperature change. However, in the irregular patterns, this result could again be the resulting effect of previous temperature changes. Finally, almost all of the sudden patterns from cold to hot illustrated a higher current TSV than the PMV. The PMV gave neutral and slightly warm thermal perception (from 0 to+1); however, the current TSV illustrated uncomfortable values towards the warm side in the seminar room: 'slightly warm' and 'warm' (from +1 to +2). In section 5.3, it was revealed that most of the sudden patterns in the lobby unit occurred during winter. This indicates that the air temperature could be reduced in seminar rooms in winter, since participants found it uncomfortable upon arriving. Reflecting on this, if lectures are usually one hour long and it was found from the literature that people require at least 30 minutes to reach their thermal equilibrium, the reduction of air temperature by some degrees (±2°C) should not provoke immediate discomfort.

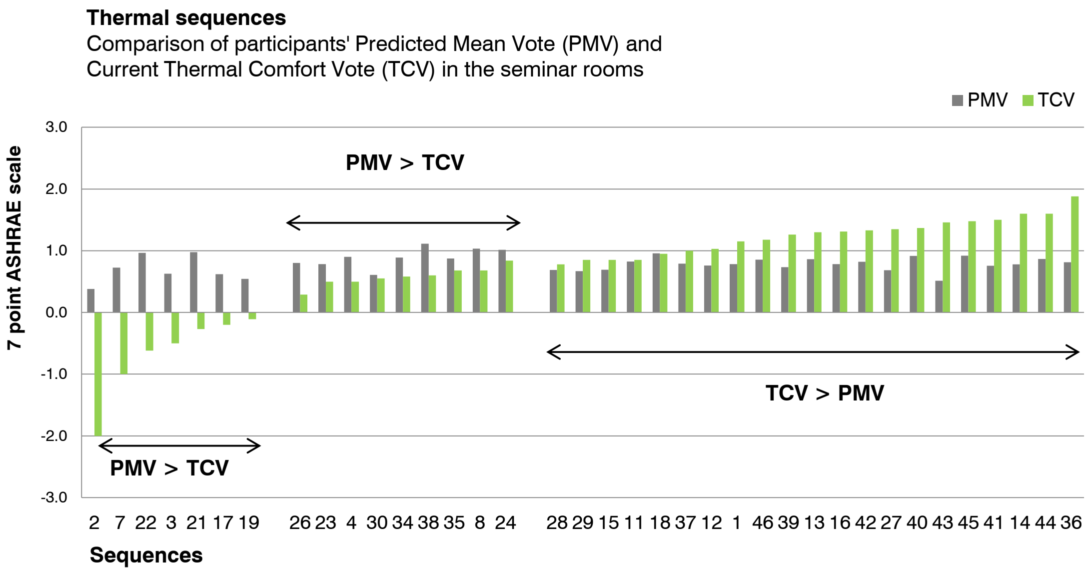


Figure 5-33 Comparison of participants' Predicted Mean Vote (PMV) and their Current Thermal sensation vote (TSV) in the seminar rooms

Regarding participants' PPD, most of the sudden and irregular patterns reflected a lower PPD than the CPD (Figure 5-34). Therefore, a larger percentage from 30 to 80% of participants was uncomfortably warm with the interior air temperature (20 to 23°C) than the percentage given by the PPD (up to 20% dissatisfied). Again, this confirms that participants perceived the air temperature in the seminar rooms as uncomfortable. Finally, the PPD was higher than CPD in most irregular and flat patterns, and participants were more comfortable with the seminar thermal conditions than the values resulting from the PPD suggested.

In short, the PMV is not accurate in predicting participants' thermal comfort perception when people are in dynamic conditions since their thermal perception changes very quick in only a few metres

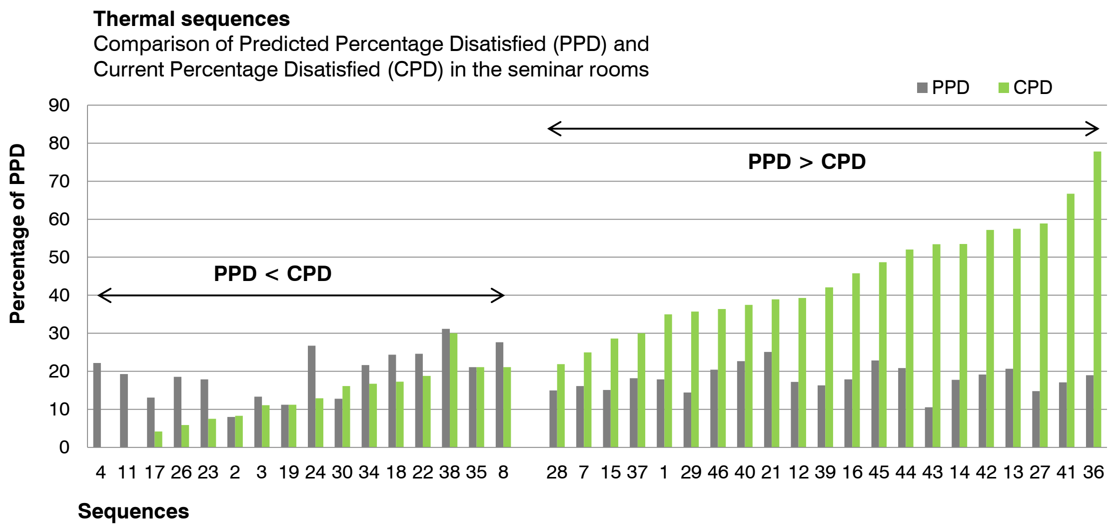


Figure 5-34 Comparison of participants' Predicted Percentage Dissatisfied (PPD) and Current Percentage Dissatisfied (CPD) in the seminar rooms

An important consideration to take into account when looking at the previous indicators (PPD, PMV, TSV and CPD) are the limitations of the equipment used to measure the globe temperature and wind speed described in Section 3.6.4.1. These limitations could have affected the accuracy of the calculations to an extent. In addition, the possibility of thermal patterns affecting the calculation of thermal indices needs to be developed further.

5.10. Conclusions

In this chapter, typical and new alterations (patterns) in participants' thermal perception were identified. One of the aims of this thesis is to evaluate in which extent it is possible to modify participants' thermal perception in the short-term in a positive way towards a better adaptation. Results from three new identified sequence types (flat, sudden and irregular) revealed that temperature changes from one space to another have a significantly different effect in participants' perception depending on the type of sequence and exterior air temperature ranges, since this significantly shapes the thermal conditions of the interior spaces. The combination of these two factors alters in different way participants' thermal perception in relation to the same temperature difference between spaces (ΔT).

In flat patterns with gradual temperature changes (±2 °C) towards the same direction, people had a better thermal adaptation in their final destination. In the temperature range from 14°C up to 23°C, an increase in temperature larger than 3°C was significant. However, temperature increments from 1°C to 3°C or decrements from 1°C to 2°C were not always significant, presumably because people found this temperature range comfortable as shown in previous results. Sudden patterns with the same thermal direction had a positive effect on participants' thermal perception in certain extent.

Findings in this work illustrated 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. However, it was found that sudden temperatures changes from cold to hot are not always optimum, since people expresses after few minutes that they preferred colder temperatures in the inside. Finally, irregular patterns are more complex to evaluate, since they involved change of thermal direction in temperature, resulting in variable thermal responses. However, in temperatures exceeding 24 °C, an increase of temperature from 1°C to 4°C was significant in all the cases, since the majority of people exposed at this temperature preferred to be colder. Overall, the identification of these newly thermal patterns in transitional spaces can have a strong influence in participants' thermal perception, depending on temperature ranges in the space, at the exterior and in the interior of the building.

Chapter 6

6. Design implications in the lobby unit from short-term thermal history findings

6.1. Introduction

One of the objectives of this thesis is to evaluate the implication of key findings that can potentially be applied in building design and policies in order to reduce energy demand in buildings. This chapter discusses in depth the most significant findings that have emerged from the results presented in Chapters 4 and 5. Three key themes are explored further, attempting to link research findings with their wider implications in relation to building design, building operation and policy considerations:

1. Thermal patterns in lobby units and their implications in design
2. Participants' short-term thermal history in lobby units
3. Policy implications for transitional lobby units

The first theme highlights key findings from the newly identified thermal patterns (flat, sudden, and irregular) and their applications in relation to the design of 'dynamic transitional spaces'. It discusses how knowledge about thermal connections and thermal variability in lobby units could help to increase understanding of people's thermal perception in the interior environment and how this can be related to helping design intentions align more closely to reality. It also describes the importance of understanding how people react to different temperature changes in a real situation. The second theme reflects on the potential application of people's thermal history to the implementation of long-term strategies to provide better conditions for thermal adaptation, reduce the use of AC and reduce energy consumption in buildings. It brings to light implications for building design in relation to people's seasonal thermal adaptation and the possible positive effect on people's thermal perception of repeated short-term experiences. Finally, the information gap regarding transitional spaces in international standards and codes is reflected on in relation to policy implications. This theme describes the applications of key outcomes from this thesis that could help to develop better policy guidance to help improve building design.

6.2. Thermal patterns in lobby units and their implications for design

One of the most significant findings in this research is the strong evidence of the existence of thermal patterns (patterns of exterior-interior thermal variability) in the lobby unit across even in a small series of spaces interconnected over only a few meters (exterior space, draught lobby, circulation space and seminar room). Outcomes from section 4.7 quantify the existence of more variable thermal connections in the lobby unit compared to documented standards and current research, in both NV and AC buildings, which need to be taken into account in the building design process, building operation, post occupancy evaluations, building design policy and building rating system.

In section 5.3, three new thermal patterns were identified in the lobby units (flat patterns, sudden patterns and irregular patterns). One of the most significant findings reported in section 5.5, 5.6 and 5.7 is the strong relationship between participants' thermal comfort perception and the identified patterns. Findings provide information about the seasonal climatic effect on air temperature in the lobby units, about participants' thermal perception to temperature changes between the spaces comprising the lobby units, and about new insights are provided in relation to what is expected about participants' thermal perception in relation to the thermal patterns in the lobby unit. This information can support architects in the design process of buildings. Results from the *thermal sequences* could also be used to inform designers about how people will experience certain types of thermal sequences and temperature changes within the building, and about which season is the time to start the implementation of strategies to adjust temperature configurations in buildings in order to reduce energy demand.

'Flat patterns' appear to be prevalent in late spring and summer, in temperatures between 20 and 23 °C. Moderate temperatures were registered in the lobby unit (mean=21.9°C), and temperature changes were from 0 to 2°C between the four spaces (exterior, draught lobby, circulation space and seminar room). Comfortable thermal perception that people reported when moving through flat sequences in late spring and summer in NV buildings (figures 5.5) confirms the opportunity to reduce the set point temperature in AC lobby units to be closer to the exterior air temperature with ±3°C difference between the exterior and lobby unit. Moreover, it confirms the possibility of a total elimination of AC during summer in UK buildings and also in other regions with similar mild climates. In summer and late spring, participants' thermal perception is comfortable in flat sequences and the use of the lobby unit clearly does not have a large effect on participants' thermal perception, since the temperature difference from exterior to interior is small. However, it is important to highlight that air temperatures between 20°C and 23°C in the flat sequences could have very different effects in other climates, for example in hot humid climates.

For a seasonal application of *'flat patterns'* in the UK, it is important to take into account as a starting point the exterior air temperature in which participants' answers were within the comfortable band ('slightly cool', 'neutral' and 'slightly warm') in the four seasons of the year. Findings reported in section 4.11 can be used for this purpose. Building adjustments could include a gradual transition in air temperature from exterior to interior using different air temperatures in the spaces comprising the 'lobby unit'. In autumn and winter, due to the large temperature difference between the exterior and interior, these gradual changes could start from the exterior where possible, by using additional external elements (canopies, walls and semi open corridors), and by reducing the air temperature heating set point in the lobby unit.

'Sudden patterns' were prevalent in autumn and winter, and reflect the largest temperature difference between the exterior and interior environment , with up to 13°C added to the cold

temperature range registered in the cold seasons (winter mean= 9.5°C and autumn mean =14.2°C), due to the buildings operating with heated spaces. Importantly, the uncomfortable sensation registered by participants in this thermal pattern indicates the need to implement strategies in the lobby unit design, to provide more *gradual thermal transitions* in the cold seasons. Sudden temperature changes (from cold to hot) can immediately satisfy participants' thermal perception; however, they do not help to trigger a better thermal adaptation in the following spaces. The total effect of the temperature changes in the lobby unit arrived some minutes later, and although participant were immediately comfortable warm in the circulation and seminar rooms, their thermal preferences quickly changed they preferred to be 'colder' after only a few minutes or even seconds (section 5.6). Therefore, thermal comfort design should not attempt to immediately satisfy people's thermal preferences; on the contrary, it should help people to experience optimal gradual thermal transitions to reach an appropriate comfort level. In addition, participants moving gradually from cold to hot (Group A) expressed less 'sudden' perception of temperature changes (section 5.6).

When the exterior temperature was between 8℃ and 19℃, temperature increases from 1°C up to 9°C were always significant in this thesis. The temperature increase did not have an uncomfortable effect until one to two minutes later, when people arrived at the seminar room. This is consistent with other results, presented by Jin Q (2011), which express a 'hysteresis' effect (delay) in participants' thermal perception when moving from cold to warm conditions. Therefore, providing a gradual temperature change from cold to hot is a better way to satisfy people's thermal perception, rather than trying to immediately provide warmer temperatures, such as those provided by AC and warm air 'curtains' at entrances of some buildings.

In contrast to the sudden patterns, in the '*irregular patterns'* air temperature differences of even ±1°C were significant on participants' thermal perception in temperature ranges from 8°C to 16°C, and when moving from cold to hot. The explanation of this particular effect seems to be the 'change of thermal direction' that people experience on their way, in this case from outside to inside environments. This alteration has a rapid effect on people's thermal perception and preferences. However, further work needs to be conducted to explore this issue in depth. Building designers need to be aware of this effect when providing temperature changes that do not follow a thermal direction, because this could cause thermal discomfort and more variable or unexpected thermal perception from people.

In short, findings from the different thermal patterns suggest that the lobby unit should be considered as a 'dynamic thermal connection space'. Specifically, the spaces near to the main entrance need to be able to be in constant thermal change. Since these spaces are both interior and exterior, the thermal connections and regulations in them need to be able to respond to the exterior climatic conditions in order to balance the spatial thermal connections, and lead to a smoother transition that help people to adapt to a wider interior temperature set point (less cold in summer and less warm in winter). This can be done by ensuring that the draught lobby design has a closer thermal connection with the exterior environment. There are different ways to do this depending on the designers' creativity, e.g. using the properties of materials, reducing insulation, reducing door thickness, etc. For example, the draught lobby could be NV most of the year, without any heating during winter, or it could have a lower air temperature set point than the interior spaces, or the air temperature could vary in a way that is always at in the mid-point between the exterior and interior temperature.

6.2.1. Linking the exterior with the interior environment in design

This thesis has shown that thermal comfort in the lobby unit starts from the understanding of people's thermal perception in the outdoor environment and from people in dynamic state, rather than from the interior and steady state understanding. Therefore, the direct exterior environments surrounding the buildings are key spaces that affect people's thermal perception indoors. There are two possible ways to smooth the thermal transition between the exterior and interior air temperatures. Firstly, when possible, including design strategies involving the immediate exterior environment as a way to extend the gradual thermal transition to before arriving in the lobby unit. Secondly, implementing a very effective *'dynamic lobby unit'* able to equilibrate the climatic conditions between the exterior and interior environments.

6.2.1.1. The exterior environment as the starting point of 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 trees placement (shade), pavement colours, greenery, geometric configurations, landscape interventions, water features and canopies. All of these can help to moderate the daily and momentary changes in external environmental temperatures in all seasons. For example, high albedo material could help to reduce heat gain close to the building entrance, and improve pedestrian thermal comfort in urban areas (Erell et al. 2014). Light coloured materials seems to be able to reduce air temperature by 1.3-1.9 °C (Santamouris et al. 2011) depending on the scenario tested. Using trees (as an extension) along the entrance path to the building could help to reduce the air temperature: depending on the amount of shading street geometry and meteorological conditions, trees in urban areas can cool the air up to 1.5°C (Coutts et al. 2015). Green walls can also cool the air immediately next to them, the effect of this can vary depending on the plant species. Researchers have reported 2°C difference in air temperature (Tan et al. 2014) 0.5 metres far from the wall and from 3°C to 6.3°C just next to the green wall (Cameron et al. 2013). Finally, water bodies act as cooling elements and can reduce the air temperature of their surroundings by up to 0.8 °C (Theeuwes et al. 2013). However, this also vary from case to case, other authors have reported a decrease in air temperature of up to 2.5°C above the water body in rural environments (Marsiero and Lucas de Souza 2015). During summer, these strategies could be used at the exterior of the building in order to reduce the differences between the exterior and interior air temperatures and therefore to eliminate or reduce the use of AC in the lobby unit.

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. If previous research has confirmed that green spaces have a significant effect on people's psychological and physical thermal perception, then these findings need to be included as part of the research into transitional spaces connecting the interior with the exterior environment.

6.2.1.2. The dynamic lobby unit as a design proposition

In this thesis, findings from participants' seasonal thermal adaptation (section 4.10) and the seasonal climate affecting the thermal patterns in the lobby unit (section 5.3) demonstrate the need for different seasonal design strategies in the lobby unit. It was also illustrated that variable degrees of correlations occur between spaces comprising the lobby unit (exterior-draught lobby, draught lobby-circulation space, circulation space-seminar room, exterior-seminar room, etc.). The different configurations of thermal patterns identified in this research propose the consideration of the lobby unit as a dynamic thermal connection space which is able to offer a flexible range of changes according to different local climatic situations in moderate climates such as the UK. This involves designing the lobby unit as an independent and complex sub-system of the building in terms of design, operation and people's experience and perception. This should include a wider range of temperatures configured by season and more frequent changes in building operation mode in the lobby unit, in order to provide a gradual thermal transition between the exterior and interior environments which is also balanced accordingly with the prevalent seasonal exterior climatic conditions. This requires careful design and selection of mouldable and adjustable elements and materials comprising the lobby unit. For example, the use of dynamic (perhaps movable) elements to add or reduce shelter for rain (canopies or temporal semi-open structures) and wind (windbreakers). Exterior elements, which react independently and quickly to sudden exterior-interior temperature changes during the day could be operated by the Building Management System (BMS) in response to the exterior conditions. Different modes of operation of the main door and draught lobby door (manual and automatic) could help to balance the air volume exchange between the exterior and interior.

At a deeper level, the *dynamic lobby unit design* should integrate wider options for different types of user (staff, visitors or residents) and activities (walking, waiting and socializing), perhaps with well-defined spatial boundaries for each type of activity. Designers need to be aware that in large lobby units hosting different activities and different types of users, people's thermal perception will be very variable. Therefore, the spatial design needs to provide different adaptive opportunities to allow people to reach comfort. For example, in winter, thermal variability in the lobby unit could include local heaters in the social areas only, access of solar radiation through windows in the social areas and lower temperatures in the circulation areas of the lobby. During summer, it could include access to manually operable window close to the social area, window blinds, etc. These strategies will help users to move from one area to another to reach comfort and will use the lobby unit space more effectively by having different options for temperature rather than one fixed temperature. Design strategies should not be limited to the physical elements of the lobby unit and thermal connections alone. They need to consider a deeper level of understanding of people's thermal perception when moving between the exterior and interior environments. Once again, the correlations of findings from different research areas are key. Perhaps understanding people's thermal expectations before arriving in the buildings (Jitkhajornwanich 1999), and other psychological factors, along with the expected seasonal thermal patterns, could help designers to introduce an early change in people's thermal expectations from the exterior experience.

6.2.1.3. Spatial opportuities for transition

Transitional spaces have also been referred as buffer spaces (section 2.8). Transitional spaces also have been strongly linked with atrium and covered courtyards spaces. Lobby design in HEI in the UK (Section 3.2.1.4) shows a varied lobby typology with 30% including double or triple height spaces, this configuration worked as or connected with an atrium space. Over time, the typical position of atria, centralized, semi-enclosed, attached or linear (Moosavi et al. 2014) has been variable; however, in most of the cases, the atrium has been strongly connected with the lobby area.

Glazed atriums have been widely used as buffer spaces in building design for decades, also incorporating different uses over the years apart from the main purpose as a buffer space (Ayoob and Izard 1994). This transitional area has been a potential tool to work as a filter and regulator of different physical factors such as acoustics, sunlight, views, ventilation and thermal comfort, including in adjacent spaces (Moosavi et al. 2014). Moreover, atriums are potential spaces to reduce energy consumption in NV buildings by working differently during summer than winter, through including and manipulating openings in the top to provide ventilation (Hung and Chow 2001).

An experiment conducted in 1983 in a primary school in Cambridge, UK, demonstrated that atriums can operate with unheated NV over the year (Penz 1986). During winter, the atrium space could be used as a transitional space since the air temperature was always higher than outside (from 5 to 9°C warmer than outside). From March onwards, the atrium space reached air temperatures above 18°C during certain hours, pointing to its potential to be used for temporary activities. The space also registered temperatures above 26°C in early spring and summer when the atrium roof windows were totally closed. Results from this experiment (1983) reflected on the stratification of air temperatures at different point of the atrium and the effect of adjacent heated spaces on it.

Transitional spaces such as lobbies, atriums and glazed courtyards can be implemented in a wide range of building size and uses. Experiments conducted in dwellings in Amsterdam, The Netherlands, demonstrated that transitional atrium spaces should also be flexible in design and be able to operate from closed to totally open according to seasonal variations at the exterior. In this case study, results illustrated that from May to August the atrium can have a flexible operation while providing thermal comfort (Taleghani et al. 2014).

Currently, lobby areas also work as atrium spaces and host different activities. Different uses can also take advantage of thermal variability over the seasons and time of day, expanding the possibilities of lobby use beyond circulations areas. Detailed thermal variations in different points of atrium spaces have been reported by Pitts (2010) in an experiment conducted in Sheffield, UK.

Results were mentioned with the outcomes of this thesis in section 4.7. Results presented in this thesis regarding thermal variability at the four measurement points (exterior, draught lobby, circulation space and seminar rooms) give a useful overview of the range of thermal variability in the horizontal plane in the lobby area, and can be linked with findings from other buffer spaces

6.3. People's thermal history

People's exposure to the changing seasonal thermal conditions affects their thermal perception in the short-term. The discrete thermal adaptation that people experience in every season of the year can significantly change the way that they tag their thermal perception to the same air temperature value. There is a clear difference in the way that people perceive their surrounding environment in every season of the year, altering at the same time their thermal comfort judgment. Findings in section 4.10 revealed that the majority of participants were comfortable with the exterior climatic conditions in most of the seasons (except winter). Furthermore, it seems that participants accept the 'naturalness' of seasonal climatic changes and therefore it is not surprising that their thermal responses match better with the exterior than with the interior thermal conditions. This suggests that a 'seasonal adaptation factor' (section 4.11) should be taken into account in the interpretation of thermal comfort studies. This has a significant impact for policy and design in relation to thermal comfort regulation in moderate climates, as it shows that people's comfortable temperature varies seasonally and their comfortable perception is not attached to the same temperature over the whole year. For example, people's thermal perception within the comfortable band (slightly cool, neutral and slightly warm) varies by up to 10°C ΔT between summer and winter. Therefore, wider temperature variations (section 4.7) need to be considered in thermal comfort regulations.

Moreover, the methodologies used to analyse thermal comfort scales need to be adjusted in a way that reflects the effect of the seasonal thermal adaptation. Although research has explored the effect of participants' thermal perception in the four seasons of the year, no one has proposed a 'seasonal factor' which could reflect the effect of seasonal adaptation in participants' answers that are used in equations and models. Furthermore, no one has proposed a 'long-term thermal history factor' and 'short-term thermal history factor' that could add more accuracy in people's thermal perception including the findings from previous studies (Candido et al. 2011; De Vecci et al. 2012; Marialena Nikolopoulou 2001; Nikolopoulou and Steemers 2003). In short, extensive further study is now needed to explore single experiences in time and space, to include the effect of combinations of different previous experiences reflected at specific points and time periods, in order to propose a mathematical algorithm and equations to determine a short-term 'thermal history factor'. This factor could reflect the real variations in the temperatures at which people express comfort. Therefore, special attention needs to be considered in the interpretation of thermal comfort surveys if participant's thermal histories have not been taken into account, especially in those repeated experiences that people experience in their everyday lives.

The knowledge of people's thermal history (long-term and short-term) is useful information for designers and building operators to understand the range of people's thermal tolerance to temperature changes in the building. For example, people in AC buildings need different thermal adaptation strategies from people in NV buildings. Depending on the building type and use (short-term or long-term), the temperature configurations need to be different, since in some cases such as in transport terminal, shopping centres or museums, people are in a more dynamic state. Therefore, the temperature configurations vary on a case-by-case basis depending on the building design, mode of operation, density of people, etc.

6.3.1. Thermal history and short-term repeated experiences related to energy savings

More countries are already implementing strategies to reduce energy consumption by adjusting the AC set points in buildings and increasing personal adaptive opportunities to people. For example, the campaign piloted in Japan 'Cool Biz', 'Cool Asia', Cool United Nations 'Cool UN' (Lakeridou et al. 2012) and 'Warm Biz' . In the same way, since 2006, The British Trade Union Congress has been implementing a policy called 'Cool Work' (Lakeridou et al. 2012) in which it is attempted to increase cooling set points from 22±2°C to 24± 2°C. It seems that increasing the cooling set-point is an affordable strategy to promote reduction in energy consumption in existing and new buildings without involving major changes to AC systems. This demonstrates a potential approach to reduce energy. However, researchers have pointed out that little is known about people's habits and behaviours that could allow a better implementation of this strategy in reality (Lakeridou et al. 2014). Little is known about people's limits of thermal comfort in real situations, since people express unpredictable thermal perception. This creates speculation about hidden factors affecting people's thermal perception, or about unexplored joint effects of certain variables. This knowledge gap risks the success of these kinds of campaigns, and is one that this thesis attempts to partially address.

A one-year study of people's thermal history, along with a detailed quantification of the indoor thermal variability and key thermal connections through transitional spaces, could provide the knowledge for improving building thermal performance over the whole life cycle. Better thermal comfort strategies for building operation which take into account the findings from this thesis (section 6.5) could significantly benefit energy saving strategies. The results suggest different strategies of building operation over the year. Lobby units operating with AC, MM and NV with heated spaces, need to take into account the changing of different temperature configurations in lobby units for each season of the year, not only summer and winter temperature set points, as is typically the case in many existing UK buildings.

In naturally ventilated buildings, knowledge about people's thermal perception in lobby units can also help to adjust existing thermal sequences in the indoor environment to create better, smoother thermal transitions. Finally, one year of building thermal monitoring could help to predict future thermal effects (patterns) in the indoor environment and therefore anticipate thermal adjustments in the lobby unit operation. In short, lobby units need more detailed 'thermal calibration' in relation to the exterior and interior environment and people's thermal perception, which extends upon existing building management systems that only predict required indoor temperatures based on external temperatures. By using data from the BMS more effectively, it could be possible to establish typical exterior and interior air temperature patterns in lobby units over the year in existing buildings. It can be useful to have anticipated temperature configurations to help to create a *flat thermal transition* between the exterior and interior environment using the lobby unit. The thermal conditions in the lobby unit could vary monthly or weekly depending on the BMS outcomes. Moreover, they could vary over the day, for example between peak and non-peak hours of use.

In this thesis, it is suggested that repeated short-term thermal experiences which are deliberately designed to influence people's long-term thermal perception could help them to adapt to internal thermal regimes in buildings which are more aligned with the external regime, thus saving energy. However, further research is required to validate the outcome of repeated short-term thermal experiences over the long-term. Additional work in this direction could help to quantify energy reduction from strategies that gradually build a wider thermal tolerance in people's thermal perception. In addition to the monitoring suggested earlier, a range of short-term repeated experiences need to be monitored in the long-term, in order to determine the extent of these to positively alter people's thermal perception and adaptation. Again, however, this needs to work, taking advantage in parallel with people's long-term thermal cycle.

Participants' thermal history, along with typical thermal patterns experienced in buildings, could perhaps indicate key periods in the UK during which people could move to new long-term thermal conditions in interior environments, allowing them to experience a gradual acclimatization process. For example, when building occupiers plan to shift from AC to NV buildings, perhaps people with a long-term thermal history in AC environments require a gradual shift to NV buildings.

Designers and energy modellers can use the results of this study (section 6.5) to explore air temperature set points in transitional spaces that allow a gradual thermal transition between the exterior and interior environments, knowing that the PMV and PPD used to calculate satisfactory thermal conditions in the indoor are not applicable in the lobby unit (section 5.9). Based on the design of the lobby unit and the thermal variations that the simulations reflect (type of thermal patterns), adjustments can be made (section 6.5) in order to create a gradual thermal transition from the exterior to the interior. The seasonal temperature set point variations would depend on people's seasonal thermal adaptation and the temperature range in which they express comfort. Still more work is required in order to develop an algorithm that can predict people's thermal comfort in transitional spaces and include it in simulation software. Results from this thesis allow a better understanding of people's reaction in dynamic state, specifically how quickly participants' thermal perception can change in some key transitional connections in buildings and spaces. In the long-term, thermal variability outcomes from this thesis could contribute to energy simulation software to take into account more detailed daily climatic variability in models e.g. IES, energy Plus and Design Builder. Although some work in this topic (simulation tools) has suggested transitional spaces (circulations) as areas that require wider thermal adjustment (Evans 2003), models have not been completely developed due to the lack of information on people's behaviour, their thermal tolerance in variable conditions and the overall complexity of the topic.

6.4. Policy Implications

Unquestionably, the development of design guidelines for transitional spaces is a significant problem to be addressed. There is a need for detailed guidelines to be implemented providing ranges of thermal differences between different transitional spaces, for types of thermal connections and building uses (Jitkhajornwanich and Pitts 2002; Kotopouleas and Nikolopoulou 2014). One of the first obstacles is the lack of quantification of transitional spaces in buildings, in relation to different types of building. This is a problem, for example, when calculating the potential energy savings in a building typology that could be made possible by implementing strategies in transitional spaces. In the same way, it is an obstacle when trying to visualize the scope and adjustments of design guidelines and international standards.

Although international standards include adaptive models (such as ASHRAE 55), the thermal acceptability limits still generate controversy; recent applications in hot-humid climates suggest that adjustments in the acceptability limits are yet not finished and additional improvements are needed (De Vecchi et al. 2015). One contribution of this thesis is the increased knowledge of hidden factors driving people's' thermal comfort in dynamic and transient states. The data from this thesis extend previous research and brings significant insights that could benefit international standards (ASHRAE, CIBSE, ISO 7730, ISO 10551, and BS EN 15251) with outcomes from people's thermal comfort perception in transitional spaces that could help to establish dynamic thermal comfort parameters. This could also help in other international codes, which currently do not include any specific requirement to take the thermal adaptation generated by transitional spaces and thermal connections in buildings into account. For example, LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) rating systems completely overlook people's thermal comfort related with thermal transitions between the exterior and interior and between the interior spaces. Furthermore, general consideration to take into account when designing transitional lobby units (section 6.5), should be extended to the criteria for undertaking commissioning of heating and ventilation services, as well the post occupancy evaluations.

Regarding the EN ISO 7730:2005 (moderate climates) standard used to calculate PMV and PPD, only limited information was found regarding non steady state thermal environments and transient conditions. No specific and detailed information is found in this standard that can be used to predict people's TSV and PPD in real situations. Although a number of studies are trying to develop accurate methods and models to predict people's thermal perception in non-uniform environments (Wu and Mahdavi 2014; Zhao et al. 2014), not much data (equations) has been incorporated in international standards. Also, in the CIBSE TM52-2013 standard (the limits of thermal comfort), there is a small section including the importance of designing for thermal variability in the indoor environment. This shows a big gap that needs to be covered in international standards. Finally, the seasonal adjustment reported in section 4.10 and 4.11 regarding participants' thermal comfort judgment adjustments could contribute to the BS EN ISO 10551:2001 standard by taking into account the effect of people's thermal history in their thermal responses, including a *'seasonal adjustment'* on the interpretation and tagging of air temperatures in the different seasons of the year.

