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Thermal performance and occupant comfort in UK Higher Learning Environments

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Thermal Performance and Occupant Comfort in UK Higher Learning Environments

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Ethics Approval

Certificate of Ethical Approval

Applicant:

Mina Jowkar

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Evaluation of thermal comfort in higher learning environments in cold and extremely cold climates

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Abstract

Higher learning environments accommodate a variety of students in terms of climatic background, thermal expectation, age, gender, academic discipline, dress code and so forth. Such diversity often results in different perceptions of thermal comfort and (heating/cooling) energy waste in an environment. Given that thermal comfort affects academic productivity, understanding the thermal comfort requirements in higher educational buildings cannot only improve the students' academic performance, but also ~~can~~ reduce energy waste due to overheating or overcooling.

This study investigates the potential physiological and psychological human characteristics that lead to this diverse thermal perception and evaluates the students' thermal comfort in UK higher learning environments. A field study was conducted through objective measurement (including environmental monitoring) and subjective evaluation (including paper-based cross-sectional questionnaire surveys and observation) in eight mixed-mode buildings at two university campuses in Edinburgh and Coventry, UK. A total of 4100 students were surveyed between October 2017 and March 2018. The influence of the subjects' climatic backgrounds (long-term thermal history) and perceptions of control in different classroom types were examined as psychological drivers. The influence of the subjects' age- and gender-related differences and acclimatisation were also assessed as physiological drivers of thermal comfort.

The results regarding the psychological human characteristics demonstrated almost similar thermal comfort requirements in the lecture rooms, design studios and computer laboratories. Also, a closer relation between the prevalent operative temperature and a student's comfort temperature was revealed in the design studios (due to the physiological and psychological thermal adaptation results from the longer occupancy period and the students' higher perception of control over the space) compared to the other classroom types. In terms of a student's climatic background (long-term thermal history), thermal comfort votes were shown to vary according to the climatic background. Warmer climatic background groups showed cooler mean thermal sensations (–0.28) and warmer preferences (–0.10) compared to the cooler background group and the UK native residents (mTSV: 0.14, mTP: 0.12). The physiological

drivers of thermal comfort showed a similar comfort temperature for both genders (≈23°C) and age groups(23–24°C), but warmer sensation for women than men. Furthermore, a higher comfort temperature, warmer sensation and cooler preferences was revealed for the acclimatised subjects in Coventry (23.5°C, –0.1, 0.04 ASHRAE scale, respectively) compared to Edinburgh (22.1°C, 0.4, –0.3 ASHRAE scale, respectively).

The overall findings show the complex nature of thermal comfort in higher learning environments through 1) showing that the same thermal environment in a classroom tends to be perceived differently from person to person, therefore, a specific environmental criterion cannot provide comfort for all the occupants; 2) explaining how the subjective factors influence thermal perceptions in higher learning environments and 3) introducing the comfort and acceptable temperature ranges for more than 80% of the students in three different classroom types.

The output of this study can be used to develop energy efficient and sustainable environmental, architectural or refurbishment design strategies to offer different thermal zones inside classrooms in a way that students can choose the desired zone based on their thermal preferences.

List of Publications

Journal papers:

- **Mina Jowkar,** Hom B. Rijal, James Brusey, Azadeh Montazami, Alenka Temeljotov-salaj 'Influence of acclimatization, age and gender-related differences on thermal perception in university buildings: case studies in Scotland and England' – *Building and Environment Journal* (Resulted from Chapter 4)
- **Mina Jowkar**, Hom B. Rijal, James Brusey, Azadeh Montazami, Salvatore Carlucci, Terry, C. Landsdown 'Comfort temperature and preferred adaptive behaviour in various classroom types in the UK higher learning environments' – *Energy and Buildings journal* (Resulted from Chapter 5)
- **Mina Jowkar,** Richard de Dear, James Brusey 'Influence of long-term thermal history on thermal comfort and preferences' *Energy and Buildings journal* (Resulted from Chapter 6)
- **Mina Jowkar**, Richard de Dear, James Brusey 'How short-term thermal history influences thermal comfort assessment in multidisciplinary environments' Ongoing (Resulted from Chapter 6)
- **Mina Jowkar**, James Brusey 'The physiological and psychological human characteristics affecting diverse thermal perceptions in university buildings, A review article' Ongoing (Resulted from Chapter 2)

Conference papers:

- **Mina Jowkar,** Hom B.Rijal, James Brusey 'Environmental design criteria for the university buildings in the Northern and Southern regions of the UK' – Windsor Conference, Windsor, 2020
- **Mina Jowkar**, Hom B.Rijal, James Brusey 'Thermal comfort in different classroom types in higher educational buildings' – Comfort at the Extremes Conference, Dubai, 2019
- **Mina Jowkar**, Azadeh Montazami 'Thermal Comfort in the UK Higher Educational Buildings: The Influence of Thermal History on Students' Thermal Comfort' – Windsor Conference, Windsor, 2018
- **Mina Jowkar**, Azadeh Montazami 'Investigation of the impact of students' background on their thermal perception in higher education buildings' – PLEA Conference, Edinburgh 2017

Poster presentations:

- **Mina Jowkar** 'Thermal comfort for the students in different disciplines' – poster, presented at the Doctoral Capability Conference, Coventry, 2018
- **Mina Jowkar** 'Climatic background and thermal comfort' poster (*awarded the best poster prize*), presented at Coventry University research symposium, Coventry, 2017
- **Mina Jowkar** 'Students' Thermal Comfort in the Mixed-Mode Educational Buildings' – poster, presented at Coventry University research symposium, Coventry, 2018

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To Ehsan Nikjoo

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Chapter 1

1. Introduction

1.1. Background

Thermal comfort is an essential factor in learning environments to optimise the students' educational achievements and to enhance learning performance and mental ability (Mendell and Heath 2005; Zeiler and Boxem 2009; Barbhuiya and Barbhuiya 2013; Haverinen-Shaughnessy et al. 2015; Ricciardi and Buratti 2018). Exposure to indoor temperatures significantly higher or lower than the comfort zone reduces students' learning and cognitive performances as well as their ability to grasp instructions (Ward, Ogbonna and Altan 2008; Carbon Trust 2010). Therefore, students' thermal satisfaction is a priority in the environmental design of educational buildings. However, considering that space heating is the most expensive and the largest source of energy consumption in educational buildings (Carbon Trust 2010), the energy consumption and related emissions associated with such heating should also be considered.

Higher education in the UK is growing in scale and scope as a big industry providing a skilled workforce, creating employment and is a source of foreign investment with a substantial impact on the UK economy (Ward, Ogbonna and Altan 2008). This expansion is followed by an annual growth in the number of students and in the courses offered by the universities, which obviously leads to a higher energy demand due to an extensive need to provide equipment and facilities (Ward, Ogbonna and Altan 2008). Considering the large amount of energy consumption and related emissions in the existing university buildings (Anon 2006a), this expansion can lead to huge energy use and emissions in this sector that need more monitoring strategies.

The influence of thermal comfort on students' well-being and productivity combined with the considerable energy consumption in higher learning environments in the UK has attracted substantial attention among researchers in recent years. Nevertheless, despite the importance of these mentioned factors, no conclusive study, which investigates the thermal comfort and the potential thermal energy savings in different classroom types of the UK university buildings was found by the author to date.

Existing guidelines such as CIBSE (Anon 2019a), ASHRAE (*ASHRAE 55* 2010) and EN ISO 7730 (*EN ISO 7730* 2005), recommend general environmental criteria for 'lecture halls', 'teaching spaces' and 'classrooms' in educational buildings with no classification based on educational level. This suggests applying the same environmental criteria for school buildings to universities and colleges without considering the potential differences between the occupants in each level, which cannot be applicable due to the following reasons:

1. University students are less homogeneous in terms of gender and age and thus may have diverse perceptions of thermal comfort perceptions (Cena, Spotila, and Ryan 1988; Choi, Aziz, and Loftness 2010; Fanger 1970; Hwang and Chen 2010; Karjalainen 2007; Karyono 2000).
2. Classrooms in universities are shared by students from various climatic backgrounds who thus tend to have different thermal perceptions (Amin et al. 2016; Amin, Teli, and James 2018; Brychkov, Garb, and Pearlmutter 2018).
3. The students' greater levels of freedom for either environmental or personal adaptive behaviours in higher learning environments may lead to different thermal comfort perceptions in such spaces compared to primary, secondary and high schools, where the ambient environment is usually controlled by the teachers (Brager, Paliaga and de Dear 2004; Teli, Jentsch and James, 2012; Liu, Yao and McCloy, 2014).
4. Students in higher learning environments study various subjects and are exposed to different classroom types with variable occupancy periods and activities. This variation can also affect their thermal comfort evaluations (Fadeyi 2014; Lin et al. 2015).

Therefore, a thorough investigation of the occupants' thermal comfort in such environments not only helps to provide thermal satisfaction and to improve the students' academic productivity, but also helps to evaluate the potential energy savings through avoiding over-heated or over-cooled thermal environments in this sector.

1.2. Research aim and research questions

This study aims to investigate the thermal comfort perceptions, acceptable temperature range and preferred adaptive behaviours of students in UK higher learning environments by addressing the following Research Questions (RQ):

RQ 1. Taking account of the different climatic conditions in the northern (Scotland) and southern (England) regions of the UK, are the same thermal comfort criteria applicable in higher educational buildings throughout the UK?

RQ 2. How do age- and gender-related differences among students affect thermal perceptions in higher learning environments?

RQ 3. What are the thermal comfort requirements of students in diverse disciplines exposed to various classroom types? Can the same thermal comfort criteria be applicable in all classroom types in university buildings?

RQ 4. How does climatic background/long-term thermal history influence students' in-the-moment thermal perceptions inside the classrooms?

The output of this study can be used to determine thermally comfortable, energy efficient and sustainable environmental, architectural or refurbishment design strategies to offer different thermal zones inside the classrooms in a way that students can choose the desired zone based on their thermal preferences. This can lead to reducing energy demand in the education sector and help to meet the UK target for emissions reduction by 2050.

1.3. Thesis outline

This thesis consists of seven chapters and the content of each chapter is summarised as follows:

Chapter 1: Introduction

Chapter 1 provides an overview of the research including the background, hypothesis, aim, objectives and the scope of this study.

Chapter 2: Literature Survey

Chapter 2 reviews the theories applied to the main contents of this study. Prior to the review, the importance of thermal comfort in educational buildings is described. Furthermore, the challenges in providing thermal comfort in higher learning environments, including conflicts between the occupants' thermal comfort requirements as a result of physiological and psychological human characteristics are studied. Findings regarding the impact of each factor on thermal perceptions are critically reviewed and the key results are highlighted. The recommended thermal comfort criteria for university buildings and the limitations in these standards are also discussed.

Chapter 3: Research Methods

Chapter 3 explains the methods of data collection and statistical analysis covering the survey locations, case study buildings, details of the field data collection, measuring instruments, subjects and questionnaire surveys.

Chapter 4: Acclimatisation and Thermal Comfort in England & Scotland

Chapter 4 presents the outline of the environmental conditions and subjects' thermal comfort votes in terms of thermal sensations, preferences, thermal neutrality and acceptability. In addition, the results of the data analysis on the influence of acclimatisation on the occupants' thermal comfort perceptions in higher learning environments in England and Scotland are provided. Findings are also extended to the thermal comfort perceptions of the occupants in different gender and age groups.

Chapter 5: Thermal Comfort in Different Classroom Types

Chapter 5 provides an overview of the environmental thermal conditions in three different types of classrooms: lecture rooms, studios and PC labs, occupied by students in different disciplines with various exposure durations. Students' thermal perceptions corresponding to the prevalent operative temperature are analysed, the results of which determine the acceptable and comfort temperature ranges in each classroom type. This chapter also provides the students' preferences and priorities for adaptive behaviours inside the classrooms which tend to be affected by levels of freedom they perceive over the environment.

Chapter 6: Diverse Climatic Background and Thermal Perception: Influence of Thermal History

Chapter 6 discusses how the perception of thermal comfort differs among students coming from different climates who tend to evaluate learning environments differently, depending on their past climatic exposures and thermal experiences (their long-term thermal history). The results in this chapter present the thermal sensations and preference votes, thermal acceptability, sensitivity, neutrality, comfort and preferred temperatures of the students with warmer and cooler climatic backgrounds compared to the UK residents. The analysis is followed by a proposed architectural design solution that can provide thermal comfort for students with diverse climatic backgrounds in the same classroom.

Chapter 7: Discussion and Conclusion

Chapter 7 discusses the findings of the study, concludes the research work and provides recommendations for further work in this field.

Appendix 1

Contains the Journal and conference articles resulted from this thesis

Appendix 2

Includes the survey questionnaire used for data collection in this research

Chapter 2

2. Literature Survey

2.1. Introduction

In this chapter, an overview of the literature relevant to the field of research is presented. This chapter reviews the influential factors on thermal comfort that are applied to occupants of higher educational buildings. The implementation of existing guidelines for such spaces is also reviewed.

2.2. Thermal comfort definition and assessment methods

Thermal comfort can be defined as “the state of mind that expresses satisfaction with the existing environment” (*ASHRAE 55* 2010b).

Occupants' thermal satisfaction can be achieved as a result of a balance between the existing physical environment and subjective comfort expectations (Luo et al. 2016). According to the definition of thermal comfort, “state of mind”, in terms of thermal comfort can be different due to the various expectations, cultural, personal and social factors (Nicol and Humphreys 2002; Singh, Mahapatra and Atreya 2011; Katafygiotou and Serghides 2014). Hence, the same thermal environment may be perceived differently by occupants due to their personal characteristics (Singh, Mahapatra and Teller 2015).

So far, extensive investigations have been conducted to develop commonly accepted criteria and comfort standards to evaluate a thermal environment. The two main approaches established over the years and adopted in international standards for the definition and evaluation of thermal comfort are 1) the PMV model (Fanger 1970) and 2), the adaptive comfort approach (de Dear and Brager 1998; Nicol and Humphreys 2002).

2.2.1. Static/PMV model

Fangers' model (the PMV model) is the method most used in practice in the heat balance/static approach category (Jones 2002). Fanger's Predicted Mean Vote (PMV) model was developed in the 1970s based on studies in a climate chamber, where participants were dressed in similar clothing and were involved in similar activities while exposed to different thermal environments (Charles 2003). The main basis of the static/PMV model are four environmental variables and two personal parameters including indoor air temperature, mean radiant temperature, indoor air relative humidity, indoor air velocity as environmental factors and the subjects' metabolic rates and clothing insulation as personal parameters (Fanger 1970). Fanger's PMV model is based on thermoregulation and heat balance theories (Lee and Strand 2001) indicating that the human body employs physiological processes (e.g. sweating, shivering, regulating blood flow to the skin) in order to maintain the balance between the core body heat generated by the metabolism and the body heat lost to the surrounding environment (Fanger 1970). This balance for the heat exchange between the human body and the environment can be expressed through the following equation:

$$H - E_d - E_{sw} - E_{re} - L = K = R + C \tag{2-1}$$

H: Internal heat production in the human body
E_d *: heat loss by water vapor diffusion through the skin*
E_{sw} *: heat loss by evaporation of sweat from the surface of the skin*
E_{re} *: latent respiration heat loss*
L *: dry respiration heat loss*
K*: heat transfer from the skin to the outer surface of the clothed body*
R*: heat loss by radiation from the outer surface of the clothed body*
C*: heat loss by convection from the outer surface of the clothed body*

Fanger's model combines the theory of heat balance with the physiology of thermoregulation to determine the occupants' comfort temperatures (Djongyang, Tchinda and Njomo 2010). However, in practice, the PMV index could not predict the thermal acceptability level of an environment (Fanger 1970). Hence, the Predicted Percentage Dissatisfied (PPD) index was developed, which states the percentage of people who are thermally dissatisfied in a space. Experiments in this model were conducted in two ways: 1) the thermal sensation votes of the participants were recorded using the seven-point ASHRAE thermal sensation scale in a thermal environment set by the researcher, 2) the participants were free to control the thermal environment themselves, adjusting the temperature until they felt thermally ‘neutral’ (i.e. TSV=0 on the ASHRAE thermal sensation scale, feeling neither hot nor cold) (Charles 2003). Nevertheless, Humphreys (2015), Nicol (1993) and Donald (1987) raised the question of whether this laboratory-based approach could be valid to assess thermal perception in the real world (uncontrolled actual buildings).