In the CIBSE Guide A-2015, the suggested operative temperature for building entrances and halls/lobbies in AC educational buildings is 19-21°C in winter and in 21-25°C in summer (Lawrence 2006). However, findings from this thesis demonstrate that this threshold can be expanded in transitional lobby spaces in the UK to ±3°C (section 4.7 and 6.5). Firstly, because participants' thermal comfort in these specific areas depends significantly on the exterior temperatures, which are very variable. Therefore, the immediate temperature change in the lobby unit does not need to be dramatic. Since people typically arrive in a dynamic state (met= from 1.9 to 2.4 / BS EN ISO 7730-2005), lobby units with this temperature (19-21°C) in the immediate areas close to the entrance are likely to result in a uncomfortable hot sensation. In Chapter 4, the variations in participants' responses in each season of the year were demonstrated. Taking advantage of this natural adaptation, lobby units can dramatically reduce the use of heating systems during winter by considering people's thermal comfort perception in the exterior environment as starting point and adjusting the air temperature of the lobby unit and interior space to be closer to the exterior temperature. In this thesis, it is also revealed that participants' thermal preferences dramatically change after only a few minutes or seconds when moving from outside to inside. In winter, while participants want to be 'warmer' while outside, after moving to the interior space their preferences suddenly change to be 'cooler'. Findings in Chapter 4 clearly highlight that although 19-21°C temperature (during the year) in the lobby unit can provoke an immediate comfortable reaction, after a few seconds (due to the delay of participants' responses) this temperature can provoke uncomfortable responses towards the warm side ('warm' and 'hot') in the following circulation areas and even in the interior spaces. Also, the winter temperature (19-21°C) in the lobby unit needs to be adjusted with a 'clothing factor', since people typically have additional layers while using the lobby areas in some building types. For this reason, it is also important that standards include a more detailed a classification of different lobby uses by building type. For instance, while in some cases the lobby is used as a social space and for long periods (e.g. hotel), in other cases it is used more in a dynamic way, merely as a transitional area (e.g. university buildings and offices).

Finally, other codes and procedures involving thermal comfort evaluation in the built sector need also to implement more detailed considerations of the dynamic state of people's thermal comfort. For example, in post occupancy evaluations, it has been reported that one of the most prevalent user complaints in buildings is thermal discomfort (Leaman and Bordass 2007). Although a number of sources of thermal dissatisfactions have been reported in thermal comfort papers, in reviewing the literature no data was found on thermal comfort problems addressing a wider range of spaces, such as transitional spaces in more detail. A few documents from the National Health Services (NHS) in the UK have identified usual problems detected in the building entrance, such as unwanted cold or hot winds, draughty feelings, and sudden uncomfortable temperature changes. These problems also cause additional concerns reporting the location of the reception counter, door operations, temperature set up, heat loss through the main doors and additional energy consumption.

Findings from this research can benefit Estates and Facilities Managers (EFM) in Higher Educational Institutions (HEI) in the UK to support their aims to meet CO_2 emissions target set by The Higher Education Founding Council for England (HEFCE) in 2010 (HEFCE 2010). By understanding the thermal perception of the international undergraduate community living in the UK, and the way that buildings are thermally connected, the EFM could adjust the temperature set points of the lobby units and also other transitional areas, which could also benefit thermal perception in other interior spaces.

Health service buildings are another clear example where outcomes from this thesis could benefit specific design guidelines. Interestingly, this sector recognizes the lobby unit as an important space for patient and visitor perception. In 1989-1992, the NHS in the UK focused on design guidelines to develop high quality entrances and lobby areas for patients, followed by The National Health Service in Scotland in 1993 (NHS 1993). For example, the Estates and Facilities from The University of Southampton in the UK has an *Entrance Design Guidelines* (NHS 2004),document which takes into account the importance of the draught lobby dimensions for the best protection from exterior weather. It also considers the importance of the selection of doors, and most importantly, it mentions the importance of thermal transition in the draught lobby. Although the focus on the lobby unit as a key thermal transition has not been extensive in all building types, the health sector is a good example illustrating the importance of specific guidelines regarding the thermal transition in the lobby unit.

The draught lobby

"The space immediately inside the entrance doors – the draught lobby – provides the user with their first experience of the interior of the hospital. The transition from outside to inside the draught lobby should not be too abrupt (for example, changes in air temperature and lighting intensity should not be too great). The prime function of the draught lobby is to control loss of heat from the building and prevent wind and rain from entering. In exceptionally exposed locations, a second set of doors is provided to form a modifying draught lobby"

(NHS 2004).

6.5. Design guidelines for transitional lobby units

A number of considerations and recommendations based on the key finding from this work are proposed, in order to provide a comfortable thermal environment to people using transitional lobby units in moderate climates. New temperature configurations are proposed for the lobby unit and seminar rooms, based on a seasonal analysis of the exterior and interior thermal conditions, participants' seasonal thermal perception, thermal patterns in the lobby unit and temperature changes between the exterior and interior environments (Table 6-1). It is important to note that the seasonal strategies might vary depending on each case study and the typical identified thermal patterns. An example with information taken from outcomes of the three case studies buildings in this thesis is illustrated in Table 6.2. As a reference each section is referred to a chapter section.

Table 6-1 Considerations and recommendation to provide thermal comfort in transitional lobby units in moderate climates

		CONSIDERATIONS		
Type of Lobby (use) (section 2.9)	Social space		Transitional space	
Type of lobby (Section 2.8)	Type 1: contained within the building Type 2: connected to the building Type 3: independent from the building (Chun and Kwok,2004) Type A: linear with façade connection Type B: central with exterior connection Type C: linear with central connection Type D: perimeter-linear connected with the façade (Pitts and Saleh, 2007)		A) whit draught lobby B) with no draught lobby	
PEOPLE				
Time : Lobby unit user: (section 2.7)	Transient user	Visitor user	Resident user	
People's demographics: (Section 4.9)	Age group:		Nationality (long-term thermal history) -single nationality -different nationalities	
People's activity (CIBSE Guide A,2015)	Dynamic (walking): 0.9 $m.s^{-1}$ / Met=2.0 1.3 $m.s^{-1}$ / Met=2.6 1.8 $m.s^{-1}$ / Met=3.8		Social (resting) Resting: met from 0.7 to 1.2 Seated work: met from 1.0 to 1.2	
Clothing value (used in the lobby unit) (section 4.14)	Outdoors clothing (clo values) (extra layers: coats, hats, scarfs, jackets, gloves)		Indoors clothing (clo values)	
Lobby density (section 3.7)	Non-peak hours Number of people=		Peak hours: Number of people=	
People's thermal history	Large exposure to AC environments: Yes No		Other considerations:	
Thermal direction people moving from: (Section 3.7)	-Exterior-interior -Interior-exterior	cold to hot	hot to cold	irregular
		SEASONAL THERMAL PATTERNS		
EXTERIOR				
Mean exterior air temperature °C (section 4.4)	Spring	Summer	Autumn	Winter
Typical exterior air temperature range per season °C (section 4.7)	Spring	Summer	Autumn	Winter
Mean temperature changes (ΔT) patterns exterior-interior (SR) (Section 4.7)	Spring ΔT	Summer ΔT	Autumn ΔT	Winter ΔT
Mean exterior relative humidity (section 4.4)	Spring	Summer	Autumn	Winter

Mean exterior wind speed (section 4.4)	Spring	Summer	Autumn	Winter
Comfortable exterior air temperature °C (section 4.11)	Spring	Summer	Autumn	Winter
Exterior air temperature : 'no change' (section 4.14)	Spring	Summer	Autumn	Winter
Seasonal exterior ΔT (exterior) in people's comfortable TSV (section 4.11)	Summer with spring (ΔT) =	Autumn with summer (ΔT) =	Winter with autumn (ΔT) =	Spring with winter (ΔT) =
INTERIOR				
Building operation: (Section 3.3)	Spring	Summer	Autumn	Winter
Typical thermal patterns (connections) between spaces: Typical sequences: Type 1: Flat Type 2: Sudden from cold to hot Type 3: Sudden from hot to cold Type 4: Irregular (Vargas and Stevenson,2015)	Spring ΔT	Summer ΔT	Autumn ΔT	Winter ΔT
Mean interior (SR) air temperature (section 4.4.2)	Spring	Summer	Autumn	Winter
Comfortable interior air temperatures (4.11)	Spring	Summer	Autumn	Winter
Interior air temperature: 'no change' (section 4.16)	Spring	Summer	Autumn	Winter
People's mean clothing value (clo) (section 4.14)	Spring	Summer	Autumn	Winter
		RECOMMENDATIONS		
Maximum temperature changes (ΔT) (section 5.8)	Spring **±3.0°C**	Summer **±3.0°C**	Autumn **up to 2.0°C**	Winter **up to 2.0°C**
Recommended T_{op} ranges	Spring	Summer	Autumn	Winter
Draught lobby	**±3.0°C** ΔT based on the comfortable (TSV) exterior air temperature		**±2.0°C** ΔT based on the comfortable (TSV) exterior air temperature	
Circulation areas	**±3.0°C** ΔT warmer than the draught lobby and cooler than the seminar room		**±2.0°C** ΔT warmer than the draught lobby and cooler than the seminar room	

Operative air temperature in interior spaces (seminar rooms)	**No more than 20°C**	**Around 24°C**	**No more than 19°C**	**No more than 18°C**
Comments	-Early spring could still have sudden temperature changes, and late spring more flat thermal patterns. ±2°ΔT is recommended in early spring if necessary	-People's limit of comfort was 24°C in the seminar room, it is recommended to avoid operative temperatures above 24°C in the seminar rooms. -Avoid change of thermal direction in air temperature	-In Autumn and winter, it is recommended to avoid interior temperatures less than 17°C in the draught lobby (people's limit of comfort at the exterior was 14°C) -It is recommended to avoid temperature changes larger than 2°C, since people react very quickly to temperature changes of even 1°C in cold temperatures, having a significant effect on their thermal perception. Large temperature changes will be uncomfortable after a few minutes since people are in a dynamic state. -Gradual temperature change of ±2°C is recommended -Avoid change of thermal direction in air temperatures	

It is recommended to consider different operative temperature configurations in the lobby unit and interior spaces in each season, in order to gradually create a temperature change in building settings from season to season. In this way people will not experience sudden temperature changes in the building operation.

In all seasons it is recommended to incorporate joined thermal strategies starting from the exterior environment in order to offer a longer thermal transition to people, with more gradual temperature changes (section 6. 2.2)

It is recommended to take into account the effect of the number of people increasing the air temperature of the seminar rooms

Additional psychological factors that need more research include people's thermal expectations and the psychological effect of short-term thermal experiences.

Table 6-2 Example of the considerations taken from outcomes of this thesis to provide thermal comfort in transitional lobby units in moderate climates

CASE STUDY: Higher Educational Institution, Sheffield, UK				
CONSIDERATIONS				
Type of Lobby (use) (section 2.9.1)	Social space		**Transitional space**	
Type of lobby (Section 2.8)	**Type 1: contained within the building** Type 2: connected to the building Type 3: independent from the building (Chun and Kwok,2004) Type A: linear with façade connection **Type B: central with exterior connection** Type C: linear with central connection Type D: perimeter-linear connected with the façade (Pitts and Saleh, 2007)		**A) whit draught lobby** B) with no draught lobby	
PEOPLE				
Time Lobby unit user: (section 2.7.1)	**Transient user**	Visitor user	Resident user	
People's demographics: (Section 4.9)	Age group: **81% undergraduate students from18 to 24 years old**		Nationality (long-term thermal history) **-45% UK students** **-55% international students** **(83 different countries)**	
People's activity (CIBSE Guide A,2015)	**Dynamic (walking):** **0.9 m.s^{-1} / Met=2.0** 1.3 m.s^{-1} / Met=2.6 1.8 m.s^{-1} / Met=3.8		Social (resting) Resting: met from 0.7 to 1.2 Seated work: met from 1.0 to 1.2	
Clothing value (used in the lobby unit) (section 4.14)	**Outdoors clothing** (extra layers: coats, hats, scarfs, jackets, gloves)		Indoors clothing (no extra layers)	
Lobby density (section 3.7)	**Non-peak hours** Maximum 5 people using the lobby unit		Peak hours:	
People's thermal history	Large exposure to AC environments: **No**		Other:	
Thermal direction people moving from: (Section 3.7)	**-Exterior-interior** -Interior-exterior	**cold to hot**	**hot to cold**	irregular
SEASONAL THERMAL PATTERNS (RESULTS)				
EXTERIOR				
Mean exterior air temperature °C (section 4.4.1)	Spring **19.1 °C**	Summer **23.1 °C**	Autumn **14.2 °C**	Winter **9.5 °C**
Typical exterior air temperature range per season °C (section 4.7)	Spring **14-25°C**	Summer **17-30°C**	Autumn **8-25°C**	Winter **6-17°C**
Mean temperature changes (ΔT) patterns exterior-interior (SR) (Section 4.7)	Spring ΔT **+2.8 °C**	Summer ΔT **+0.4 °C**	Autumn ΔT **+6.9 °C**	Winter ΔT **+10.5 °C**

Mean exterior relative humidity (section 4.4.1)	Spring **50%**	Summer **51%**	Autumn **70%**	Winter **61.7%**
Mean exterior wind speed (section 4.4.1)	Spring **0.5 m/sec**	Summer **1.0 m/sec**	Autumn **0.9 m/sec**	Winter **0.5 m/sec**
Comfortable exterior air temperature °C (section 4.11)	Spring **(16 to 21°C) Mean=18 °C**	Summer **(21 to 23°C) Mean=22°C**	Autumn **(14 to15°C) Mean=14.5°C**	Winter **(9 to 11°C) Mean=10°C**
Exterior air temperature : 'no change' (section 4.14)	Spring **(14 to 25°C) Mean=19.8°C**	Summer **(17 to 30°C) Mean=22.6°C**	Autumn **(8 to 20°C) Mean=15°C**	Winter **(6-17°C) Mean=9.8°C**
Seasonal exterior ΔT (exterior) in people's comfortable TSV (section 4.11)	Summer with spring **(ΔT) =+3.3°C**	Autumn with summer **(ΔT) =-7.0°C**	Winter with autumn **(ΔT) =-5.4°C**	Spring with winter **(ΔT) =+9.2°C**
INTERIOR				
Building operation: **Natural Ventilated (NV)** (Section 3.3)	Spring **NV**	Summer **NV**	Autumn **NV *With heated spaces**	Winter **NV *With heated spaces**
Typical thermal patterns (connections) between spaces: (section5.4)	Spring -Flat patterns ΔT **0 - 2°C**	Summer -Flat patterns -Irregular patterns ΔT **0 - 10°C**	Autumn -Sudden patterns (from cold to hot) ΔT **0 - 13°C**	Winter -Sudden patterns (from cold to hot) ΔT **0 - 13°C**
Mean interior (SR) air temperature (section 4.4)	Spring **21.9 °C**	Summer **23.5 °C**	Autumn **21.1 °C**	Winter **20.0 °C**
Comfortable interior air temperatures (4.11)	Spring **21-22 °C**	Summer **23.0 °C**	Autumn **21.0 °C**	Winter **19-20 °C**
Interior air temperature: 'no change' (section 4.16)	Spring **20-24 °C Mean=21.5**	Summer **22-26 °C Mean=23.4**	Autumn **20-22 °C Mean=20.5**	Winter **18-22 °C Mean=19.5**
People's mean clothing value (clo) (section 4.14)	Spring **0.72 clo**	Summer **0.57 clo**	Autumn **1.01 clo**	Winter **1.06 clo**
LOBBY UNIT DESIGN STRATEGY				
Maximum temperature changes (ΔT) (section 5.8)	Spring **±3.0°C**	Summer **±3.0°C**	Autumn **up to 2.0°C**	Winter **up to 2.0°C**
Recommended T_{op} ranges	Spring	Summer	Autumn	Winter
Draught lobby	**±18.0°C**	**±23.0°C**	**±15.0°C**	**±14.0 °C**
Circulation areas	**±19.0°C**	**±23.0°C**	**±17.0°C**	**±16.0 °C**
Operative air temperature in seminar rooms	**up to 20.0°C**	**24.0 °C**	**up to 19.0°C**	**up to 18.0 °C**

6.6. Conclusions

This chapter evaluated the implications of key findings that can potentially be applied in building design and policies, in order to reduce energy demand in buildings, while providing thermal comfort. Chapter 6 has shown how the understanding of thermal patterns and people's thermal history can directly contribute to aiding building operators and designers to implement more realistic and viable strategies than those based on the specific conditions of each building and each pattern of use. This can be achieved by detecting the typical thermal patterns in the lobby unit, understanding people's seasonal thermal adaptation, understanding the thermal variability existing in the buildings and understanding the thermal connections between the exterior and interior environments through extensive building monitoring in existing buildings and in new building using simulation tools as a starting point. The outcomes would help to determine the design strategies for each case study.

The building sector needs to acknowledge the important role that transitional lobby units play in buildings, as key thermal connectors between the exterior and interior environments, which can influence occupants thermal comfort levels. It is very clear that transitional spaces, such as lobby areas, need independent thermal comfort guidelines, which can benefit people's health, thermal perception and provide a better thermal adaptation in the interior environment in the long-term. This chapter has highlighted the impact of the study of people in dynamic state for policy makers, since specific information and detailed requirements of transitional spaces do not exist in international standards (ASHRAE-55, CIBSE, Guide A 2015, ISO 7730;2005, ISO 10551, and BS EN 15251) and design guidelines (LEED and BREEAM). Key standards can directly benefit from the findings of this study, by taking into account people's thermal comfort perception in dynamic state and understanding the significance of people's thermal history.

Overall, the discussions in this section conclude that transitional spaces have been overlooked as potential thermal connectors that can help people to have a better thermal experience in the built environment (by gradually adjusting their repeated short-term thermal experiences, which could alter their thermal perception in the long-term). This could also help to reduce energy consumption by reducing the AC set points and reducing the heated spaces configuration in NV buildings, gradually altering people's thermal perception both in the short-term as they enter the building and in the long-term, as a gradual adaptation to local climates.

Chapter 7

7. Conclusions

This thesis aimed to investigate people's thermal perception in a dynamic state (walking), in a real situation and in a moderate climate, incorporating the study of their short-term thermal history. The purpose was to focus on a typical repeated short-term thermal experience that people experience in their everyday lives. The different problems arising from climate change are challenging thermal comfort researchers to study people's thermal comfort perception in more complex and dynamic interactions with their environment, in order to reduce energy demand and carbon emissions while still providing a comfortable interior environment. The literature review in Chapter 2, identified a big gap in the research of how people experience different thermal connections in the short-term in moderate climates. In addition, the majority of the few studies in this area were conducted in laboratories, raising concern about their relation to people's reality. This highlights the importance of this study using methodologies that mirror real situations and contribute to the understanding of people's thermal perception in their everyday lives, which can help to improve the design strategies and campaigns that provide a better thermal adaptation to people in their everyday thermal experiences.

This study used a transitional lobby unit as a case study, which reproduces one of the key representative thermal connections (exterior-interior environments) that people experience in their daily routines. The lobby unit in this study comprises the draught lobby and the circulation area immediately adjacent to the main entrance which connects with other interior spaces. This chapter summarises the main findings that help to answer the research questions raised in Chapter 1 and set out in the objectives of this thesis. Findings are based on one year (2013-2014) of fieldwork research and simultaneous physical measurements of the exterior and the lobby unit conducted in three buildings (Higher Educational Institutions) located in the moderate climate of Sheffield UK, operating with NV and heated spaces in winter.

Results from this study identified key thermal variations in the lobby unit and classified them into three new thermal patterns (flat, sudden and irregular). People's short-term thermal experiences and their limits of thermal comfort were identified based on the thermal patterns, temperature changes and temperature ranges that the participants experienced in the short-term. Gradual thermal transitions were identified as the best way to transfer people from exterior to interior temperatures. In addition, it was evaluated that temperature configurations in the lobby unit need to be reduced in wintertime. The understanding of people's long-term thermal history (over one year of study) and short-term thermal history also proposed design strategies that can be implemented in new and existing buildings. The design implications from the outcomes of this thesis propose a smoother thermal connection from the exterior to the interior environment, taking into account the importance of the exterior environment affecting people's thermal perception in the interior space. A dynamic lobby unit, and design strategies that integrate the exterior environment, are proposed as a way to regulate sudden thermal transitions. The outcomes of this thesis point to where they can contribute within the development of international standards and design guidelines. Although there is still much to investigate in this topic, this work provides a good overview of people's thermal perception in the short-term in moderate climates. In this chapter, the answers to the research questions are discussed. In addition, it also summarizes the strengths and limitations of the work presented in this thesis. Finally, in this chapter the answers to the research questions are demonstrated and it also provides a number of recommendations for further work.

7.1. How much thermal variation can be identified in the indoor environments operating with NV and space heating in winter?

Results discussed in Chapter 4 and 5 reveal a number of interesting findings. During the period in which the buildings were operating fully with natural ventilation (late spring, summer and early autumn), a strong positive correlation existed between the physical variables (air temperature, relative humidity and wind speed) of the immediate exterior environment and its effect on the interior environment. However, this correlation reduced in relation to the distance of the interior spaces from the exterior. In the four seasons of the year, the draught lobby was the interior space with the most thermal variation, due to its immediate connection with the exterior environment. This was followed by the close circulation areas connected with the draught lobby. The mean air temperature in the seminar rooms was mostly steady (around 21°C) when they were occupied by fewer than maximum 12 people. The annual temperature range was between 16°C and 25°C. During winter, when the buildings were operating with heated spaces, the temperature difference between the interior and exterior was the largest from the four seasons ($\Delta T=10.5°$). However, the temperature in the following spaces (circulation and seminar rooms) was more stable for most of the year and remained around 21°C. In both cold and warm seasons, the largest temperature difference occurred from exterior to interior environment, highlighting the key role that this connection plays in people's thermal comfort perception.

A very interesting finding was the identification of new thermal patterns (typical temperature changes between spaces) shaped by the season of the year. A range of temperature changes were identified in each type of pattern, 'flat patterns' (From min=0°C to max=2°C), 'sudden patterns' (from min=0°C to max=13°C) and 'irregular patterns' (from min=0°C to max=10°C). Although these patterns seem to be shaped by the long-term thermal conditions of the seasons of the year, they are also likely to change over the day depending on the effect and number of people using the spaces. However, the understanding of these patterns as a background of people's thermal perception is a significant contribution in this thesis. This is because it was demonstrated that a gradual thermal transition from the exterior to the interior (flat sequences) allows people to have a better thermal adaptation in the inside of the buildings, specifically when there are large temperature differences between the exterior and interior environments. It was also demonstrated that the air temperature in the lobby unit during winter caused discomfort to the participants. Sudden temperature changes with no single thermal direction also caused discomfort; however, gradual changes with the same thermal direction were more effective when providing thermal comfort to participants. Finally, the irregular patterns had a significant impact on people's thermal perception, provoking a wide range of thermal responses, due to the effect of different temperature changes in different thermal directions.

7.2. 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?

This study has demonstrated that transitional lobby areas can significantly impact people's thermal perception and preferences, depending on the thermal pattern generated between the spaces comprising the transitional lobby unit and the season of the year. Apart from the seasonal change in people's thermal perception, results presented in Chapter 4 and 5 confirm that people's thermal perception and preferences are strongly influenced by their immediate thermal experiences. This short-term experience, when people move from the exterior towards an interior environment using the transitional lobby area, can change people's thermal perception and thermal preferences dramatically and even in seconds. In contrast to steady state studies, this work reveals that a number of long term thermal experiences (previous exposure to AC, age, weight and height) do not have a significant effect when people are in dynamic state. It seems that this could be due to the greater effect of other variables (metabolic rate, clothing value, gender and years of residence in Sheffield) in dynamic state.

The way that the spaces are thermally connected (physical factors: air temperature, relative humidity and wind speed) can potentially significantly modify people's thermal perception and preferences in seconds. However, the thermal perception that people express at a given point in time and space is the resulting effect of all previous thermal conditions. 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 (from cold to hot) 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. 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. These cases were few, yet they exist and need to be further explored.

One of the main contributions of this thesis is the understanding of the effect of different temperature changes in different configurations of thermal connections in transitional spaces. For instance, although people were able to identify $\pm 1°C$ difference between two spaces, in some cases this small change did not significantly alter their thermal perception. However, in other cases (extreme thermal conditions), the same temperature change triggered a significant alteration in people's thermal perception and preferences.

7.3. How can the use of the transitional lobby unit further modify people's thermal perception in the normal ways that people use connected spaces?

Transitional lobby units are spaces that people experience repeatedly in their everyday lives, when moving from one building to another. This repeated thermal experience can be used to 'calibrate' people's thermal experiences in order to tolerate interior spaces with a wider range of thermal variability. For example, a gradual transition from the exterior to the interior can be extended with gradual changes in the settings of AC systems. This thermal transition can also initiate from the exterior areas, taking advantage of design elements and landscape. In this way, the entire thermal experience can start growing gradually from the exterior until the final destination. It is demonstrated in this thesis that people are strongly influenced by their previous thermal experiences in real life, which in turn affect their experience of transitional lobby units. Finally, the understanding of people's seasonal thermal history in repeated short-term thermal experiences can also potentially influence a better thermal adaptation, which could help to gradually reduce the use of AC and heated spaces in NV buildings. All this supported with a good understanding of how thermal connections in buildings work. The thermal connections of transitional spaces (thermal patterns), along with temperature ranges, thermal direction and temperature differences from one space to another anticipates (to an extent) the way that people are likely to perceive transitional spaces. Therefore, it is also possible to shape people's thermal perception in the short-term using these spaces.

7.4. Does this temporal interaction provide an opportunity to adjust and influence people's perception of the thermal state of their final destination to help reduce energy demands?

Outcomes from Chapter 5 and 6 confirm that the lobby area can offer a potential opportunity to reduce energy consumption, particularly in the cold seasons, while maintaining comfortable levels of temperature. During the warm seasons, although buildings were operating with NV, the way that the spaces are thermally connected can also enhance people's experience, shaping their preferences towards NV environments. It is proven that, although a sudden temperature change (from cold to hot) produces immediate satisfaction during the cold seasons, people's thermal perception and preferences change dramatically a few seconds later, preferring to be cooler and contradicting their previous inclination. This important finding indicates that a gradual thermal transition during winter is possible and desirable by reducing the temperature set points in AC buildings 3°C lower than 19-21°C (CIBSE-GuideA 2015) , and reducing the air temperature of heated spaces close to the entrance in NV buildings and gradually increasing the set point and air temperature towards the interior spaces. This can vary depending on the main use of the lobby unit. The implications of the natural seasonal thermal adaptation that people reflect in their clothing also plays an important role, since people use their outdoor clothes in transitional spaces. This extra layer can be used to delay the use of AC or heated spaces in the lobby unit.

It is also important to consider the seasonal temperature variations in which people express comfort. In this study it was identified air temperature differences from 3.3 °C to 11°C between seasons. This information can also be a reference to modify seasonal air temperature settings, which also will be reflected in annual energy saving. Finally, the understanding of people's thermal history and their reactions to temperature changes (thermal connections) can also help in the better implementation of long term strategies to reduce energy consumption in buildings when adjusting temperature set point in AC buildings and air temperature in heated spaces in NV buildings.

7.5. How can outcomes from people's thermal perception in real situations influence building design, building operation and thermal comfort policies?

From the literature review, it was identified that researchers claim the importance of incorporating specific information regarding transitional spaces into international standards such as ASHRAE, CIBSE, ISO 7730, ISO 10551, and BS EN 15251 and international design guidelines such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) rating systems.

This thesis contributes to the understanding of people's thermal perception, in relation to the lobby unit design and its connection with the exterior environment. People's limits of comfort, in relation to lobby unit thermal patterns, is useful information for designers, in order to consider a gradual thermal connection between the exterior and interior environment taking as a starting point comfortable temperature ranges in which people express thermal comfort in each season of the year. The way that participants reacted to different temperature changes can help designers to plan for more gradual temperature changes and for a reduction in air temperature in the lobby unit in relation with the exterior thermal conditions. A *dynamic transitional lobby unit* was described in section 6.2 as a way to exemplify integrated design strategies between the exterior and interior lobby unit. Design solutions in the lobby unit will vary on a case-by-case basis, since conditions in the lobby unit can be altered by very variable exterior thermal conditions that are shaped by the building's surroundings. The understanding of people's thermal history and their thermal adaptation over a year of study can also bring valuable information to determine seasonal design strategies that provide a better thermal transition for people. Section 6.5 provides a list of considerations to take into account that can support designers in their design decisions when designing lobby units.

Regarding building and thermal comfort policies, this thesis contributes by proposing new temperature set points in lobby units in moderate climates (section 6.5), depending on the air temperature ranges in which people feel comfortable in the exterior environment and lobby unit, taking into account the typical thermal patterns in each season. Therefore, since the lobby unit need to vary according to the exterior environment, a single fixed temperature value that applies for all types of buildings does not exist. However, the list of considerations presented in section 6.5 is a guide for analysis on a case-by-case basis. International standards do not have a specific section regarding transitional spaces, due to a lack of information; the contribution of this work is to add outcomes to the limited information available in relation to transitional spaces. In the long term, findings from this work could help to develop new seasonal temperature set points in lobby units that need to be integrated in international standards. Still, a vast amount of research work is needed in this topic before attempting to develop specific design guidelines in relation to transitional spaces. However, valuable insights can be found in this thesis along with some thermal parameters presented in section 6.5 that could contribute to the development of thermal guidelines in international standards in the future.

7.6. Study Strengths

There are a number of strengths in this research: one of the most significant considerations is that it reflects people's thermal perception in a real situation, using a large sample size. In contrast to the majority of previous studies, this research also takes into account the different effects of all four seasons of the year. The careful planning and pre-testing of the survey design resulted in the creation of a very short and quick survey that could be completed while participants were using the lobby area in a very similar way how they use it in a typical day. In addition, the study includes an entire sequence of transitional and final destination spaces that represents a typical connection existing in real HEI buildings, which came out of an extensive scoping study for the case study selection. This adds extra value, since previous studies have considered only isolated temperature changes (involving individual analysis of only one temperature change between two spaces). Finally, this work has covered a large gap identified from exploring previous studies in the literature by looking at a range of different temperature changes, thermal connections and sequences likely to occur in moderate climates.

7.7. Study Limitations

This research encountered a number of limitations which need to be considered. The study was focused on a typical real situation that people experience in their daily life. However, findings from this specific situation need to be interpreted with caution because they might not apply to all lobby designs, building types, building operations, climate regions or to other types of transitional spaces and building connections. Yet, this research provides solid findings and launches significant concepts that can be taken into account in further research and practice.

In relation to the building use, a limitation is that the transitional lobby unit only reflects a basic typical lobby layout unit in Higher University Institutions (HEI) in the UK. Although the lobby area can have different functions and uses, the research explores the lobby area in its function of spatial connection, considering that people use it in continuous movement walking slowly (met = 2.0) from outdoors towards a specific indoor space.

Regarding the sample population, 80% of the participants in this study were undergraduate students from 18 to 24 years old, involving different nationalities and was not focused on a single ethnic group(cultural effects based on nationalities were outside of the scope of study).

There is a limitation on using outcomes from this study in other climatic regions. This study was conducted in a moderate climate only (Sheffield, UK). The temperature range during the year of experiments in a year was from 6°C (winter) up to 30°C (summer). The range of temperature differences form one space to another was from 1°C up to 13°C within the previously mentioned temperature range.

Another limitation is that the three case study buildings were operating with NV, with heated spaces in winter. Although outcomes from NV are used to demonstrate that AC buildings can reduce temperature set points, the results from this study do not reflect people's thermal perception in AC buildings. Also, the thermal variability and temperature changes between naturally ventilated spaces were not controlled; they were shaped by the natural temperature connections from the outside and inside, through the normal operation of open and closure of the main doors. However, for data analysis, the data was carefully organized into thermal bins based on exterior climatic conditions. Although results from the three buildings illustrate very similar seasonal patterns, this does not completely limit the seasonal range of thermal patterns and combinations of patterns existing in buildings in a single season.

Due to the nature of the research approach, while conducting fieldwork, there was no control on people's behaviour, clothing, previous activities or the previous thermal conditions that people experienced outside. Therefore, results could be also influenced by additional variables that were not controlled or quantified in this study. Finally, due to the large sample size and limited time available for volunteers to participate, it was not possible to explore at the same time the effect of other psychological, social or cultural factors that could be correlated with the findings. This also limited the execution of other qualitative methods in parallel with this study.

A final limitation is related to the equipment used to measure the wind speed and globe temperature (see Section 3.6.4.1), which is not the best recommended for this type of field survey. However, this was the best available way to measure these two physical factors with the limited budget available. Due to these limitations, this thesis is focused on the air temperature as the main physical factor when reporting results. Be aware that these limitations could have an effect on the calculations of the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) illustrated in Section 5.9. It is important to take this into consideration when interpreting results from this section.

7.8. Direction for future research

7.8.1. People's behaviour in transitional spaces

A very important area for future research is related with people's behaviour in transitional spaces in their everyday lives. A robust database reflecting how people interact when moving between the exterior and interior environments does not exist. This area of research demands more ethnographic observations and qualitative research work, which is currently missing from most studies in this area. For thermal comfort research in transitional spaces, more work should be undertaken in different types of buildings and different climatic regions to understand how people experience their everyday routine using transitional spaces.

Key research questions arising from the findings of this thesis include: How much time do people spend on average in transitional spaces between the indoor and outdoor environments? How many significant thermal transitions do people experience per day/month/year? How frequently do people move from one space to another in the indoor environment? Do people always change their outdoor clothing (coats, scarfs, hats and gloves) before they arrive at their place of work or final destination in the indoor environment? How does outdoor clothing affect people's thermal perception when using the lobby and other transitional areas? All of this information could help to bring a platform in which previous studies can go further, and quantify the effect of previous findings in a real world context. For example the identification of routes that people typically follow in the indoor environments and the recognition of repeated experiences in which people experience significant temperature changes.

Future investigations should also consider in more detail to what extent people's outdoor clothing and the additional items that they carry with them in transitional areas (e.g. backpacks, bags, umbrellas, prams and bags) have an influence on their thermal comfort perception in a dynamic state.

7.8.2. Quantification of transitional spaces

Further work is required to quantify in square metres different types of transitional spaces in the indoor environment in different building types. A robust database can help to accurately quantify the potential energy savings to be made in transitional areas by reducing the use of air conditioning and heated spaces. Also, future findings on this topic can help to feed simulations and models related with quantifying energy savings during buildings operation.

Future research projects can also explore further the thermal variability in the indoor environment, reporting findings from entire buildings (NV, MM and AC) with different uses. It is essential to break down the thermal conditions of the indoor environment with a detailed quantification of temperature differences between different spaces. The analysis should be at different levels of time, orientation and building type. Research questions that could be asked include how the interior spaces in a (NV/AC/MM) building are thermally interconnected.

7.8.3. People's thermal history

A significant future work recommendation is to explore the effect of repeated thermal experiences on people's thermal perception. This involves the study of permanent building users during a number of years while the building operation is gradually modified in terms of air temperature configurations, specifically in transitional spaces, to provide better thermal connections. This area of study is strongly connected with the application of previous findings in real life strategies. This would reveal to what extent adjustments in repeated short-term thermal experiences in the lobby unit can gradually modify people's thermal perception and thermal expectations in the long-term.

In future research it might be possible to compare thermal perception in transitional areas between different user types (visitors, residents and transient people).

Further research projects can also study for the effect of time of exposure to previous thermal conditions in relation with short-term experiences, in other words the interconnection between time and transient conditions. This would help to identify previous thermal experiences that can significant influence people's thermal perception in the short-term, and quantify people's thermal tolerance in terms of time to thermal conditions that usually are tagged as uncomfortable.

Further study with more focus on the interaction between people's short-term and long-term thermal history in transient situations is therefore suggested, perhaps the exploration of people from different nationalities, backgrounds and cultures experiencing the same transient or dynamic conditions. This will help to better understand the influence of people's background and long-term thermal history (from different climatic regions) on their current thermal perception. In buildings with international user this could help to propose wider and flexible thermal design strategies.

7.8.4. Building design

Further research should investigate the effect of different lobby design areas on people's thermal perception, for instance, work linked with environmental psychology and interior design exploring different categories of design features such as lobby dimensions, colours, materials and spatial layouts. In addition, the exploration of other aspects of building design linked with function, such as the lobby area as a waiting area and a social area hosting activities that last longer. Combinations of different activities in the same lobby area would also be very significant.

7.8.5. Additional variables

A very important line of research can be to examine the effect of changes in thermal direction on people's thermal perception in transitional spaces, considering that people are more likely to experience different thermal directions in real life rather than always going from hot to cold or from cold to hot. This could also help to explain the delay effect that people experience in irregular patterns of temperature changes.

Further studies on the current topic can explore the effect of wind and humidity in transitional spaces as additional elements to positively modify people's thermal perception in the short term.

7.8.6. Climatic regions

A deeper exploration of transitional spaces and people's thermal perception in cooler and moderate climates, where there is more possibility to reduce the use of air conditioning in buildings in the future, is recommended for future work.

7.8.7. Research Approach, methodology and survey procedure

An important issue for future research on people's thermal perception in transitional spaces is to consider the implementation of different methodologies in the research process. For instance, software simulations, interconnection between quantitative and qualitative research, comparison of longitudinal and transversal findings and qualitative research that include psychological, social, cultural and health aspects correlated with people's thermal perception in the short therm.

Further work is required to explore the effect of the density (or number) of people using transitional spaces, specifically those that move a large number of people at the same time. This would depend on the building type and peak hours. This would help to determine specific thermal requirements in lobby units with high density users, since the number of people is an additional factor increasing the air temperature in spaces. This also can help to define a more detailed schedule of thermal requirements in lobby units at specific peak hours.

A significant future extension of this work would be the study of a wider range of trajectories that people use in buildings, including a different number of spaces and combinations of transitional spaces (stairs, lifts, corridors, lobby units, etc.), over different distances and time periods. The study of a more complete and complex trajectory when people move from the exterior to the interior environment, would also help to determine changes on people's thermal perception in relation to time and distance. Perhaps the effect of time-distance-metabolic rate on the time they require to reach their thermal equilibrium can be taken into account to adjust air conditioning configurations.

7.8.8. Building operation

Further work is recommended to compare temperature patterns of transitional spaces between different modes of building operation. For example, buildings fully NV, fully AC and operating in MM, in order to determine more accurately long-term strategies to reduce air conditioning configurations or adjustments in NV and MM buildings due to people's long term thermal history created by the effect of the building operation.

7.8.9. Equations and predictive models

It is important to develop a proper equation to calculate the Predicted Mean Vote for people in dynamic state with different variations; for example, for transitional spaces, perhaps by exploring more dynamic simulation techniques rather than attempting to modify the existing steady-state PMV equations. It seems that a new method or equation for dynamic conditions needs to be structured independently from steady state considerations, including different factors from different areas of study. In the long term, algorithms developed from results could be incorporated in the thermal design process in software such as IES, Energy Plus, Design Builder, etc.

7.8.10. Applications

Studies can lead to apply findings from laboratory models in real situations. At least one year of post occupancy evaluation would bring deeper knowledge on people's experiences in transitional spaces to light.

7.9. Recommendations for similar field work research

A recommendation for similar research exploring real situations is to control a number of variables, yet without altering the natural way that the event of study is usually experienced. The control of specific variables can be managed from the selection of participants (nationality, age and culture), building type, mode of building operation (NV, AC or MM) or building design, in order to explore people within more limited parameters of study that can help to bring outcomes from focused groups. Also, it is highly recommended to incorporate different methodologies when studying transitional spaces (e.g. qualitative, quantitative and ethnographic) in order to cross correlate the findings and increase their validity. Another recommendation is to translate the main outcomes into applicable recommendations for use in the design process and later incorporated into international design standards.

When managing a large sample size survey that involves continuous participation over short periods of time, is to consider the use of one unit of equipment (data-logger) into which it is possible to connect different measuring devices to read different physical variables (wind speed, globe temperature and relative humidity).

It is recommended to avoid using manual devices or equipment from different brands which require different protocols (procedures) to set up and the use of different software programs. The incorporation of other electronic devices that help to automatically transfer data from questionnaires and equipment into the main database is highly recommended.

A number of limitations regarding selection of the equipment have been described in Chapter 3 which should be paid attention. It is recommended to be aware of the existing discrepancies between previous thermal comfort experiments, addressed by Johansson (2014), resulting from the lack of standardization in instruments and methods.

In this work, the use of seven point scales to measure wind speed and relative humidity was not the best option. It was detected during the survey that participants found it difficult to assess their perception of these two physical factors. This could be due to the lack of extreme climatic conditions in moderate climates; a wide range of choices (7 points) could be difficult for the participants to use. Therefore, it is recommended to try a three point scale indicating the extremes and neutral ranges in moderate climates.

Finally, regarding the questionnaire design, it is not recommended to include questions without a proper scale to measure people's perception as used in this study (refer to Appendix 7, Section 1-exterior, question 5). Although the intention was to use these questions as a way for a quick verification of people's responses, this did not work since the answers did not reflect the specific time of the survey. Therefore, results in section 4.15 can be used as a general overview of people's perception.

7.10. Final Conclusions

The overall contribution of this thesis has been to demonstrate a new understanding of people's thermal perception in a moderate climate, in dynamic and transient states, when moving from the exterior to the interior environment using the transitional lobby unit. The originality of this thesis is reflected in the evaluation of a repeated short-term thermal experience in a real situation, including a trajectory from the exterior to a final destination in the interior environment that is very close to the way that people experience it in reality. Results from this work have filled knowledge gaps in people's thermal perception in a dynamic state in moderate climates. The most important findings of this work are the identification of thermal patterns in the lobby unit and the dynamic interplay between these thermal patterns and people's short-term thermal perception. The quantification of different air temperature ranges and temperature changes in relation to the identified thermal patterns bring to light a new understanding of the variability of people's thermal perception and preferences in the short-term. Outcomes demonstrated the importance of a gradual thermal transition, in a single thermal direction, between the exterior and interior environment, which can modify people's thermal perception gradually and positively in their final destination. These findings contribute to the development of long term strategies that attempt to reduce the AC usage configurations or to adjusting thermal connections in NV buildings in order to enhance people's thermal experiences and reduce energy use in buildings. A final thought when studying people's thermal perception in the built environment, is the importance of understanding people's thermal perception in a dynamic context in real life. The understanding of people's thermal comfort perception at steady state in interior spaces seems to start from the understanding of people in dynamic state, their thermal perception at the exterior and their long-term and short-term thermal history rather than a single thermal exposure.

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Appendix 1 Thermal Comfort Indices

PMV Predicted mean vote	The **Predicted Mean Vote** is a thermal index used to assess if a given thermal environment complies with the comfort criteria. The PMV predicts the mean value of the votes on thermal sensation of a large sample size, based on the heat balance of the human body, using a 7-point scale. It can be calculated using equations when people are in a steady-state condition and there are minor fluctuations in the variables of the equation (BS EN ISO 2005)
PPD Predicted Percentage Dissatisfied	The PPD is an index that predicts the percentage of thermally dissatisfied people. It is not possible to specify a thermal environment in which all people can feel satisfied, due to personal variables. However, it is possible to identify environments in which the majority of the population can feel comfortable. The Predicted Percentage Dissatisfied is a thermal index that is used to predict the percentage of individuals likely to feel thermally dissatisfied in a sample population exposed to the same thermal conditions .In other words, people who vote within the uncomfortable thermal bands (warm, hot, cool and cold) when using a 7-point scale. (BS EN ISO 2005)
T eq Equivalent Temperature	The **Equivalent Temperature** is referred as the temperature at which the majority of people under the same climatic conditions can feel thermally comfortable.
ET* New Effective Temperature	The **New Effective Temperature** is an improved thermal index from (ET=Effective Temperature) that represents the combined effect of dry-bulb temperature, humidity and air velocity on the human body thermal sensation (warm or cold). It is the temperature of a given unvarying space where the relative humidity is 50%, and which would produce the same net heat exchange by radiation, convection and evaporation as the environment in question. At this temperature, 80% of the population can experience thermal comfort.
SET* Standard Effective Temperature	**The Standard Effective Temperature** (SET*) it is an improved version of the Effective Temperature (ET*) that provides a resulting value from the combination of the environmental factors, clothing and metabolic rate of a given environment. Using the ET* the thermal conditions of a given space can be compared with a standardized room with a mean radiant temperature equal to air temperature and a constant relative humidity of 50%. Using the improved ET* and the resulting SET*
Out-SET*	The **Outdoor Standard Effective Temperature** is a subcategory of SET* that is used to evaluate outdoor environments
PET Physiological Equivalent Temperature	PET is an index based on the basic thermoregulatory processes and thermo physiological heat balance model. It is the equivalent air temperature at which the human body can reach heat balance in a thermally controlled given space and complying whit a certain number of assumptions. It has been used in outdoor conditions.
NT Neutral Temperature	The **thermo-neutral zone** is referred to as the ambient temperature at which the body is able to maintain its core temperature in balance due to the equilibrium between heat loss and heat production. In other words, the heat that is transferred from skin to the environment is equal to the heat transferred from to the body core to the skin (Kingma et al. 2014).
Top Operative Temperature	The operative temperature is an abstract index that results from the interaction of the mean radiant temperature and air temperature. This involves the effect of heat transfer by convection and radiation on people's surroundings, therefore it is what people perceive thermally and it is used to represent a spatial temperature. It cannot be measured directly, but can be calculated using different equations (Nicol, Fergus, Humphreys & Roaf 2012). In thermal comfort studies the 40mm globe thermometer is used to measure the mean radiant temperature and therefore to determine the operative temperature. In some cases, in indoor environments only, the mean air temperature and globe temperature are very close At indoor speed below 0.1m.s-1 ,and therefore v=0.1 $T_{op} = \frac{1}{2} T_a + \frac{1}{2} T_r$ Where T_r =mean radiant temperature, T_a= air temperature and T_{op}=operative temperature.

Appendix 2 Research related to transitional spaces

Transitional Spaces						
(Jitkhajornwanich and Pitts 2002)	Bangkok, Thailand	Summer Winter	2-AC schools 3-NV offices	Field work: Questionnaires Physical Measurements	N=1,143	-Thermal expectations and preferences -TCV
(Nakano 2003)	Waseda, Japan	Summer Autumn Winter	Semi-outdoors Environments	Field work Laboratory Experiments	N=120 N=406	TCV TSV ESV
(Chun et al. 2004)	Yokohama, Japan	Autumn Winter	2 lobbies 2 balconies 2 pavilions	Field work: Physical Measurements Observations	---	-Long and short term of physical measurement s
(Chun and Tamura 2005)	Yokohama, Japan	Summer Autumn Winter	Train station Passageway Shopping Mall	Laboratory work Field work	N=36 (lab) N=45 (fw)	-Spatial sequences -Thermal adaptation
(Nagano et al. 2005)	Kyushu, Japan	Summer	Climatic Chamber	Laboratory work	N=30 males	-Mean skin temperature -TSV
(Kaynakli and Kilic 2005)	Bursa, Turkey	---	---	Mathematical Model	---	-Body thermal perception
(Pitts and Bin Saleh 2007)	East Pennines area, UK	Summer Winter	4 types of transitional spaces	Simulation Tool	Simulation tool	-Energy saving in transitional spaces/when PMV±1.0
(Yokoe et al. 2007)	Nagoya, Japan	Winter	Thermally controlled buffer space	Field work Laboratory	N=15(lab) N=8(fw)	TCV -Skin temperatures
(Hwang et al. 2008)	Taichung, Taiwan	Summer	AC building Service Centre	Field work: Questionnaires Physical Measurements	N=587	-Thermal history -Step changes Temperature -Expectations
(Chun et al. 2008)	Seoul, Korea Yokohama, Japan	Summer	University Campus and Climatic Chamber	Field work Laboratory Experiment	N=51	Thermal history Indoor TCV
(Pitts et al. 2008)	Sheffield, UK	Spring	University Building Transitional Spaces (AC, NV)	Field work Surveys	N=123	TCV
(Pitts 2010)	Sheffield, UK	Spring Summer Autumn Winter	NV Academic Building	Field work Surveys Physical Measurements	N=72	TCV AMV PMV
(Ghaddar et al. 2011)	Beirut, Lebanon	Summer	Bio-heat model	Parametric study Fieldwork validation	--- N=12 N=9	PMV Skin and core temperature
(Kwong and Adam 2011)	Putra, Malaysia	Autumn	AC Lift lobby	Fieldwork	N=113	TCV TP
(Parkinson et al. 2012)	Australia	Spring Autumn	Climatic Chamber	Laboratory Experiment	N=6	TCV TS Skin Temperature
(Pitts 2013)	Review of previous work	4 seasons	AC NV	Field work	Review of previous work	PMV TCV
(Wu and Mahdavi 2014)	Vienna, Austria	Spring Winter	Thermal Chamber	Laboratory Experiments	N=313 (s) N=84 (w)	TCV,TSV Sequences Thermal-Distance

(Du et al. 2014)	Chongqing, China	Spring (fw) Winter (lab)	Climatic Chamber AC Offices	Laboratory Fieldwork	N=12	TCV TA
Non-uniform environments						
(Potvin 2000)	Cardiff, UK	Summer Winter	Arcades	Field work Surveys	---	Thermal Variability
(Zhang et al. 2004)	Berkeley, California USA	Spring Summer Winter	Climatic Chamber	Laboratory Experiment	N=109	Skin and core temperature TCV TS
(Nakano et al. 2006)	Tokyo, Japan	Summer Winter	Train Station	Fieldwork Surveys	N=1,099	TCV TCP TS, TA
(Hwang and Lin 2007)	Taiwan	Summer Winter	Outdoors Spaces	Fieldwork Surveys	N=1,644	SET* TCV TP
(Kelly and Parson 2010)	Loughborough, UK	Winter Spring Summer	Thermal Chamber	Laboratory Experiment	N=24	TCV PMV Step-change temperature
(Kelly 2011)	Loughborough London UK	Spring Winter	Train Journeys	Laboratory Fieldwork Experiments	N=18 N=24 N=48 N=44 N=32	TCV PMV-TRANS Pleasantness Stickiness Draught
(Vasilikou and Nikolopoulou 2013)	London, UK Rome, Italy	Summer Winter	Pedestrian Routes	Field work Surveys Interviews	N=314	Thermal Variability
(Kotopouleas and Nikolopoulou 2014)	Manchester and London, UK	Summer Winter	Airport Terminals	Field work Questionnaires Measurements	N=3,087	TCV TCP
Temperature Changes						
(Chen et al. 2011)						
(Tsutsumi et al. 2007)	Tokyo, Japan	Hot-Humid Climate	Climatic Chamber AC	Laboratory work	N=12	TCV Productivity
(Jin et al. 2011)	Liaoning, China	Summer Winter	Climatic Chamber	Laboratory work	N=23	
(Liu et al. 2014)	Chongqing, China	Summer	Climatic Chamber	Laboratory work	N=20	TCV Skin temperature
Thermal History						
(Chun et al. 2008)	Seoul, Korea Yokohama, Japan	Summer	Climatic Chamber Outdoors	Field work Laboratory Experiment	N=52	TCV
(Candido et al. 2011)	Maceio, Brazil	Summer Winter	AC NV Buildings	Field work Laboratory Experiments	N(AC)=445 N(NV)=530	TCV TE
(Song et al. 2011)	Singapore	---	University Building AC	Field work	N=36	TCV
(Kim et al. 2011)	Seoul, Korea Portland, Oregon Yokohama, Japan	Spring Summer Autumn	AC Buildings	Fieldwork	N=713 N=807 N=213	TCV TCP
(De Vecci et al. 2012)	Florianopolis, Brazil	Summer Autumn Spring	AC NV University Building	Field work Surveys	N=544 Q=2,292	TCV TA TCP
Short Term Occupancy						
(Nakano et al. 2006)	Tokyo,Japan	Summer Winter	Train stations	Fieldowork	N=1,099	TCV

Appendix 3 Previous Studies in non-uniform environments Methodology Summary

Transitional Spaces	Place	Season	Case Study	Method	Sample Size	Parameters
(Jitkhajornwanich and Pitts 2002)	Bangkok, Thailand	Summer Winter	2-AC schools 3-NV offices	Field work: Questionnaires Physical Measurements	N=1,143	-Thermal expectations preferences -TCV
(Nakano 2003)	Waseda, Japan	Summer Autumn Winter	Semi-outdoors Environments	Field work Laboratory Experiments	N=120 N=406	TCV TSV ESV
(Chun et al. 2004)	Yokohama, Japan	Autumn Winter	2 lobbies 2 balconies 2 pavilions	Field work: Physical Measurements Observations	---	---
(Chun and Tamura 2005)	Yokohama, Japan	Summer Autumn Winter	Train station Passageway Shopping Mall	Laboratory work Field work	N=36 (lab) N=45 (fw)	-Spatial sequences -Thermal adaptation
(Nagano et al. 2005)	Kyushu, Japan	Summer	Climatic Chamber	Laboratory work	N=30 males	-Mean skin temperature -TSV
(Kaynakli and Kilic 2005)	Bursa, Turkey	---	---	Mathematical Model	---	-Body thermal perception
(Pitts and Bin Saleh 2007)	East Pennines area, UK	Summer Winter	4 types of transitional spaces	Simulation Tool	Simulation tool	-Energy saving in transitional spaces/when PMV±1.0
(Yokoe et al. 2007)	Nagoya, Japan	Winter	Thermally controlled buffer space	Field work Laboratory	N=15(lab) N=8 (fw)	TCV -Skin temperatures
(Hwang et al. 2008)	Taichung, Taiwan	Summer	AC building Service Centre	Field work: Questionnaires Physical Measurements	N=587	-Thermal history -Step changes Temperature
(Chun et al. 2008)	Seoul, Korea Yokohama, Japan	Summer	University Campus and Laboratory	Field work Laboratory Experiment	N=51	Thermal history Indoor TCV
(Pitts et al. 2008)	Sheffield, UK	Spring	University Building AC and NV	Field work Surveys	N=123	TCV
(Pitts 2010)	Sheffield, UK	Spring Summer Autumn Winter	NV Academic Building	Field work Surveys Physical Measurements	N=72	TCV AMV PMV
(Ghaddar et al. 2011)	Beirut, Lebanon	Summer	Bio-heat model	Parametric study Fieldwork validation	--- N=12 N=9	PMV Skin and core temperature
(Kwong and Adam 2011)	Putra, Malaysia	Autumn	AC Lift lobby	Fieldwork	N=113	TCV TP
(Parkinson et al. 2012)	Australia	Spring Autumn	Climatic Chamber	Laboratory Experiment	N=6	TCV TS Skin Temperature
(Pitts 2013)	Review of previous work	Spring Summer Autumn Winter	AC NV	Field work	Review of previous work	PMV TCV
(Wu and Mahdavi 2014)	Vienna, Austria	Spring Winter	Thermal Chamber	Laboratory Experiments	N=313 (s) N=84 (w)	TCV,TSV Sequences Thermal-Distance
(Du et al. 2014)	Chongqing, China	Spring (fw) Winter (lab)	Climatic Chamber AC Offices	Laboratory Fieldwork	N=12	TCV TA

Non-uniform environments						
(Potvin 2000)	Cardiff, UK	Summer Winter	Arcades	Field work Surveys	---	Thermal Variability
(Zhang et al. 2004)	Berkeley, California USA	Spring Summer Winter	Climatic Chamber	Laboratory Experiment	N=109	Skin and core temperature TCV TS
(Nakano et al. 2006)	Tokyo, Japan	Summer Winter	Train Station	Fieldwork Surveys	N=1,099	TCV TCP TS, TA
(Hwang and Lin 2007)	Taiwan	Summer Winter	Outdoors Spaces	Fieldwork Surveys	N=1,644	SET* TCV TP
(Kelly and Parson 2010)	Loughborough, UK	Winter Spring Summer	Thermal Chamber	Laboratory Experiment	N=24	TCV PMV Step-change temperature
(Kelly 2011)	Loughborough London UK	Spring Winter	Train Journeys	Laboratory Fieldwork Experiments	N=18 N=24 N=48 N=44 N=32	TCV PMV-TRANS Pleasantness Stickiness Draught
(Vasilikou and Nikolopoulou 2013)	London, UK Rome, Italy	Summer Winter	Pedestrian Routes	Field work Surveys Interviews	N=314	Thermal Variability
(Kotopouleas and Nikolopoulou 2014)	Manchester and London, UK	Summer Winter	Airport Terminals	Field work Questionnaires Physical Measurements	N=3,087	TCV TCP
Temperature Changes						
(Tsutsumi et al. 2007)	Tokyo, Japan	Hot-Humid Climate	Climatic Chamber AC	Laboratory work	N=12	TCV Productivity
(Jin et al. 2011)	Liaoning, China	Summer Winter	Climatic Chamber	Laboratory work	N=23	
(Liu et al. 2014)	Chongqing, China	Summer	Climatic Chamber	Laboratory work	N=20	TCV Skin temperature
Thermal History						
(Chun et al. 2008)	Seoul, Korea Yokohama, Japan	Summer	Climatic Chamber Outdoors	Field work Laboratory Experiment	N=52	TCV
(Candido et al. 2011)	Maceio, Brazil	Summer Winter	AC NV Buildings	Field work Laboratory Experiments	N(AC)=445 N(NV)=530	TCV TE
(Song et al. 2011)	Singapore	---	University Building AC	Field work	N=36	TCV
(Kim et al. 2011)	Seoul, Korea Portland, Oregon Yokohama, Japan	Spring Summer Autumn	AC Buildings	Fieldwork	N=713 N=807 N=213	TCV TCP
(De Vecci et al. 2012)	Florianopolis, Brazil	Summer Autumn Spring	AC NV University Building	Field work Surveys	N=544 Q=2,292	TCV TA TCP
Short Term Occupancy						
(Nakano et al. 2006)	Tokyo,Japan	Summer Winter	Train stations	Fieldowork	N=1,099	TCV

Appendix 4 Ethics Form

The University Of Sheffield.

School Of Architecture.

Ms Gloria Vargas
School of Architecture
University of Sheffield
The Arts Tower
Western Bank
Sheffield
S10 2TN

14th May 2013

Rosie Parnell

School of Architecture
The Arts Tower
Western Bank
Sheffield
S10 2TN

Telephone: +44 (0) 114 2220327
Fax: +44 (0) 114 279826
Email: r.parnell@sheffield.ac.uk

Dear Gloria,

PROJECT TITLE: The temporality of thermal comfort, thermal history and memory in transitional spaces

On behalf of the University ethics reviewers who reviewed your project, I am pleased to inform you that on 14/05/2013 the above-named project was unconditionally **approved** on ethics grounds, on the basis that you will adhere to the following document that you submitted for ethics review:

- University research ethics application form (13.05.2013)
- Participant information sheet
- Participant consent form

If during the course of the project you need to deviate significantly from the above-approved document please inform me since written approval will be required. Please also inform me should you decide to terminate the project prematurely.

Yours sincerely,

Rosie Parnell
Ethics Coordinator

UNIVERSITY OF SHEFFIELD SCHOOL OF ARCHITECTURE

2011 THE AWARDS AWARD WINNER UNIVERSITY OF THE YEAR

The University Of Sheffield.

School Of Architecture.

Ms Gloria Vargas,
School of Architecture

Rosie Parnell

School of Architecture
The Arts Tower
Western Bank
Sheffield
S10 2TN

Telephone: +44 (0) 114 2220327
Fax: +44 (0) 114 279826
Email: r.parnell@sheffield.ac.uk

13th June 2013

Dear Ms Vargas,

PROJECT TITLE: The temporality of thermal comfort, thermal history and memory in transitional spaces

The University ethics reviewers have now reviewed your research ethics application form. However, they have not been able to approve the application as it stands as they have a number of concerns, which are listed below:

(i) Check all dates and amend as necessary

(ii) Required changes to the participant information sheet

a. Personal data including weight will be collected. Please explain the relevance of this data to the research to avert/address any potential concerns from the participants. (This should also be addressed in the application form)

b. What is the 'thermal comfort vote'? Explain/rephrase.

c. Clarify where the photographs might be published and whether or not the participants would potentially be identifiable - e.g. would their faces be visible? (This should also be addressed in the application form)

(iii) Required changes to the consent form

a. Consent for publication of photos should be added (either within the current item which addresses the taking of photos, or else separately).

(iv) Required changes to the application form

a. See ii)a and ii)c above
b. A10: the application says that the data will be stored securely by the researcher – please detail how storage will be made secure (both electronic and hard copies).

Ethics approval is subject to the above points being addressed satisfactorily. I would be very grateful if you could amend the application form and information sheet appropriately to address the above points, and resubmit them (with the new date in the footer).

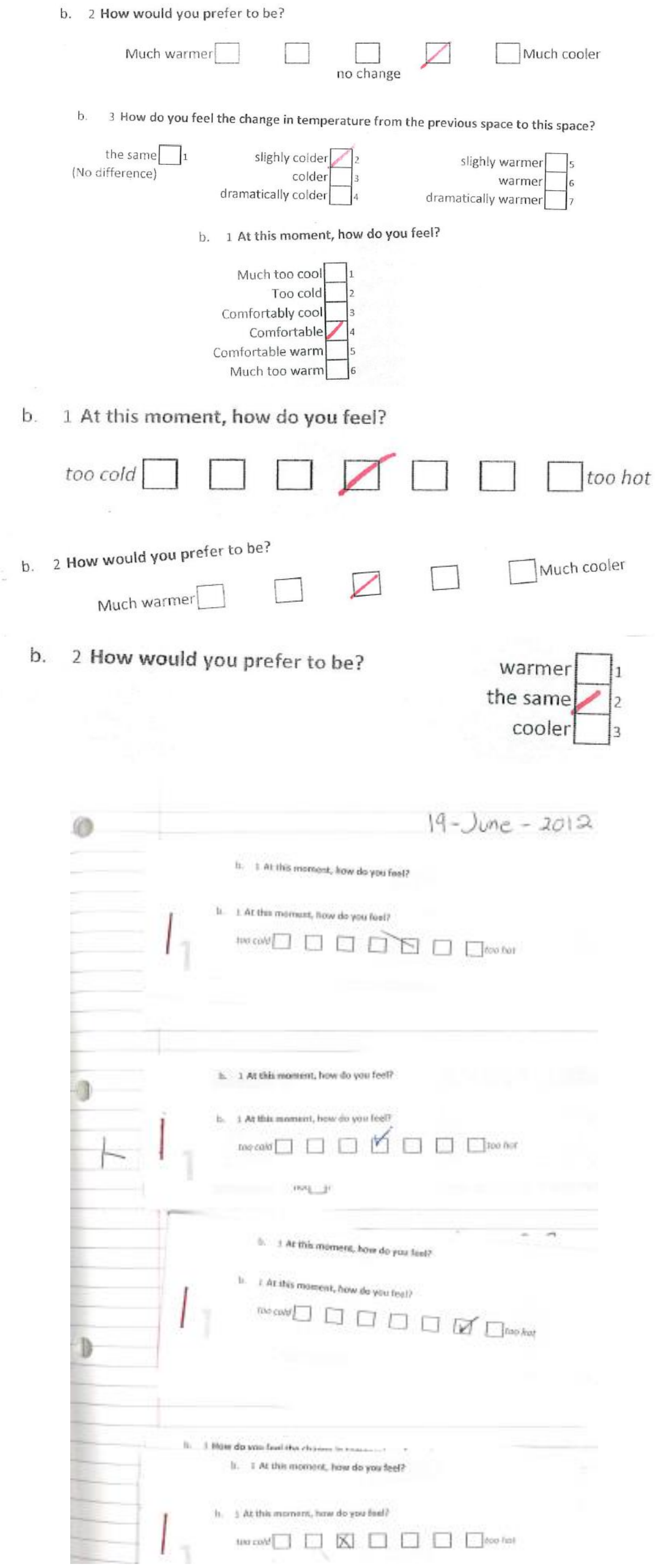
Should you have any queries as regards what is being requested please do not hesitate to contact me, either by email or by phone *r.parnell@sheffield.ac.uk tel 20327.*

Yours sincerely

Rosie Parnell
Ethics Coordinator

UNIVERSITY OF SHEFFIELD SCHOOL OF ARCHITECTURE

Appendix 5 Pilot questionnaire


b. 2 How would you prefer to be?

Much warmer ☐ ☐ ☐ ☐ ☐ Much cooler

no change

b. 3 How do you feel the change in temperature from the previous space to this space?

the same (No difference) ☐ 1
slighly colder ☐ 2
colder ☐ 3
dramatically colder ☐ 4
slighly warmer ☐ 5
warmer ☐ 6
dramatically warmer ☐ 7

b. 1 At this moment, how do you feel?

Much too cool ☐ 1
Too cold ☐ 2
Comfortably cool ☐ 3
Comfortable ☐ 4
Comfortable warm ☐ 5
Much too warm ☐ 6

b. 1 At this moment, how do you feel?

too cold ☐ ☐ ☐ ☐ ☐ ☐ ☐ too hot

b. 2 How would you prefer to be?