Results from some studies conducted in actual buildings indicated considerable discrepancies between the occupants’ actual thermal sensation votes and those predicted by the PMV-PPD model (Nicol and Humphreys 1973; De Dear and Brager 2002; Nicol 2004). The PMV model was shown to correctly predict the preferred operative temperature in air-conditioned office buildings, but in naturally ventilated buildings (in warm climatic conditions), PMV overestimated the occupants’ warm sensations (de Dear and Brager 1998). A similar conclusion was drawn from other investigations showing that the static/PMV model may work properly in air conditioned buildings, but it may not be a good predictor of human thermal comfort in naturally ventilated environments (de Dear and Brager 1998; De Dear and Brager 2002; Humphreys and Fergus Nicol 2002; Charles 2003). Later, it was revealed by Humphreys and Nicol (2002) and supported by Moujalled et al. (2008) that the errors and inaccuracies of the PMV model in predicting thermal comfort was not only limited to NV buildings. They also happened in AC environments but were masked by the narrow range of thermal environmental variations.

In most practical settings, such a discrepancy presumably happens due to inaccurate measurements of an individual’s clothing insulation and activity level (Brager and de Dear 1998; De Dear and Brager 2002). Furthermore, influential factors on perceptions of thermal comfort were overlooked, such as exposure to outdoor air (Höppe 2002; Charles 2003), the occupants’ interactions with the surrounding environment by adaptive behaviours (Nicol and Humphreys 1973, 2002; de Dear and Brager 1998; Charles 2003; Nicol 2004) and their ability to adapt thermally to a changing thermal environment through modifying their expectations and mental preferences (Nicol and Humphreys 1973; Charles 2003; Nguyen, Singh and Reiter 2012). These can be considered as other reasons why the PMV model fails to accurately predict people’s thermal comfort. Each of these effects may be a minor source of error in itself, however, considering them together causes significant errors in the theoretical relationship (Nicol and Humphreys 1973).

PMV's inability to predict actual thermal sensation votes as well as the ensuing environmental impact and mismanagement of energy resources caused by the unreliable prediction of thermal environments led to developing the 'adaptive comfort model' which takes account of the influence of outdoor air temperature on occupants' thermal comfort evaluations (Humphreys 1978; Auliciems 1981).

2.2.2. Adaptive model of thermal comfort

The fundamental assumption of the adaptive model is expressed by the adaptive principle that if a change causes discomfort, people will react to restore their comfort (Brager and de Dear 1998). The adaptive model of thermal comfort regards occupants as active recipients of the thermal environment who play an active role in creating their own thermal preferences (de Dear and Brager,1998). This method also believes that contextual factors and past thermal histories can also affect occupants' expectations and thermal preferences (de Dear and Brager 1998). This model claims that satisfaction with an indoor thermal environment results from matching the actual thermal conditions prevailing in a given context with the subject's thermal expectations of what the indoor environment should be like in that same context (Auliciems 1981; Nicol 1993; de Dear and Brager 1998). In other words, satisfaction happens when people adapt to an indoor thermal environment. Adaptation can be interpreted broadly as "the gradual diminution of the organism's response to repeated environmental stimulation" (de Dear and Brager 1998). Based on this, de Dear and Brager (1998) distinguished three categories of thermal adaptation:

1) Physiological: physiological adaptation refers to the physiological changes due to exposure to a thermal environment that lead to a greater tolerance in such a climatic condition. The two subcategories considered for physiological adaptation include genetic adaptation (intergenerational) and acclimatisation (within the individual's lifetime).

2) Psychological: psychological adaptation is the thermal perception of the environment, which results from previous thermal experiences and expectations. Such an adaptation suggests that personal comfort setpoints are far from thermostatic.

3) Behavioural adjustment: this includes responses to an uncomfortable thermal environment through personal (e.g. adjustment of clothing), technological (e.g. using an air conditioner), or cultural (e.g. a siesta in the heat of the day) behaviours.

The adaptive model of thermal comfort posits that the factors beyond the fundamental physics and physiology interact with thermal perception. Subjective differences in terms of inter-individual factors (such as mood, cultural background, etc.) and social factors play a considerable role in the perception of thermal comfort in an environment (Nicol and Humphreys 2002; Singh, Mahapatra and Atreya 2011; Katafygiotou and Serghides 2014; Villadiego and Velay-Dabat 2014). Overall, the dynamic and individual-dependency nature of thermal comfort is widely accepted in the thermal environment research community. It has also been confirmed by recent studies conducted all over the world, that a generalised standard cannot be developed for thermal comfort (Nicol and Humphreys 2010; Singh, Mahapatra and Atreya 2011; Nicol and Stevenson 2013; Singh, Mahapatra and Teller 2015) as it is dependent on how people adapt to, perceive and interact with their surrounding environment (Vargas and Stevenson 2014). Shipworth et al. (2016) categorised human characteristics influencing thermal comfort into two main groups of physiological and psychological aspects, where each factor may exert its impact on the other characteristic. Both physiological and psychological human characteristics affect the individual assessment of a thermal environment and may potentially affect individuals' comfort related behaviours.

The adaptive comfort model set principles to evaluate the comfort and acceptability level of a thermal environment (Humphreys, Nicol, and Raja 2007) based on the findings from key field surveys from 1995 to 2011 (e.g. (Nicol et al. 1999; McCartney and Nicol 2001; Raja et al. 2001; Wong and Khoo 2003; Hwang, Lin and Kuo 2006; G. Zhang et al. 2007; Corgnati, Ansaldi and Filippi 2009; Hwang et al. 2009; Indraganti and Rao 2010; Mors et al. 2011)). The common method used in all these studies include people's subjective ratings of a thermal environment, simultaneous with measurements of the environmental variables, followed by statistical analysis of the subjects' responses corresponding to the exposed thermal condition. For the practical use of the adaptive comfort model, an algorithm was developed to relate the comfort temperature to the running mean outdoor temperature (exponentially weighted mean outside temperature) (McCartney and Nicol 2002).

2.2.3. Comparison of the models toward an index for thermal comfort evaluation

Compared to the static heat balance models, the adaptive model of thermal comfort is shown to be more energy efficient in predicting the required heating and cooling load in a thermal environment. Results from a study of an office building in the UK revealed that the comfort cooling load with the set temperature limits based on the adaptive comfort model was approximately 30% of the cooling load corresponding to the fixed temperature set-point (McCartney and Nicol 2002). It was confirmed in another investigation that a combination of environmental and design strategies (e.g. better insulation, shading, new control strategies) along with the application of adaptive comfort limits can lead to an environment with very close to zero energy demand for heating and cooling (Tuohy et al. 2010). According to de Dear and Brager (de Dear and Brager 1998), the adaptive model of thermal comfort can be considered as "complementary" to the heat-balance method, which also considers the impact of behavioural, physiological and psychological thermal adaptations (De Dear and Brager 2002).

The adaptive comfort model has been criticised as it only considers the impact of operative temperature on thermal sensations regardless of other environmental factors such as air velocity, relative humidity, metabolic rate and clothing insulation (factors incorporated in the PMV model) (Ole Fanger and Toftum 2002; Teli 2013). However, it has been shown that the above-mentioned variables do not affect the predictive power of the model (Humphreys and Fergus Nicol 2002; McCartney and Nicol 2002). As a result, operative temperature is introduced as a sufficient index to predict thermal comfort in an environment (de Dear and Brager 1998). Operative temperature can successfully combine features of both static and adaptive models of thermal comfort (Humphreys and Nicol 2002; McCartney and Nicol 2002).

2.3. Thermal comfort in educational buildings

It is well documented that the environmental quality of a space contributes to the occupants' thermal comfort, health and productivity (Fisk 2000). This subject is more vital in learning environments as perceptions of thermal comfort can improve educational achievements as well as enhancing learning productivity and mental tasks (Wyon 1970; Mendell and Heath 2005). Although the human body is highly adaptive, a student may struggle with perceiving or processing information in the classrooms if the physical environment is not comfortable (Teli 2013). Accordingly, Schoer and Shaffran (1973) examined the performance of students in both air-conditioned (as a thermally comfortable environment) and non-air-conditioned classrooms. A statistically significant greater performance was revealed for students in the cooled environment than in the other classrooms. Results from Wargocki and Wyon's study (2007) indicated that changes in thermal sensations from too warm to neutral led to a significant improvement in the students' performance in numerical and language-based tasks. The improvement was in terms of speed with no effect on errors. Witterseh et al. (2002) reported a decrease in subjects' self-assessed performance and an increased difficulty in thinking and concentrating by moving from 22°C to 26°C and 30°C. Similar results were reported by Pepler and Warner (1968) and Wyon et al. (1979), showing a decrease in the students' speed of work in a warm to hot environment in educational buildings.

Overall, temperatures both lower and higher than the comfort zone were shown to reduce students' performance and their ability to grasp instructions. A cold temperature reduced manual dexterity and speed while a warm environment affected the students' productivity. The more complex the task, the more likely the performance would be worsened in hot environments (Enander and Hygge 1990).

However, given the large energy consumption of HVAC services in an environment (U.S. Energy Information Administration 2009; The European Parliament 2010a; Xiong et al. 2015), an incorrect prediction of the occupants' thermal comfort in a classroom can be at the cost of environmental impact from excessive energy consumption and concomitant greenhouse gas emissions. Therefore, care is needed to avoid it.

The rapidly growing worldwide use of energy raises concerns over supply difficulties, exhaustion of energy resources and heavy environmental impacts (Pérez-Lombard, Ortiz and Pout 2008). During the last two decades, worldwide energy use has grown by 49% with an average annual increase of 2%. It is also predicted to grow by 67% in the non-domestic sector in the next 20 years (Pérez-Lombard et al. 2008).

European educational buildings are responsible for a considerable part of the energy used for heating purposes. Typical annual energy use for heating in some European educational buildings is presented in Table 2-1. In the UK, 157 kWh/m2 mean annual energy consumption is reported for educational buildings, 58% of which is used for space heating (Carbon Trust 2010). Thus, regulations and strategies have been developed to mitigate energy use and related emissions in some countries such as Denmark (Danish Energy Agency 2016), Finland, the Netherlands, Italy and Portugal (d'Ambrosio Alfano et al. 2010), Belgium, Slovakia and Austria (EPBD 2013) and the UK (Anon 2010c). Furthermore, several studies have been conducted around the world to determine a thermally acceptable and energy efficient criteria for learning environments: primary schools in the UK (Teli 2013; Teli, James and Jentsch 2013; Montazami, Gaterell, et al. 2017; Teli et al. 2017), Italy (De Giuli, Da Pos and De Carli 2012), the Netherlands (Zeiler and Boxem 2009; Mors et al. 2011) and Taiwan (Liang, Lin and Hwang 2012); secondary schools in Italy (Corgnati, Ansaldi and Filippi 2009; Ambrosio Alfano, Ianniello and Palella 2013), Portugal (Dias Pereira et al. 2014) and Cyprus (Katafygiotou and Serghides 2014); and university buildings in Italy (Nico, Liuzzi and Stefanizzi 2015; Ricciardi and Buratti 2018), the Netherlands (Mishra et al. 2017), Japan (Mustapa et al. 2016; Zaki et al. 2017), Brazil (Cândido, de Dear and Lamberts 2011) and India (Mishra and Ramgopal, 2015a; Singh et al. 2018).

Table 2-1. Typical annual energy consumption in educational buildings in some European countries

Authors	Country	Annual energy consumption (kWh/m^2)
(Butala and Novak 1999)	Ireland	96
(Desideri and Proietti, 2002; Corgnati, Corrado and Filippi 2008)	Italy	100
(Hernandez, Burke and Lewis 2008)	Slovenia	192
(Santamouris et al. 1994)	Greece	67
(Dragicevic et al. 2013)	Serbia	234.5
(Carbon Trust 2010)	UK	157

2.3.1. UK educational buildings

Educational buildings account for almost 15% of the UK's public sector emissions (DCSF 2010). Considering the commitment to reduce greenhouse gas releases by 80% by 2050 compared to 1990 (Agreement 2015), the UK government Department for Children, Schools and Families (Anon 2010c) introduced some energy saving strategies to minimise energy use and running costs in educational buildings in this country.

Higher learning environments in the UK have demonstrated a strong commitment to global efforts to combat climate change by reducing greenhouse gases emissions over the last decade. The mean annual energy consumption in this sector is reported to be 5.2 billion kWh (Climate Change: The UK Programme 2006), which shows the ability and resources to make significant contributions to the global climate change effort (Paul and Patton 2018). Energy demand in higher educational buildings in the UK is expected to even grow further in subsequent years due to the following reasons:

- Increase in the research activities in terms of volume and complexity that leads to a higher energy demand for intensive equipment (*HEFCE* 2011).
- A significant increase in enrolments in subjects allied to medicine, biological sciences and computer science, etc. (UK Universities 2013), resulting in an increased demand for laboratory equipment often associated with higher energy and water demands (Altan 2010).
- A 50% increase in the enrolment of postgraduate students between 1997 and 2006, representing above 20% of the student population (UK Universities 2013), meaning an increased intensity and longer periods of use for facilities and buildings (Altan 2010).
- Diversification of academic activities with an increased use of IT and sophisticated equipment in buildings (*HEFCE* 2011).

High energy use in the UK combined with the dramatic expansion of higher education in scale and scope puts more pressure on this sector to formally develop and implement policies and practices to minimise energy consumption (Ward, Ogbonna and Altan 2008). Therefore, targeting such spaces for energy saving and emission drops in the UK is recommended (Climate Change: The UK Programme

2006; Hawkins et al. 2012; Paul and Patton 2018). This requirement is in place in all regions of the UK including England, Scotland, Wales and Northern Ireland through their respective funding councils and devolved governmental departments (Paul and Patton 2018).

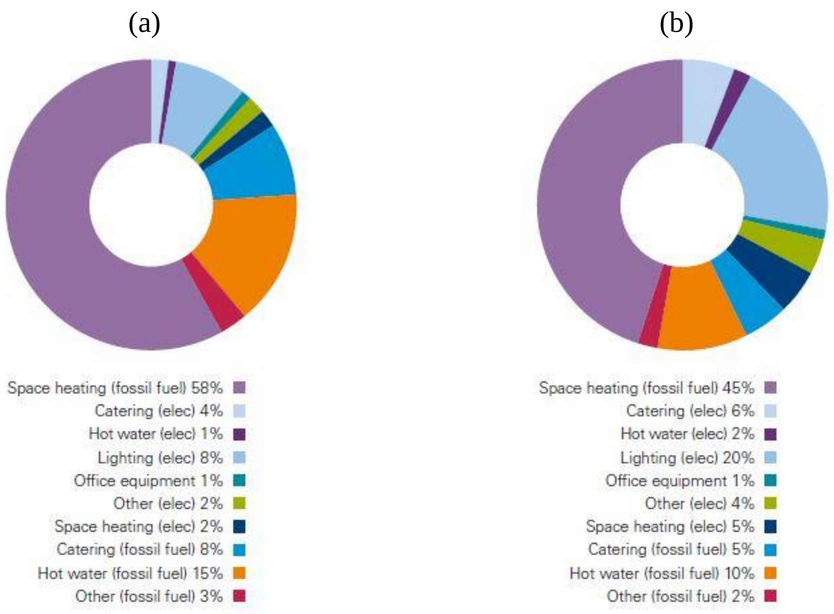


Figure 2-1. Percentage of energy use (a) and energy cost (b) in UK educational buildings (graph copied from Carbon Trust 2010)

As shown in Figure 2-1, space heating accounts for the largest and the most expensive energy consumption in the education sector (Carbon Trust 2010). This suggests more investigations on the potential energy savings through the thermal environment of such buildings. Nevertheless, given the significant influence of thermal comfort on students' productivity in academic environments (section 2.3), occupants' thermal comfort should be considered when acting to improve energy efficiency or to reduce the carbon footprint in higher learning environments. Considering the large energy consumption for space heating/cooling in an environment (U.S. Energy Information Administration 2009; The European Parliament 2010b; Xiong et al. 2015), inaccurate predictions of thermal comfort can lead to overheated or overcooled environments, at the same time as energy waste and harmful emissions.

Thus, a clear understanding of the occupants' thermal requirements, the pattern of their adaptive behaviour and their response to the context is essential to successfully identify a comfortable and energy efficient environmental design strategy for UK university buildings (Shahzad et al. 2019).