Much warmer ☐ ☐ ☐ ☐ ☐ Much cooler

b. 2 How would you prefer to be?

warmer ☐ 1
the same ☐ 2
cooler ☐ 3

19-June-2012

b. 1 At this moment, how do you feel?

too cold ☐ ☐ ☐ ☐ ☐ ☐ ☐ too hot

Figure 1 Pilot questionnaires exploring people's answers using different 7 point scales

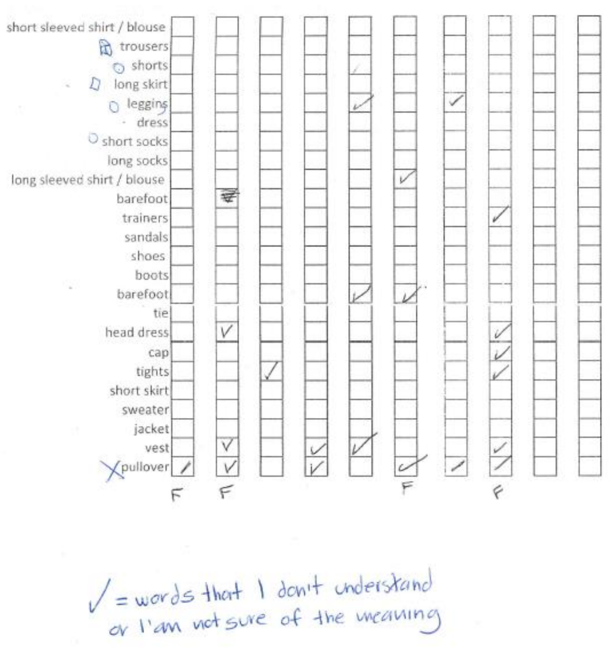


Figure 2 Pilot questionnaire exploring typical words that international students find difficult to understand in the questionnaires, in this image words related to clothing

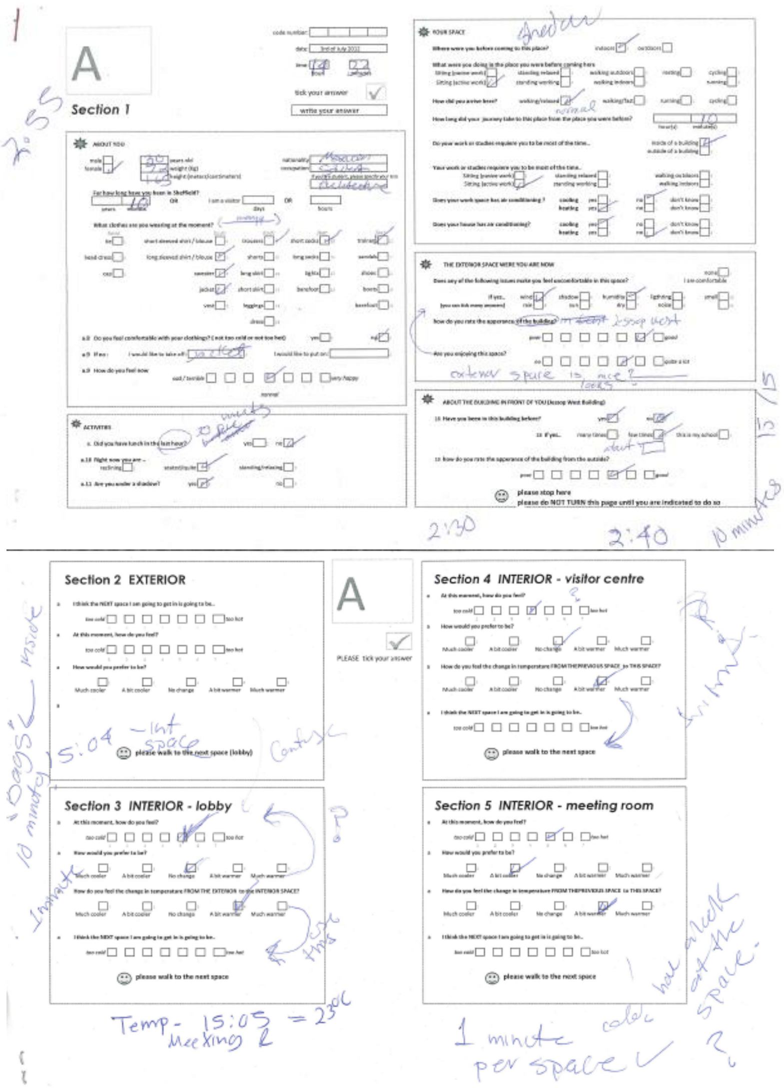


Figure 3 Pilot questionnaire used to measure survey time, while participants were walking in through different spaces.

Pilot Questionnaire used in the pilot experiment 1, and pictures of participants

group A

participant code number:

date: 3rd of July 2012

time: hour : minutes am pm

please tick your answer

ABOUT YOU

male 1 female 2 | age 3 | weight (Kg) 4 | height (meters/centimeters) 5 | nationality 6 | occupation 7

a1 How long have you been in Sheffield? years months 1 OR I am a visitor days 3 OR hours 4

a2 What clothes are you wearing at the moment? (tick as many as appropriate)

HEAD: head dress / veil 1; hat /cap 2

BODY: dress 3; short sleeved shirt/blouse 5; vest 8; shorts 11; long sleeved shirt/blouse 6; trousers 9; long skirt 12; jacket 4; sweater 7; leggings 10; short skirt 13

FEET: short socks 14; tights 16; trainers 18; shoes 20; long socks 15; NO socks/tights 17; sandals 19; boots 21

a3 Do you feel comfortable with your clothing? (not too hot or cold) yes 1 no 2

a4 If no : I would like to take off: 1 I would like to put on: 2

YOUR ACTIVITIES and SPACE

a5 Have you eaten in the last 30 minutes? yes 1 no 2

a6 Where were you before coming here? indoors 1 outdoors 2

a7 How were you behaving in the place you were BEFORE coming here?
Sitting (pasive work) 1; Sitting (active work) 2; standing relaxed 3; standing working 4; walking outdoors 5; walking indoors 6; resting 7; cycling 8; running 9

a8 How did you arrive here? walking/relaxed 1; walking/fast 2; running 3; cycling 4

a9 How long did your journey take to this place? (from the place you were before) hour(s) minute(s)

a10 Your work or studies require you to be mostly... inside of a building 1; outside of a building 2

a11 Your work or studies require you to be mostly... Sitting (pasive work) 1; Sitting (active work) 2; standing (relaxed) 3; standing (working) 4; walking outdoors 5; walking indoors 6

a12 Does your work place have air conditioning?
cooling yes 1 no 2 don't know 3
heating yes 1 no 2 don't know 3

a13 Does your house have air conditioning?
cooling yes 1 no 2 don't know 3
heating yes 1 no 2 don't know 3

ABOUT THIS EXTERIOR SPACE

a14 Do any of the following issues make you feel uncomfortable in this space? (tick as many as appropriate)
wind 1; rain 2; shadow 3; sun 4; humidity 5; dry 6; lighting 7; noise 8; smell 9; none 10 I am comfortable

a15 Do you like this space? no 1 2 3 4 5 6 7 quite a lot

a16 Are you under a shadow? yes 1 no 2

ABOUT THE BUILDING (Jessop West Building)

a17 Have you been in this building before? no 1; a few times 3; many times 4; this is the fist time 2; this is my work place 5

a18 how do you rate the apperance of the building from the outside? poor 1 2 3 4 5 6 7 good

a19 How do you feel now? - Much too cold 3; Too cool 2; Comfortably cool 1; Comfortable 0; Comfortably warm 1; Too warm 2; Much too warm 3 +

a20 How would you prefer to be? - Much cooler 2; A bit cooler 1; No change 0; A bit warmer 1; Much warmer 2 +

a21 How do you feel now? normal 1; very happy 2; happy 3; calm 4; worried 5; stressed 6; nervous 7; disappointed 8; angry 9

please stop here
please do NOT TURN this page until you are told to do so

A

Space 1 exterior

a22 How do you feel now?
- 3 2 1 0 1 2 3 +
much too cold ... much too warm

a23 How would you prefer to be?
- Much cooler 2; A bit cooler 1; No change 0; A bit warmer 1; Much warmer 2 +

a24 I think the NEXT space I am going to enter will be...
- much too cold 3; too cool 2; comfortably cool 1; comfortable 0; comfortably warm 1; too warm 2; much too warm 3 +

please stop here
please do NOT TURN this page until you are told to do so

A

Space 3 interior-visitor centre

a29 How do you feel after moving from the PREVIOUS SPACE to this SPACE?
- Much cooler 2; A bit cooler 1; No change 0; A bit warmer 1; Much warmer 2 +

a30 How do you feel now?
- 3 2 1 0 1 2 3 +
much too cold ... much too warm

a31 How would you prefer to be?
- Much cooler 2; A bit cooler 1; No change 0; A bit warmer 1; Much warmer 2 +

a32 How do you rate the apperance of this space?
poor 1 2 3 4 5 6 7 good

please turn the page and move on the next place

A

Space 2 interior-lobby

a25 How do you feel after moving FROM THE EXTERIOR to this INTERIOR SPACE?

- ☐ Much cooler ☐ A bit cooler ☐ No change ☐ A bit warmer ☐ Much warmer +

a26 How do you feel now?

- ☐ much too cold ☐ ☐ ☐ ☐ ☐ ☐ much too warm +

a27 How would you prefer to be?

- ☐ Much cooler ☐ A bit cooler ☐ No change ☐ A bit warmer ☐ Much warmer +

a28 How do you rate the apperance of this space?

poor ☐ ☐ ☐ ☐ ☐ ☐ ☐ *good*

please turn the page and move on the next place

A

Space 4 interior-meeting

a33 How do you feel after moving from the PREVIOUS SPACE to this SPACE?

- ☐ Much cooler ☐ A bit cooler ☐ No change ☐ A bit warmer ☐ Much warmer +

a34 How do you feel now?

- ☐ much too cold ☐ ☐ ☐ ☐ ☐ ☐ much too warm +

a35 How would you prefer to be?

- ☐ Much cooler ☐ A bit cooler ☐ No change ☐ A bit warmer ☐ Much warmer +

a36 How do you rate the apperance of this space?

poor ☐ ☐ ☐ ☐ ☐ ☐ ☐ *good*

please turn the page and move on the next place

Space 5 exterior

A

a37 How do you feel after moving from the INTERIOR SPACE to THE EXTERIOR SPACE?

- ☐ Much cooler ☐ A bit cooler ☐ No change ☐ A bit warmer ☐ Much warmer +

a38 How do you feel now?

- ☐ much too cold ☐ ☐ ☐ ☐ ☐ ☐ much too warm +

a39 How would you prefer to be?

- ☐ Much cooler ☐ A bit cooler ☐ No change ☐ A bit warmer ☐ Much warmer +

after walking in the interior spaces...

a40 How do you rate the apperance of THE INTERIOR SPACES?

poor ☐ ☐ ☐ ☐ ☐ ☐ ☐ *good*

a41 Did you enjoy walking in the building?

no ☐ ☐ ☐ ☐ ☐ ☐ ☐ *a lot*

a42 What do you like of the INTERIOR spaces that you walked? (you can tick more than one answer)

colours ☐	skylight ☐	smell ☐	forms ☐	stairs ☐
materials ☐	lighting ☐	sounds ☐	views ☐	windows ☐
textures ☐	daylighting ☐	acoustic quality ☐	fabrics ☐	walls ☐
furniture ☐	dimensions ☐	(not noisy)		doors ☐

a43 What DON'T you like of the INTERIOR spaces? (you can tick more than one answer)

colours ☐	skylight ☐	smell ☐	forms ☐	stairs ☐
materials ☐	lighting ☐	sounds ☐	views ☐	windows ☐
textures ☐	daylighting ☐	acoustic quality ☐	fabrics ☐	walls ☐
furniture ☐	dimensions ☐	(not noisy)		doors ☐

group B

participant code number: ☐☐☐☐

date: 3rd of July 2012

time: ☐ : ☐
hour minutes
☐ am ☐ pm

☑ please tick your answer

ABOUT YOU

male ☐1 female ☐2

3 ☐ age
4 ☐ weight (Kg)
5 ☐ height (meters/centimeters)

nationality ☐6
occupation ☐7

b1 How long have you been in Sheffield?
1 ☐ years ☐ months 2 **OR** I am a visitor ☐ days 3 **OR** ☐ hours 4

b2 What clothes are you wearing at the moment? (tick as many as appropriate)

HEAD head dress / veil ☐1 hat /cap ☐2

BODY
dress ☐3 short sleeved shirt/blouse ☐5 vest ☐8 shorts ☐11
long sleeved shirt/blouse ☐6 trousers ☐9 long skirt ☐12
jacket ☐4 sweater ☐7 leggings ☐10 short skirt ☐13

FEET
short socks ☐14 tights ☐16 trainers ☐18 shoes ☐20
long socks ☐15 NO socks/tights ☐17 sandals ☐19 boots ☐21

b3 Do you feel comfortable with your clothing? (not too hot or cold) yes ☐1 no ☐2

b4 If no : I would like to take off: ☐1 I would like to put on: ☐2

YOUR ACTIVITIES and SPACE

b5 Have you eaten in the last 30 minutes? yes ☐1 no ☐2
b6 Where were you before coming here? indoors ☐1 outdoors ☐2

b7 How were you behaving in the place you were BEFORE coming here?
Sitting (pasive work) ☐1 standing relaxed ☐3 walking outdoors ☐5 resting ☐7 cycling ☐8
Sitting (active work) ☐2 standing working ☐4 walking indoors ☐6 running ☐9

b8 How did you arrive here?
walking/relaxed ☐1 walking/fast ☐2 running ☐3 cycling ☐4

b9 How long did your journey take to this place? (from the place you were before)
☐ hour(s) ☐ minute(s)

b10 Your work or studies require you to be mostly...
inside of a building ☐1 outside of a building ☐2

b11 Your work or studies require you to be mostly...
Sitting (pasive work) ☐1 standing (relaxed) ☐3 walking outdoors ☐5
Sitting (active work) ☐2 standing (working) ☐4 walking indoors ☐6

b12 Does your work place have air conditioning?
cooling yes ☐1 no ☐2 don't know ☐3
heating yes ☐1 no ☐2 don't know ☐3

b13 Does your house have air conditioning?
cooling yes ☐1 no ☐2 don't know ☐3
heating yes ☐1 no ☐2 don't know ☐3

ABOUT THIS EXTERIOR SPACE

b14 Do any of the following issues make you feel uncomfortable in this space? (tick as many as appropriate)
wind ☐1 shadow ☐3 humidity ☐5 lighting ☐7 smell ☐9
rain ☐2 sun ☐4 dry ☐6 noise ☐8 none ☐10
I am comfortable

b15 Do you like this space?
no ☐ ☐ ☐ ☐ ☐ ☐ ☐ *quite a lot*
1 2 3 4 5 6 7

b16 Are you under a shadow? yes ☐1 no ☐2

ABOUT THE BUILDING (Jessop West Building)

b17 Have you been in this building before? no ☐1 this is the fist time ☐2
a few times ☐3 many times ☐4 this is my work place ☐5

b18 how do you rate the apperance of the building from the outside?
poor ☐ ☐ ☐ ☐ ☐ ☐ ☐ *good*
1 2 3 4 5 6 7

b19 How do you feel now?
- ☐3 Much too cold ☐2 Too cool ☐1 Comfortably cool ☐0 Comfortable ☐1 Comfortably warm ☐2 Too warm ☐3 Much too warm +

b20 How would you prefer to be?
- ☐2 Much cooler ☐1 A bit cooler ☐0 No change ☐1 A bit warmer ☐2 Much warmer +

b21 How do you feel now?
normal ☐1 very happy ☐2 calm ☐4 stressed ☐6 disappointed ☐8
happy ☐3 worried ☐5 nervous ☐7 angry ☐9

please stop here
please do NOT TURN this page until you are told to do so

B

☑ Space 5 exterior

b22 How do you feel now?
- ☐3 much too cold ☐2 ☐1 ☐0 ☐1 ☐2 ☐3 much too warm +

b23 How would you prefer to be?
- ☐2 Much cooler ☐1 A bit cooler ☐0 No change ☐1 A bit warmer ☐2 Much warmer +

b24 I think the NEXT space I am going to enter will be...
- ☐3 much too cold ☐2 too cool ☐1 comfortably cool ☐0 comfortable ☐1 comfortably warm ☐2 too warm ☐3 much too warm +

please stop here
please do NOT TURN this page until you are told to do so

B

Space 3 interior-visitor centre

b29 How do you feel after moving from the PREVIOUS SPACE to this SPACE?
- ☐2 Much cooler ☐1 A bit cooler ☐0 No change ☐1 A bit warmer ☐2 Much warmer +

b30 How do you feel now?
- ☐3 much too cold ☐2 ☐1 ☐0 ☐1 ☐2 ☐3 much too warm +

b31 How would you prefer to be?
- ☐2 Much cooler ☐1 A bit cooler ☐0 No change ☐1 A bit warmer ☐2 Much warmer +

b32 How do you rate the apperance of this space?
poor ☐ ☐ ☐ ☐ ☐ ☐ ☐ *good*
1 2 3 4 5 6 7

please turn the page and move on the next place

B

Space 4 interior-meeting

b33 How do you feel after moving from the EXTERIOR SPACE to this INTERIOR SPACE?

- ☐ Much cooler ☐ A bit cooler ☐ No change ☐ A bit warmer ☐ Much warmer +

b34 How do you feel now?

- ☐ much too cold ☐ ☐ ☐ ☐ ☐ ☐ much too warm +

b35 How would you prefer to be?

- ☐ Much cooler ☐ A bit cooler ☐ No change ☐ A bit warmer ☐ Much warmer +

b36 How do you rate the apperance of this space?

poor ☐ ☐ ☐ ☐ ☐ ☐ ☐ *good*

please turn the page and move on the next place

B

Space 2 interior-lobby

b25 How do you feel after moving from the PREVIOUS SPACE to this SPACE?

- ☐ Much cooler ☐ A bit cooler ☐ No change ☐ A bit warmer ☐ Much warmer +

b26 How do you feel now?

- ☐ much too cold ☐ ☐ ☐ ☐ ☐ ☐ much too warm +

b27 How would you prefer to be?

- ☐ Much cooler ☐ A bit cooler ☐ No change ☐ A bit warmer ☐ Much warmer +

b28 How do you rate the apperance of this space?

poor ☐ ☐ ☐ ☐ ☐ ☐ ☐ *good*

please turn the page and move on the next place

Space 1 exterior

B

b37 How do you feel after moving from the INTERIOR SPACE to THE EXTERIOR SPACE?

- ☐ Much cooler ☐ A bit cooler ☐ No change ☐ A bit warmer ☐ Much warmer +

b38 How do you feel now?

- ☐ much too cold ☐ ☐ ☐ ☐ ☐ ☐ much too warm +

b39 How would you prefer to be?

- ☐ Much cooler ☐ A bit cooler ☐ No change ☐ A bit warmer ☐ Much warmer +

after walking in the interior spaces...

b40 How do you rate the apperance of THE INTERIOR SPACES?

poor ☐ ☐ ☐ ☐ ☐ ☐ ☐ *good*

b41 Did you enjoy walking in the building?

no ☐ ☐ ☐ ☐ ☐ ☐ ☐ *a lot*

b42 What do you like of the INTERIOR spaces that you walked? (you can tick more than one answer)

colours ☐	skylight ☐	smell ☐	forms ☐	stairs ☐
materials ☐	lighting ☐	sounds ☐	views ☐	windows ☐
textures ☐	daylighting ☐	acoustic quality ☐	fabrics ☐	walls ☐
furniture ☐	dimensions ☐	(not noisy)		doors ☐

b43 What DON'T you like of the INTERIOR spaces? (you can tick more than one answer)

colours ☐	skylight ☐	smell ☐	forms ☐	stairs ☐
materials ☐	lighting ☐	sounds ☐	views ☐	windows ☐
textures ☐	daylighting ☐	acoustic quality ☐	fabrics ☐	walls ☐
furniture ☐	dimensions ☐	(not noisy)		doors ☐


Jessop
West

Pilot Questionnaire used in pilot experiment 2 and pictures of participants

***IMPORTANT** : You will be asked several times, at the different locations of the building, to give your thermal perception of the space. Please do it carefully, considering each time your actual experience at that specific moment.*

SECTION 1 / EXTERIOR

please tick your answer

21 How do you feel at this precise moment?
☐1 cold ☐2 cool ☐3 slightly cool ☐4 neutral ☐5 slightly warm ☐6 warm ☐7 hot

22 How would you prefer to be?
☐1 cooler ☐2 no change ☐3 warmer

23 How do you feel at this precise moment in terms of air flow?
☐1 much too still ☐2 still ☐3 slightly still ☐4 just right ☐5 slightly breezy ☐6 too breezy ☐7 much too breezy

still = not moving *breezy= a light current of air, a gentle wind*

24 How do you feel at this precise moment in terms of humidity?
☐1 much too dry ☐2 too dry ☐3 slightly dry ☐4 just right ☐5 slightly humid ☐6 too humid ☐7 much too humid

25 How do you judge this environment (weather)?
acceptable ☐1 unacceptable ☐2

26 Do you feel comfortable (not too hot or cold) with the clothes you are wearing now?
yes ☐1 no ☐2

27 Do any of the following issues make you feel uncomfortable in this space? (tick as many as appropriate)
wind ☐1 shade ☐1 humidity ☐1 noise ☐1
rain ☐2 sun ☐2 dryness ☐2 smell ☐2

SECTION 3 / CORRIDOR

please tick your answer

32 How do you feel at this precise moment?
☐1 cold ☐2 cool ☐3 slightly cool ☐4 neutral ☐5 slightly warm ☐6 warm ☐7 hot

33 How would you prefer to be?
☐1 cooler ☐2 no change ☐3 warmer

34 How do you feel the change in temperature between this space (corridor) and the previous space (entry doors) ?
☐1 sudden ☐2 gradual ☐3 little /no change

sudden = occurring quickly and unexpectedly gradual = progressing slowly or by degrees

35 How do you judge this interior space in terms of temperature?
☐1 acceptable ☐2 unacceptable

SECTION 2 / ENTRY DOORS

please tick your answer

28 How do you feel at this precise moment?
☐1 cold ☐2 cool ☐3 slightly cool ☐4 neutral ☐5 slightly warm ☐6 warm ☐7 hot

29 How would you prefer to be?
☐1 cooler ☐2 no change ☐3 warmer

30 How do you feel the change in temperature between this space (entry doors) and the outside of the building?
☐1 sudden ☐2 gradual ☐3 little /no change

sudden = occurring quickly and unexpectedly *gradual = progressing slowly or by degrees*

31 How do you judge this space in terms of temperature?
☐1 acceptable ☐2 unacceptable

SECTION 4 / LECTURE THEATRE

please tick your answer

36 How do you feel at this precise moment?
☐1 cold ☐2 cool ☐3 slightly cool ☐4 neutral ☐5 slightly warm ☐6 warm ☐7 hot

37 How would you prefer to be?
☐1 cooler ☐2 no change ☐3 warmer

38 How do you feel the change in temperature between this space (lecture theatre) and the previous space (corridor)?
☐1 sudden ☐2 gradual ☐3 little /no change

sudden = occurring quickly and unexpectedly gradual = progressing slowly or by degrees

39 How do you judge this interior space in terms of temperature?
☐1 acceptable ☐2 unacceptable

Now you can take a seat in the room and answer the last section of the questionnaire

ABOUT YOU

please tick your answer

1 Gender male ☐1 female ☐2

2 Nationality ____________

3 Age years ______ months ______

4 Occupation student ☐1 other (specify) ______

4 Weight kilograms ______ (1 kilo = 2.2 pounds 1 kilo = 0.15 stone)

5 Height Metres/centimetres ______

6 How long have you been in Sheffield?
years ______ months ______

7 What clothes are you wearing now? (tick as many as appropiate)

Head
head scarf/ veil ☐1 hat/cap ☐2

Mid layer
short sleeved shirt / blouse ☐3 leggings ☐5 long skirt ☐8
long sleeved shirt / blouse ☐4 trousers ☐6 short skirt ☐9
shorts ☐7 dress ☐10

Outer layer
jacket ☐11 sweater ☐12 vest ☐13

Footwear
shoes /trainers ☐14 tights ☐17 short socks ☐19
boots ☐15 NO socks/tights ☐18 long socks ☐20
sandals ☐16

8 Are you carrying something (bag) with you?
No ☐1 backpack ☐2 hand bag ☐3

ABOUT YOUR ACTIVITIES

9 Have you been in this building before?
this is the first time ☐1 a few times ☐2 many times ☐3

10 Where were you before coming here? indoors ☐1 outdoors ☐2

11 In which building were you before coming here? ______

12 How were you behaving in the place you were BEFORE coming here?
sitting (passive work) ☐1 standing relaxed ☐3 walking outdoors ☐5
sitting (active work) ☐2 standing working ☐4 walking indoors ☐6
resting ☐7

13 How did you arrive here?
walking/relaxed ☐1 running ☐3 other ☐4
walking/fast ☐2 cycling ☐4 (specify) ______

14 How long did your journey take to this place? (from the place you were before)
hours ______ minutes ______

15 Have you eaten in the last 30 minutes? yes ☐1 no ☐2

16 Your work or studies require you to be mostly…
indoors ☐1 outdoors ☐2

17 Your work or studies require you to be mostly in a laboratory at a specific temperature?
yes ☐1 no ☐2

18 Your work or studies require you to be mostly…
Sitting (passive work) ☐1 standing (relaxed) ☐1 walking outdoors ☐5
Sitting (active work) ☐2 standing (working) ☐2 walking indoors ☐6

19 Does the place you usually use to work have air conditioning?
cooling yes ☐1 no ☐2 don't know ☐3
heating yes ☐2 no ☐2 don't know ☐3

20 Does your accommodation in Sheffield have air conditioning?
cooling yes ☐1 no ☐2 don't know ☐3
heating yes ☐2 no ☐2 don't know ☐3

***IMPORTANT** : You will be asked several times, at the different locations of the building, to give your thermal perception of the space. Please do it carefully, considering each time your actual experience at that specific moment.*

SECTION 1 / EXTERIOR

please tick your answer

21 How do you feel at this precise moment?

☐1 cold ☐2 cool ☐3 slightly cool ☐4 neutral ☐5 slightly warm ☐6 warm ☐7 hot

22 How would you prefer to be?

☐1 cooler ☐2 no change ☐3 warmer

23 How do you feel at this precise moment in terms of air flow?

☐1 much too still ☐2 still ☐3 slightly still ☐4 just right ☐5 slightly breezy ☐6 too breezy ☐7 much too breezy

still = not moving *breezy= a light current of air, a gentle wind*

24 How do you feel at this precise moment in terms of humidity?

☐1 much too dry ☐2 too dry ☐3 slightly dry ☐4 just right ☐5 slightly humid ☐6 too humid ☐7 much too humid

25 How do you judge this environment (weather)?

acceptable ☐1 unacceptable ☐2

26 Do you feel comfortable (not too hot or cold) with the clothes you are wearing now?

yes ☐1 no ☐2

27 Do any of the following issues make you feel uncomfortable in this space? (tick as many as appropriate)

wind ☐1 shade ☐1 humidity ☐1 noise ☐1
rain ☐2 sun ☐2 dryness ☐2 smell ☐2

SECTION 2 / LECTURE THEATRE

please tick your answer

36 How do you feel at this precise moment?

☐1 cold ☐2 cool ☐3 slightly cool ☐4 neutral ☐5 slightly warm ☐6 warm ☐7 hot

37 How would you prefer to be?

☐1 cooler ☐2 no change ☐3 warmer

38 How do you feel the change in temperature between this space (lecture theatre) and the previous space (corridor)?

☐1 sudden ☐2 gradual ☐3 little /no change

sudden = occurring quickly and unexpectedly gradual = progressing slowly or by degrees

39 How do you judge this interior space in terms of temperature?

☐1 acceptable ☐2 unacceptable

Now you can take a seat in the room and answer the last section of the questionnaire

ABOUT YOU

please tick your answer

1 **Gender** male ☐1 female ☐2

2 **Nationality** ____________

3 **Age** years ________ months ________

4 **Occupation** student ☐1 other (specify) ________

4 **Weight** kilograms ________ (1 kilo = 2.2 pounds 1 kilo = 0.15 stone)

5 **Height** Metres/centimetres ________

6 **How long have you been in Sheffield?**

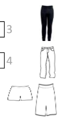
years ________ months ________

7 **What clothes are you wearing now? (tick as many as appropiate)**

Head

head scarf/ veil ☐1  hat/cap ☐2

Mid layer

 short sleeved shirt / blouse ☐3  leggings ☐5  long skirt ☐8
long sleeved shirt / blouse ☐4 trousers ☐6 short skirt ☐9
shorts ☐7 dress ☐10

Outer layer

 jacket ☐11  sweater ☐12  vest ☐13

Footwear

 shoes /trainers ☐14  tights ☐17  short socks ☐19
 boots ☐15 NO socks/tights ☐18 long socks ☐20
 sandals ☐16

8 **Are you carrying something (bag) with you?**

No ☐1  backpack ☐2  hand bag ☐3

ABOUT YOUR ACTIVITIES

9 **Have you been in this building before?**

this is the first time ☐1 a few times ☐2 many times ☐3

10 **Where were you before coming here?** indoors ☐1 outdoors ☐2

11 **In which building were you before coming here?** ________

12 **How were you behaving in the place you were BEFORE coming here?**

sitting (passive work) ☐1 standing relaxed ☐3 walking outdoors ☐5
sitting (active work) ☐2 standing working ☐4 walking indoors ☐6
resting ☐7

13 **How did you arrive here?**

walking/relaxed ☐1 running ☐3 other ☐4
walking/fast ☐2 cycling ☐4 (specify) ________

14 **How long did your journey take to this place? (from the place you were before)**

hours ________ minutes ________

15 **Have you eaten in the last 30 minutes?** yes ☐1 no ☐2

16 **Your work or studies require you to be mostly…**

indoors ☐1 outdoors ☐2

17 **Your work or studies require you to be mostly in a laboratory at a specific temperature?**

yes ☐1 no ☐2

18 **Your work or studies require you to be mostly…**

Sitting (passive work) ☐1 standing (relaxed) ☐1 walking outdoors ☐5
Sitting (active work) ☐2 standing (working) ☐2 walking indoors ☐6

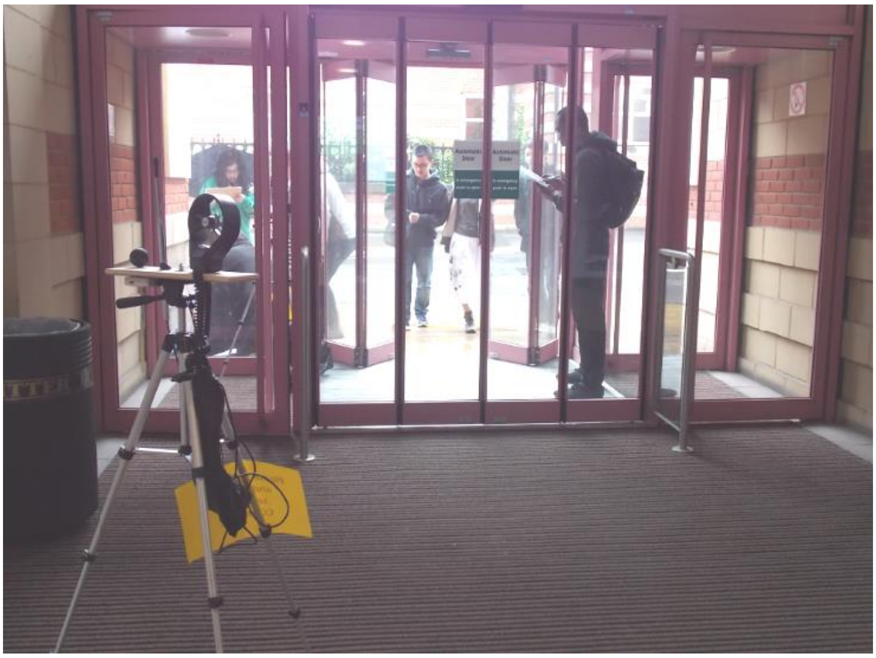
19 **Does the place you usually use to work have air conditioning?**

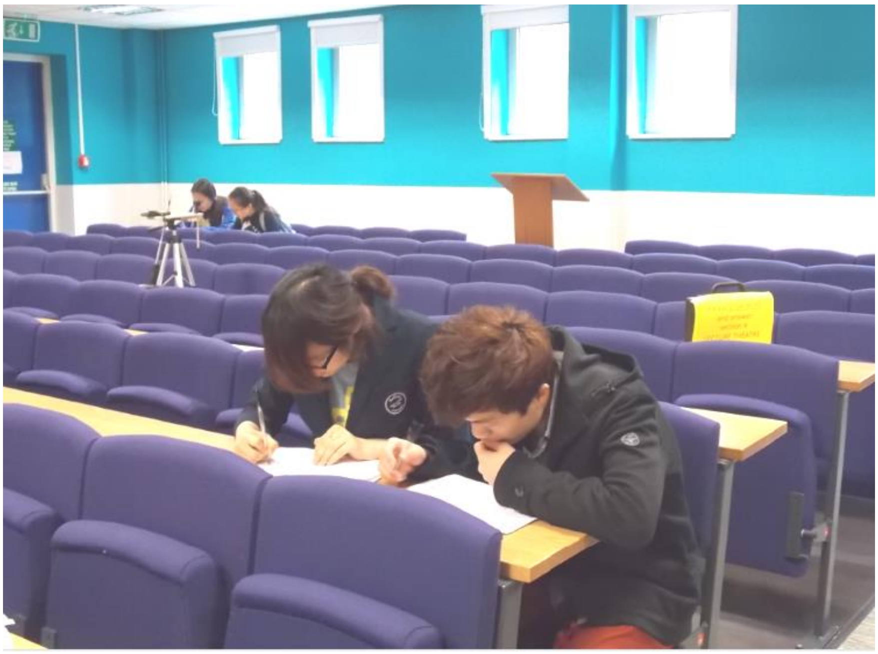
cooling yes ☐1 no ☐2 don't know ☐3
heating yes ☐1 no ☐2 don't know ☐3

20 **Does your accommodation in Sheffield have air conditioning?**

cooling yes ☐1 no ☐2 don't know ☐3
heating yes ☐1 no ☐2 don't know ☐3


The University Of Sheffield.





Appendix 6 Pilot experiments

1. Pilot Experiment 1

The pilot experiment was conducted at The University of Sheffield's Jessop West Building on 3rd of July 2012 with 20 university students. July was selected because is typically one of the hottest months in Sheffield (Met-Office-UK 2015) and the aim was to measure people's thermal perception in largest possible temperature differences from the exterior to the interior environments. The time of the test was from 2:30 to 3:15pm because is within the hourly range were the maximum temperature occurs in this period (based on climatic records form Sheffield-Weston Park Museum Weather Station). The experiment included six different spaces: three different exterior areas, the entry doors space, the circulation space and a seminar room. A total of six people helped the researcher to run the pilot experiment survey. Two people guided the groups A and B to their corresponding routes, three people helped to take measurements with the manual equipment used in this work, and finally one person was in charge to coordinate that both groups started walking at the same time and make sure that all the equipment was setup on time.

1.9. Preliminary work

The preliminary work included previous authorization from The University's Estates and Facilities Management department to carry out the pilot experiment at the Jessop West building, training to the people that were supporting the researcher, equipment setup, preliminary measurements, few simulations with Ecotect software to analyse the proper location of equipment, precondition of meeting room, and questionnaires design.

1.9.1. Questionnaires

Two questionnaires were designed A and B, for each group respectively. Both include the same information, but varied in the sequence of the questions according to the route of each group; the questionnaires had three sections. The first section included questions about people's background, previous thermal experiences and clothing (using AHSRAE 55-2004 tables). The second section included the thermal comfort survey; people's thermal comfort perception was collected using the 7 point ASHRAE scale (Jitkhajornwanich and Pitts 2002), people's thermal comfort preferences and 5 point scale for thermal preferences (Nicol et al. 2012), and 5 point scale for thermal preferences for step-changed temperatures (Jitkhajornwanich and Pitts 2002; Parkinson et al. 2012). The questions were designed to be answered immediately after change from one space to another at specific measurement points where the equipment was located. During the questionnaire design, preliminary testing was conducted with 10 undergraduate students in order to check that the questionnaires were comprehensible and comprehensive; question's wording, subjective measurement scales and answering time were tested.

1.9.2. Temperature setup in the seminar room

During the pilot experiment, the Jessop West operated with natural ventilation. However, in order to create a larger temperature difference between the outdoor and indoor environments, only the seminar room was preconditioned to 24°C in order to create step changes temperatures with approximately 3°C of difference from the current exterior temperature, following the criteria used by Chun (2005). The preconditioning of the room was conducted 30 minutes before the survey, to allow enough time to the room to reach the requires temperature. In this exercise it was not possible to calibrate the equipment, however, the Building's Management System (BMS) was set to record temperature every 5 minutes (the minimum possible sampling time) to measure the temperature at the exterior of the building, corridor and meeting room. Data from the BMS was planned to be further compared with the data loggers' measurements.

1.9.3. Pilot Study physical measurements

At the exterior, air temperature (T_a) and air humidity (RH) were measured with hygrometer i-button (Thermochron) inside of a waterproof capsule. In the interior spaces, data logging equipment HOBO-U12 was used (**Figure 4**). Air velocity was measured with a digital anemometer hand held RS1480-7111. Because of the limited number of equipment at this stage of research the wind velocity was measured with a single instrument at specific times: in the exterior (30, 20, 10 and 5 minutes before the survey), entry doors space (two times when group a and B were in this space) and circulation space (one time when both groups were crossing this space). In the seminar room, air velocity was measured with a hot wire anemometer (Testo 405-V) taking the reading manually every 5 seconds while participants were inside and 30,20,10 and 5 minutes before the survey started. Globe temperature was measured using a small data logging device (Thermochron i-button) inside of a black painted 40mm table tennis ball, the sampling time was every 5 seconds. Finally, radiant temperature (T_r) was measured with a thermo camera (FLIR E40bx-Series) when people were in the measurement points at the exterior, entry doors space, circulation space and seminar room. For a detailed analysis of the procedure, few sections of the process were filmed with two small video cameras (FLIP video Mino HD-Cisco) with people's consent. The camera were hidden, one in the circulation space another in the seminar room. This allowed further calculation of the time that people spent answering the questionnaires.

Figure 4 Equipment used in the pilot experiment: a) data logging equipment HOBO-U12, b) globe thermometer, c) hot wire anemometer Testo 405-V, d) Four in one temperature kit, e) thermo camera FLIR
Pilot experiment procedure

All the equipment was located in the building spaces and set to start measurements at 2:15pm on July 3rd 2012. Participants arrived at 2:30pm at the exterior starting point. The pilot experiment procedure involved a preliminary 30 minutes of thermal stability followed by the survey.

1.9.4. Thermal stability

In the first stage, all participants experienced 30 minutes under the same thermal conditions in order to create a similar short-term thermal history before the survey. Laboratory experiments have added this first step in order to reach a thermal equilibrium state and reduce the thermal effect of people's previous experiences (Chun, 2008; Parkinson, 2012; DeVicchi, 2012). This consideration is generally included because dramatic changes in activity or environment can last in people's short term thermal history for 60 minutes or more (Nicol, 2012). Despite this pilot experiment's aim to study the effect of the exterior environment, this step was important to reduce the variables affecting people's perception. In this case, the preliminary 30 minutes thermal exposure did not involve fixed or controlled conditions, as it was a fieldwork the objective was to have participants with similar previous thermal experiences. During this period participants remained standing at the exterior under a shadow. This time was used to give instructions to participants, also they were asked to answer the first section of the questionnaire to collect demographic data, clothing and previous activities. In the remaining time participants will not be allowed to change from a passive position, drink hot or cold water or eat. After 30 minutes, participants were divided randomly in two groups of 10 people with similar number of males and females. At this point he second phase of the experiment started.

1.10. Thermal comfort survey in the pilot experiment 1

This was the dynamic process of the pilot experiment; at this stage it was assumed that people had created a new similar short thermal history influenced by the climatic conditions of the exterior space. Both groups, A and B, were asked to walk to the same interior space, but, via different routes, route A and B respectively (**Figure 5**).

Group A: exterior 1 – exterior 2 - entry door space – circulation area - meeting room – exterior 3

Group B: exterior 1 - exterior 3 - meeting room – circulation area – entry door space - exterior 2

The use of different routes was studied before in urban areas by Chun and Tamura (2004) using different departures arriving at the same place. However, in this study, people will have the same starting and ending point. Route A included the use of the transitional lobby area (entry doors and circulation spaces), while route B has a direct link from the exterior to the seminar room (**Figure 6**). In addition, group B continued walking through the same spaces as group A but in a different direction. This step will help to deeply analyse the short thermal history by including the opposite directions factor mentioned by Potvin (2000) in his research. Participants were asked to walk at the same speed and avoid running or any activity which can modify their metabolic rate. Simultaneous physical measurements (air temperature) were conducted along the routes while participants were answering specific section of the questionnaire at different points.

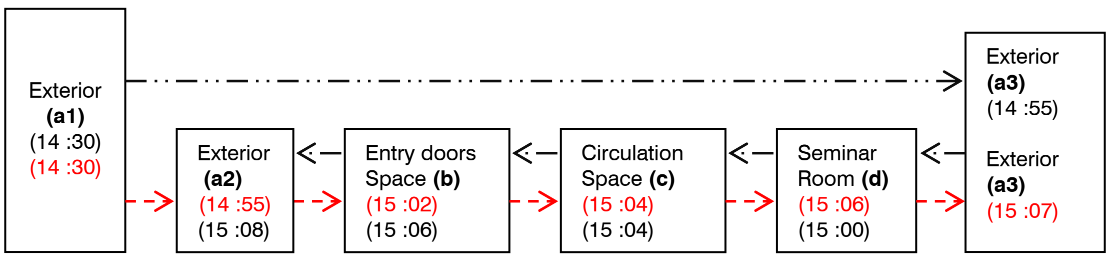
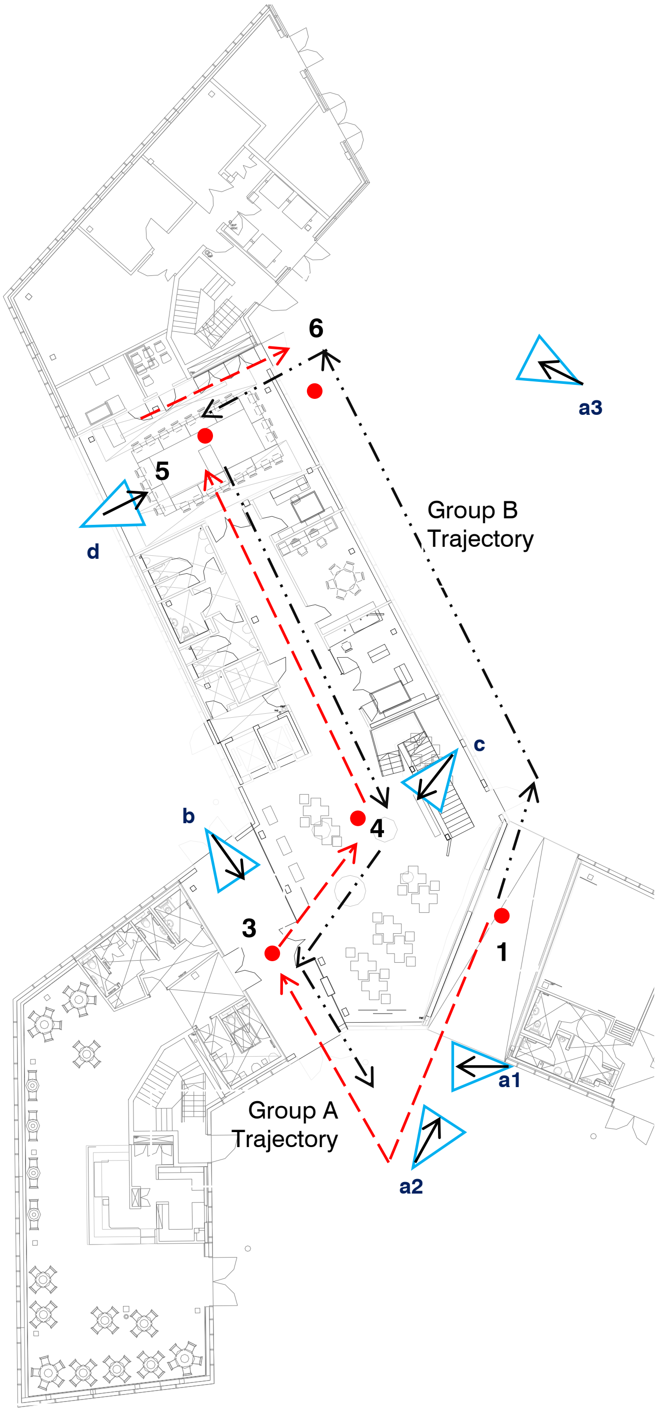


Figure 5 Pilot experiment procedure diagram: route A is illustrated in red and route B in black



a1 Exterior

a2 Exterior

b Entry doors

c Circulation area

d Seminar room

1 Exterior (30 minutes)
2 Exterior
3 Entry doors space
4 Circulation space
5 Seminar room
6 Exterior

Location of the equipment

Group A route

Group B route

Picture view

a3 Exterior

Figure 6 Pilot experiment procedure

1.11. Pilot Experiment results

Twenty international university students participated in the experiment, 6 female and 14 males between 24 to 31 years old. The metabolic rate was assumed to be the same for all participants because their activities were controlled during the first 30 minutes and during the experiment. Met were: 1.6 for standing position and 1.9 met. for walking slowly (ASHRAE 2004). In addition, the 85% of participants were indoors performing sedentary activities before the survey. They also arrived to the building walking relaxing, which not dramatically have an effect on people's metabolic rate during the first 30 minutes. Their clothing insulation was calculated using ASHAREE-55 2004 clothing tables, resulting a mean value of 0.76clo (min=0.38 and max=1.2). The participants showed very similar short-term activities (sedentary activities and walking relaxing), data from the questionnaires suggested that, overall, and people in the experiment did not show any special activity that could dramatically influence results.

1.11.1. Physical measurements

Exterior climate data was obtained from the data loggers located at the exterior of the building. In addition, data from the Jessop West Building Management System (BMS) and Weston Park Weather station were used as a reference. The exterior temperature during the experiment was from 21.10°C to 21.95°C. It was raining for few minutes at the beginning of the survey and with variable exterior wind velocity up to 2 m/sec. The relative humidity at the exterior was from 59%. In the interior spaces, the air temperature was variable from space to space (**Figure 7**). Slightly different values between A and B routes were noted, presumably caused by people **(Figure 8**). The air velocity in the entry doors and seminar room were variable from 0.8 to .05m/sec. As there was only one piece of equipment available, wind velocity was limited to few measurements. The air humidity was also variable in each space in a range from 52 to 64%. The seminar room temperature was preconditioned to 24°C, but it varied from 24 to 25°C, it was noticed that when participants were inside the space the air temperature increased in few seconds. In short, both groups experienced the same temperatures in the spaces. From this results it was importantly determined the extent to which the exterior temperature can modify the interior spaces (entry door, circulation and seminar room spaces) in naturally ventilated buildings, and just how variable the interior temperatures fluctuations can be. Since the pilot experiment reflected only one scenario it was important to explore more the further measurements and the thermal relationship between the spaces in naturally ventilated buildings. Therefore, it was also decided to run the main experiment with the seminar rooms operating with natural ventilation.

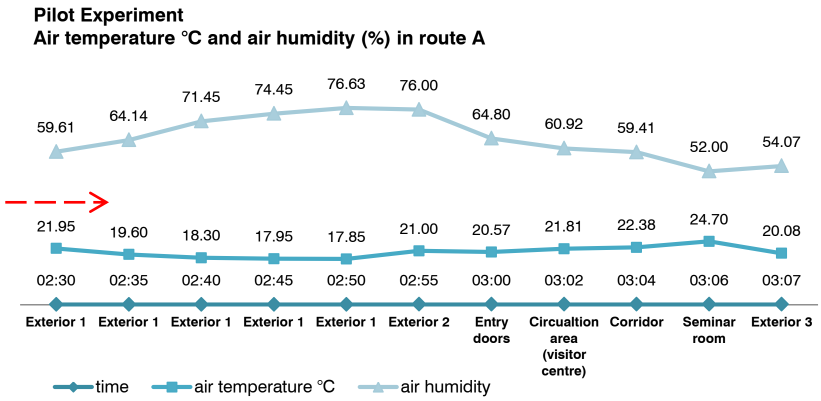


Figure 7 Physical conditions in route A during the pilot experiment

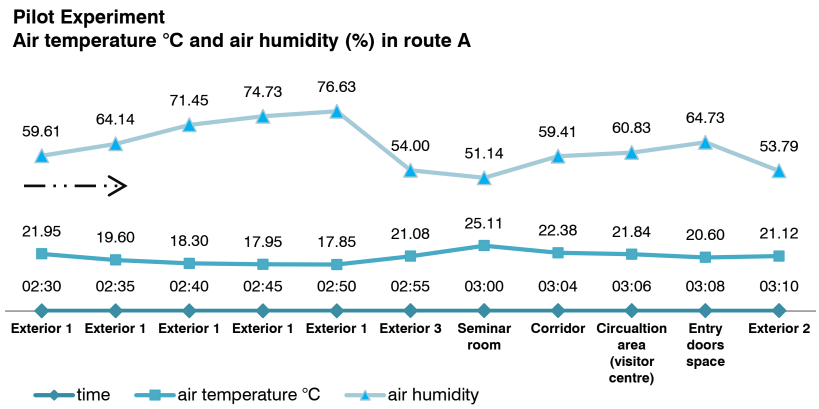
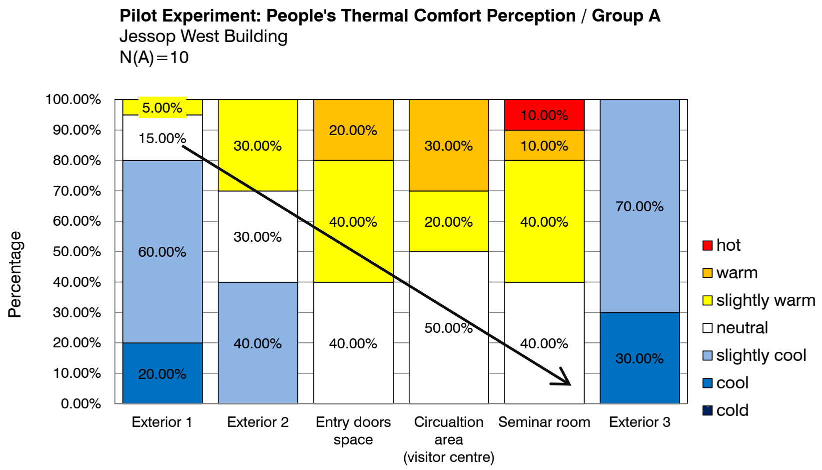


Figure 8 Physical conditions in route B during the pilot experiment

1.11.2. Thermal comfort perception

One of the main findings of the pilot experiment was that people in group A perceived the same spaces different than group B. It was noticed that their thermal perception was strongly influenced by the current, previous temperature and the effect of temperature change between the two spaces. However, it was difficult to determine patterns that could explain the effect of this phenomenon since the sample size was small and results reflected the conditions of single thermal conditions between spaces. Another key finding was the quickly change on people's thermal perception after few minutes and the different thermal perception in the different spaces even with small temperature changes. At this point it was not possible to generalize under which conditions (thermal setting or temperature changes) people dramatically changed their thermal perception. These results helped to take some considerations to get this information in further surveys, highlighting the importance of the study of people under different thermal settings in the same space. It was not

In the pilot experiment, when people were outside they thermal perception was towards the cold side (%). Afterwards, after group A and B moved to the exterior of the main door and fire doors respectively, their thermal perception changed. This helped to reflect about the effectiveness of considering exposing people to the same climatic conditions 30 minutes before starting the survey or if few minutes are enough to change their thermal perception when they are in dynamic state. Before entering to the inside both groups were within the comfortable band (slightly cool, neutral and slightly warm), however, group B with more answers towards the warm side. Both groups experienced the spaces in opposite way, while group A changed from cold to warm, group B moved from warm to cool side answers (**Figure 9**). Surprisingly, in the seminar room, group B were more comfortable (90%) than group A (80%). Also group B had more 'neutral answers (50%) compared with group A (40%). It can be suggested that as group A had a longer walking trajectory before entering the meeting space, their metabolic rate could change altering their short-term thermal history. Another reason could be that their previous thermal exposure (5 minutes outside the door) altered their thermal perception in a way that made them feel more comfortable in the seminar room than group A. Further exploration of people under different and similar settings could explain the possible reasons on the change of their thermal perception.



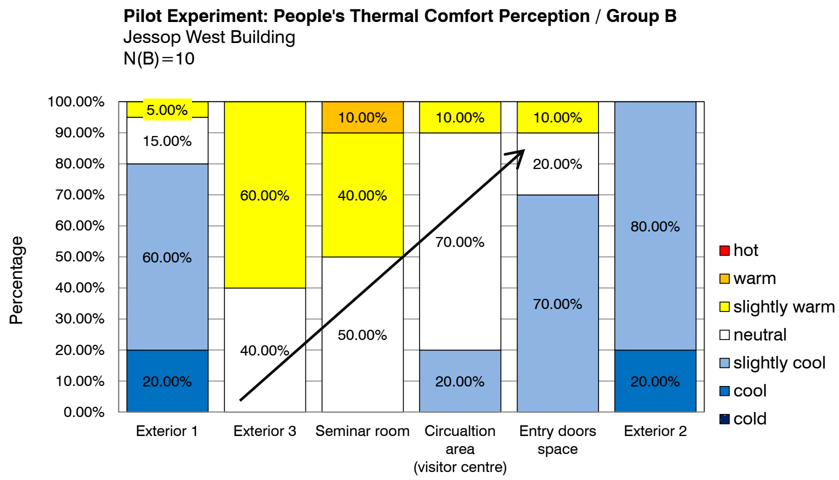


Figure 9 People's thermal comfort perception in routes A and B

1.11.3. Thermal preferences

In this case, results showed that the use of transitional spaces gradually shaped people's thermal preferences to prefer to be cooler (90%) in the seminar room than group B (10%). In addition, group B showed a more variable set of answers than group A (**Figure 10**). It seems that gradually increase of temperatures could have a positive effect on people's thermal perception, however this need to be studied in a wider context of thermal variation to better understand and generalize the positive effect. Thermal comfort votes and thermal preferences matched with the air temperature variations; therefore the pilot experiment was a very good exercise to better understand people's responses.

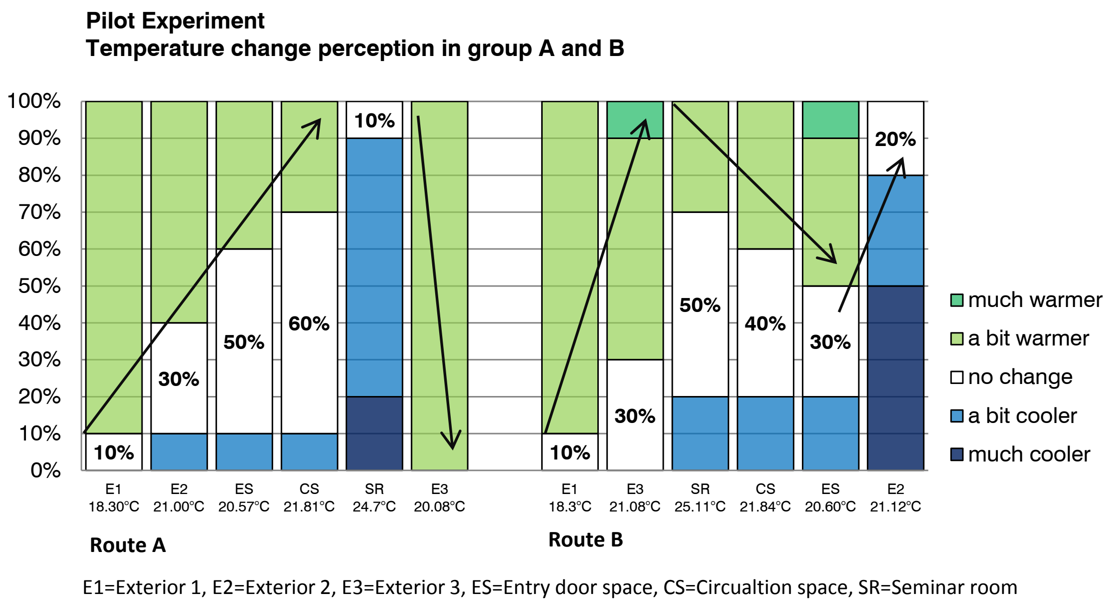


Figure 10 Thermal Preferences

1.11.4. Temperature changes

The way people perceived temperature changes was also a key point of analysis. From these preliminary results was noticed that the dimension of temperature changes could have a significant impact on people's thermal perception in dynamic state. However, in certain extent, people could also tolerate or not identify certain temperature differences based on previous thermal experiences or preferences. Further exploration with a bigger sample size and thermal settings could provide better understanding of factors influencing changes on people's thermal perception when moving from different spaces. In this exercise , it was found that I both groups the most significant temperature changes that people experienced was from exterior to interior and from interior to exterior (**Figure 11**). However, in the interior spaces, their thermal perception were variable, not a clear pattern was found in this stage, yet can be noted that group B had more similar responses than group A.

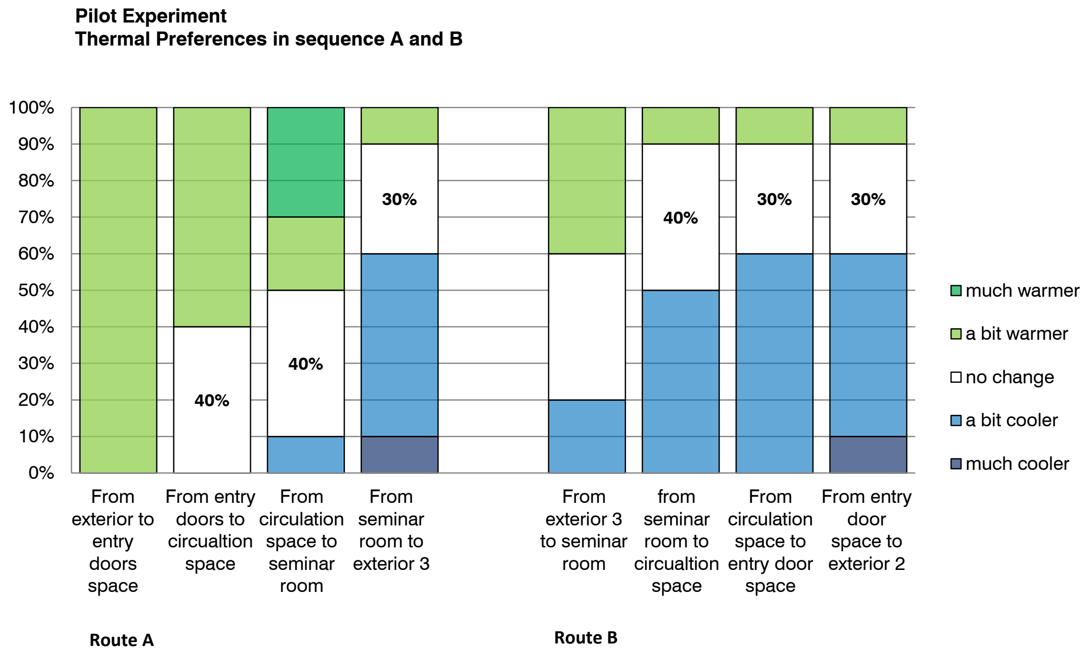


Figure 11 Temperature change perception

1.12. Pilot experiment 2

Figure 12 Additional signal instruction after running the second pilot experiment.

Figure 13 second pilot experiment, participants at the exterior and interior

Appendix 7 Questionnaire type A

QUESTIONNAIRE A/B

Date: TH 2013

Time: pm

INSTRUCTIONS

This experiment is about <u>thermal perception.</u>- How do you feel <u>now</u> with the environment (weather) around you in terms of temperature.
How hot or cold do you feel in the exterior and interior of this building?

This questionnaire has different sections that need to be answered **<u>at 4 different locations in the building</u>**.

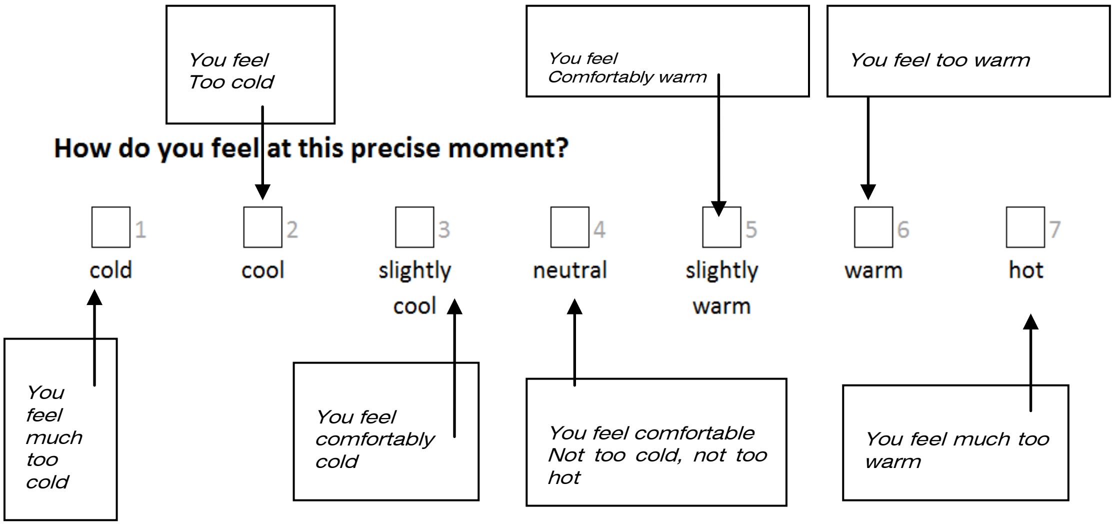
1. Exterior
2. Entry doors
3. Lobby
4. Seminar Room or Lecture theatre

You will find on your walking route **<u>green signs</u>** indicating which section you have to answer. For example

PLEASE STOP HERE
AND ANSWER SECTION 1

You will be asked 4 times to stop momentarily and give your thermal perception (how hot or cold you feel in each space). <u>Please answer carefully, considering each time your actual experience at that specific moment.</u>

Before you start, have a look to the following example and get familiar with the meaning of each answer.



Before start, please sign the ethics form on the reverse of this sheet
If you have a question at any point please feel free to ask

Thank you very much!

Ethics form attached in page 2 in questionnaires A and B used in one year survey 2013-2014

Participant Consent Form

Title of Research Project: **THERMAL PERCEPTION**

Name of Researcher: **Gloria Vargas** **Please TICK boxes** ✓

Participant Identification Number for this project: **N/A**

1. I confirm that **I have** read and **understand the information** ☐

2. Explaining the above research project and **I have** had the opportunity to **ask questions** about the project. ☐

3. I understand that **my participation is voluntary** and that I am free to withdraw at any time without giving any reason and without there being any negative consequences. In addition, should I not wish to answer any particular question or questions, I am free to decline. ☐

4. **I understand that my responses will be kept strictly confidential**. I give permission for members of the research team to have access to my **anonymised responses**. I understand that my name will not be linked with the research materials, or included in the presentations or publications that result from the research. ☐

5. **I consent to taking part** in the thermal comfort experiment ☐

6. I consent to my photo being taken ☐
7.
(No person will be identified individually, and pictures will contribute to illustrate the overall experiment design and procedure. Pictures will always be taken to show groups of participants) ☐

8. I agree for the data collected from me to be used in future research

Participant ________________ **Signature**

Gloria Vargas
Lead Researcher Signature

To be signed and dated in presence of the participant
Copies:
Once this has been signed by all parties the participant should receive a copy of the signed and dated participant consent form, the letter/pre-written script/information sheet and any other written information provided to the participants. A copy of the signed and dated consent form should be placed in the project's main record (e.g. a site file), which must be kept in a secure location.