2.3.2. Diverse thermal perceptions in UK higher learning environments

The subjective nature of thermal comfort and differences between individuals in terms of thermal perceptions in the same indoor climatic condition are well known (de Dear and Brager 1998; McCartney and Nicol 2001, 2002; Nicol, Humphreys and Roaf 2012). Nicol et al. (2012) showed a considerable diversity of thermal sensations (from 'much too warm' to 'much too cold') and neutralities in each given operative temperature under the same environmental conditions. Such diversity is highlighted in higher learning environments, which accommodate a variety of students in terms of climatic background, thermal expectation, age, gender, academic discipline, dress code, etc. These differences, which often result in conflicting thermal comfort for the occupants and energy waste, are explained as follows:

1. University students are less homogeneous in terms of gender and age and thus may have diverse perceptions of thermal comfort (Fanger 1970; Cena, Spotila and Ryan 1988; Karyono 2000; Karjalainen 2007; Choi, Aziz and Loftness 2010; Hwang and Chen 2010). Figure 2-2 shows the percentage of students in each age group in UK university buildings between 2007-08 to 2016-17 (Patterns and Trends in UK Higher Education 2018). Different age groups are shown among both under- and post-graduate students. An upward trend is indicated for the students in the *20 years and under* and *21-24 years* groups in undergraduate and postgraduate students, respectively. Regarding gender differences, Table 2-2 confirms this variation showing the percentage of each gender group and domicile.

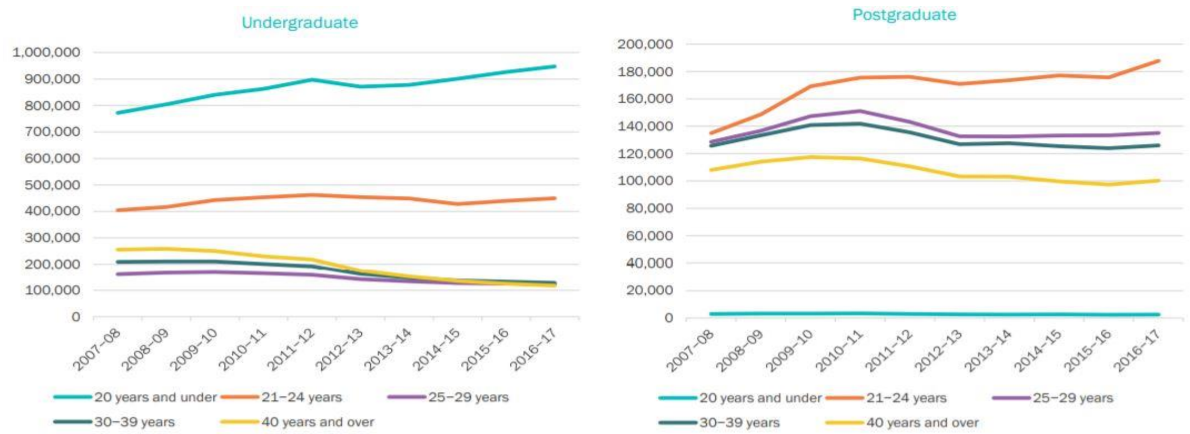


Figure 2-2. The trend of students registrations in each age group (copied from Patterns and Trends in UK Higher Education, 2018)

Table 2-2. Gender of students over 2016-17 in UK higher learning environments (source: Patterns and Trends in UK Higher Education, 2018)

	Female	Male
	% of total students	
UK	58	42
Other EU	55	45
Non-Eu	53	47

2. According to HESA statistics (HESA 2018), every year the UK hosts students from different countries and climates, who thus tend to have different thermal perceptions (Amin et al. 2016; Amin, Teli and James 2018; Brychkov, Garb and Pearlmutter 2018). Table 2-3 indicates a brief summary of this diversity (HESA 2018).

Table 2-3. regional share of the non-UK students, (source: Patterns and Trends in the UK Higher Education, 2018)

	2007-08	2016-17
	% of students	
EU	36.6	35.3
Africa	9.5	6.8
Asia	40.4	43.5
Australia	0.7	0.6
Middle east	4.9	6.6
North America	6.7	6.5
South America	1.2	1.2

3. The students' greater freedom level for either environmental or personal adaptive behaviours in higher learning environments (compared to school buildings, where the ambient environment is usually controlled by the teachers (Brager, Paliaga and de Dear 2004; Teli, Jentsch and James 2012; Liu, Yao and McCloy 2014)), combined with the students' diverse preferences for adaptive behaviours can lead to different levels of thermal adaptations and consequently dissimilar thermal perceptions in the same classroom.

4. Students in university buildings study different subjects and are exposed to different classroom types with various occupancy periods (Patterns and Trends in UK Higher Education 2018). For instance, students in science-based subjects (e.g. engineering or mathematics) may spend two or three hours in lecture rooms or PC labs listening to the lecturer, making notes and working with the computers. However, students in art-based subjects (e.g. architecture or graphic design) are in studio-type classrooms for more than 4 or 5 hours a day, making mock-ups, drawing, or working on computer modelling. Different occupancy periods in various classroom

types can affect students' thermal adaptation to the exposed environment and can lead to different thermal comfort perceptions (Fadeyi 2014; Lin et al. 2015).

Shipworth et al. (2016) and Schweiker et al. (2018) describe this variety of thermal comfort votes as a result of numerous factors affecting individuals' thermal perceptions. These parameters are grouped into contextual factors (building related properties) and human physiological and psychological properties that result from the contribution of skin temperature, core body heat generation and the subject's state of mind. In the following sections, the applicable factors in higher learning environments are reviewed and the key studies on how each physiological and psychological characteristic influences thermal perceptions are discussed.

2.3.2.1. Physiological human characteristics

In this section, the available literature on physiological human characteristics affecting thermal perception are reviewed and the key findings are discussed. Parameters including age, gender, metabolism and physiological adaptation to a thermal environment are investigated in the following sections.

- **Age**

There are contradictory opinions regarding the influence of age-related differences on thermal perceptions. Some studies found age-related differences in perceptions of thermal comfort, whilst another group of studies found similar thermal comfort level in different age groups (Rupp Vásquez and Lamberts 2015; Schweiker et al. 2018; Wang et al. 2018). Table 2-4 summarises the reviewed studies and the main findings. Indraganti et al. (2015) found a 0.7°C higher comfort temperature for younger adults (below 25 years old) than the older group (above 25 years old) in office buildings, within four seasons. Jiao et al. (2017) found a 0.5°C lower neutral temperature in winter and a 0.3°C higher neutral temperature in summer for elderly people (over 70), compared to the PMV model. Likewise, age-related differences were shown in comfort and preferred temperatures and in thermal sensations in residential buildings (Cena, Spotila and Ryan 1988; Hwang and Chen 2010), offices (Karyono 2000;

Choi, Aziz and Loftness 2010) and controlled chambers (Taylor, Allsopp and Parkes 1995; Tsuzuki and Ohfuku 2002; Schellen et al. 2010).

However, no significant age-related differences were shown in thermal sensations (Peng 2010; Thapa 2019), preferences (Natsume et al. 1992; Taylor, Allsopp and Parkes 1995; Tsuzuki and Ohfuku 2002; Hwang and Chen 2010) and neutrality (Becker and Paciuk 2009; Indraganti and Rao 2010; Rupp et al. 2018) in different age groups in the majority of the previous studies, which might be due to the balance between the older adults' core body heat generation and heat lost to the surrounding environment. Older adults' lower core body heat generation and consequently lower skin temperature is followed by less body heat loss to the surrounding environment compared to the younger group. Therefore, the body heat balance among the elderly groups presumably lead to the same thermal comfort votes as younger adults (Young and Lee 1997; Fanger 2006; Schellen et al. 2010).

In summary, due to the opposite results regarding the thermal comfort requirements of the different age groups, more investigation is needed to understand exactly how ageing affects the perception of thermal comfort.

Table 2-4. Summary of studies on age-related differences on thermal comfort

Author, Reference	Country	Season	Building function	Sample size	Age groups	Outcome	Level of age-related differences/similarities		
							Sig.	Poor	Cons.
(Karyono2 000)	Indonesia	Whole year	office	596	under and over 40	Warmer TP for elderly group			✓
(Hwang and Chen 2010)	Taiwan, China	Summer Winter	residential	87	71±6 years old	Narrower $T_{comfort}$ range for older subjects		✓	
(Cena, Spotila and Ryan 1988)	Canada	Winter	residential	101	73 years old	Higher $T_{comfort}$ for elderly group			✓
(Choi, Aziz and Loftness 2010)	USA	Whole year	Office	402	under and over 40 years old	Higher thermal satisfaction for elderly group, in the cooling seasons	✓		✓
(Tsuzuki and Ohfuku 2002)	Japan	Winter	Controlled chamber	209	72.4 and 23.5 years old	Cooler TSV for elderly group Less sensitivity for older adults Similar TP for both groups			✓
(Jiao et al. 2017)	China	Summer Winter	Residential	672	Over 70 years old	Lower $T_{neutral}$ in winter (0.5°C) and higher neutral temperature in summer (0.3°C) for elderly people compared to PMV for younger adults			✓
(Thapa 2019)	India	Whole year	College, office, residential	405	12-65 years old	Higher comfort temperature for the younger than the older group			✓
(Indraganti, Ooka and Rijal 2015)	India	Winter	Office	6046	Over and under 25 years old	0.7°C higher $T_{comfort}$ for younger subjects than the older group			✓
(Peng 2010)	China	Summer Winter	Residential	600	-	Similar TSV of different age groups		✓	
(Natsume et al. 1992)	Japan	Summer Winter	Controlled chamber	12	21-30 and 71-76 years old	Decreased TSV by aging, Less sensitivity to cold for the elderly group in summer			✓
(Taylor, Allsopp and Parkes 1995)	Australia	Summer Winter	Controlled chamber	-	22.9 and 66.9 years old	Lower skin temperature for older adults Cooler TSV for older adults in cold-induced change point, but similar TSV in heat-induced conditions			
(Becker and Paciuk 2009)	Israel	Summer Winter	Residential	394	20 and over 75 years old	Similar thermal comfort for the age groups			✓
(Indraganti and Rao 2010)	India	Summer	Residential	100	Under 20 to above 60	Different thermal comfort requirements for the age groups	✓	✓	
(Rupp et al. 2018)	Brazil	Whole year	Office	7564	Under and above 50 years old	Different thermal comfort range for older and younger groups		✓	
(Schellen et al. 2010)	The Netherlands	-	Controlled chamber	16	22-25 and 67-73 years old	Lower TSV and higher TP for older adults			✓

Sig. statistically significant, $T_{comfort}$: Comfort temperature, TSV: thermal sensation (vote), $T_{neutral}$: Neutral temperature, TP: Thermal preference, T: Temperature, Cons.: Considerable difference/similarity, Poor: poor difference/similarity

- **Gender**

Similar to the influence of age on thermal comfort, there are conflicting results regarding the thermal comfort of each gender in the existing literature. As summarised in Table 2-5, the first set of investigations indicated lower thermal sensation (Cena, Spotila and Ryan 1988; EPBD 2013), lower thermal acceptability/satisfaction (Cena and de Dear 2001; Fato, Martellotta and Chiancarella 2004; Karjalainen 2007; Choi, Aziz and Loftness 2010), warmer thermal preference (Nakano, Tanabe and Kimura 2002; Karjalainen 2007, 2012; Lan et al. 2008), and higher comfort temperature/neutrality (Cena and de Dear 2001; Nakano, Tanabe and Kimura 2002; Lan et al. 2008; Indraganti and Rao 2010; Karjalainen 2012; Lu et al. 2018) for women than men. In contrast, other studies showed no difference in the genders' thermal comfort (Karyono 2000; Becker and Paciuk 2009; Peng 2010).

Lower skin temperature, quicker awareness of thermal discomfort and a wider range between upper and lower skin temperature for women compared to men presumably provide the reasons for higher thermal preferences among females than males (Natsume et al. 1992; Indraganti, Ooka and Rijal 2015).

Table 2-5. Summary of studies on gender-related differences on thermal comfort

Author, Reference	Country	Season	Building function	Sample size	Outcome	Level of gender-related differences/similarities		
						Sig.	Poor	Cons.
(Katafygiotou and Serghides 2014)	Cyprus	Summer, Winter	Secondary school	60 males, 40 females	Different thermal comfort perceptions			✓
(Karyono 2000)	Jakarta, Indonesia	Whole year	office	345 men, 227 women	Different $T_{neutral}$, TP and $T_{comfort}$		✓	
(Choi, Aziz and Loftness 2010)	USA	Whole year	Office	190 male, 212 female)	Less satisfaction and more sensitivity for women than men in cooling months Similar sensitivity for males and females in heating & swing seasons			✓
(Becker and Paciuk 2009)	Israel	Summer, Winter	Residential	229, 106 men	Similar thermal comfort of males and females			✓
(Indraganti and Rao 2010)	India	Summer	Residential	100	Higher thermal sensation and warmer preferences for women than men	✓	✓	
(Cena and de Dear 2001)	Australia	Winter	Office	641 males, 585 females	Cooler TSV for females	✓	✓	
(Karjalainen 2007)	Finland	Summer, Winter	Residential, office, university	2018 males, 2086 females	Higher sensitivity for women than men Higher TP for women			✓
						✓		✓
(Fato, Martellotta and Chiancarella 2004)	Italy	Summer, Winter	Office, library, classroom	1165 males, 675 females	Higher $T_{neutral}$ for females than males, strictly depending on the clothing insulation values			✓
(Nakano, Tanabe and Kimura 2002)	Japan	Whole year	Office	222 males, 184 females	3°C higher $T_{comfort}$ for women than men	✓		✓
(Lan et al. 2008)	China		Controlled chamber	19 males, 19 females	Higher $T_{comfort}$ and TP for women than men & higher sensitivity for women than men			✓
(Lu et al. 2018)	China		Residential	991 males, 953 females	0.5ºC higher $T_{neutral}$ for women than men			✓
(Wang 2006)	China	Winter	Residential	59 males, 61 females	Higher $T_{neutral}$ for women than men (1°C)			✓
(Maykot, Rupp and Ghisi 2018)	Brazil	Winter	Office	30	Higher thermal preference and cooler TSV for women than men			✓
(Lan et al. 2008)	China		Controlled chamber	19 males 19 females	Higher $T_{comfort}$ and TP for women Higher TSV for women than men			✓
(Wang 2006)	China	Winter	Residential	59 males, 61 females	1°C higher Tneutral for women than men			✓
(Maykot, Rupp and Ghisi 2018)	Brazil	Winter	Office	30	Higher thermal preference and lower TSV for women than men			✓

Sig. statistically significant, AC: Air Conditioned, NV: Naturally Ventilated, $T_{comfort}$: Comfort temperature, TSV: thermal sensation (vote), Tneutral: Neutral temperature, T: Temperature, TA: Thermal Acceptability, TP: Thermal preference, TSV: Thermal Sensation Vote, Cons.: Considerable difference/similarity, Poor: poor difference/similarity

- **Metabolism**

Metabolic heat generation is one of the key parameters in maintaining the human body's heat balance with the surrounding environment (Haddad et al. 2014). Metabolism is introduced as a bio-chemical activity to maintain the human body's internal temperature at approximately 37˚C (Goulding, Lewis and Steemers 1992; Havenith, Holmér and Parsons 2002). The metabolic rate corresponds to the heat generation of the human body, a variation of which plays an important role in individuals' skin temperatures and, as a results, thermal sensations (Vaughn Bradshaw 2006). It works based on body physiological conditions such as activity levels, age, gender and body surface area (Vaughn Bradshaw 2006).

According to Havenith et al. (2002), investigations on metabolism can be categorised into two groups: 1) direct measurement of the human basal metabolic rate, which is assumed to be on average, 58.15 W/m^2 for adults, 2) measurement of the changes of body heat generation and metabolic rate as a result of personal activities or exposure to physiological/environmental factors. A summary of the studies in both groups is presented in Table 2-6. To evaluate basal metabolic rate, the relation between age and gender and human core body heat generation has been the basis of investigations over the past two decades (Fanger 1970; Tsuzuki and Ohfuku 2002; Ji and Dai 2005; Novieto and Zhang 2010; Choi, Loftness and Lee 2012; Schaudienst and Vogdt 2017; Luo et al. 2018; Salata et al. 2018). Age and gender are both shown as influential factors on the metabolic rate in previous studies; aging causes a lowering metabolism and lessening core body heat generation in both actual thermal environments and climate chambers (Goulding, Lewis and Steemers 1992, 1992; Tsuzuki and Ohfuku 2002; Ji and Dai 2005; Vaughn Bradshaw 2006; Schaudienst and Vogdt 2017; Salata et al. 2018). It has been shown that body heat generation (metabolism) increases to its peak by 10 years of age and then drops again as the body ages (Vaughn Bradshaw 2006). In terms of gender, a lower basal metabolic rate, less core body heat generation and consequently, a lower skin temperature for females has been concluded in previous investigations (Goulding, Lewis and Steemers 1992; Schaudienst and Vogdt 2017; Salata et al. 2018). Therefore, people of different age groups and genders tend to have different metabolic heat generations, skin temperatures and consequently, various thermal sensations when exposed to the same environment.