Sections of Questionnaire A

SECTION 1 / EXTERIOR

Tick your answer

A

PLEASE ANSWER THIS SECTION AT THE EXTERIOR OF THE BUILDING

1 How do you feel at this moment ?

☐1 **cold** ☐2 cool ☐3 slightly cool ☐4 neutral ☐5 slightly warm ☐6 warm ☐7 **hot**

2 How would you prefer to be in this moment?

☐1 cooler ☐2 no change ☐3 warmer

3 Is this temperature at this moment in your oppinion…?

☐1 perfectly bearable ☐2 slightly difficult to bear ☐3 fairly difficult to bear ☐4 very difficult to bear ☐5 unbereable

to bear *= to support or tolerate*

unbearable *= insupportable or intolerable*

4 How do you judge this weather at this moment?

acceptable ☐1 unacceptable ☐2

5 Which of the following issues make you feel uncomfortable at this moment?
*** if you have more than one option please write a number inside of each box to show priority**

wind ☐1 humidity ☐3 sun radiation ☐5 ☐7 none /I am comfortable

temperature (too cold) ☐2 rain ☐4 dryness ☐6

temperature (too hot) ☐2a

6 How do you feel at this moment in terms of air flow (wind) ?

☐1 much too still ☐2 still ☐3 slightly still ☐4 just right ☐5 slightly breezy ☐6 too breezy ☐7 much too breezy

still *= not moving*

breezy *= a light current of air, a gentle wind*

7 How do you feel at this moment in terms of humidity ?

☐1 much too dry ☐2 too dry ☐3 slightly dry ☐4 just right ☐5 slightly humid ☐6 too humid ☐7 much too humid

dry *= free from moisture / no wet*

humid *= wet / amount of water in the air*

8 Do you feel comfortable (not too hot, not too cold) with the clothes you are wearing now?

yes ☐1 no ☐2

☐ Tick your answer　　**A**

SECTION 2 / ENTRY DOORS

PLEASE ANSWER THIS SECTION BETWEEN THE TWO ENTRY DOORS

9 How do you feel at this moment?

☐1	☐2	☐3	☐4	☐5	☐6	☐7
cold	cool	slightly cool	neutral	slightly warm	warm	hot

10 How would you prefer to be at this moment?

☐1	☐2	☐3
cooler	no change	warmer

11 How do you feel the change in temperature between this space (ENTRY DOORS) and the OUTSIDE of the building?

☐1	☐2	☐3
sudden	gradual	little /no change

sudden *= occurring quickly and unexpectedly*

gradual *= progressing slowly or by degrees*

12 How do you feel at this moment in terms of air flow?

☐1	☐2	☐3	☐4	☐5	☐6	☐7
much too still	still	slightly still	just right	slightly breezy	too breezy	much too breezy

still *= not moving*

breezy *= a light current of air, a gentle wind*

13 How do you feel at this moment in terms of humidity?

☐1	☐2	☐3	☐4	☐5	☐6	☐7
much too dry	too dry	slightly dry	just right	slightly humid	too humid	much too humid

dry *= free from moisture / no wet*

humid *= wet / amount of water in the air*

Tick your answer

A

SECTION 3 /CORRIDOR

PLEASE ANSWER THIS SECTION IN THE CORRIDOR

14 How do you feel at this moment?

☐1 cold ☐2 cool ☐3 slightly cool ☐4 neutral ☐5 slightly warm ☐6 warm ☐7 hot

15 How would you prefer to be?

☐1 cooler ☐2 no change ☐3 warmer

16 How do you feel the change in temperature between this space (CORRIDOR) and the previous space (ENTRY DOORS)?

☐1 sudden ☐2 gradual ☐3 little /no change

sudden *= occurring quickly and unexpectedly*

gradual *= progressing slowly or by degrees*

17 How do you feel at this precise moment in terms of air flow?

☐1 much too still ☐2 still ☐3 slightly still ☐4 just right ☐5 slightly breezy ☐6 too breezy ☐7 much too breezy

still *= not moving*

breezy *= a light current of air, a gentle wind*

18 How do you feel at this precise moment in terms of humidity?

☐1 much too dry ☐2 too dry ☐3 slightly dry ☐4 just right ☐5 slightly humid ☐6 too humid ☐7 much too humid

dry *= free from moisture / no wet*

humid *= wet / amount of water in the ai*

☐ Tick your answer

A

SECTION 4 /SEMINAR ROOM

PLEASE ANSWER THIS SECTION INSIDE THE SEMINAR ROOM OR LECTURE THEATRE

19 How do you feel at this precise moment?

1	2	3	4	5	6	7
cold	cool	slightly cool	neutral	slightly warm	warm	hot

20 How would you prefer to be?

1	2	3
cooler	no change	warmer

21 How do you feel the change in temperature between this space (SEMINAR ROOM) and the previous space (CORRIDOR)?

1	2	3
sudden	gradual	little /no change

sudden *= occurring quickly and unexpectedly*

gradual *= progressing slowly or by degrees*

22 How do you judge this interior environment in terms of temperature?

1	2
acceptable	unacceptable

23 How do you feel at this precise moment in terms of air flow?

1	2	3	4	5	6	7
much too still	still	slightly still	just right	slightly breezy	too breezy	much too breezy

still *= not moving*

breezy *= a light current of air, a gentle wind*

24 How do you feel at this precise moment in terms of humidity?

1	2	3	4	5	6	7
much too dry	too dry	slightly dry	just right	slightly humid	too humid	much too humid

dry *= free from moisture / no wet*

humid *= wet / amount of water in the air*

ABOUT YOU

PLESE TAKE A SEAT AND ANSWER SECTION 5

25 **Gender** male ☐ 1 female ☐ 2

26 **Nationality or Country** ______________________

27 **Age** years ____________

29 **Weight** kilograms ______________ **OR** stones / pounds ____________

30 **Height** Metres/centimetres ____________ **OR** feet / inches ____________

31 **How long have you been in Sheffield?**

____________ **or** ____________ **or** ____________ **or** ____________

How many years? How many months? How many days? how many hours?
I am visitor

32 **What clothes <u>are you wearing right NOW</u> ?**

* <u>tick twice</u> or more if you are wearing many layers of the same clothes

UNDERWEAR (tick as many as appropiate)

male (one piece) ☐ 1 (0.03) **female** (two pieces innerwear) ☐ 3 (0.04)

 **(male)**long underwear buttons ☐ 2 (0.15)  long underwear top ☐ 4 (0.20)

MID LAYER (tick as many as appropiate)

 short sleeved shirt / blouse ☐ 5 (0.17)

 long sleeved shirt / blouse ☐ 6 (0.34)

 leggings ☐ 7 (0.15)

 trousers ☐ 8 (0.24)

 shorts ☐ 9 (0.08)

 long skirt ☐ 10 (0.23)

 short skirt ☐ 11 (0.14)

 dress ☐ 12 (0.29)

OUTER LAYER (tick as many as appropiate)

 jacket ☐ 13 (0.42)

 sweater ☐ 15 (0.25)
or jumper

 sleeveless vest ☐ 16 (0.17)

 coat ☐ 14 (0.48)

FOOTWEAR (tick as many as appropiate)

 shoes /trainers ☐ 17 (0.02)

 boots ☐ 18 (0.10)

 sandals ☐ 19 (0.02)

 tights ☐ 20 (0.02)

NO socks or tights ☐ 21 (0.0) 

 short socks ☐ 22 (0.02)

 long socks ☐ 23

Are you carrying a backpack with you?

 No ☐ 1 yes ☐ 2

ABOUT YOU

33 Have you been in this building before?

this is the first time ☐ 1 a few times ☐ 2 many times ☐ 3

34 Where have you been most of the time during the last 30 minutes?

indoors ☐ 1 outdoors ☐ 2

35 How did you arrive to this building from the place or building you were before?

walking/relaxed ☐ 1 2.0 running ☐ 3 3.8 other ☐ 5

walking/fast ☐ 2 2.6 cycling ☐ 4 4.0

36 How long did your journey take to this place from the building or interior space you were before?

minutes ________________

37 Have you had lunch or breakfast during the last hour?

yes ☐ 1 no ☐ 2

38 What were you doing in the last 30 minutes in the place or building you were before coming here?

sitting (passive work) ☐ 1
reading 1.0
writing
computer work
attending a lecture

sitting (active work) ☐ 2
laboratory work 1.2
active work with arms
workshop

standing relaxed ☐ 3
reading 1.6
writing
computer work

standing working ☐ 4
active laboratory work 2.0
active work with arms

high activity ☐ 5
workshop 3.0

doing execise ☐ 8
3.6

40 Does the place you usually use to work or study have air conditioning (cooling) during summer?

yes ☐ 1 no ☐ 2

41 Does the place you usually use to work or study have air conditioning (heating) during winter?

yes ☐ 1 no ☐ 2

42 Does your accommodation or house have air conditioning (cooling) in summer?

yes ☐ 1 no ☐ 2

42 Does your accommodation or house have air conditioning (heating) during winter?

yes ☐ 1 no ☐ 2

x

Appendix 8 Questionnaire type B

Tick your answer

B

SECTION 1 / EXTERIOR

PLEASE ANSWER THIS SECTION AT THE EXTERIOR OF THE BUILDING

1 How do you feel at this moment?

☐1 cold ☐2 cool ☐3 slightly cool ☐4 neutral ☐5 slightly warm ☐6 warm ☐7 hot

2 How would you prefer to be?

☐1 cooler ☐2 no change ☐3 warmer

3 Is this environment (weather) at this moment in your oppinion...?

☐1 perfectly bearable ☐2 slightly difficult to bear ☐3 fairly difficult to bear ☐4 very difficult to bear ☐5 unbereable

to bear *= to support or tolerate* ***unbearable*** *= insupportable or intolerable*

4 How do you judge this weather at this precise moment?

acceptable ☐1 unacceptable ☐2

5 Do any of the following issues make you feel uncomfortable now?

wind ☐1 humidity ☐3 sun radiation ☐5 ☐7 none / I am comfortable

temperature (too cold) ☐2 rain ☐4 dryness ☐6

temperature (too hot) ☐2a

6 How do you feel at this precise moment in terms of air flow?

☐1 much too still ☐2 still ☐3 slightly still ☐4 just right ☐5 slightly breezy ☐6 too breezy ☐7 much too breezy

still *= not moving* ***breezy*** *= a light current of air, a gentle wind*

7 How do you feel at this precise moment in terms of humidity?

☐1 much too dry ☐2 too dry ☐3 slightly dry ☐4 just right ☐5 slightly humid ☐6 too humid ☐7 much too humid

dry *= free from moisture / no wet* ***humid*** *= wet / amount of water in the air*

8 Do you feel comfortable (not too hot, not too cold) with the clothes you are wearing now?

yes ☐1 no ☐2

☑ Tick your answer

B

SECTION 2 /SEMINAR ROOM

PLEASE ANSWER THIS SECTION INSIDE THE SEMINAR ROOM OR LECTURE THEATRE

19 How do you feel at this moment?

☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
cold	cool	slightly cool	neutral	slightly warm	warm	hot

20 How would you prefer to be?

☐ 1	☐ 2	☐ 3
cooler	no change	warmer

21 How do you feel the change in temperature between this space (SEMINAR ROOM) and the EXTERIOR environment?

☐ 1	☐ 2	☐ 3
sudden	gradual	little /no change

sudden *= occurring quickly and unexpectedly*

gradual *= progressing slowly or by degrees*

22 How do you judge this interior environment in terms of temperature?

☐ 1	☐ 2
acceptable	unacceptable

23 How do you feel at this precise moment in terms of air flow?

☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
much too still	still	slightly still	just right	slightly breezy	too breezy	much too breezy

still *= not moving*

breezy *= a light current of air, a gentle wind*

24 How do you feel at this precise moment in terms of humidity?

☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7
much too dry	too dry	slightly dry	just right	slightly humid	too humid	much too humid

dry *= free from moisture / no wet*

humid *= wet / amount of water in the air*

x

- ***Note: Cover, ethics form and last section of the questionnaire B area the same used in questionnaire A**

Appendix 9 Equipment specifications

1.1. Wind speed data logger

0 to 100 MPH (0 to 160 KPH) Range
• 0.085 MPH Resolution at a 10 Second Sampling Rate
• ± 2.5% Calibrated Accuracy over 10 to 100 MPH (16 to 160 KPH) Range
• 10 Year Battery Life
• 1 Second Reading Rate
• Multiple Start/ Stop Function
• Ultra High Speed Download
• 500, 000 Reading Storage Capacity
• Battery Life Indicator
• Optional Password Protection
• Field Upgradeable

Specifications
Measurement Range: 0 to 100 mph (0 to 45 m/ s)
Resolution: 0.085 mph at 10 second reading interval
Accuracy: ± 2.0 mph from 0 to 10 mph; ± 2.5% of reading from > 10 to 100 mph
Starting Threshold: 1.75 mph
Reading Rate: 1 reading every second to 1 every 24 hours
Memory: 500, 000 readings; software configurable memory wrap 250, 000 readings in multiple start/ stop
Memory Wrap Around: Yes
Start Modes: Immediate start, delay start up to 18 months, multiple pushbutton start/ stop
Stop Modes: Manual through software, timed (specific date and time)
Multiple Start/ Stop Mode: Start and stop the device multiple times without having to download data or communicate with a PC
Multiple Start/ Stop Mode Activation:
Real Time Recording: The device may be used with PC to monitor and record data in real-time
LED Functionality:
Green LED Blinks: 10 second rate to indicate logging; 15 second rate to indicate delay start
Red LED Blinks: 10 second rate to indicate low battery and/ or full memory;
1 second rate to indicate an alarm condition
Password Protection: An optional password may be programmed into the device to restrict access to configuration options. Data may be read out without the password
Engineering Units: MPH, KPH, M/ S, KNOTS (software selectable)
Battery Type: 3.6V lithium battery (included) ; user replaceable
Battery Life: 10 years typical, dependent upon frequency and duty cycle
Time Accuracy: ± 1 minute/ month at 20º C (68º F) , stand alone data logging
Computer Interface: USB (interface cable required) ; 115, 200 baud
Software: XP SP3/ Vista and Windows® 7 (32 and 64-bit)
Anemometer Operating Environment: -55 to 60º C (-67 to 150º F) ; 0 to 100% RH
Operating Environment: -20 to 60º C (-4 to 150º F) , 0 to 100% RH non-condensing
IP Rating: IP65
Anemometer Dimensions: 54 H x 192 mm D (2.1 x 7.5 ")
Dimensions:
Data Logger:
74 H x 148 W x 39 mm D (2.9 x 5.8 x 1.5 ")
Enclosure:
93 H x 62 W x 24 mm D (3.7 x 2.5 x 0.9 ")
Weight: 513 g (18.1 oz)

Source: http://www.indonetwork.co.id/cvandalanprimase/4047017/omega-wind-speed-data-logger-om-cp-wind101a-kit.htm

1.2. Hotwired anemometers used in the interior spaces

C-1

SPECIFICATIONS

Display: 52 x 38 mm (2.05 x 1.5") LCD with green backlight (on/off)
Measurement Units:
Velocity: m/s, km/h, ft/min, knots, mile/hr
Temperature: °C or °F
Sensor Construction: Glass bead thermistor
Sampling Time:
Auto: 1 to 3600 seconds
Manual: Push the data logger button once; will save data one time
Memory Card: SD memory card
Temperature Compensation: Automatic
Display Update: At 1 second
Data Output (RS232/USB): With optional cable/software
Operating Temperature: 0 to 50°C (32 to 122°F)
Operating Humidity: Less than 85% RH
Power: 6 "AAA" alkaline or heavy-duty batteries (included), or 9V power adaptor (optional)
Current Draw: 15 mA DC (without SD card or backlight), 36 mA (all functions)
Weight: 515 g (1.13 lb)
Dimensions:
Instrument: 203 L x 76 W x 38 mm D (8 x 3 x 1.50")
Probe: 12 mm (0.47") diameter, 280 to 940 mm (11 to 37") length
Air Temperature Measuring Range: 0 to 50°C (32 to 122°F)
Resolution: 0.1°C (0.1°F)
Accuracy: ± 0.8°C (1.5°F)

Measurement	Range	Resolution	Accuracy (Reading)
m/s	0.2 to 5 m/s	0.01 m/s	±(5% + a) reading or ±(1% + a) full scale whichever is greater
	5.1 to 25 m/s	0.1 m/s	
km/h	0.70 to 18 km/h	0.01 km/h	
	18 to 72 km/h	0.1 km/h	
mile/h (mph)	0.50 to 11.20 mph	0.01 mph	
	11.2 to 44.7 mph	0.1 mph	
knot	0.40 to 9.70 knot	0.01 knot	
	9.7 to 38.8 knot	0.1 knot	
ft/min	40 to 3940 ft/min	1 ft/min	
(a = 0.1 m/s, 0.3 km/h, 0.2 mile/h, 0.2 knot, 20 ft/min)			

Note: *m/s = meters per second, km/h = kilometers per hour, ft/min = feet per minute, mile/h = miles per hour, knot = nautical miles per hour (international knot)*

Type K/J Thermometer (Sensor Sold Separately)

Sensor	Resolution	Range	Accuracy
K	0.1°C	-50 to 1300°C	±(0.4% + 0.5°C)
		-50.1 to -100°C	±(0.4% + 1°C)
	0.1°F	-58 to 2372°F	±(0.4% + 1°F)
		-58.1 to -148°F	±(0.4% + 1.8°F)
J	0.1°C	-50 to 1200°C	±(0.4% + 0.5°C)
		-50.1 to -100°C	±(0.4% + 1°C)
	0.1°F	-58 to 2192°F	±(0.4% + 1°F)
		-58.1 to -148°F	±(0.4% + 1.8°F)

Source: http://www.omega.co.uk/pptst/HHF-SD1.html

1.3. HOBBO Data logger U-12

Measurement range:
Temperature: -20° to 70°C (-4° to 158°F)
RH: 5% to 95% RH
Light intensity: 1 to 3000 footcandles (lumens/ft2) typical; maximum value varies from 1500 to 4500 footcandles (lumens/ft2)
Analog channels:
0 to 2.5 Vdc (w/CABLE-2.5-STEREO); 0 to 5 Vdc (w/CABLE-ADAP5); 0 to 10 Vdc (w/ CABLE-ADAP10); 4-20 mA (w/CABLE-4-20MA)
Accuracy:
Temperature: ± 0.35°C from 0° to 50°C (± 0.63°F from 32° to 122°F), see Plot A
RH: ±2.5% from 10% to 90% RH (typical), to a maximum of ±3.5%, see Plot B
Light intensity: Designed for indoor measurement of relative light levels, see Plot D for light wavelength response
External input channel (see sensor manual): ± 2 mV ± 2.5% of absolute reading
Resolution:
Temperature: 0.03°C at 25°C (0.05°F at 77°F), see Plot A
RH: 0.03% RH
Sample Rate:
1 second to 18 hours, user selectable
Drift:
Temperature: 0.1°C/year (0.2°F/year)
RH: <1% per year typical; RH hysteresis 1%
Response time in airflow of 1 m/s (2.2 mph):
Temperature: 6 minutes, typical to 90%
RH: 1 minute, typical to 90%
Time accuracy: ± 1 minute per month at 25°C (77°F), see Plot C
Operating temperature:
Logging: -20° to 70°C (-4° to 158°F); 0 to 95% RH (non-condensing)
Launch/readout: 0° to 50°C (32° to 122°F), per USB specification
Battery life: 1 year typical use
Memory: 64K bytes (43,000 12-bit measurements)
Weight: 46 g (1.6 oz)
Dimensions: 58 x 74 x 22 mm (2.3 x 2.9 x 0.9 inches)

1.4. I-button DS1922L

Automatically Wakes up, Measures Temperature and Stores Values in 8KB of Datalog Memory in 8- or 16-Bit Format
Digital Thermometer Measures Temperature with 8-Bit (0.5°C) or 11-Bit (0.0625°C) Resolution
Accuracy of ±0.5°C from -10°C to +65°C (DS1922L), ±0.5°C from +20°C to +75°C (DS1922T) with Software Correction
Water resistant or waterproof if placed inside DS9107 iButton capsule (Exceeds Water Resistant 3 ATM requirements)
Sampling Rate from 1s up to 273hrs
Programmable Recording Start Delay After Elapsed Time or Upon a Temperature Alarm Trip Point
Programmable High and Low Trip Points for Temperature Alarms
Quick Access to Alarmed Devices Through 1-Wire Conditional Search Function
512 Bytes of General-Purpose Plus 64 Bytes of Calibration Memory
Two-Level Password Protection of All Memory and Configuration Registers
Communicates to Host with a Single Digital Signal at up to 15.4kbps at Standard Speed or up to 125kbps in Overdrive Mode Using 1-Wire Protocol
Operating Range: DS1922L: -40 to +85°C; DS1922T: 0 to +125°C
Meets UL 913, 5th Ed., Rev. 1997-02-24; Intrinsically Safe Apparatus, Approved under Entity Concept for use in Class I, Division 1, Group A, B, C, and D Locations
Certified to meet EN 12830:1999 standard for Temperature Recorders for use in the Transportation, Storage and Distribution of Chilled, Frozen, deep/quick-frozen food and ice cream.
Memory Type: NVSRAM
Memory Size: 512 bytes
Data Logger Size: 8192 byte
Data Logger Sample Rate: 1s to 273 hours
Data Logger Accuracy: correctible to +/- 0.5°C
Data Logger Resolution: Selectable
8-bit = 0.5°C
11-bit = 0.0625°C
Measurement Range: -40 to +85°C
Thermal Response time: up to 130 seconds
Security Features: password protected
Programmable Alarm: Temperature High/Low
Real Time Clock: Yes
RTC Accuracy: depends on temperature, @ 20'C drift ~ 1 minute/month.
Weight: 3.3g
Size: diameter 17.35 x 5.9mm
IP Rating: IP56
Battery Life: depends on number of factors such as Temperature and Logging rate.
E.g. 8-bit logging @ 20'C at 30 second intervals, the battery should last around 300 days. Record every 10 minutes in 8-bit mode @ 20'C, the battery should last around 5.5 years

Source: http://www.measurementsystems.co.uk/data-logging/

1.5. I-button Hygrometer DS1923

Digital Hygrometer Measures Humidity with 8-Bit (0.6%RH) or 12-Bit (0.04%RH) Resolution
Operating Range: -20°C to +85°C; 0 to 100%RH (see *Safe Operating Range* Graph in the full data sheet)
Automatically Wakes Up, Measures Temperature and/or Humidity and Stores Values in 8KB of Datalog Memory in 8- or 16-Bit Format
Digital Thermometer Measures Temperature with 8-Bit (0.5°C) or 11-Bit (0.0625°C) Resolution
Temperature Accuracy Better than ±0.5°C from -10°C to +65°C with Software Correction
Built-in Humidity Sensor for Simultaneous Temperature and Humidity Logging
Capacitive Polymer Humidity-Sensing Element
Hydrophobic Filter Protects Sensor Against Dust, Dirt, Contaminants, and Water Droplets/Condensation
Sampling Rate from 1s up to 273hrs
Programmable Recording Start Delay After Elapsed Time or Upon a Temperature Alarm Trip Point
Programmable High and Low Trip Points for Temperature and Humidity Alarms
Quick Access to Alarmed Devices Through 1-Wire Conditional Search Function
512 Bytes of General-Purpose Memory Plus 64 Bytes of Calibration Memory
Two-Level Password Protection of All Memory and Configuration Registers
Communicates to Host with a Single Digital Signal at Up to 15.4kbps at Standard Speed or Up to 125kbps in Overdrive Mode Using 1-Wire Protocol
Individually Calibrated in a NIST-Traceable Chamber
Calibration Coefficients for Temperature and Humidity Factory Programmed into Nonvolatile (NV) Memory
Meets UL 913, 5th Ed., Rev. 1997-02-24; Intrinsically Safe Apparatus, Approved under Entity Concept for use in Class I, Division 1, Group A, B, C, and D Locations
Underwriters Laboratories (UL) Recognized

Memory Type: NVSRAM
Memory Size: 512 bytes
Data Logger Size: 8192 byte
Data Logger Sample Rate: 1s to 273 hours
Data Logger Accuracy: correctible to +/- 0.5'C
Data Logger Resolution: Selectable
8-bit = 0.5'C
11-bit = 0.0625'C
Measurement Range - Temperature: -20 to +85'C
Measurement Range - Humidity: 0 to 100% RH
Security Features: password protected
Programmable Alarm: Temperature High/Low, Humidity High/Low
Real Time Clock: Yes
Weight: 5g
Size: diameter 17.35 x 5.9mm
IP Rating: IP56

Source: http://www.measurementsystems.co.uk/data-logging/

1.6. Air flow vane LCA501

	LCA501
Temperature	+
Velocity	+
100 mm reversible head	+
Flow, sweep mode	+
Telescoping handle (optional)	+
Data logging, recall, review, download	+
Use with Aircone flow hoods	+
Free Certificate of Calibration	+

Velocity
Range 0.25 to 30 m/s (50 to 6,000 ft/min)
Accuracy ±1.0% of reading ±0.02 m/s (±4 ft/min)
Resolution 0.01 m/s (1 ft/min)

Duct Size
LCA501 0 - 46.45 m² (0 - 500 ft²)

Volumetric Flow rate
Range Actual range is a function of velocity and duct area

Resolution
LCA501 <100; 0.01 l/s, 0.01 m³/hr, 0.01 ft³/min

Temperature
Range 5 to 45°C (40 to 113°F)
Accuracy ±1.0°C (±2.0°F)
Resolution LCA301 0.1°C (1°F)
Resolution LCA501 0.1°C (0.1°F)

Instrument Temperature Range
Operating 5 to 45°C (40 to 113°F)
Storage -20 to 60°C (-4 to 140°F)

Data Storage Capabilities (LCA501 only)
Range 12,700+ samples and 100 test IDs

Logging Interval (LCA501 only)
From 1 second to 1 hour

Time Constant (LCA501 only)
User selectable

External Meter Dimensions:
LCA501 8.4 cm x 17.8 cm x 4.4 cm (3.3 in. x 7 in. x 1.8 in.)

Meter Weight with batteries:
LCA501 270 g (9.6 oz.)

Power Requirements:
LCA501 9-volt battery

TSI | AIRFLOW INSTRUMENTS

CERTIFICATE OF CALIBRATION AND TESTING

TSI Instruments Ltd, Stirling Road, Cressex Business Park
High Wycombe Bucks HP12 3RT England
Tel: (Int +44) (UK 0) 1494 459200 Fax: (Int +44) (UK 0) 1494 459700 http://www.airflowinstruments.co.uk

ENVIRONMENT CONDITION		
TEMPERATURE	20.9	°C
RELATIVE HUMIDITY	40.93	%RH
BAROMETRIC PRESSURE	1003.4	hPa

MODEL	LCA501
SERIAL NUMBER	LCA501018010

☒ AS LEFT ☒ IN TOLERANCE
☐ AS FOUND ☐ OUT OF TOLERANCE

– CALIBRATION VERIFICATION RESULTS –

VELOCITY — SYSTEM RV02-01 — *Unit: m/s*

#	STANDARD	MEASURED	ALLOWABLE RANGE	#	STANDARD	MEASURED	ALLOWABLE RANGE
1	0.51	0.52	0.48~0.53	5	5.07	5.12	5.00~5.15
2	0.76	0.76	0.73~0.79	6	7.61	7.67	7.52~7.71
3	1.02	1.03	0.99~1.05	7	15.24	15.21	15.07~15.41
4	2.54	2.57	2.49~2.59	8	30.49	30.51	30.16~30.81

TEMPERATURE — SYSTEM RV02-01 — *Unit: °C*

#	STANDARD	MEASURED	ALLOWABLE RANGE	#	STANDARD	MEASURED	ALLOWABLE RANGE
1	20.2	20.7	19.1~21.3				

TSI does hereby certify that the above described instrument conforms to the original manufacturer's specification (not applicable to As Found data) and has been calibrated using standards whose accuracies are traceable to members of the European co-operation for Accreditation (EA) (for example: UKAS, SWEDAC, DKD) or has been verified with respect to instrumentation whose accuracy is traceable to some member of EA, or is derived from accepted values of physical constants. TSI's calibration system meets ISO-9001:2000 and meets the requirements of ISO 10012:2003.

Measurement Variable	System ID	Last Cal.	Cal. Due
Pressure	E006005	31-03-10	31-03-11
Pressure	E006024	31-03-10	31-03-11
RVA	E006045	18-11-09	18-11-10

Measurement Variable	System ID	Last Cal.	Cal. Due
DC Voltage	E006009	31-03-10	31-03-11
Temperature	E006062	31-03-10	31-03-11

P. McBain — CALIBRATED

28 April, 2010 — DATE

Doc. ID: CERT_DEFAULT

Figure 14 Equipment description and certificate of calibration of the equipment used in the experiment
Information source: http://www.tsi.com/

1.7. Hand manual anemometer TA 410

Velocity

Range (TA410)	0 to 20 m/s (0 to 4,000 ft/min)
Range (TA430, TA440)	0 to 30 m/s (0 to 6,000 ft/min)
Accuracy (TA410)[1&2]	±5% of reading or ±0.025 m/s (±5 ft/min), whichever is greater
Accuracy (TA430, TA440)[1&2]	±3% of reading or ±0.015 m/s (±3 ft/min), whichever is greater
Resolution	0.01 m/s (1 ft/min)

Duct Size (TA430, TA440)

Dimensions	1 to 635 cm in increments of 0.1 cm (1 to 250 inches in increments of 0.1 in.)

Volumetric Flow Rate (TA430, TA440)

Range	Actual range is a function of velocity, and duct size

Temperature

Range (TA410, TA430)	-18 to 93°C (0 to 200°F)
Range (TA440)	-10 to 60°C (14 to 140°F)
Accuracy[3]	±0.3°C (±0.5°F)
Resolution	0.1°C (0.1°F)

Time Constant (TA430, TA440)
User selectable

External Meter Dimensions
8.4 cm x 17.8 cm x 4.4 cm (3.3 in. x 7.0 in. x 1.8 in.)

Meter Weight with Batteries
0.27 kg (0.6 lbs.)

Meter Probe Dimensions

Probe Length	101.6 cm (40 in.)
Probe Diameter of Tip	7.0 mm (0.28 in.)
Probe Diameter of Base	13.0 mm (0.51 in.)

Articulating Probe Dimensions

Articulating Section Length	19.7 cm (7.8 in.)
Diameter of Articulating Knuckle	9.5 mm (0.38 in.)

Power Requirements
Four AA-size batteries or AC adapter

Relative Humidity (TA440 only)

Range	5 to 95% RH
Accuracy[4]	±3% RH
Resolution	0.1% RH

Wet Bulb Temperature (TA440 only)

Range	5 to 60°C (40 to 140°F)
Resolution	0.1°C (0.1°F)

Dew Point (TA440 only)

Range	-15 to 49°C (5 to 120°F)
Resolution	0.1°C (0.1°F)

Instrument Temperature Range

Operating (Electronics)	5 to 45°C (40 to 113°F)
Model TA410, TA430 Operating (Probe)	-18 to 93°C (0 to 200°F)
Model TA440 Operating (Probe)	-10 to 60°C (14 to 140°F)
Storage	-20 to 60°C (-4 to 140°F)

Data Storage Capabilities (TA430, TA440)

Range	12,700+ samples and 100 test IDs

Logging Interval (TA430, TA440)
1 second to 1 hour

Specifications subject to change without notice.

TSI and the TSI logo are registered trademarks, and Airflow, the Airflow logo and LogDat2 are trademarks of TSI Incorporated.

	TA410	TA430, TA430-A	TA440, TA440-A
Velocity range 0 to 20.00 m/s (0 to 4000 ft/min)	+		
Velocity range 0 to 30.00 m/s (0 to 6000 ft/min)		+	+
Temperature	+	+	+
Flow		+	+
Humidity, wet bulb, dew point			+
Probe	Straight	Straight or -A articulated	Straight or -A articulated
Variable time constant		+	+
Manual data logging		+	+
Auto save data logging			+
Statistics		+	+
Review data		+	+
LogDat2 downloading software		+	+
Free Certificate of Calibration	+	+	+

[1] Temperature compensated over an air temperature range of 5 to 65°C (40 to 150°F).
[2] The accuracy statement begins at 30 ft/min through 4000 ft/min (0.15 m/s through 20 m/s) for the Model TA410, and 30 ft/min through 6,000 ft/min (0.15 m/s through 30 m/s) for Models TA430 and TA440.

TSI AIRFLOW INSTRUMENTS

CERTIFICATE OF CALIBRATION AND TESTING

TSI Instruments Ltd, Stirling Road, Cressex Business Park
High Wycombe Bucks HP12 3ST England
Tel: (Int +44) (UK 0) 1494 459200 Fax: (Int +44) (UK 0) 1494 459700 http://www.airflowinstruments.co.uk

Environment Condition		
Temperature	20.4	°C
Relative Humidity	20.07	%RH
Barometric Pressure	1017.3	hPa

Model	TA410
Serial Number	TA4101205008

☒ As Left ☒ In Tolerance
☐ As Found ☐ Out of Tolerance

– Calibration Verification Results –

Temperature Verification — System T-200 — Unit: °C

#	Standard	Measured	Allowable Range	#	Standard	Measured	Allowable Range
1	0.0	0.1	−0.3~0.3	2	60.0	60.1	59.7~60.3

Velocity Verification — System V-351 — Unit: m/s

#	Standard	Measured	Allowable Range	#	Standard	Measured	Allowable Range
1	0.00	0.00	−0.03~0.03	7	3.58	3.59	3.40~3.76
2	0.15	0.15	0.13~0.18	8	6.10	6.16	5.80~6.41
3	0.31	0.31	0.28~0.33	9	9.66	9.54	9.18~10.14
4	0.51	0.52	0.49~0.54	10	13.71	13.66	13.02~14.39
5	1.02	1.02	0.97~1.07	11	19.41	19.30	18.44~20.38
6	2.04	2.04	1.94~2.14				

TSI does hereby certify that the above described instrument conforms to the original manufacturer's specification (not applicable to As Found data) and has been calibrated using standards whose accuracies are traceable to members of the European co-operation for Accreditation (EA) (for example: UKAS, SWEDAC, DAkkS) or has been verified with respect to instrumentation whose accuracy is traceable to some member of EA, or is derived from accepted values of physical constants. TSI's calibration system is registered to ISO-9001:2008 and meets the requirements of ISO 10012:2003.

Measurement Variable	System ID
DC Volts	E006008
Temperature	E006127
Pressure	E006001
DC Voltage	E006012
Pressure	E006059

Measurement Variable	System ID
Temperature	E006007
Temperature	E006020
Pressure	E006000
Temperature	E006021
Velocity	E006017

P. McBain.   0 8 FEB 2012

Doc. ID: CERT_GEN_WCC

Figure 15 Equipment description and certificate of calibration of the equipment used in the experiment, information source: http://www.tsi.com/Airflow-Instruments-Velocity-Meter-TA410/

1.8. Globe thermometer, diagrams of assembly

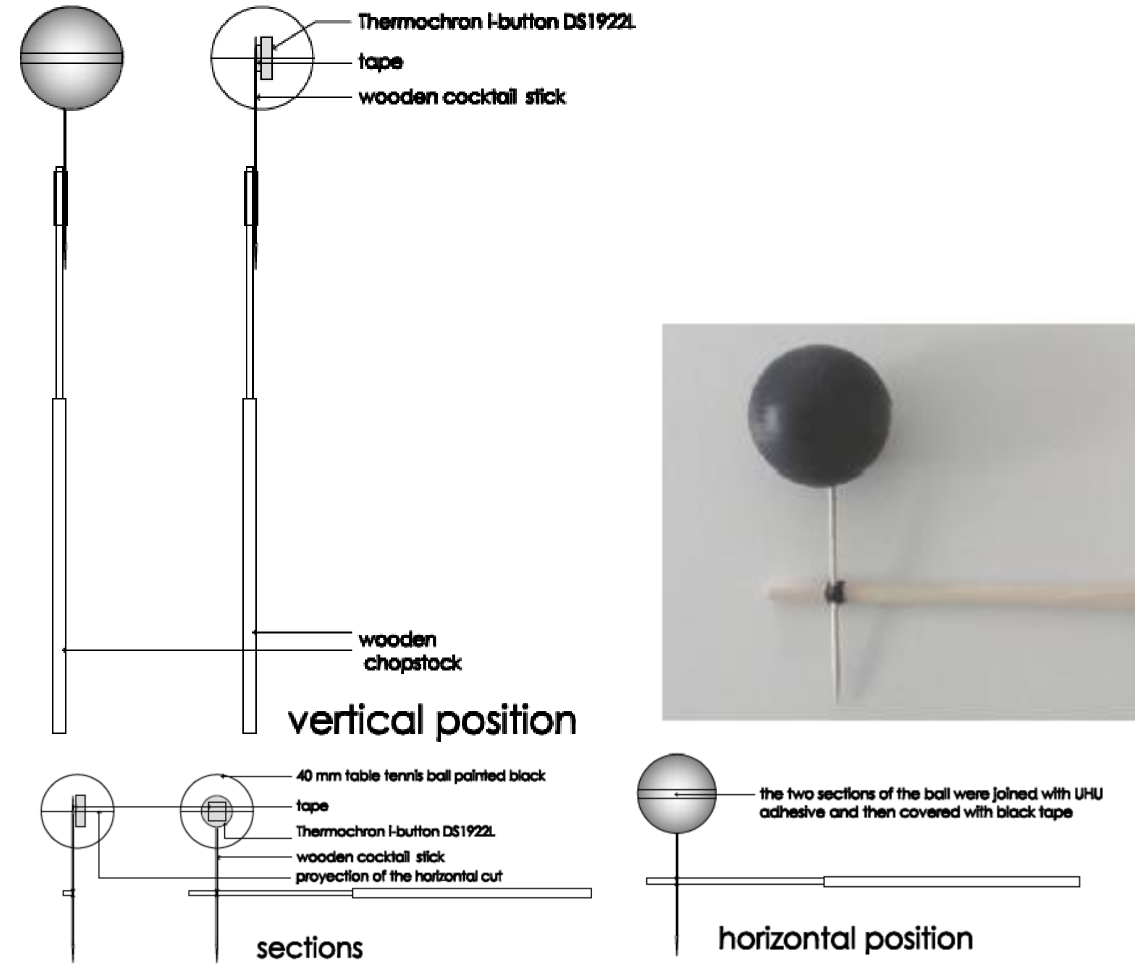
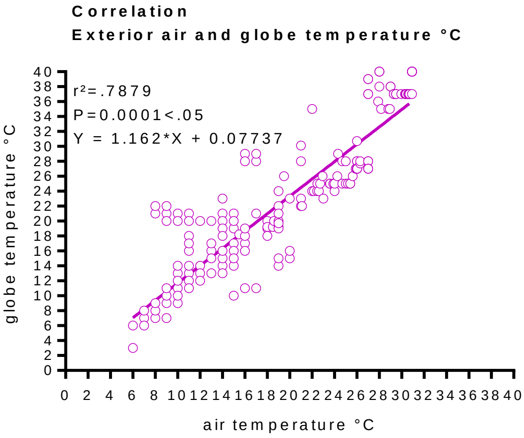


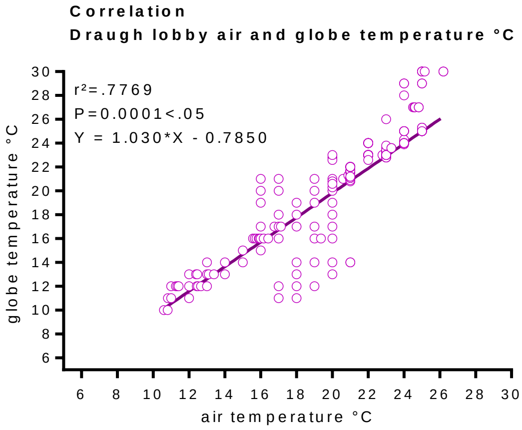
Figure 16 Assembly of globe thermometer using a 40mm table tennis ball painted with back paint, inside and i-button DS1922L is attached. The graphs illustrate the correlation between the air temperature and globe thermometer temperature.

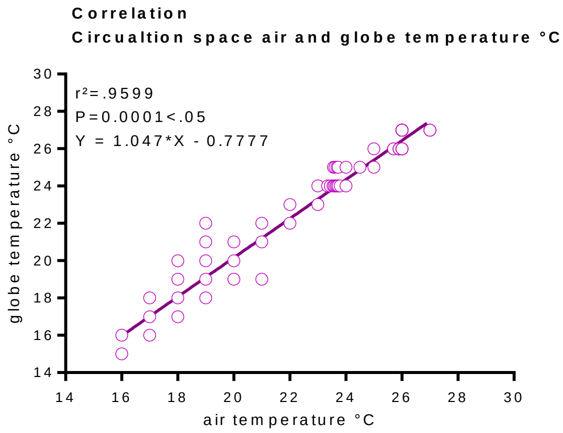
Appendix 10 Operative temperature

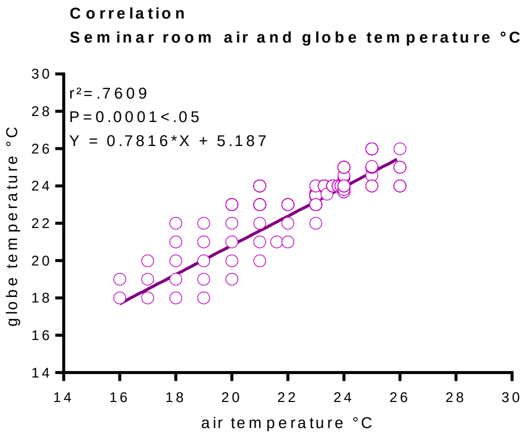
Correlation between the globe temperature, air temperature and operative temperature in the four spaces (exterior, draught lobby, circulation space and seminar room)

10.1 Correlation between air temperature and globe temperature



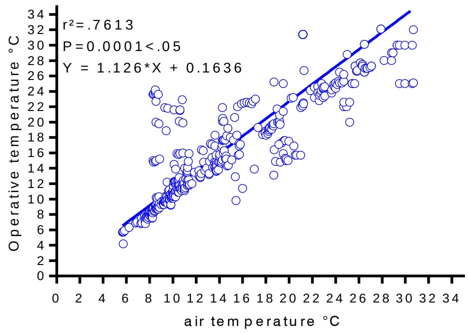




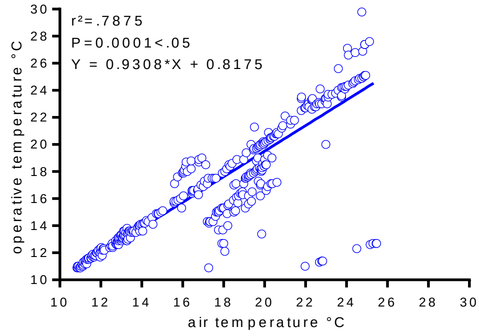


10.2 Correlation between air temperature and operative temperature

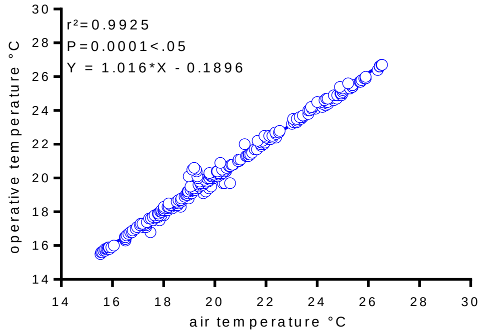
Correlation
Exterior operative and air temperature °C



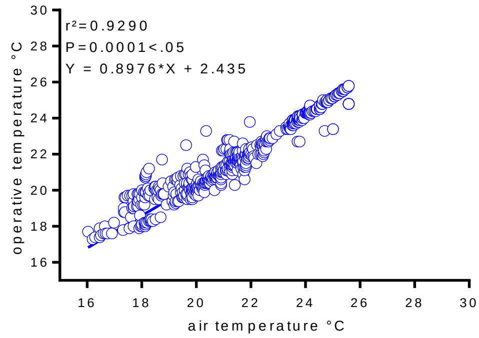
Correlation
Draught lobby operative and air temperature °C



Correlation
Circulation operative and air temperature °C

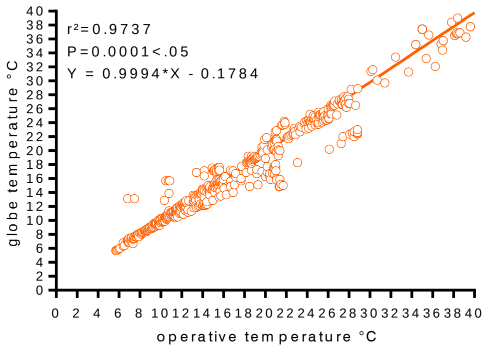


Correlation
Seminar room operative and air temperature °C

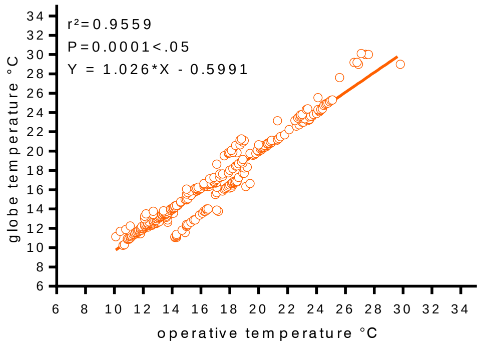


10.3 Correlation between operative temperature and globe temperature

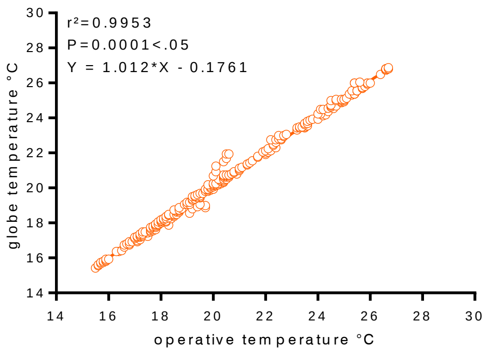
Correlation
Exterior operative and globe temperature °C



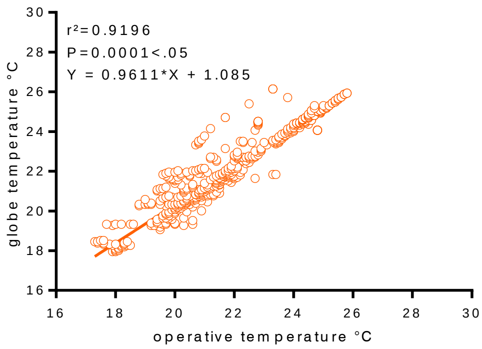
Correlation
Draught lobby operative and globe temperature °C



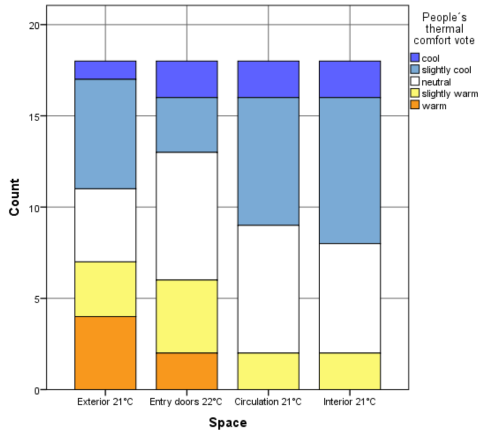
Correlation
Circulation operative and globe temperature °C

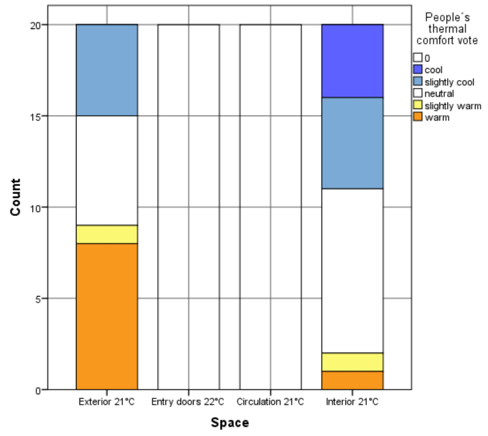


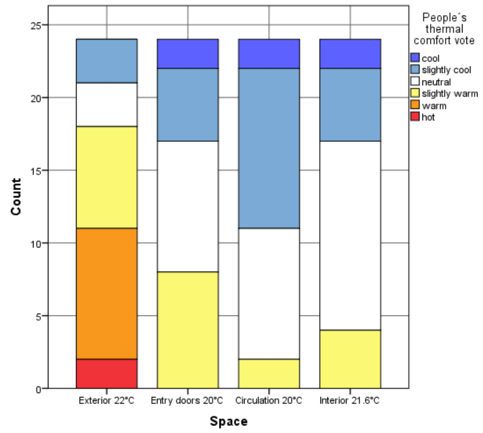
Correlation
Seminar rooms operative and globe temperature °C

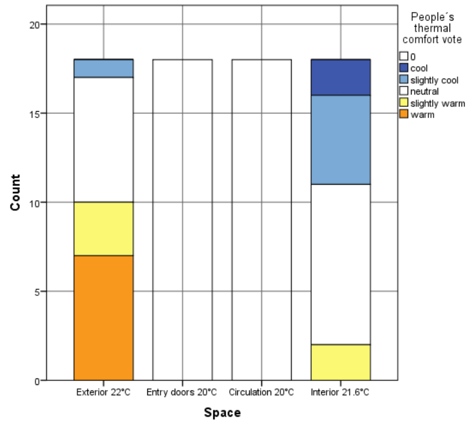


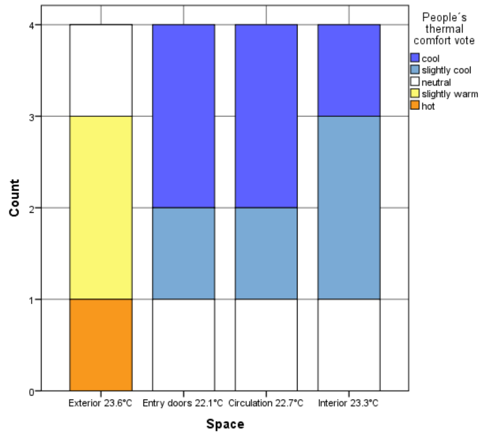
Appendix 11 Flat sequences graphs

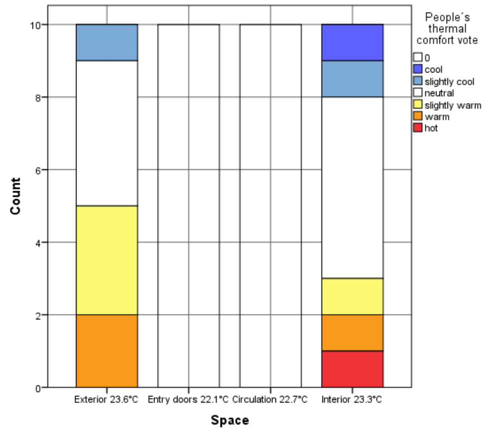


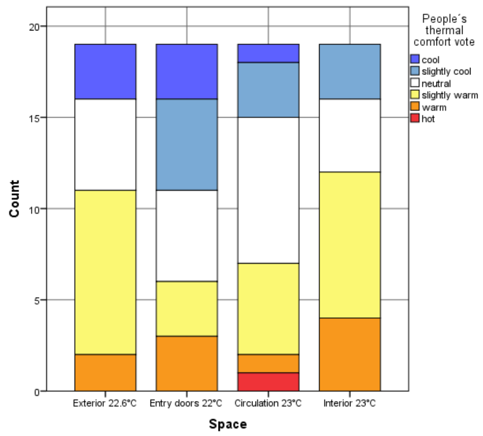


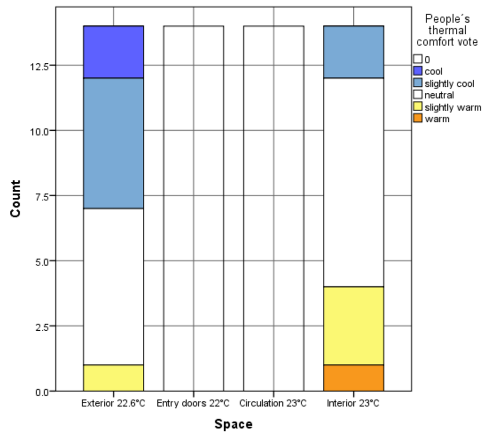




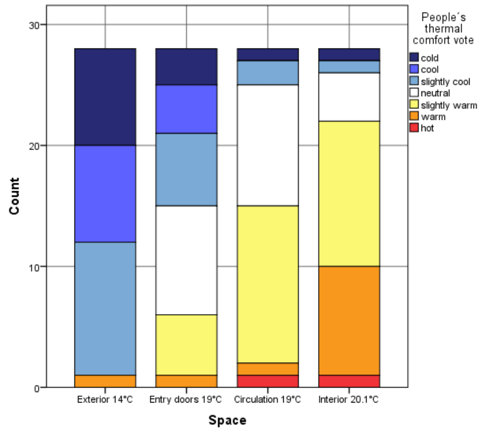


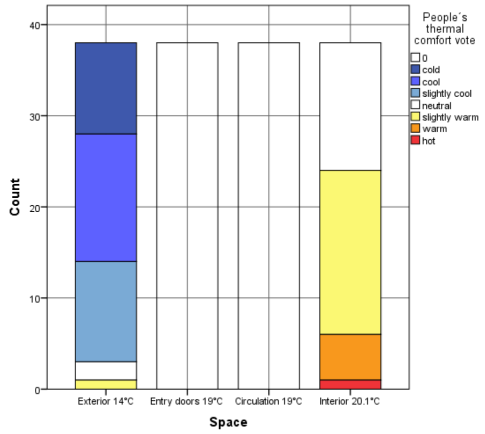


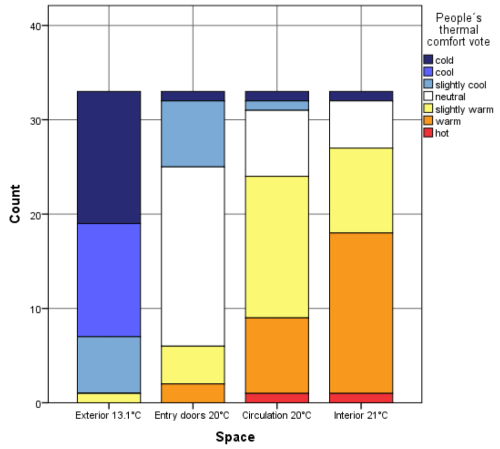


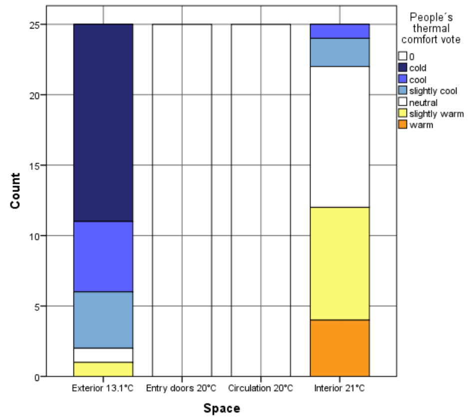


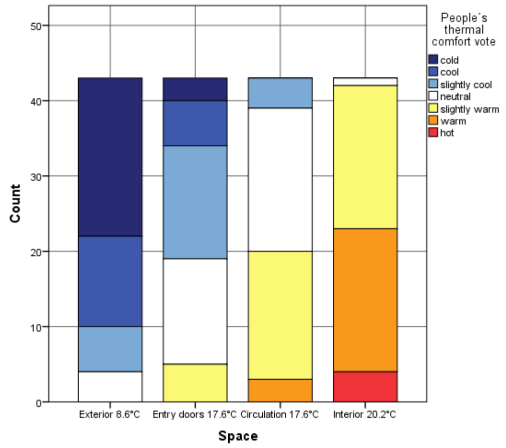
Appendix 12 Sudden sequences graphs

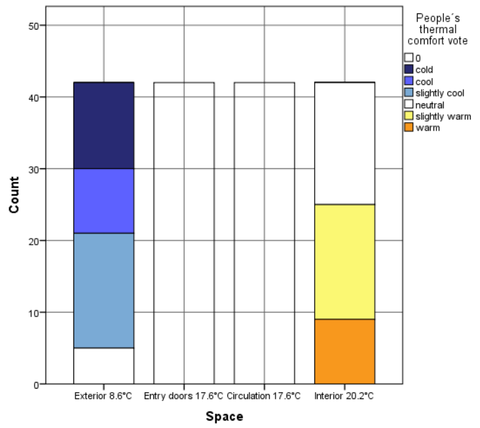


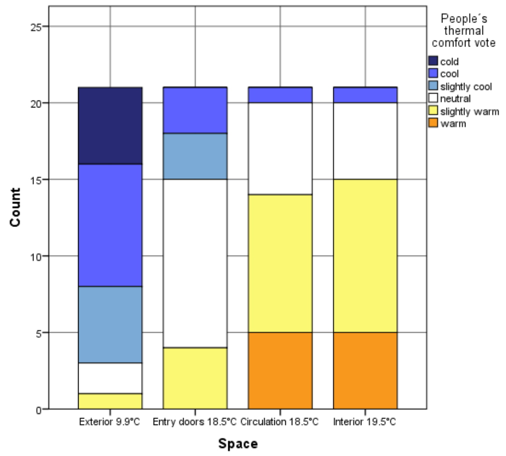


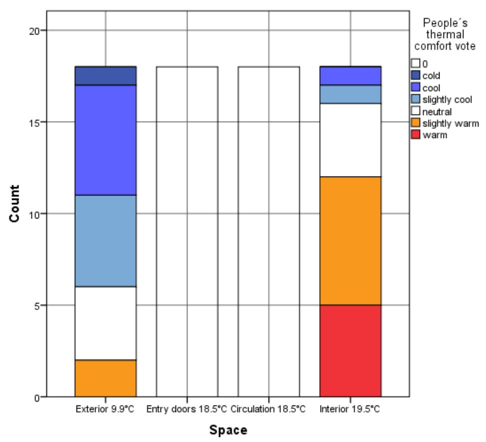


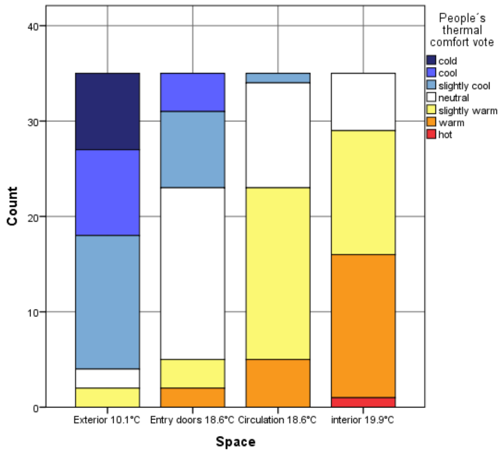


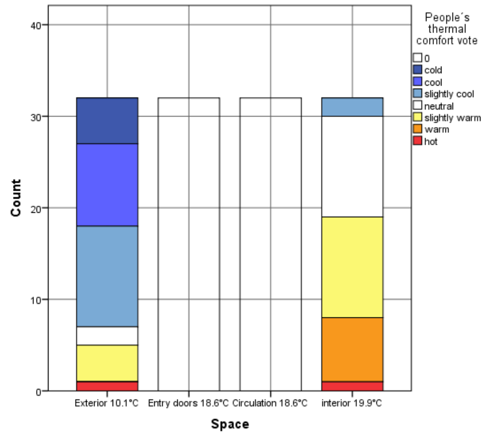


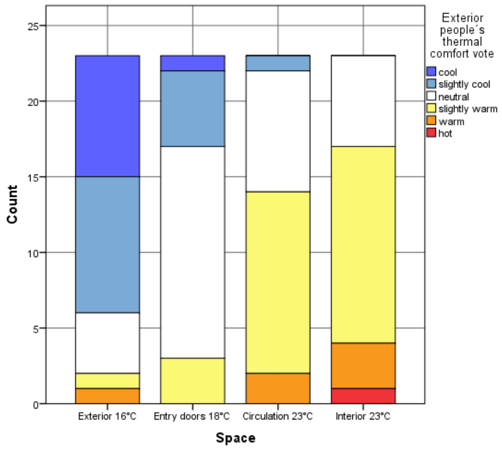







People´s thermal comfort vote
cold
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 10.1°C
Entry doors 18.6°C
Circulation 18.6°C
interior 19.9°C
Space


People´s thermal comfort vote
0
cold
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 10.1°C
Entry doors 18.6°C
Circulation 18.6°C
interior 19.9°C
Space


Exterior people´s thermal comfort vote
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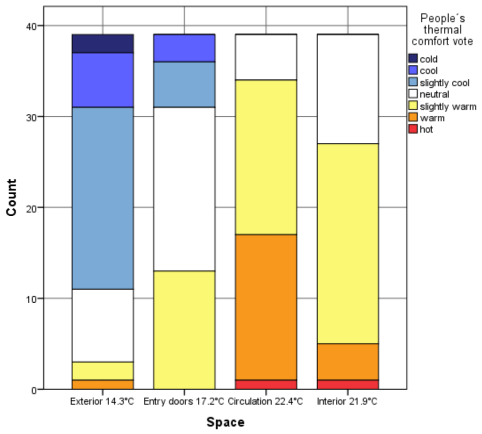
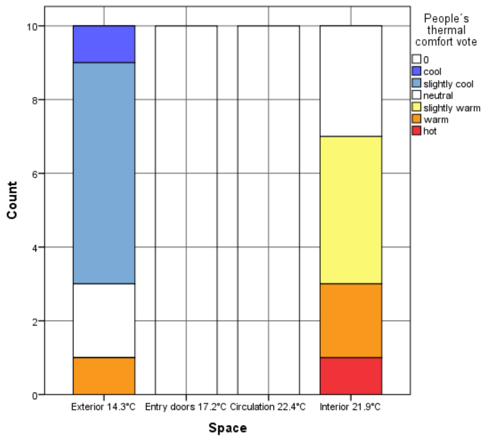
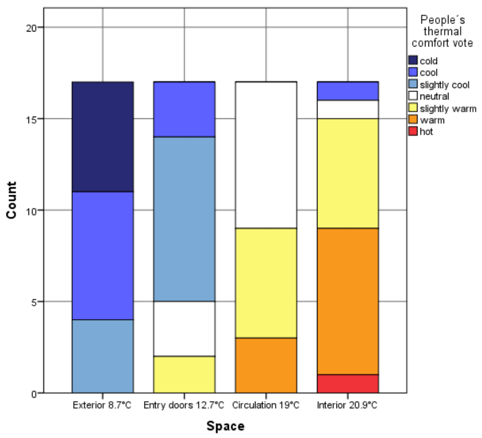
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 16°C
Entry doors 18°C
Circulation 23°C
Interior 23°C
Space


People´s thermal comfort vote
cold
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 14.3°C
Entry doors 17.2°C
Circulation 22.4°C
Interior 21.9°C
Space


People´s thermal comfort vote
0
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 14.3°C
Entry doors 17.2°C
Circulation 22.4°C
Interior 21.9°C
Space


People´s thermal comfort vote
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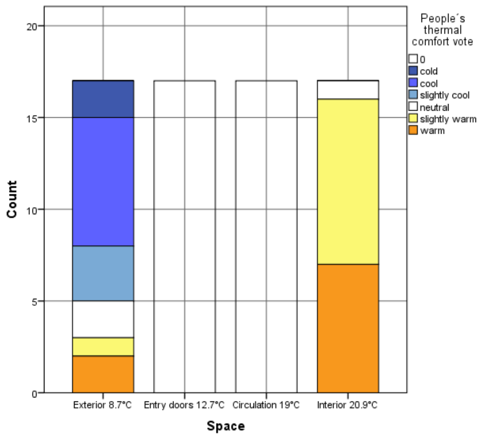
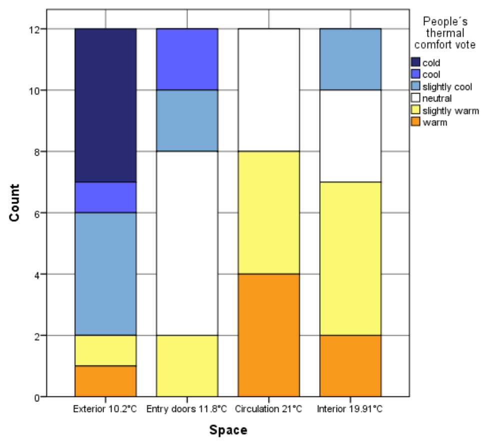
Exterior 8.7°C
Entry doors 12.7°C
Circulation 19°C
Interior 20.9°C
Space


People´s thermal comfort vote
0
cold
cool
slightly cool
neutral
slightly warm
warm
Count
Exterior 8.7°C
Entry doors 12.7°C
Circulation 19°C
Interior 20.9°C
Space