Regarding the second group of investigations on metabolism, there is a positive correlation between changes in activity levels and corresponding metabolic rate has been indicated, which shows a growth of the metabolic rate as a result of increased physical activities (Goto et al. 2000; Olesen 2000; Haddad et al. 2014; Wang and Hu 2016; Abu Bakar et al. 2017; Ji et al. 2018; Marn, Chung and Iljaž 2019; Zhai et al. 2019). Abu Bakar et al. (2017) studied individuals' skin temperatures during three sets of office activities to figure out their impact on thermal sensation in a controlled chamber. They confirmed a strong positive linear relationship between activity levels, metabolic rate, skin temperature and as a result, thermal sensation vote. Likewise, Wang et al (2016) found a growth in the metabolic and sweat rate following increased activity levels, which ultimately affected the thermal sensation votes. Thermal preference was also affected by metabolic rate. The influence of dynamic metabolic rate on preferred temperature was confirmed by Mihara et al. (2019) and Gao et al. (2018), showing a decrease in thermal preference votes as a result of a decreased metabolic rate and vice versa. More detailed studies showed that shifting activity from seated to standing can increase the metabolic rate by 0.1 met (Gao et al. 2018) or 0.3 met (Olesen 2000), which leads to a preferred temperature drop of approximately 1ºC (Gao et al. 2018) or 2.4ºC (Olesen 2000), respectively.

The time required for a metabolic rate to settle after physical activities varies based on the activity levels. Ji et al. (2018) investigated the variation of the human metabolic rate under different exercise periods and the time taken for recovery. Results indicated that it takes 5–6 minutes for a human body to reach a new exercising metabolic level, while 7–9 minutes is needed to recover from exercise to a normal sedentary state (Ji et al. 2018). Time needed for a settled metabolic rate after a physical activity is reported to be from 7-9 minutes (Ji et al. 2018) to 15-20 minutes (Goto et al. 2000; Teli, Jentsch and James 2012). However, to get to a safe margin, 30 minutes is recommended as sufficient in some investigations in the field of thermal comfort (Teli, Jentsch and James 2012; Haddad et al. 2014; Montazami, M. Gaterell, et al. 2017).

The second group of studies on metabolism have come to the common conclusion that a dynamic metabolic rate can affect a subject's thermal sensations (Wang and Hu 2016; Abu Bakar et al. 2017; Ji et al. 2018; Zhai et al. 2019), preferences (Gao et al. 2018; Mihara et al. 2019) and thermal acceptability (Zhai et al. 2019).

Table 2-6. Summary of studies on the influence of metabolism on thermal comfort

Author, Reference	Region	Season	Building function	Sample size	Outcome
(Tsuzuki and Ohfuku 2002)	Japan	Winter	Controlled chamber	209	**Age-related** differences in metabolic rate (lower for older adults, 70% of the younger group)
(Novieto and Zhang 2010)	(Simulation-based)	-	-	-	**Age-related** differences in metabolic rate (lower for older adults) & overcooling of the older adult's body in exposure to cold, which cannot be rectified by putting on warm clothes.
(Havenith 2007)	The Netherlands	Winter	School	81	**Age-related** difference in metabolic rate (higher for children during seated activities compared to seated office work activities, based on ISO Standards)
(Ji and Dai 2005)	China	Whole year	Office	1814	**Age-related** difference in metabolic rate (Lower metabolic rate and cooler thermal sensation for elderly subjects)
(Schaudienst and Vogdt 2017)	Data from Germany	-			**Gender & age-related** differences in metabolic rate (lower for older group and women) & higher thermal preferences for elderly people and women
(Uğursal and Culp 2013)	USA	Winter	Controlled chamber	40 (21 males and 19 females)	**Gender-related** differences in metabolic rate during an activity (faster rise in women's metabolic rate)
(Haddad et al. 2014)	Iran	Summer Winter	School	1600	**Age-related** differences in metabolic rate (Higher actual metabolic rate for children in educational buildings compared to PMV)
(Wang and Hu 2016)	China	-	Controlled chamber	16	**Increased activity, increased metabolic rate** (Over estimate of PMV model for adults' two types of activities: treading in situ and up-and-down a step)
(Goto et al. 2000)	Denmark	-	Controlled chamber	24	**Warmer perceptions & Cooler TP with increased metabolic rate** (Even low activity variations affect thermal perceptions and preferences & 15 minutes of constant activity as time required for a settled metabolism)
(Abu Bakar et al. 2017)	Malaysia	-	Controlled chamber	15	**Increased activity, increased metabolic rate & Warmer TSVs** (A strong linear relationship between activity levels and metabolic rate with skin temperature & a greater increase of thermal sensation at a metabolic rate of 1.6 met)
(Zhai et al. 2019)	China	Winter, spring, autumn	Controlled chamber	59	**Increased activity, increased metabolic rate** (higher activity, more time required for a settled metabolic rate & longer time for 1 unit change of thermal sensation votes than time for a settled metabolic rate)
(Ji et al. 2018)	China	Spring	Controlled chamber	31	**Different time for increasing and decreasing (to normal) metabolic rate** (5-6 minutes for human body to reach a new exercise metabolic rate, but 7-9 minutes to reach the normal sedentary state metabolic rate) & **Increased metabolic rate, increased TSV & Thermal Perception** (higher metabolic rate, warmer TSV & warmer perception)
(Mihara et al. 2019)	Singapore	Winter	Controlled chamber	26	**Change of metabolic rate (in transient thermal conditions), Immediate change of TSV, TA and Thermal Perceptions** (Warmer TP due to decreased metabolic rate)
(Gao et al. 2018)	China	Winter	Controlled chamber	20	**Reverse relation between metabolic rate and TP** (Under estimation of PMV model for adults with high metabolic rate)
(Yang, Yin and Fu 2016)	China	-	University	2129	**Significant effect of air T on fluctuation of metabolic rate** (relative humidity and air velocity as the next influential environmental factors)

TSV: thermal sensation (vote), TA: Thermal Acceptability, TP: Thermal preference, $T_{comfort}$: Comfort temperature, $T_{neutral}$: Neutral temperature, T: Temperature

In summary, the literature search on metabolism (Table 2-6) reveals that basal metabolic rate tends to differ between genders and age groups. Regarding the dynamic metabolic rate, it is revealed that the human body's metabolic rate and core body heat generation goes up following a physical activity, which consequently leads to warmer thermal sensations and cooler thermal preferences. Therefore, in multidisciplinary environments, such as higher learning environments which accommodate occupants from different genders and age groups with various activity levels (based on the teaching style and subject studied), diverse thermal perceptions are to be expected.

- **Physiological adaptation to a thermal environment**

The word 'adaptation' can be defined as "changes that reduce the physiological strain produced by stressful components of the total environment" (IUPS Thermal Commission 2001). The human body physiologically adapts to a broad range of thermal conditions through direct interaction with the surrounding environments, called "thermoregulation" (Humphreys, Nicol and Roaf 2015). These physiological adjustments maintain human body core temperature at around 37ºC to provide subjective health and well-being (Humphreys, Nicol and Roaf 2015); and to provide an individual's comfort against environmental fluctuations (e.g. over different seasons, over the course of a day and night, etc.) (Schweiker et al. 2018). As an example, repeated exposure to a cold or warm thermal environment can increase or decrease core body heat generation, and make a subject cold or heat adapted, respectively. Such adaptation changes the subject's perception of a thermal environment accordingly (Schweiker et al. 2018).

Overall, previous studies show subjective thermal perceptions to be a result of thermal adaptation to a climatic condition (Karyono 2008; Daghigh, Adam and Sahari 2009; Mishra and Ramgopal 2014a, 2014b), exposure to air-conditioned indoor environments (Yang and Zhang 2008; Daghigh, Adam and Sahari 2009; Cândido et al. 2010) and adaptation to seasonal weather changes (de Dear and Fountain 1994; Nicol et al. 1999; Feriadi and Wong 2004; Rijal, Yoshida and Umemiya 2010; Baizhan et al. 2011). A literature review carried out by Rupp et al. (2015) confirms university students' adjusted thermal perceptions to exposed climates in China (Yao, Liu and Li 2010; Zhang et al. 2010; Z. Wang et al. 2014), India (Mishra and Ramgopal 2014a, 2014b), Indonesia (Karyono 2008), Malaysia (Zaki et al. 2017) and Brazil (Cândido et al. 2010a and 2010b). A summary of the reviewed studies is presented in Table 2-7. Thermal adaptation to an air-conditioned environment has been confirmed in studies performed in the hot and humid climate of Brazil, showing that frequent exposure to air-conditioned environments leads to less acceptability of the dynamic conditions of naturally-ventilated environments and less adaptation to the local climate (Rupp et al. 2018). Also, it was shown that people who had adapted to air-conditioned spaces preferred this type of thermal environment, while occupants in free-running buildings did not normally prefer air conditioning (Cândido et al. 2010). Seasonal thermal adaptation has been shown in a study conducted by Wang et al. (2014), showing the subjects' higher neutral temperatures in spring than in winter months, as a result of adaptation to the prevailing weather conditions.

In the UK, climatic conditions differ from region to region. Regarding the climatic differences between Scotland (northern area) and England (southern/midland areas), the weather in Scotland is cold, damp, rainy, and windy for most of the year; whereas, in England, the climate is normally temperate with cold, cloudy and sometimes windy winters. During the winter months, the mean daily temperature drops to 4–5°C and to around 3–6°C in Scotland and England, respectively; which does not differ much from each other. However, during summer, the air temperature goes up to around 14–19°C in Scotland and to 19 to 23°C (or even 28–32°C in southern parts) in England (World Climate Guide 2019).

In summary, the human body can adjust itself to a broad range of thermal environments, from seasonal weather variations to changes of indoor air temperature in a space. Therefore, thermal perceptions tend to vary for people exposed to various local climates, meaning that the same environmental criteria cannot be applicable worldwide for all climatic conditions. This is broadly confirmed in research in the field of thermal comfort.

Table 2-7. Summary of studies on physiological adaptation to a thermal environment

Author, Reference	Region	Season	Building function	Sample size	Outcome
Zaki et al. (2017)	Malaysia and Japan	Summer	University	1428	**Thermal adaptation to the local climate** (Warmer TP in Malaysia than Japan & subjects acclimatized to the exposed climates)
Karyono (2008)	Indonesia	–	University/ controlled chamber	20	**Thermal adaptation to the local climate** (Higher $T_{neutral}$ and higher level of comfort in warmth for subjects acclimatised to warm climates)
Mishra and Ramgopal (2014a)	India	Summer, Winter	University	338	**Adaptation to AC environments** (Repeated exposure to fan operation and high TA levels in exposure to high air velocity)
Mishra and Ramgopal (2014b)	India	Spring	University	338	**Adaptation to AC environments** (Repeated exposure to fan operation and high TA levels in exposure to high air velocity)
C. Cândido et al. *(*2010)	Brazil	Summer, Winter	University	2075	**Adaptation to AC environments** (Repeated exposure to AC environments and higher air velocity preferences – subjects' adaptation to AC)
Zhang et al.*(*2010)	China	Whole year	Residential/ educational	30	**Thermal adaptation to the local climate** (Acclimatization and high comfort level in warm and lower tolerance in cold environments for subjects in hot-humid climate)
Yao, Liu and Li (2010)	China	Spring	University	3621	**Thermal adaptation to the local climate** (Wider $T_{comfort}$ range than the ASHRAE standard in non-extreme climatic condition)
Z. Wang et al. *(*2014)	China	Spring Winter	University	488	**Seasonal thermal adaptation** (Higher $T_{neutral}$ in spring than winter)
Cândido et al.(2010)	Brazil	Summer, Winter	University	975	**Adaptation to AC environments** (Repeated exposure to AC environments, adaptation to AC environments and raised comfort expectation)

AC: Air Conditioned, $T_{comfort}$: Comfort temperature, $T_{neutral}$: Neutral temperature, TA: Thermal Acceptability, TP: Thermal preference

2.3.2.2. Psychological human characteristics

According to the subjective nature of thermal comfort (Anon 2010a), psychological human characteristics are shown to affect an individual's thermal comfort at the same time as physiological parameters. The influencing psychological drivers of diverse thermal comfort in higher learning environments, including thermal history/expectation and perception of control over space, are reviewed and discussed in the following sections.

- **Thermal history and expectation**

Thermal history refers to the previous thermal conditions that were experienced by individuals which exert their influence on current thermal perception by providing a benchmark or experiential calibration frame of reference (Chun et al. 2008; van der Lans et al. 2013; Vargas, Lawrence and Stevenson 2017). Thermal sensation in a space is thought to result from a comparison between the current and previously experienced environmental conditions. This comparison and their thermal experiences form the subjects' expectations in an exposed thermal environment (Ji et al. 2017). According to the existing literature, thermal history can be classified into two groups (Vargas and Stevenson 2014):

- Short-term thermal history; referring to the effects across timescales ranging from weeks, days, hours to seconds in day-to-day thermal exposures.
- Long-term thermal history; referring to the climatic influences of where people have been living for many years.

In terms of short-term thermal history, studies have been conducted in UK higher educational buildings (Vargas and Stevenson 2014; Vargas, Lawrence and Stevenson 2017), in work environments in the hot and humid climate of Brazil (Cândido et al. 2010) and cold seasons in Pennsylvania, USA (Fadeyi 2014) and in controlled chambers under different climatic conditions (Nagano et al. 2005; Chun et al. 2008; Kelly and Parsons 2010; Yu et al. 2013; Ji et al. 2017); with various exposure durations of 30 minutes (Kelly and Parsons 2010), 1 day (Chun et al. 2008) and a 10-day period (van der Lans et al. 2013). Table 2-8 summarises some of these studies and presents the key findings.

Vargas and Stevenson (2014) investigated how short-term thermal experiences influence an individual's thermal sensations in transitional lobby spaces in a higher learning environment in the UK. It was revealed that in non-extreme weather conditions, a 1 or 2 ˚C temperature difference between the pre-exposed and currently-exposed environment could not considerably affect the subjects' in-the-moment thermal perception. Whereas in too hot or too cold pre-exposed conditions, moving people to a new environment with only a 1 or 2˚C temperature difference towards neutral could lead to a significant improvement in their thermal perceptions. It was also illustrated that in extreme thermal conditions, a sudden change in an indoor air temperature of 4˚C or more can completely recover the people's thermal comfort. Chun et al. (2008) carried out an experiment on Korean and Japanese students in a controlled chamber with 50% humidity and at 28˚C, with the same clothing value for all the occupants. The subjects' past 24 hours of thermal exposures were recorded by wearing a data logger. Results showed that the subjects exposed to temperatures above 28˚C in the past 24 h voted for 0.44 cooler thermal sensations compared to their counterparts exposed to temperatures lower than 28˚C. Nagano et al. (2005) studied the perception of step temperature changes in a controlled chamber. It was indicated that 50 minutes pre-exposure to temperatures warmer than the chamber led to a decrease in the subjects' mean skin temperatures upon commencement of exposure to the chamber. However, after 20 minutes of staying in the chamber, their mean skin temperatures and thermal sensation votes increased as a result of thermal adaption and equilibration with the current environment (Nagano et al. 2005). This finding was supported by other studies in controlled conditions with different exposure durations from 30 minutes (Kelly and Parsons 2010) to 1 day (Chun et al. 2008). All these studies lead to a common conclusion that pre-exposure to a cold thermal condition improves comfort votes in the cold and reduces shivering, while pre-exposure to a warmer thermal condition than the current environment leads to an evaluation of a cool environment as colder than it would otherwise have been in the absence of the warm pre-conditioning.

Regarding long-term thermal history, it is evident in the previous studies that long-term pre-exposure to both indoor (Kalmár 2016; Luo et al. 2016; Ning et al. 2016; Vecchi, Cândido and Lamberts 2016; Zhang et al. 2016) and outdoor climatic conditions (Amin et al. 2016; Ning et al. 2016; Amin, Teli and James 2018) affect the subject's in-the-moment thermal comfort perceptions.