People´s thermal comfort vote
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cool
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neutral
slightly warm
warm
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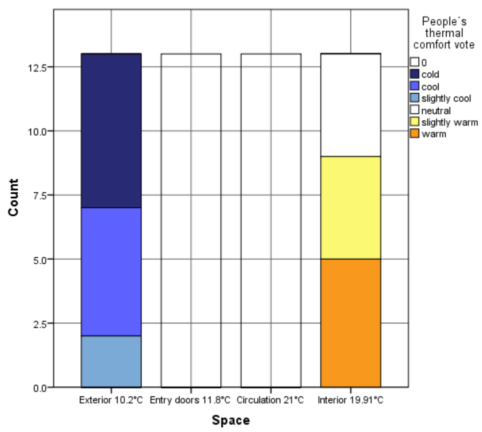
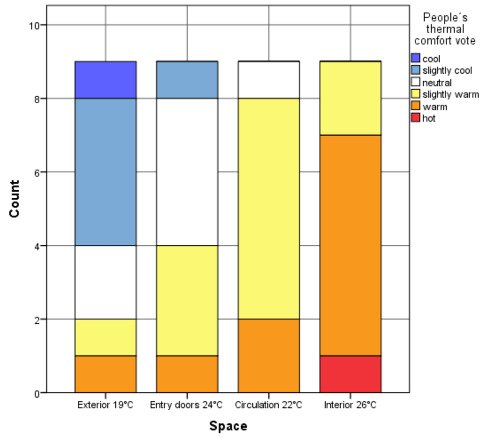
Exterior 10.2°C
Entry doors 11.8°C
Circulation 21°C
Interior 19.91°C
Space


People´s thermal comfort vote
0
cold
cool
slightly cool
neutral
slightly warm
warm
Count
Exterior 10.2°C
Entry doors 11.8°C
Circulation 21°C
Interior 19.91°C
Space


People´s thermal comfort vote
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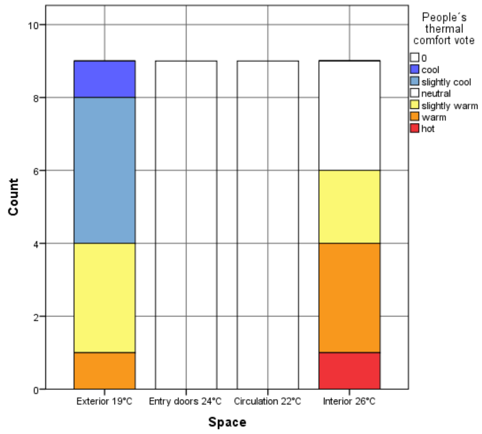
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 19°C
Entry doors 24°C
Circulation 22°C
Interior 26°C
Space


People´s thermal comfort vote
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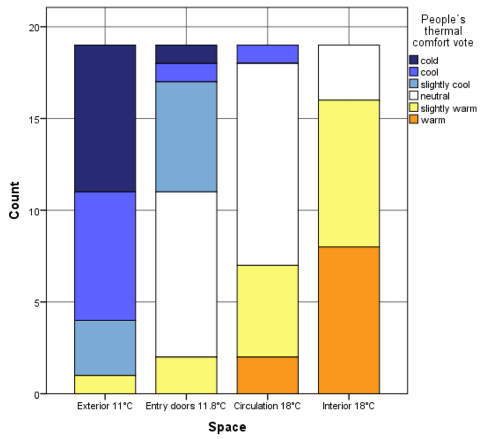
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 19°C
Entry doors 24°C
Circulation 22°C
Interior 26°C
Space


People´s thermal comfort vote
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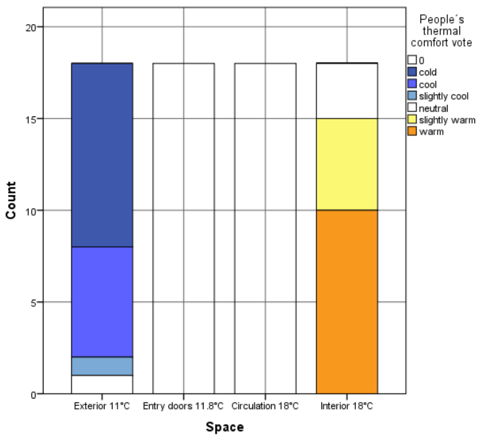
slightly warm
warm
Count
Exterior 11°C
Entry doors 11.8°C
Circulation 18°C
Interior 18°C
Space


People´s thermal comfort vote
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cold
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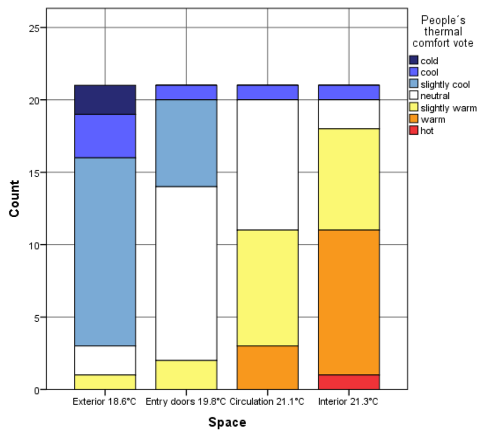
slightly cool
neutral
slightly warm
warm
Count
Exterior 11°C
Entry doors 11.8°C
Circulation 18°C
Interior 18°C
Space


People´s thermal comfort vote
cold
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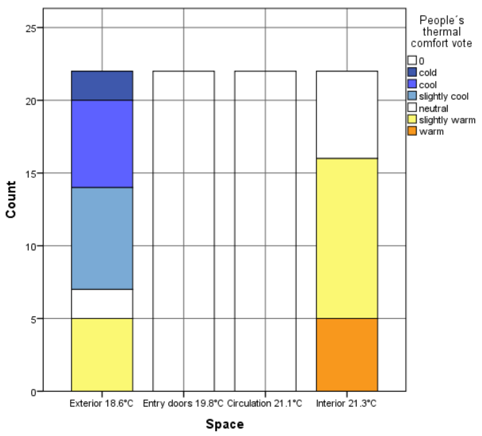
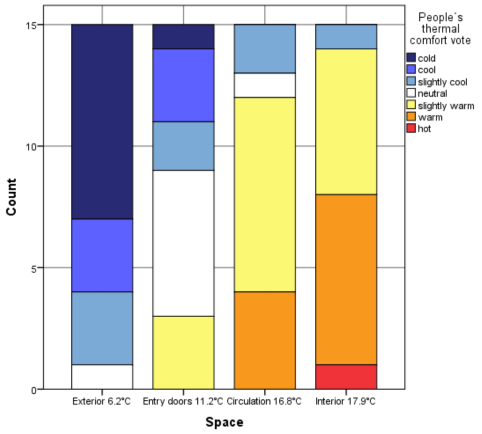
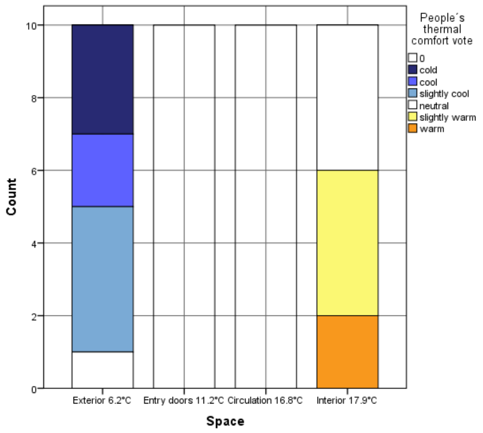
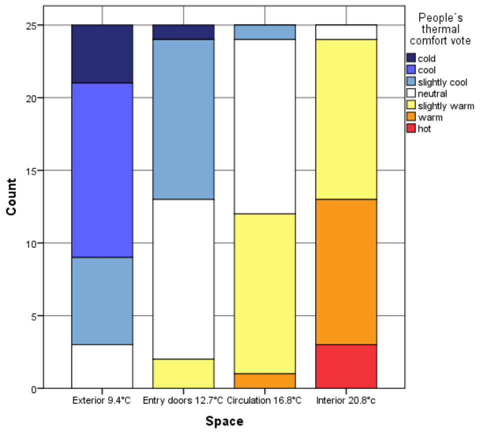
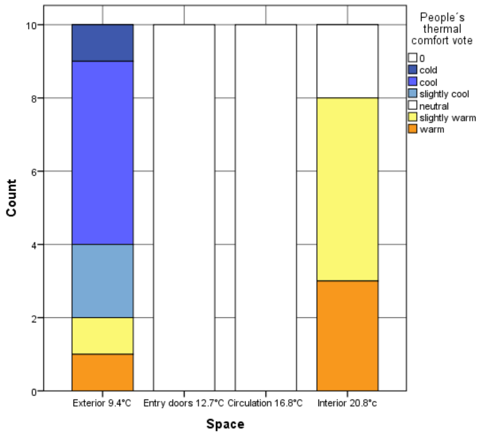
slightly warm
warm
hot
Count
Exterior 18.6°C
Entry doors 19.8°C
Circulation 21.1°C
Interior 21.3°C
Space

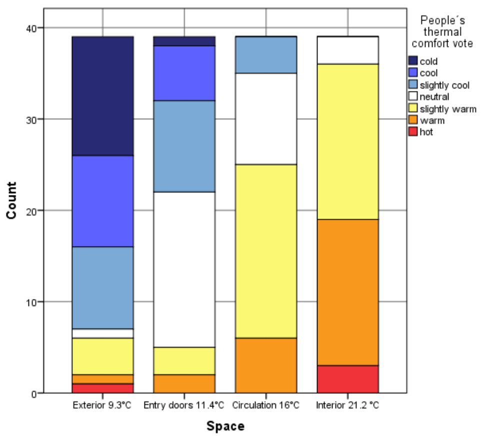

People´s thermal comfort vote
0
cold
cool
slightly cool
neutral
slightly warm
warm
Count
Exterior 18.6°C
Entry doors 19.8°C
Circulation 21.1°C
Interior 21.3°C
Space

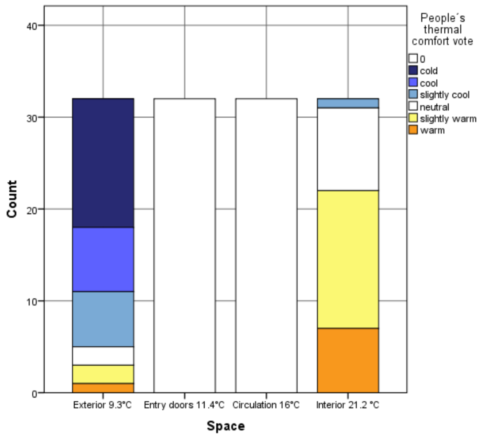

People´s thermal comfort vote
cold
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 6.2°C
Entry doors 11.2°C
Circulation 16.8°C
Interior 17.9°C
Space

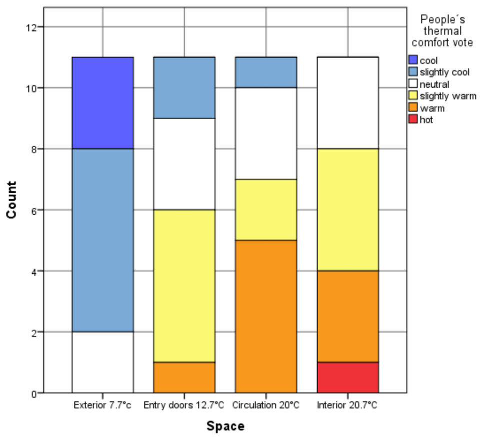

People´s thermal comfort vote
0
cold
cool
slightly cool
neutral
slightly warm
warm
Count
Exterior 6.2°C
Entry doors 11.2°C
Circulation 16.8°C
Interior 17.9°C
Space

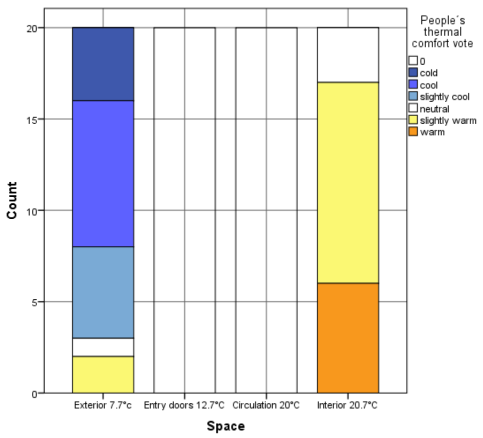

People´s thermal comfort vote
cold
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 9.4°C
Entry doors 12.7°C
Circulation 16.8°C
Interior 20.8°c
Space


People´s thermal comfort vote
0
cold
cool
slightly cool
neutral
slightly warm
warm
Count
Exterior 9.4°C
Entry doors 12.7°C
Circulation 16.8°C
Interior 20.8°c
Space

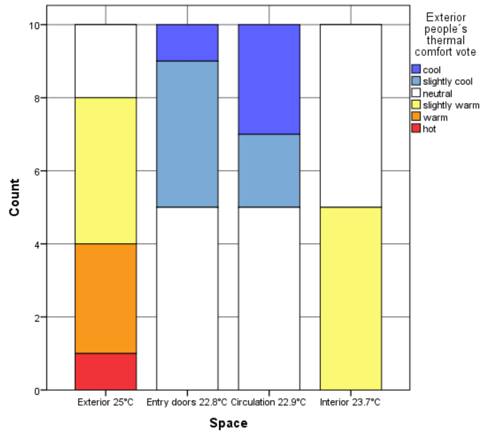

People´s thermal comfort vote
cold
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 9.3°C
Entry doors 11.4°C
Circulation 16°C
Interior 21.2 °C
Space

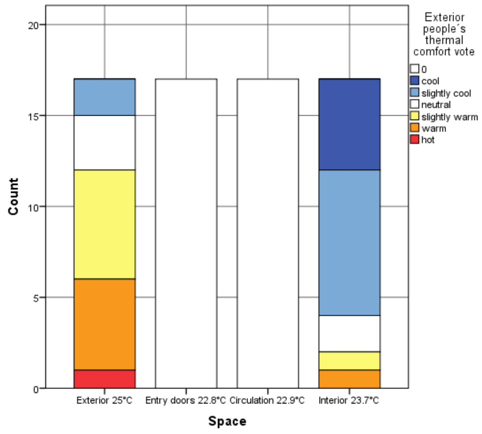

People´s thermal comfort vote
0
cold
cool
slightly cool
neutral
slightly warm
warm
Count
Exterior 9.3°C
Entry doors 11.4°C
Circulation 16°C
Interior 21.2 °C
Space

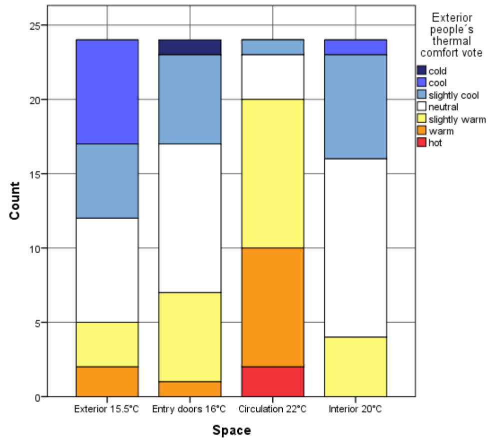

People´s thermal comfort vote
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 7.7°c
Entry doors 12.7°C
Circulation 20°C
Interior 20.7°C
Space

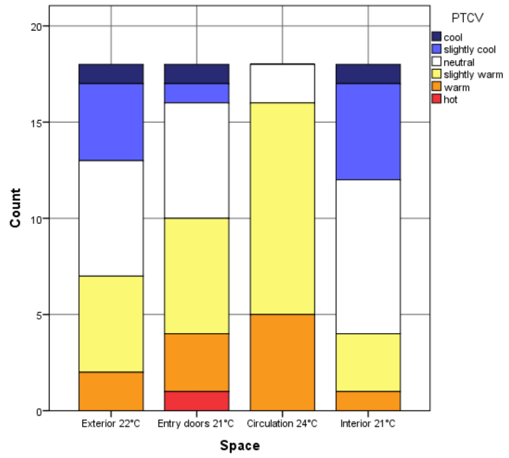

People´s thermal comfort vote
0
cold
cool
slightly cool
neutral
slightly warm
warm
Count
Exterior 7.7°c
Entry doors 12.7°C
Circulation 20°C
Interior 20.7°C
Space

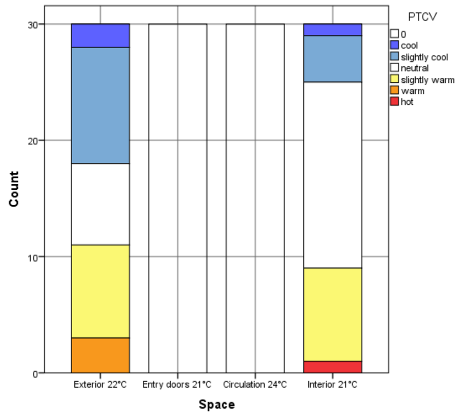
Appendix 13 Irregular patterns graphs

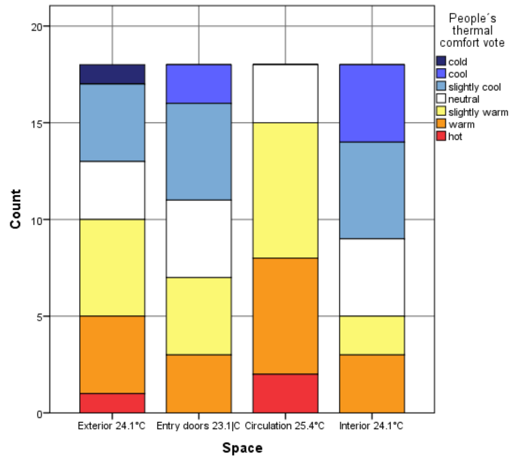


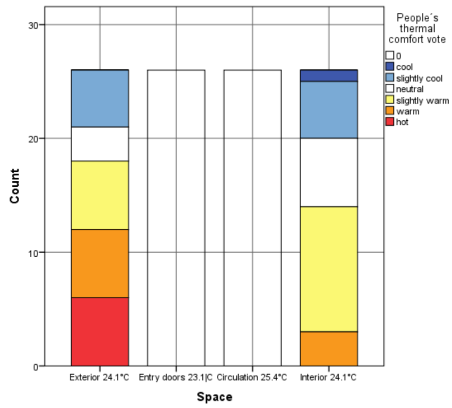


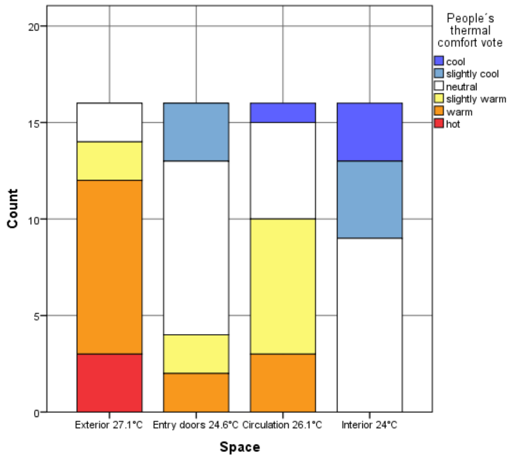




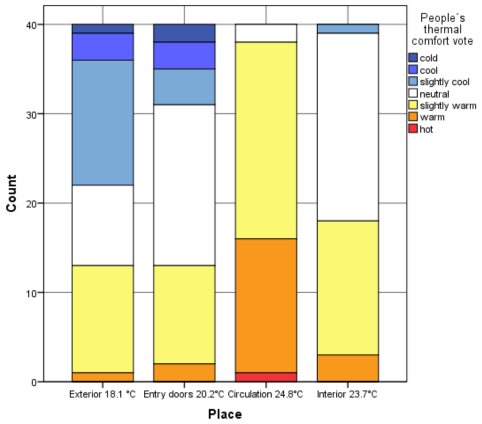


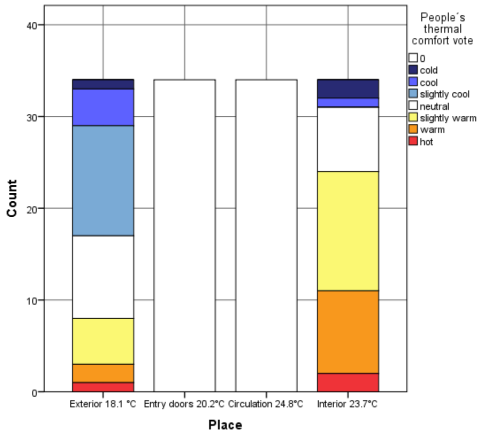


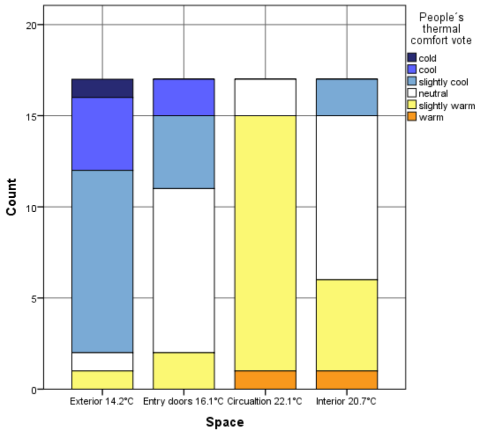


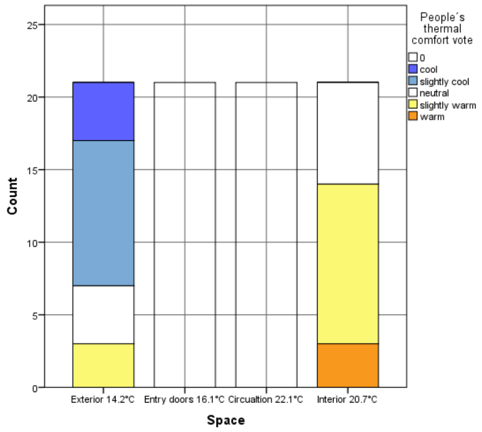


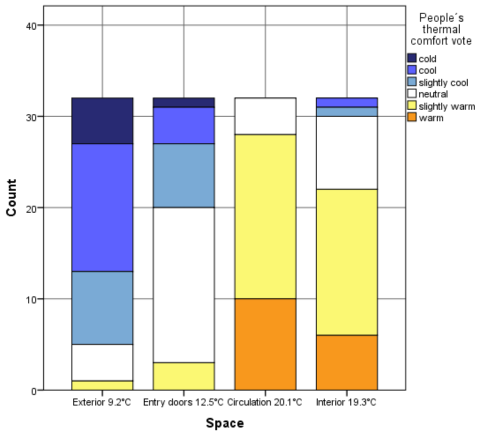
ICOSS Building sequence 23

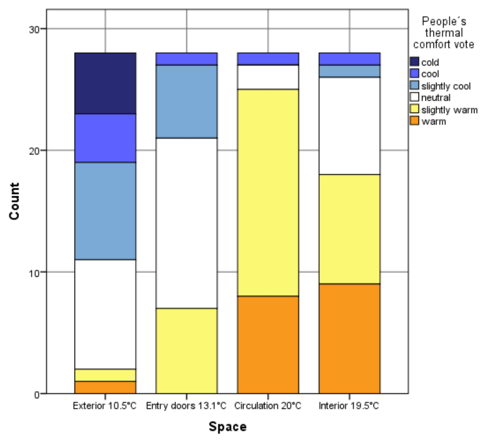


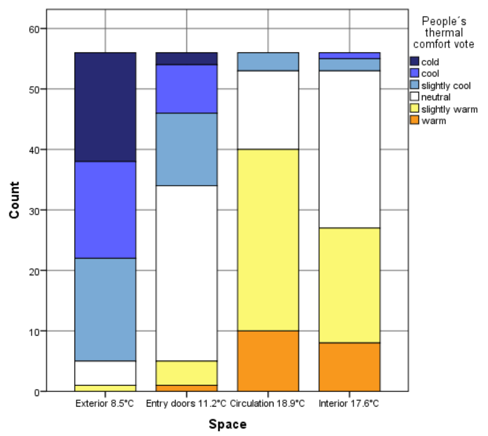


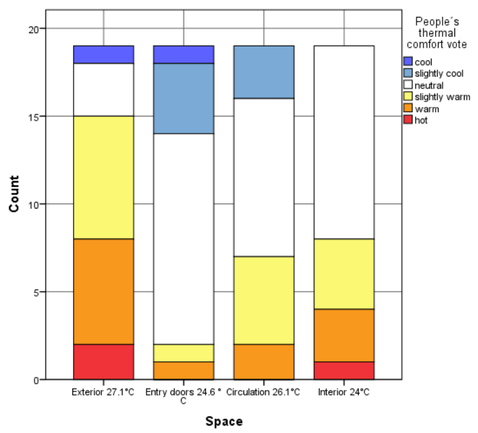


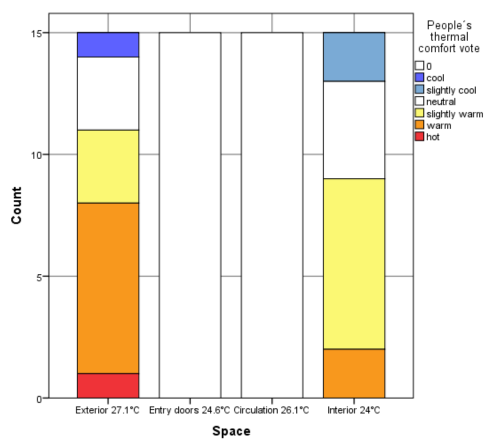


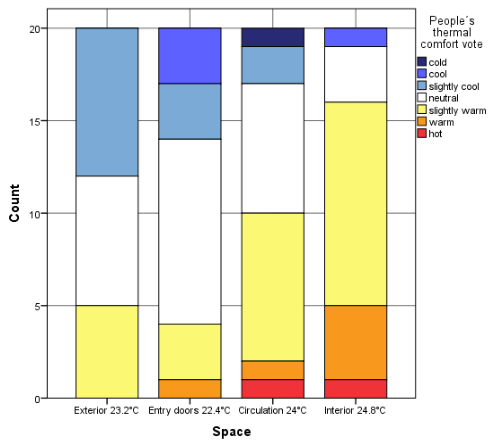


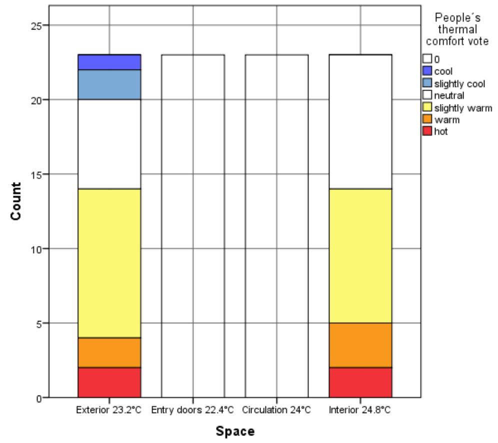

People´s thermal comfort vote
cold
cool
slightly cool
neutral
slightly warm
warm
Count
Exterior 10.5°C
Entry doors 13.1°C
Circulation 20°C
Interior 19.5°C
Space

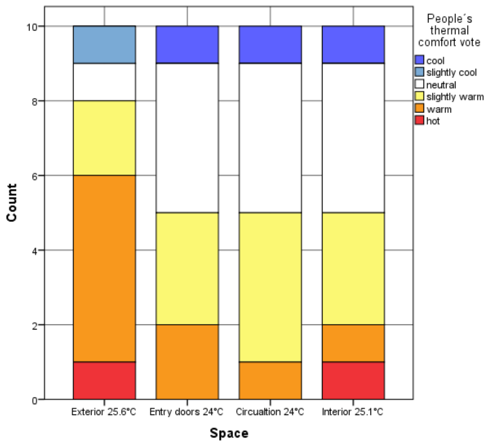

People´s thermal comfort vote
cold
cool
slightly cool
neutral
slightly warm
warm
Count
Exterior 8.5°C
Entry doors 11.2°C
Circulation 18.9°C
Interior 17.6°C
Space

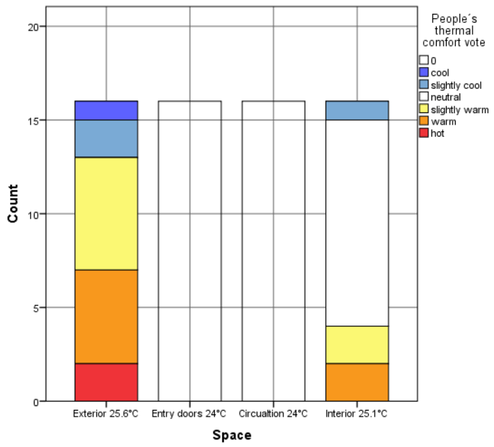

People´s thermal comfort vote
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 27.1°C
Entry doors 24.6 °C
Circulation 26.1°C
Interior 24°C
Space

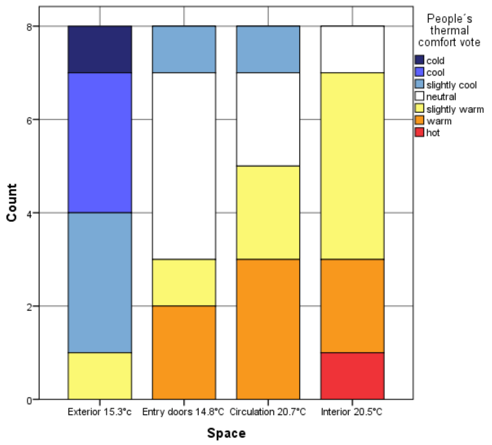

People´s thermal comfort vote
0
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 27.1°C
Entry doors 24.6°C
Circulation 26.1°C
Interior 24°C
Space

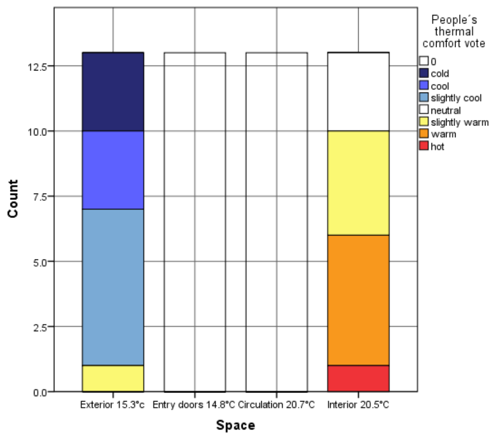

People´s thermal comfort vote
cold
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 23.2°C
Entry doors 22.4°C
Circulation 24°C
Interior 24.8°C
Space

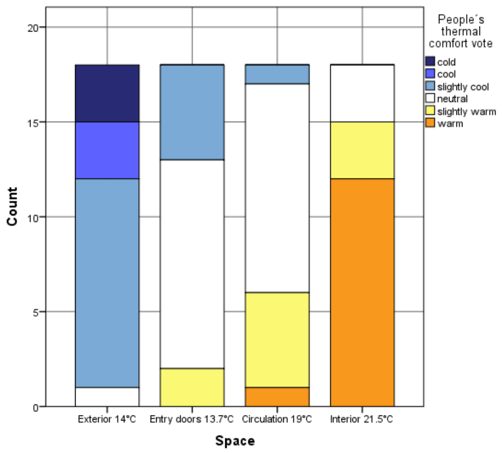

People´s thermal comfort vote
0
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 23.2°C
Entry doors 22.4°C
Circulation 24°C
Interior 24.8°C
Space

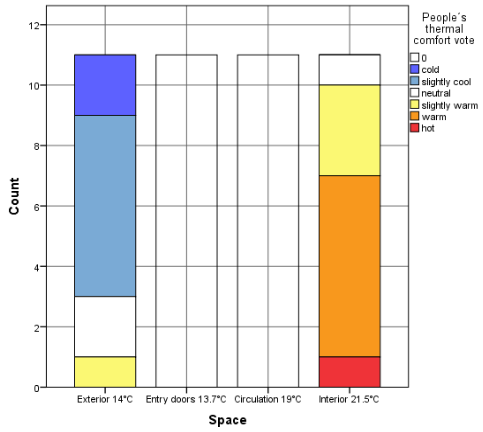

People´s thermal comfort vote
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 25.6°C
Entry doors 24°C
Circualtion 24°C
Interior 25.1°C
Space


People´s thermal comfort vote
0
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 25.6°C
Entry doors 24°C
Circualtion 24°C
Interior 25.1°C
Space


People´s thermal comfort vote
cold
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 15.3°c
Entry doors 14.8°C
Circulation 20.7°C
Interior 20.5°C
Space


People´s thermal comfort vote
0
cold
cool
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 15.3°c
Entry doors 14.8°C
Circulation 20.7°C
Interior 20.5°C
Space


People´s thermal comfort vote
cold
cool
slightly cool
neutral
slightly warm
warm
Count
Exterior 14°C
Entry doors 13.7°C
Circulation 19°C
Interior 21.5°C
Space


People´s thermal comfort vote
0
cold
slightly cool
neutral
slightly warm
warm
hot
Count
Exterior 14°C
Entry doors 13.7°C
Circulation 19°C
Interior 21.5°C
Space