Zhang et al. (2016) conducted an experiment in a controlled chamber in a hot and humid area of China with indoor temperatures from 20°C to 32°C. The subjects were 60 adults from air conditioned (AC) and naturally ventilated (NV) buildings who were born and raised in the same climate with natural acclimatisation to such weather. Results indicated that subjects exposed to AC environments with a cooler indoor thermal history had warmer thermal sensations than the other subjects coming from NV buildings. Similar results were revealed in studies conducted in a university building in the subtropical climate of southern Brazil (Vecchi, Cândido and Lamberts 2016) and in climate chambers in Hungary (during the summer months with an indoor temperature of 30°C) (Kalmár 2016) and China (in an extremely cold climate under heating mode) (Ning et al. 2016). Luo. et al. (2016) conducted a study in northern China (with ubiquitous district heating) and in southern regions of China (without district heating) during the winter to establish the influence of indoor thermal history on the occupants' comfort perceptions and expectations. Similar thermal acceptability levels were indicated for both groups although they had different thermal sensations. It was suggested that long-term exposure to a comfortable thermal environment lifts the occupants' thermal expectations, whereas experience of non-neutral thermal environments stimulates thermal adaptation. Collectively, these studies confirm that pre-exposure to an indoor thermal environment affects an individual's in-the-moment thermal comfort perceptions in an exposed thermal condition (Kalmár 2016; Luo et al. 2016; Ning et al. 2016; Vecchi, Cândido and Lamberts 2016; Zhang et al. 2016).

The relation between climatic background and a subject's thermal comfort rating was examined in a hall of residence in the UK (Amin et al. 2016; Amin, Teli and James 2018) and outdoor spaces in Israel (Brychkov, Garb and Pearlmutter 2018). Participants were people from different climatic backgrounds. Results showed higher temperature preferences and cooler thermal sensations for the residents who had been living in a warmer climate for two years before moving to the UK (Amin et al. 2016). Indoor air comfort temperature was also shown to be higher for subjects from warmer climatic backgrounds compared to the UK native residents (Amin, Teli and James 2018), showing their thermal adaptation to warmth. Likewise, warmer indoor air temperatures were reported for residents from cooler climates which can be due to their thermal adaptation to high levels of central space heating (Amin, Teli and James 2018). This finding was supported by Brychkov et al. (2018), showing how people's different "climato-cultural" backgrounds may lead to different thermal perceptions. It was concluded that in stressful but not extreme thermal conditions, warmer climatic background groups have cooler thermal sensations in winter and higher levels of comfort in summer compared to their counterparts coming from cooler climates.

The reviewed studies have so far confirmed that long-term thermal history affects in-the-moment thermal comfort perceptions. In the first group of investigations, the impact of pre-exposure to indoor thermal environments on thermal comfort perceptions was indicated. However, a negligible relation between pre-exposure to outdoor climates and current thermal expectation was shown (Kalmár 2016; Luo et al. 2016; Ning et al. 2016; Vecchi, Cândido and Lamberts 2016; Zhang et al. 2016). According to Brychkov et al. (2018), in extreme thermal exposures, the role of climatic backgrounds on current thermal perceptions tends to be diminished and consequently, similar thermal comfort votes can be observed for subjects from cooler and warmer climatic backgrounds. But these conclusions cannot be generalised to non-extreme climatic conditions. Furthermore, the research carried out in the temperate climate of the UK (Amin et al. 2016; Amin, Teli and James 2018) was based on online post-occupancy evaluations that considered only two years pre-exposure of the subjects to a climatic condition (Amin et al. 2016; Amin, Teli and James 2018). None of the studies in this literature review demonstrated clear impacts of thermal history and expectations on thermal comfort in buildings shared by multiple occupants who have grown up in diverse climatic conditions.

Table 2-8. Summary of studies on the influence of thermal history on thermal comfort

Author, Reference	Region	Season	Building function	Sample size	Outcome
(Vargas and Stevenson 2014)	UK	Summer	University	610	**Thermal memory/history affects thermal comfort perception** (Temperature differences from one space to another, temperature sequences and direction affect thermal memory and then expectations)
(Zhang et al. 2016)	China	Summer and winter	Controlled chamber	60	Indoor thermal experiences affect in-the-moment thermal comfort (Indoor thermal exposure is more influential on thermal sensation than climatic exposures).
(Vecchi, Cândido and Lamberts 2016)	Brazil	Summer and autumn	University	2292	**Thermal history in AC buildings affects TA and cooling TP** (Temperature fluctuations in AC environments affects in-the-moment thermal comfort - in warm and humid climates.)
(Kalmár 2016)	Hungry	Summer	Controlled chamber	40	**Thermal exposures to AC buildings affect TSV and TP** (Subjects accustomed to AC buildings had cooler TP and their TSV decreased in the highest rate during the 2 h of measurements)
(Ning et al. 2016)	China	Autumn	Dormitory	30	**High sensitivity to temperature reductions and warmer TA after exposure to heated environments** (Thermal adaptation to warmth in heated environments led to lower TA in cold)
(Luo et al. 2016)	China	Winter	University	960	**Thermal adaptation, a result of long exposure time** (Long-term comfortable thermal experiences lift the occupants' thermal expectations, while a non-neutral thermal environment stimulates thermal adaptation)
(Chun et al. 2008)	Korea and Japan	Summer	Controlled chamber	52	**Pre-exposure to AC environments led to warmer in-the-moment thermal sensations** (There is a strong interaction between the experienced outdoor and indoor thermal conditions and subjects' thermal comfort & Subjects higher TSV after exposure to AC environments)
(Ji et al. 2017)	China	Spring	Controlled chamber	64	**Subjective thermal evaluation depends on the past and present environments** (People's thermal comfort and discomfort resulted from the contrast between the current and previous thermal environments)
(Cândido et al. 2010)	Brazil	-	University	975	**Short-term pre-exposure to AC environment affects TP, expectations and TA in NV buildings** (Prior exposure of subjects to AC environments does not affect their TSV, but affects thermal expectations, TP and tolerance of NV environments.
(Fadeyi 2014)	USA	Winter	Office	28	**Subjects' TSV is affected by the past thermal exposures at the initial occupancy period** (At the initial occupancy period, TSV is affected by past thermal experiences; after extended occupancy period TSV depends on the exposed environment)
(Nagano et al. 2005)	Japan	Summer	Controlled chamber	30	**Downward overshoot of TSV and skin temperature, result of step temperature reduction** (After dropped TSV and mean skin temperature due to the temperature reduction, TSV rises again after an extended period of occupancy)
(Pastore and Andersen 2018)	Switzerland	Spring and summer	Office	190	**Subjects evaluate thermal environment based on their backgrounds** (Residency period, climatic and cultural background affect thermal environment evaluations)
(Brychkov, Garb and Pearlmutter 2018)	Israel	Summer, winter	University	105, interviewees 2055, questionnaire	**Climatic background affects in-the-moment thermal perception** (Under non-extreme thermal conditions, climatic background affects subjective thermal perceptions)
(Amin et al. 2016)	UK	Summer and winter	Residential (university students)	223	**Warmer TP for warmer background subjects** (Almost 2.3°C higher indoor temperature was shown for subjects from warmer than cooler backgrounds)
(Amin, Teli and James 2018)	UK	Winter and spring	Residential (university students)	47	**Cooler TP for warmer background subjects** (Resulted from adaptations to the heated environments)

AC: Air Conditioned, NV: Naturally Ventilated, TSV: thermal sensation (vote), TA: Thermal Acceptability, TP: Thermal preference, T: Temperature

- **Perceived control over a space**

The significant relation between the individuals' perceived control, thermal comfort, energy consumption and related emissions has been discussed in the existing literature. According to Paciuk (1990),there are three aspects of control over a space: available control, perceived control, and exercised control. *Available control* and *perceived control*, but not yet exercised, are the psychological aspects which affect the subjects' psychological thermal adaptation to an environment. However, *exercised control* is considered as the environmental aspect through which the occupants can modify the impact of the outdoor climate on indoor thermal conditions (Schweiker et al. 2018).

As mentioned before, occupants in a thermally uncomfortable condition tend to react to the discomfort sources in order to restore their thermal comfort either unconsciously (sweating, shivering etc.) or consciously (physical adaptive behaviours) (Nicol, Humphreys and Roaf 2012). Conscious adaptation may be through environmental behaviours (e.g. window operation, using a HVAC system), personal (e.g. clothing adjustment, changing position, having a hot/cold drink) or a combination of personal and environmental adjustments (Nicol, Humphreys and Roaf 2012).

Apart from the physiological influence of control (exercised control (Paciuk 1990)) on thermal comfort, perceived control over a space can psychologically affect the occupants' thermal neutrality and acceptability (Bauman et al. 1998; Brager, Paliaga and de Dear 2004; Yao, Liu and Li 2010; Schweiker and Wagner 2016). The human body may not be sufficiently able to physiologically and behaviourally adapt to an environment (due to the limited availability of control options) to compensate for physical discomfort. In this case, psychological adaption plays an important role in reducing thermal dissatisfaction.

People's control over a space may cause frequent changes in the thermal environment and lead to setting a new psychological benchmark in the occupants' minds that is more forgiving and as a result, helps the subjects to feel more comfortable within the space (Yao, Liu and Li 2010). A study by Bauman et al. (1998) found the considerably satisfying effect of personal control compared to a centrally controlled system in an office building. It was also confirmed in this study that users with personal control may undertake environmental behaviour only once a day, while occupants in the centrally controlled environments made a number of adaptive actions (Bauman et al. 1998). A comparison between

Shahzad et al. (2016) confirmed that higher levels of environmental control not only improved thermal comfort, but also provided a healthier thermal environment for the occupants. This study also suggested keeping a balance between the available thermal environmental control and the energy efficiency of buildings (Shahzad et al. 2016). Such findings suggest the satisfactory role of individual control (rather than central control) on subjects' thermal perceptions and show the lower sensitivity of occupants in an environment with a perception of control compared to their counterparts in centrally controlled spaces. In a comparison between two office buildings, one with personal control and one with limited control options, Shahzad et al. (2017b) presented a 35% higher user satisfaction and a 20% higher user comfort in office buildings with higher levels of control. Table 2-9 summarises the key findings from the studies on the psychological role of individual control on thermal perceptions in an environment. All these studies led to the common conclusion that apart from the physiological influence of control over a space, the perception of control also improves the occupants' thermal comfort in an environment. Also, it was shown that the occupants' level of control affected their comfort levels; the more control they had, the more comfortable they felt.

Students in higher educational buildings are exposed to different classroom types based on their subjects of study with variable occupancy periods (Patterns and Trends in UK Higher Education 2018). They are involved in different activities with various teaching styles. For instance, students in science-based subjects (e.g. engineering, mathematics) may spend two or three hours in lecture rooms or PC labs while listening to the lecturer, making some notes, etc. However, students in art-based subjects (e.g. architecture, graphic design) are in studio type classrooms for more than 4 or 5 hours a day making mock-ups, drawing, or modelling. Therefore, from a psychological point of view, students in studio type classrooms (who have higher levels of control over the space) may have different perceptions of thermal comfort compared to their counterparts in the lecture rooms and PC labs.

Table 2-9. Summary of studies on adaptive behaviour and control in thermal comfort

Author, Reference	Region	Season	Building function	Sample size	Outcome
(Raja et al. 2001)	UK	Summer	Office	909	**Subjects control and behaviour depend on TSV** Subjects modify thermal environments based on their TSVs
(Li, Zhang and Zhao 2019)	China	Summer	Office	10	**Higher level of thermal comfort and energy saving with TSV-based control strategies** (13.8% of daily energy consumption can be saved by TSV-based subjects' control rather than set point-control method)
(F. Wang et al. 2014)	China	-	Controlled chamber	25	**Higher level of thermal comfort and energy saving with subjects' perception-based control strategies** (More acceptable performance than centrally controlled strategies)
(Purdon et al. 2013) (simulation-based)	-	-	Office	8	**Higher level of thermal comfort and energy saving with individual-based control strategies** (At least 50% reduction in energy consumption without minimal impact on thermal comfort)
(Shahzad et al. 2017b)	UK, Norway	Summer	Office	164	**Higher levels of satisfaction and comfort with access the control options** (35% higher satisfaction and 20% higher comfort levels with presence of control availability)
(Shahzad et al. 2016)	UK, Norway	Summer	Office	313	**Influence of the occupants' control on sick building symptoms** (The more occupant control availability, the more health and comfort satisfaction)
(Shahzad et al. 2017a)	UK, Norway	Summer	Office	313	**The impact of the architectural design and occupant control comfort and satisfaction** (Higher levels of comfort and well-being as a result of architectural design considerations)
(Zhao et al. 2014)	China	Summer	Controlled chamber	6	**Higher level of thermal comfort with individual-based control strategies** (Higher subjects' thermal satisfaction by using transient and steady adaptive behaviours)
(Wang et al. 2016)	China	Summer, Winter	Controlled chamber	25	**More stable and energy efficient thermal environment with satisfaction-based control** (15.3% and 11.9% less energy consumption than set-point based control, at 2 test-beds)
(Chen, Wang and Srebric 2015)	USA	Winter	Controlled chamber	13	**Higher level of thermal satisfaction and energy saving with users' feedback-based control** (The PMV model tool working based on users' feedback produces better thermal comfort and energy outcomes than a fixed theoretical control method)
(Toftum 2010)	Denmark	Whole year	Office	1272	**Higher levels of thermal comfort with the occupants' perception of control** (The degree of control satisfaction affects occupants' comfort)
(Chen, Wang and Srebric 2016)	USA	Summer	Controlled chamber	24	**Significantly higher thermal comfort and energy saving with users' feedback-based control** (Higher energy saving and occupants' psychological thermal satisfactions with the proposed thermal sensation-based control strategy)
(Jaakkola, Heinonen and Seppänen 1989)	Finland	Spring	Office	333	**Higher level of satisfaction and lower sick building symptom with individuals' perception of control** (Occupants' control of temperature psychologically improves their satisfaction)
(Langevin, Wen and Gurian 2012) (ASHRAE data set)	-	-			**The level of control psychologically affects subject's thermal comfort** (Higher control perception, more comfort perception)
(Bauman et al. 1998)	USA	Spring	Office	42	**Higher levels of comfort with individual-based control** (Occupants perception of control leads to higher satisfaction with the thermal, acoustical and air quality)
(Yao, Liu and Li 2010)	China	Spring	University	3621	**Higher levels of comfort with individual's control** (Physiological and psychological influence of adaptive behaviour on subjects' comfort)
(Brager, Paliaga and de Dear 2004)	USA	Warm and cold seasons	Office	Over 1000	**Higher levels of comfort with individual's control perception** (Close neutral temperature to the exposed temperature for the subjects with personal control in the space)

TSV: thermal sensation (vote), $T_{neutral}$: Neutral temperature

2.4. Recommended comfort criteria in the existing standards

Currently existing environmental guidelines recommend criteria for indoor thermal environments based on predictions of occupants' thermal comfort in different building types. In this section, the existing thermal comfort standards at international and European levels (which can be applied to UK buildings) are briefly reviewed and the recommended comfort criteria for educational buildings are presented.

2.4.1. EN ISO 7730

EN ISO 7730 entitled *Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria* presents methods for predicting the general thermal sensations and thermal dissatisfaction of people exposed to moderate thermal environments. This guideline works based on the static/PMV model of thermal comfort enabling the interpretation of thermal comfort using calculations of PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied).

This standard provides thermal comfort criteria in moderate thermal environments for three levels of acceptability based on 3 levels of the Percentage of People Dissatisfied (PPD): 6%, 10% and 15% for categories A, B and C respectively, corresponding to 94, 90 and 85% of satisfied occupants, respectively. The recommended comfort criteria for classrooms in this guideline is indicated in Table 2-10. The comfortable operative temperature and air velocity is generally recommended for classrooms in this guideline.

2.4.2. EN 15251

EN 15251 entitled *Energy performance of buildings - ventilation for buildings. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics* (CEN 2007), provides requirements for indoor environmental parameters covering thermal environment, indoor air quality, lighting and acoustics. This guideline looks at the parameters in system design and for energy performance calculations. For mechanically heated or cooled buildings, the standard refers to ISO 7730 and delivers almost the same comfort criteria and for free running buildings (neither heated nor cooled), providing a method based on the adaptive algorithm of the European study SCATs (Teli 2013). The recommended operative temperature for each building's function is presented in Table 2-11.

Table 2-10 . Example design criteria for spaces in various types of buildings (source: EN ISO 7730 2005)

Type of building/space	Activity W/m^2	Category	Operative temperature (°C)		Maximum mean air velocity [a] m/s	
			Summer (cooling season)	Winter (heating season)	Summer (cooling season)	Winter (heating season)
Single office Landscape office	70	A	24.5 ± 1.0	22.0 ± 1.0	0.12	0.10
Conference room Auditorium		B	24.5 ± 1.5	22.0 ± 2.0	0.19	0.16
Cafeteria/restaurant Classroom		C	24.5 ± 2.5	22.0 ± 3.0	0.24	0.21 [b]
Kindergarten	81	A	23.5 ± 1.0	20.0 ± 1.0	0.11	0.10 [b]
		B	23.5 ± 2.0	22.0 ± 2.5	0.18	0.15 [b]
		C	23.5 ± 2.5	22.0 ± 3.5	0.23	0.19 [b]
Department store	93	A	23.0 ± 1.0	19.0 ± 1.5	0.16	0.13 [b]
		B	23.0 ± 2.0	19.0 ± 3.0	0.20	0.15 [b]
		C	23.0 ± 3.0	19.0 ± 4.0	0.23	0.18 [b]

a The maximum mean air velocity is based on a turbulence intensity of 40 % and air temperature equal to the operative temperature according to 6.2 and Figure A.2. A relative humidity of 60 % and 40 % is used for summer and winter, respectively. For both summer and winter, a lower temperature in the range is used to determine the maximum mean air velocity. b Below 20 °C limit (see Figure A.2).

2.4.3. ASHRAE 55

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) developed a thermal comfort standard for the specification of comfort criteria: *Standard 55: Thermal Environmental Conditions for Human Occupancy* (Anon 2010a). This guideline works based on the PMV/PPD model to determine the acceptable operative temperature (with the requirement set of PPD < 10% which corresponds to -0.5< PMV< 0.5). ASHRAE 55 gives a comfort zone with the typical values of metabolic rate (1.1met), clothing insulation (0.5 clo for summer and 1.0 clo for winter) and air speed (0.10m/s). The available thermal comfort data is for sedentary or near sedentary physical activity levels typical of office work. However, this standard may also be extended to determine appropriate environmental conditions for groups of occupants in spaces such as classrooms (Anon 2010a). The ASHRAE general comfort criteria is presented in Table 2-12.

Table 2-11. Default design values of the indoor operative temperature in winter and summer (Source: CEN 2007)

Type of building/space	Category	Operative temperature (°C)	
		Minimum for heating	Maximum for cooling
Residential buildings, living spaces (bed rooms, living rooms, kitchens, etc.) Sedentary activity ~1,2 met	I	21.0	25.5
	II	20.0	26.0
	III	18.0	27.0
	IV	16.0	28.0
Residential buildings, other spaces (utility rooms, storages, etc.) Standing-walking activity ~1,5 met	I	18.0	
	II	16.0	
	III	14.0	
Offices and spaces with similar activity (single offices, open plan offices, conference rooms, auditoria, cafeterias, restaurants, **classrooms,** Sedentary activity ~1,2 met	I	21.0	25.5
	II	20.0	26.0
	III	19.0	27.0
	IV	18.0	28.0
NOTE A 50% relative humidity level and low air velocity level (<0.1 m/s) is assumed.			

Table B.2 presents design values for the indoor operative temperature in buildings that have active heating systems in operation during winter seasons and active cooling systems during summer seasons. Assumed clothing thermal insulation levels for winter and summer (clo-value) and activity levels (met value) are listed in Table B.2. Note that the operative temperature limits shall be adjusted when clothing levels and/or activity levels are different from the values mentioned in the table.

Table 2-12. ASHRAE 55 requirement for indoor thermal comfort- acceptable thermal environment for general comfort (source: ASHRAE, 2010, ASHRAE 55, 2010b))

Acceptable thermal environment	
PPD %	PMV range
<10	-0.5 <PMV< +0.5

2.4.4. CIBSE Guide A

The Chartered Institution of Building Services Engineers (CIBSE) provides design criteria for thermal comfort in buildings entitled *Environmental design* (Anon 2006b). The recommended criteria for air-conditioned buildings is based on the PMV model but for free-running buildings (not heated or cooled), different comfort temperatures are provided based on the adaptive comfort principle. The recommended comfort criteria for different types of buildings are provided in this guideline and the assumed values for metabolic rate and clothing insulation are also indicated. The CIBSE provided standard for educational buildings is presented in Table 2-13 and the standard values for classrooms are highlighted.

Table 2-13. Recommended comfort criteria for specific applications (source: CIBSE A, 2019, (Anon 2019a)*)*

Building/ room type	Customary winter operative temperatures for stated activity and clothing levels			Customary summer operative temperatures (air-conditioned buildings†) for stated activity and clothing levels*			Suggested air supply rate/ ($L \cdot s^{-1}$ per person unless stated otherwise)	Filtration grade	Maintained illuminance/ lux	Noise criterion		
	Temp. °C	Activity met	Clothing clo	Temp. °C	Activity met	Clothing clo				NR	dBA	dBC
Educational buildings												65-75
Corridor	19-21	1.4	1.0	21-25	1.3	0.6	10	-	100	35-45	40-50	65-75
Gymnasium	-	-	-	-	-	-	-	-	300	35-45	40-50	65-70
Laboratory	19-21	1.4	1.0	21-25	1.3	0.6	10	-	100	35-40	40-45	55-65
Lecture halls	19-21	1.4	1.0	21-25	1.3	0.6	10	G4-G5	500	25-30	30-40	55-65
Seminar rooms	19-21	1.4	1.0	21-25	1.3	0.6	10	G4-G5	300	25-35	30-40	55-65
Teaching spaces	19-21	1.4	1.0	21-25	1.3	0.6	10	G4-G5	300	25-35	30-49	55-65
Workshops	16-19	1.8	0.9	-	-	-	-	depends on use	-	35-40	40-45	65-70

2.4.5. Limitations in the existing standards

The reviewed guidelines recommend standard values for the environmental variables to provide thermal comfort in different building types/functions. Regarding the recommended criteria for educational buildings, comfort criteria for educational buildings are recommended for *classrooms* (Anon 2005, Anon 2007) *teaching spaces/lecture halls* (Anon 2019a) or in general *acceptable environments* for educational buildings (Anon 2010a), with no discrimination based on the educational level. This suggests applying the same ambient environment for students from school to higher education levels, regardless of the individuals and their contextual differences, which can considerably affect the subjects' thermal perceptions in the classrooms.

Nevertheless, considering the differences between occupants in schools and university buildings, the same thermal environment cannot be applicable in these environments. School students are younger, more active and more homogeneous in terms of age and gender compared to the university students in a classroom. They have limited freedom for adaptive behaviour inside the classrooms and the ambient environment is normally controlled by their teachers (Brager, Paliaga and de Dear 2004; Teli, Jentsch and James 2012; Liu, Yao and McCloy 2014). School students tend to attend the same classroom for each academic course/period, which may lead to a better perception of comfort due to the repeated exposure to the same environment and better physiological and psychological thermal adaptations to this environment (Shipworth et al. 2016; Schweiker et al. 2018). However, students in higher learning environments are in different gender and age groups; they are from various climates and thus may have diverse thermal perceptions. University students study different subjects, attend different classroom types with various activities and exposure durations, all of which have a significant influence on their perceptions of thermal comfort in the classrooms. University students have higher freedom for adaptive behaviours in the classrooms than school students and they can take proper environmental or personal adaptive behaviour in uncomfortable thermal environments. Therefore, the environmental standards recommended for primary to high school cannot provide comfort in higher education classrooms.

In spite of the mentioned differences between school and higher education students and the challenges in providing thermal comfort in higher learning environments (section 2.3.2), as well as considering the large energy consumption for space heating purposes in university buildings, there is no specific environmental criteria for higher educational buildings in the existing guidelines. Moreover, according to Zomorodian et al. (2016), who reviewed around 100 studies on thermal comfort in educational buildings, the currently used thermal comfort standards are mainly found to be inappropriate for the assessment of classroom thermal environments and more investigation is required to provide thermally comfortable environments in educational buildings.

2.5. Chapter summary

Given the large energy use and related emissions in higher educational buildings in the UK along with the considerable influence of thermal comfort on students' productivity in academic environments, inaccurate prediction of the required thermal environments can not only lead to the students' thermal dissatisfaction and to lowering their learning performance, but can also cause a waste of energy for overheating or overcooling such buildings. Therefore, an energy efficient and thermally comfortable environmental criterion is required, which recommends the ambient environmental variables' set points in such spaces.

The literature review in this work shows a lack of investigation to determine a comfortable and energy efficient environmental criterion for UK higher learning environments, which is characterised as a multidisciplinary environment (accommodating students with diverse ages, genders, dress codes, climatic backgrounds, who study in different disciplines and are exposed to various classroom types).

Existing guidelines provide some general comfort criteria for classrooms and lecture halls in educational buildings, however, there is no specific guideline or standard for the environmental design of higher educational buildings, which are also responsible for huge energy consumption and carbon emissions in the UK education sector.

Chapter 3

3. Research Methods

3.1. Introduction

This chapter explains the outline of the field study procedure including objective and subjective evaluation. The details of the case study buildings such as architectural plan and room layout of the surveyed classrooms, methods of data collections including environmental monitoring, questionnaire surveys and observation and the description of the employed measurement equipment are also presented in this chapter.

This study was conducted using the Field Studies of Thermal Comfort (FSTC) methodology, which is a common methodology in thermal comfort research (Nicol and Roaf 2005). This approach includes a field survey of thermal comfort among subjects with a simultaneous environmental monitoring. During the field surveys, participants wear their normal clothing and go about their usual work. The results of such evaluations are analysed statistically to estimate the temperature at which the largest number of participants are comfortable (Nicol et al 2012).

The FSTC approach was initially seen as an alternative to climate chamber studies (where subjects are exposed to controlled laboratory conditions) since such results may differ from the subjects' votes in actual buildings (Nicol and Humphreys 1973; De Dear and Brager 2002; Nicol 2004). In the FSTC approach, subjects are in their familiar environment and they can adjust their clothing as they prefer based on the situation. Therefore, this approach has the advantage that it reflects the actual thermal perceptions of the subjects without making any assumptions about individual factors (Nicol and Roaf 2005). Although it is limited by the range of conditions that may lead to inaccuracy in the measurement of the environment (e.g. equipment measurement error, inappropriate location of the probes) , FSTCs have the advantage of taking place in the subjects' normal surroundings; and do not require the expense of a climate chamber (Nicol and Roaf 2005).

Students in higher learning environments tend to have control over the thermal environment inside the classroom. They can also adjust clothing based on their thermal sensations and preferences. Furthermore, considering the multidisciplinary context of the university buildings, inter-individual factors may also affect the thermal comfort requirements of the occupants (Nicol and Humphreys 2002; Singh, Mahapatra and Atreya 2011; Katafygiotou and Serghides 2014; Villadiego and Velay-Dabat 2014). Therefore, the FSTC approach (including a subjective and objective evaluations) was applied in this work as it is more likely to correctly reflect the students' thermal experiences

3.2. Location and climatic condition of Coventry and Edinburgh

The field experiments included simultaneous environmental measurements, questionnaire surveys, and observations in eight mixed-mode university buildings in Coventry (52.4068 ° N, 1.5197 ° W), England, and Edinburgh (55.9533 °N, 3.1883 °W), Scotland, United Kingdom (UK). Data collection took place between October and November 2017 in Coventry and between January and April 2018 in both Coventry and Edinburgh during the first and second academic semesters. In the following sections the detail of the field study phases, surveyed buildings, data collection, climatic conditions of the survey locations, the participants and data analysis are provided.

Coventry and Edinburgh are located in the southern regions (England) and northern parts (Scotland) of United Kingdom (UK) respectively (Figure 3-1).

In the UK, climatic conditions differ from region to region. In terms of the climatic differences between Scotland (northern area) and England (southern and middle areas), the weather in Scotland is cold, damp, rainy and windy for most of the year, while the temperature is generally lower than in other parts of the UK; whereas, England has a normally temperate maritime climate (Weather Online no date). In Scotland, the daily mean temperature drops to 4–5 °C in winter; and it goes up to around 14–19 °C during summer (World Climate Guide, 2019). Likewise, in England, winter is cold and cloudy and windy with the mean daily temperatures of around 3–6 °C, which does not differ much from Scotland in this season. However, England experiences warm summers with mean daily temperature of 19 to 23 °C (World Climate Guide, 2019).

Figure 3-1. Locations of the survey in the UK, 1: Coventry, 2: Edinburgh, adopted from World Map (worldmap.com n.d.)

Regarding the climatic condition in Coventry and Edinburgh, the weather in Coventry is temperate and cool for most of the year with a mean annual temperature of 12°C (*WOW Met-Office* 2019). The monthly mean temperature changes from 4°C in January to 18°C in June, July and August (World Climate Guide, 2019). The winter is cold in Coventry but not freezing and the mean temperature in this season does not vary much from the northern regions of the UK (World Climate Guide 2019). Spring is very cool and the temperature increases slowly; late spring is the sunniest period of the year, despite the almost daily presence of clouds. Summer is cool; the weather is variable, so that it can change from day to day, or several times during the same day. Southern England is the area most subject to hot periods, when warm air currents from Spain can bring a taste of Mediterranean summer, and the temperature may even reach 28 to 32 °C (World Climate Guide 2019). Edinburgh normally experiences cool and moist weather (cloudy and rainy) with a mean annual temperature of 10 °C. The daily average temperature ranges from 4 °C in January to 15 °C in July and August. Winter is cold, cloudy, windy and rainy but with a mean temperature above 0 °C. Wind may increase the feeling of cold, even when the temperature is not too low (World Climate Guide, 2019). Spring is cold or very cool; night temperatures may drop to below freezing in April and around freezing in May but the temperature becomes milder in the second half of May. Summer is cool and mild; the daily maximum temperature on average reaches about 19 °C in July and August (World Climate Guide, 2019). Autumn is cloudy, rainy and windy. The sun rarely appears and the days shorten rapidly in mid-September (World Climate Guide, 2019). Figure 3-2 presents the fluctuations of the outdoor air temperatures within the survey periods throughout 2017–2018, in Coventry and Edinburgh. There was a larger temperature difference between these two locations during the summer compared to the winter months. Regarding the survey period, there were minimum, mean and maximum air temperatures of 1 °C, 7 °C and 15 °C in Coventry and 2 °C, 6 °C and 13 °C in Edinburgh, respectively.

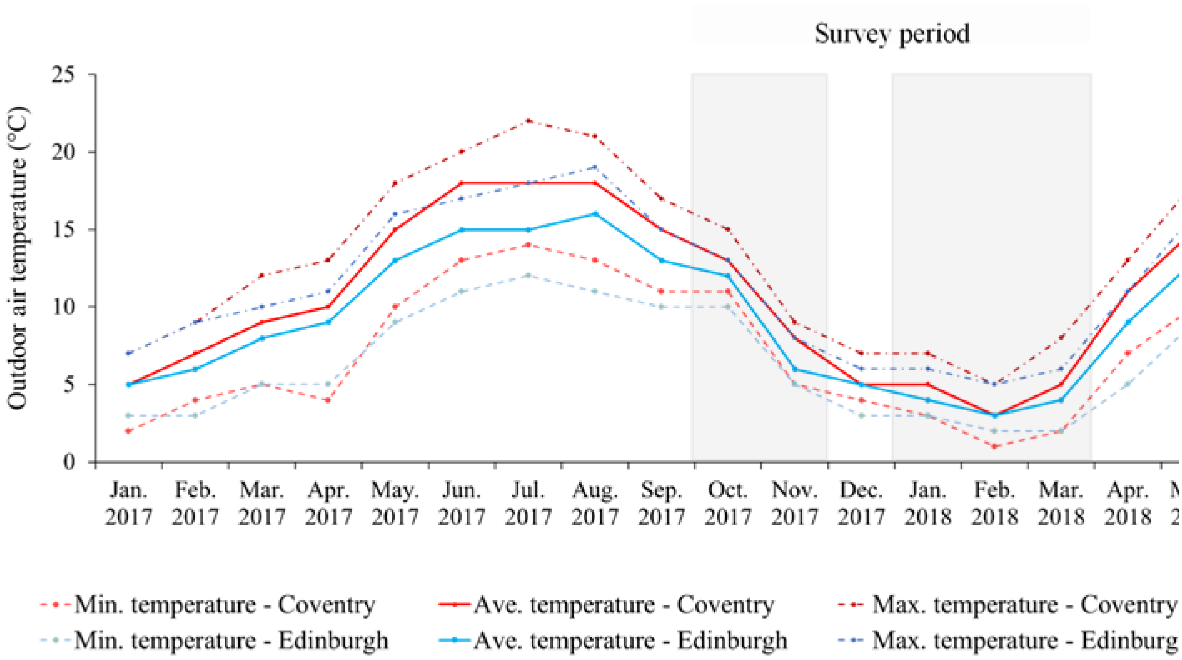


Figure 3-2. Monthly outdoor air temperatures in Coventry and Edinburgh during the survey period (source: WOW Met-Office no date*)*

3.3. Case-study buildings

Experiments were conducted in the classrooms of four mixed-mode buildings in Coventry (B1 to B4) and four buildings in Edinburgh (B5 to B8). All the buildings were equipped with HVAC systems and worked on mixed-mode changeover (where the operation mode changes between mechanical cooling and natural ventilation on a seasonal or daily basis) or concurrent (where mechanical cooling and natural ventilation operate at the same time in the same space) operation (Brager, Borgeson and Lee 2007). Comfort surveys were conducted in three different types of classrooms: lecture rooms, studios and PC labs. Classrooms were selected if the lecturers consented and all the students were involved in comparable activities. Space heating was provided through a square ceiling diffuser or radiators in all the classrooms. Space cooling was provided through ceiling supply ducts in all the buildings except B3, which were equipped with floor cooling outlets.

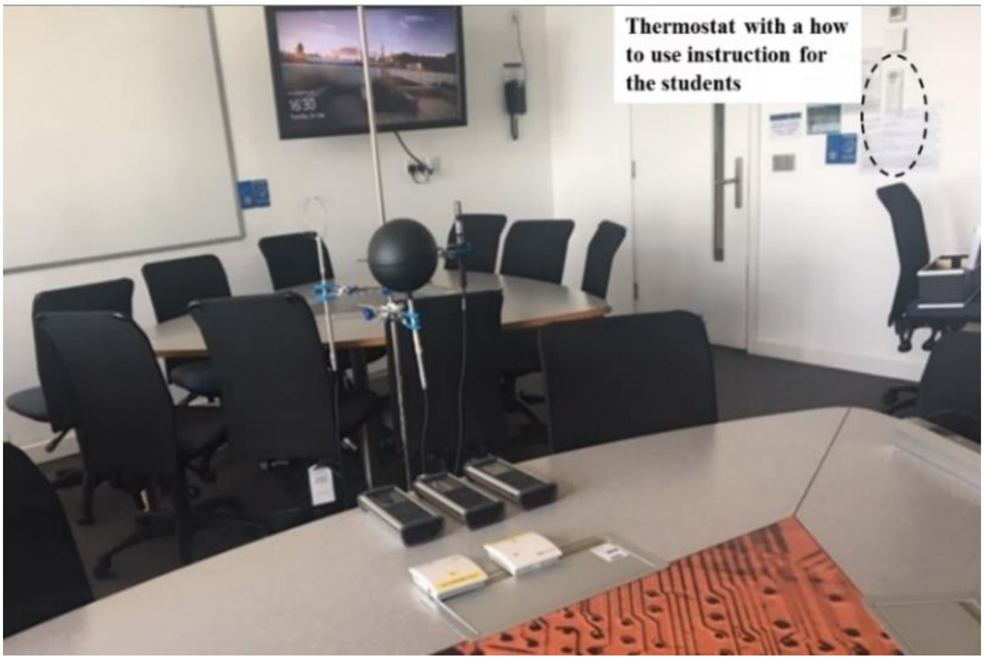


Figure 3-3. Location and accessibility of the thermostat for manual control in a classroom

Occupants were free to select the mode of operation based on the indoor ambient environment: free running (FR, neither heating nor cooling at the time of the survey), cooling (CL) or heating (HT). Natural or mechanical ventilation was achieved through operable windows or fresh air supply ducts respectively, controlled manually (Figure 3-3) or automatically (B3) based on the CO_2 level monitored in some classrooms. However, due to the presence of the top hung windows and the small extent of window openings because of safety issues, natural ventilation through the windows was not efficient enough. A summary of the investigated buildings, classroom types, frequency of the surveys and the number of participants in each building is presented in Table 3-1 and Figure 3-4.

Table 3-1. Summary of the surveyed classrooms

Location	Building	Classroom type	Mode	Average area (m^2)	No. of surveyed rooms	No. of survey repeat	Average occupancy density (m^2/person)
Coventry	B1	Lecture room	FR	100	2	2	2.5
		Studio	FR	150	4	4	5.0
	B2	Lecture room	CL, HT	120	1	8	1.2
		Studio	FR	130	1	3	3.0
		PC lab	CL, FR	90	3	7	3.5
	B3	Lecture room	CL, FR, HT	100	8	21	2.0
		PC lab	CL, FR	80	6	10	3.0
	B4	Studio	HT	150	4	5	5.0
Edinburgh	B5	Lecture room	HT	80	3	8	1.2
	B6	Lecture room	HT, FR	80	1	4	1.2
	B7	Lecture room	HT	120	1	4	1.2
	B8	Lecture room	HT, FR	120	3	15	1.2

FR: Free-running mode, HT: Heating mode, CL: Cooling mode

Table 3-2. Summary of the investigated buildings

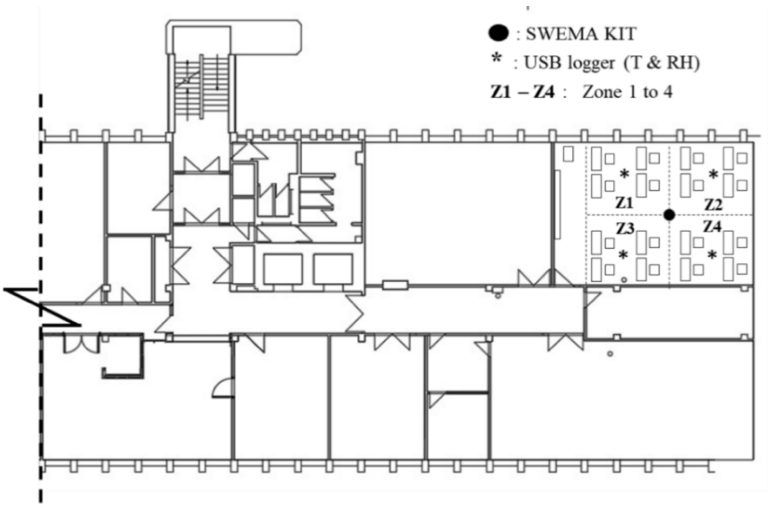
		Lecture room	Studio	PC lab	Buildings
Coventry	Surveyed rooms no.	1	5	0	
	Survey frequency	1	5	0	
	Participants no.	85	208	0	
	Total		293		
	Surveyed rooms no.	1	1	3	
	Survey frequency	8	3	7	
	Participants no.	462	92	153	
	Total		707		
	Surveyed rooms no.	9	0	5	
	Survey frequency	22	0	9	
	Participants no.	666	0	238	
	Total		904		
	Surveyed rooms no.	0	4	0	
	Survey frequency	0	5	0	
	Participants no.	0	147	0	
	Total		147		
Edinburgh	Surveyed rooms no.	3	0	2	
	Survey frequency	8	0	2	
	Participants no.	315	0	65	
	Total		380		
	Surveyed rooms no.	1	0	0	
	Survey frequency	4	0	0	
	Participants no.	154	0	0	
	Total		154		
	Surveyed rooms no.	2	0	0	
	Survey frequency	15	0	0	
	Participants no.	728	0	0	
	Total		728		
	Surveyed rooms no.	1	0	0	
	Survey frequency	4	0	0	
	Participants no.	196	0	0	
	Total		196		

3.4. Data collection methods and tools

Data gathering happened through simultaneously employing the following methods:

- Environmental measurements
- Questionnaire survey
- Observation

(a)



(b)

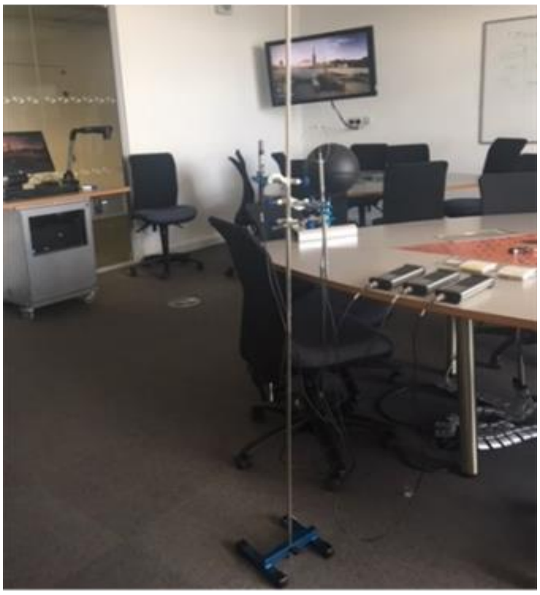


Figure 3-4. Location of instruments in one of the lecture rooms. a: architectural plan, b: photo of instruments

3.4.1. Environmental monitoring

Indoor air temperature (T_{in}), relative humidity (RH), air velocity (V_{in}) and mean radiant temperature (T_{mr}) were recorded in each surveyed classroom. Each variable was measured from the beginning to the end of the class to register all changes of the environmental variables. However, for the analysis, the recorded points averaged through the same time interval as the questionnaire surveys were conducted (the last 15 minutes of each class). Data on outdoor air temperature was obtained from the UK Meteorological Office (Anon 2019d) whose weather stations were less than 5km from the comfort field study sites.

Relative humidity, air velocity and mean radiant temperatures were recorded using a Multi-purpose SWEMA 3000 (Anon 2019c), working based on ISO 7730 with a time interval of 5 minutes. Indoor air temperature was recording using some temperature and humidity USB loggers (Anon 2019b). The surveyed rooms were divided into 4 or 5 zones, based on their physical shape. The SWEMA 3000 was placed in the middle of the room, away from any direct heating or cooling sources and the temperature and RH loggers were placed in each zone to gain the nearest environmental data on the students' sensations. Figure 3-4 (a) indicates the position of the instruments in a lecture room as an example. The black globe thermometer was placed 1.1m above the floor level on a vertical stand, as recommended by EN ISO 7726 (*EN ISO 7726* 2001). The anemometer and humidity probe were placed closely above and below the thermometer (Figure 3-4, b). An architectural plan of all the surveyed classrooms (except for B6 and B7 where the architectural plan was not available) showing the rooms' layers and the locations of the instruments are also provided in

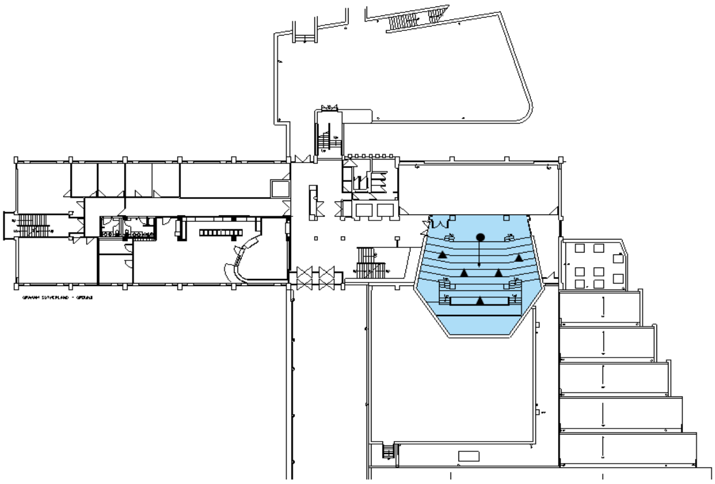
Figure 3-5.

Coventry

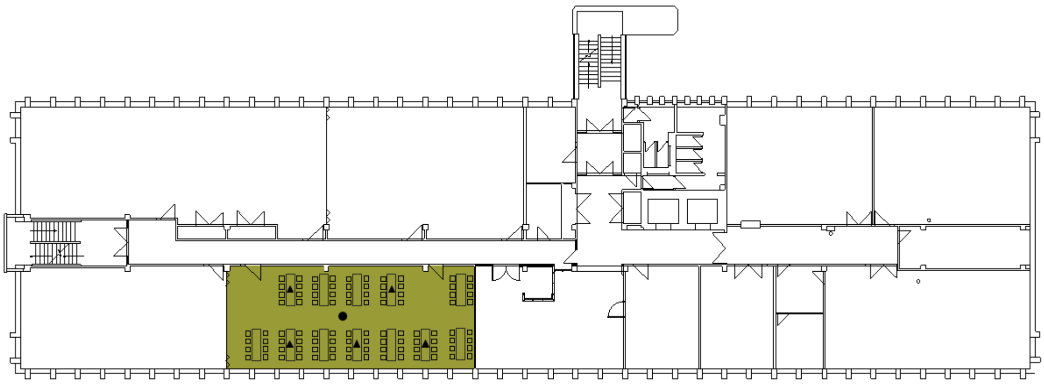
Lecture room | Studio | PC lab

B1

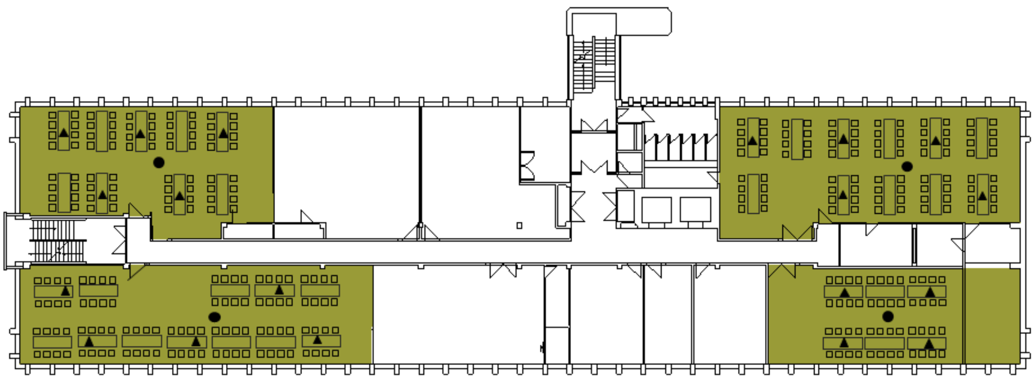
Ground floor



Third floor

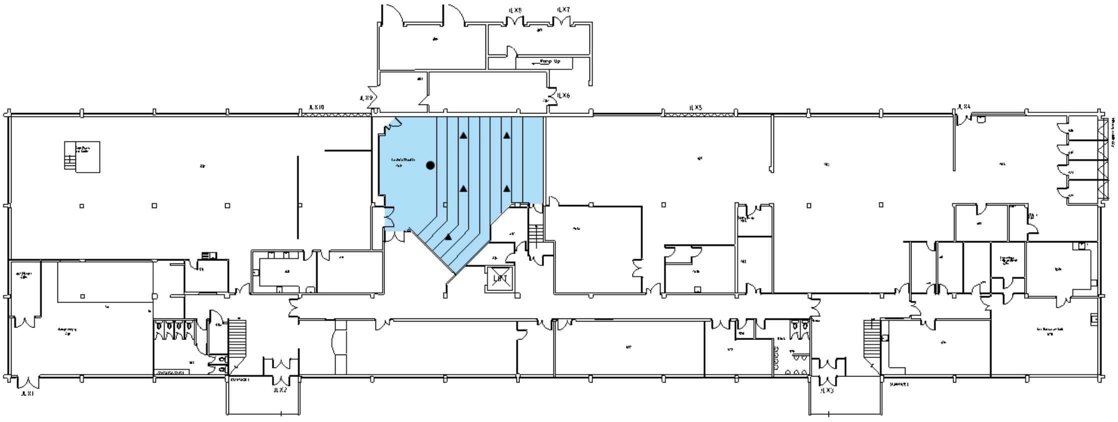


Fourth floor

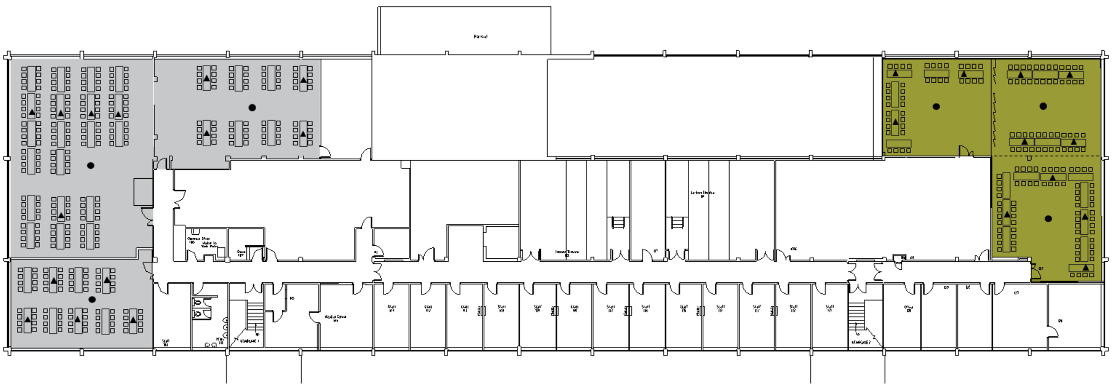


B2

Ground floor

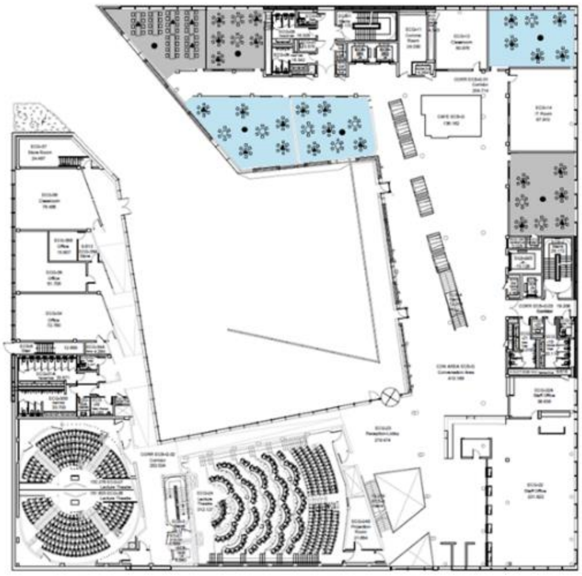


First floor



B3

Ground floor



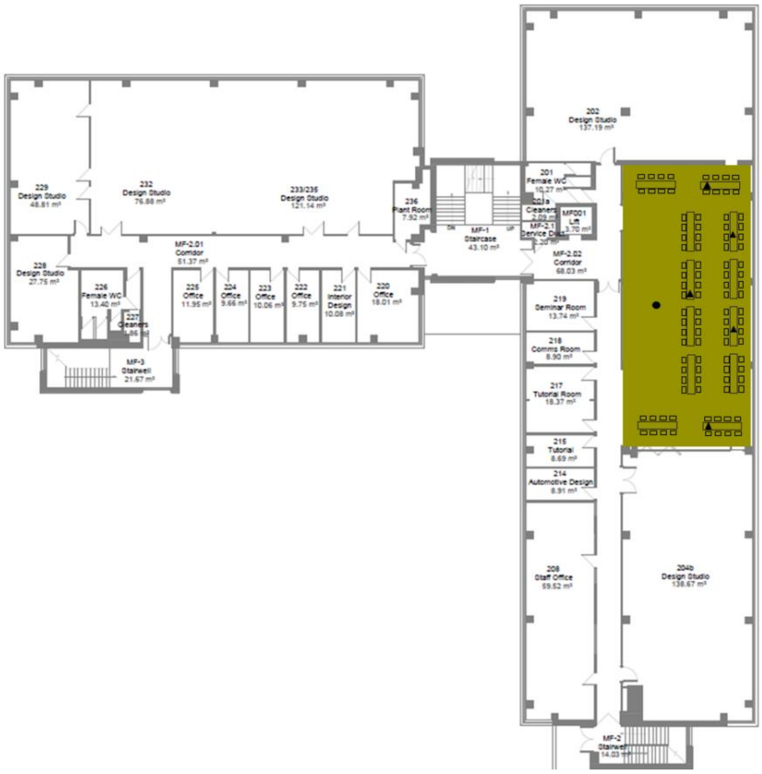
First floor

Second floor

B4

First floor

Second floor

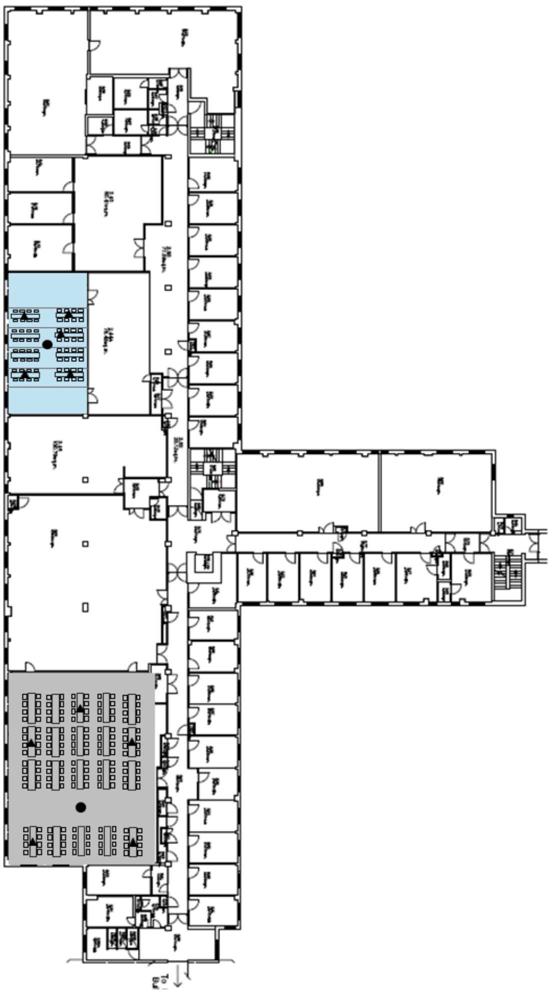


Edinburgh

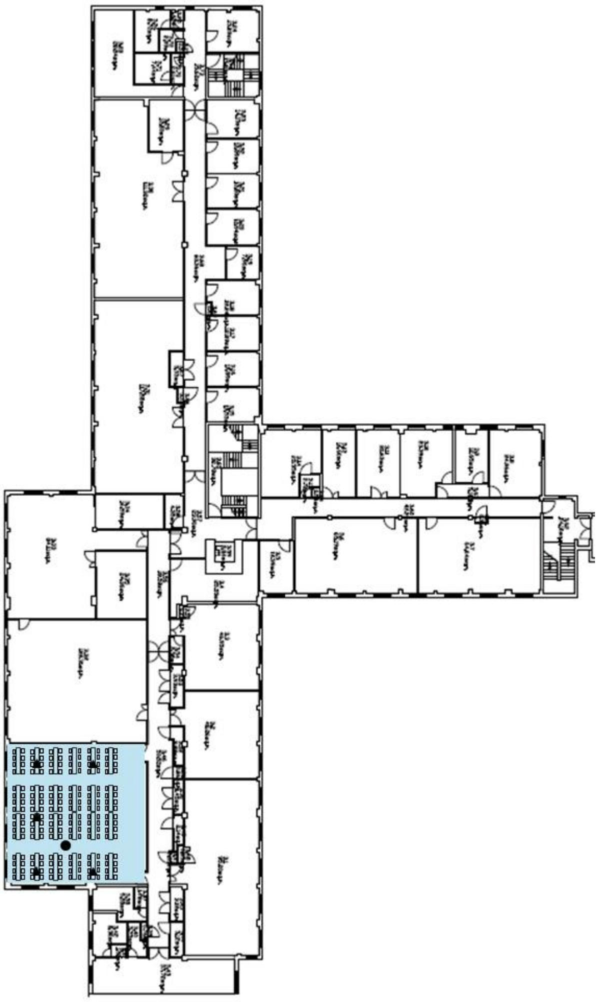
Lecture room | Studio | PC lab

B5

Second floor



Third floor



B6

Ground floor

Second floor

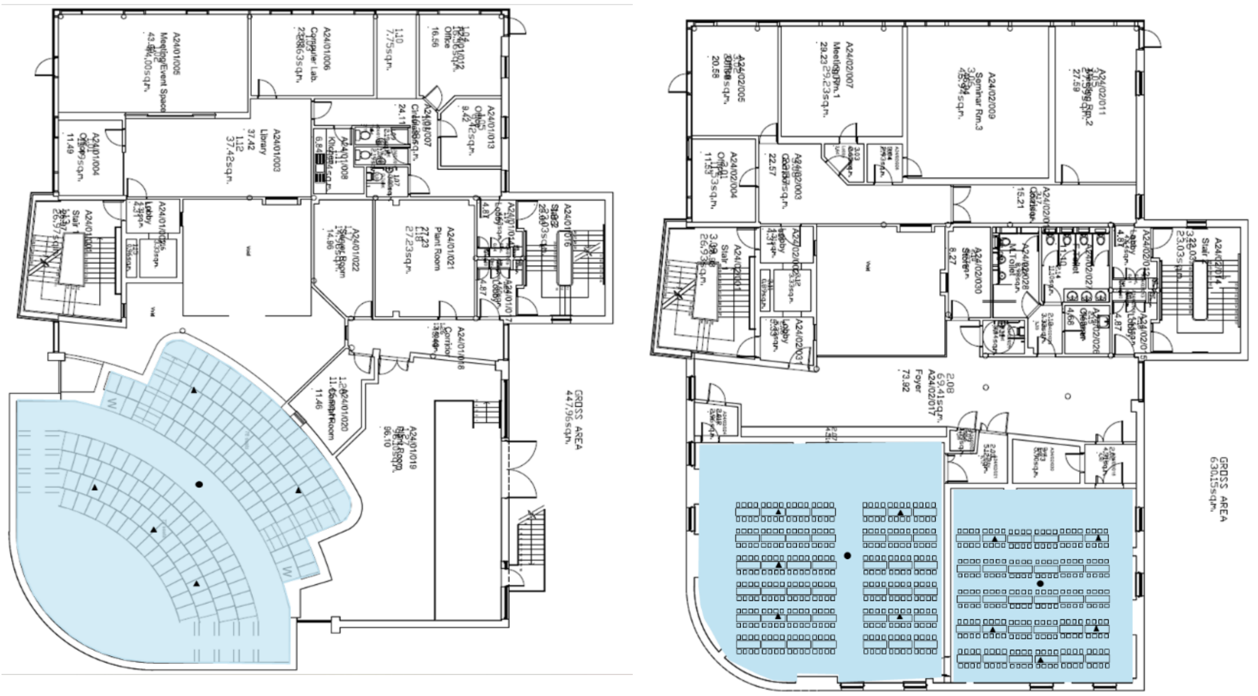


Figure 3-5. Architectural plans of the investigated buildings in Coventry and Edinburgh (architectural plans of B 6 and 7 are not available)

The multi-purpose Swema 3000 is a microprocessor-based instrument designed for measuring moderate thermal environments to comply with the standards: ISO7726 (Thermal environments – Instruments and methods for measuring physical quantities) and ISO7730 (Ergonomics of the thermal environment – Analytical determination and interpretation of satisfaction of thermal environment using calculation of the PMV and PPD indices and local thermal comfort criteria). Swema 3000 incorporates powerful built-in calculation and documentation features that simplify field work. The multi-purpose Swema measurement kit (Figure 3-6) included a high precision anemometer, air humidity probe and globe temperature sensors (Universal Instrument 2019). The recorded points were registered in three different loggers for each sensor and probe during the survey period. Indoor air temperatures were also recorded separately using several Extech temperature and humidity USB loggers.

(a) Relative humidity probe 	✓ Relative humidity: 0...100 %RH ✓ HC2-S: ±0,8 %RH at 23°C ✓ Temperature: -40...+60°C ✓ Accuracy: ± 0,3°C at 23°C ✓ Resolution: 1% ✓ Range: 0 – 100% ✓ Communication; USB ✓ Sampling frequency: Recommended 10Hz Fulfils ISO 7726 ✓ Included: Traceable calibration certificate
(b) Anemometer (air velocity probe) 	✓ Air velocity: 0,05...3,00 m/s at 15...30°C ✓ Accuracy at 23°C: ±0,03 m/s at 0,05...1,00 m/s, ✓ ±3% read value at 1,00...3,00 m/s, at 15…30°C: ±0,04 m/s, at 0,05...1,00 m/s, ±5% read value at 1,00...3,00 m/s Response time air velocity (90%): 0,2 s ✓ Resolution: 0.03 m/s ✓ Range: 0.05 – 3 m/s ✓ Temperature: 10...40°C ✓ Accuracy: at calibration temperature (approx. 23°C): ± 0,3°C, at 10...40°C: ±0,5°C ✓ Communication; USB ✓ Sampling frequency: Recommended 10Hz (up to 100Hz for one sensor) ✓ Included: Traceable calibration certificate Fulfils ISO 7726
(c) Black Globe sensor 	✓ Ø150 mm black globe sensor to measure mean radiant temperature ✓ SWEMA 05 at 0...50°C: ±0,1°C ✓ Resolution: 0.1°C ✓ Range: 0 – 50°C ✓ Communication; USB and RS485 ✓ Sampling frequency: Recommended 10Hz (up to 100Hz on some PC-installation) ✓ Fulfils ISO 7726 ✓ Included: Traceable calibration certificate
(d) Temperature and humidity logs 	✓ Measurement of both humidity in% RH and temperature ✓ Memory capacity for 32000 measurement values (16000 for% RH and 16000 for ° C) ✓ Dew point indication via Windows software ✓ LED indication via red and green LED ✓ Selectable data recording interval from 2 seconds to 24 hours ✓ 3.6 V lithium battery ✓ Windows Software (98, 2000, XP) ✓ Vista compatible analysis software

(e)

Figure 3-6. SWEMA kit sensors, probes and loggers (source: Universal Instrument 2019)

3.4.2. Questionnaire survey

Cross-sectional questionnaire surveys were conducted with students inside the classrooms. Hard copy versions of the questionnaires were distributed in the last 15 minutes of each class, after the students had sat in the classrooms for at least 1 hour. Although 15 minutes is generally regarded as enough to eliminate the influence of prior activities on thermal sensation votes (Goto et al. 2000; Teli, Jentsch and James 2012), in this study, 1 hour of sitting in a classroom was considered as a safe margin to also eliminate the influence of short-term thermal history in transitional spaces prior to attending the classroom (Nagano et al. 2005) and to minimise disruption to the class activity. All the participants were asked to complete the questionnaires at the same time to make sure that the recorded environmental variables corresponded to the thermal comfort votes.

The surveys were repeated 60 times in 11 lecture rooms, 10 studios and 8 PC labs in Coventry and 31 times in 7 lecture rooms and 2 PC labs in Edinburgh (Table 3-1). Students in the lecture rooms and PC labs were involved in sedentary activities such as listening to the lecturer, making notes or computer modelling during the surveys, while in the studios, they were involved in activities such as creating mock-ups, drawing and making samples. According to the classrooms' timetables at both universities and the author's observations, the duration of each lecture was around 1 or 2 hours, including a fifteen-minute break in between. However, studio sessions took almost half a day with a couple of breaks in between. According to the ASHRAE standard (Anon 2017), the metabolic rate was assumed to be 1.1 met for the students in all the classroom types based on their activity levels.

3.4.2.1. **Questionnaire design**

The questionnaire was designed based on the practical survey methods explained by Humphreys et al. (2015) and included four sections (Appendix 2):

1) Background questions; regarding the student's age, gender, city of origin, its climatic condition and the duration of living in the UK.

   The main purpose of this section was to evaluate the potential influence on comfort votes of individual factors, such as age, gender, climatic background and adaptation to the UK climate.

2) Clothing garment checklist; clothing values were evaluated using a checklist including upper- and lower-body underwear and outerwear items. Participants were asked to select the clothes worn at the survey time. The insulation value for each item worn was obtained from the introduced clo values in EN ISO 7730 (*EN ISO 7730* 2005), the sum of which were considered as the total clothing insulation level for each subject.

   Although knowledge of clothing insulation is not necessary for direct estimation of comfort temperature (except for the PMV model), responses to this section were employed to have a more accurate assessment of the subjects' thermal comfort votes.

3) Thermal comfort votes included thermal sensation and preference votes, thermal acceptability and overall comfort. The thermal sensation votes (TSV) were examined based on the ASHRAE 7-point sensation scale. A similar 7-point scale was used for thermal preferences (TP). Thermal acceptability and overall comfort were also assessed on 4 point scale, as in Zhang's et al. study (2007) (Table 3-3).

   This section is the main part of the research examining the students' perceptions of thermal comfort corresponding to the exposed thermal environment.

4) Preferred adaptive behaviours; students' priorities for adaptive behaviours in uncomfortably warm and cold thermal environments were investigated in this section. Possible adaptive behaviours inside the classrooms (i.e. windows operation, door operation, clothing adjustment, changing position, having hot/cold drink, variation of HVAC set point) were listed in the questionnaire and the students were asked to choose their priority for the adaptive behaviour.

   This section was designed and added to the questionnaire to examine the students' preferences for adaptive behaviours in each classroom types with different levels of freedom to change the thermal environment.

Table 3-3. Scales for thermal and overall comfort evaluations

Scale	−3	−2	−1	0	1	2	3	4
Thermal sensation (TSV)	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	
Thermal preference (TP)	Much warmer	Warmer	Slightly warmer	No change	Slightly cooler	Cooler	Much cooler	
Thermal acceptability (TA)					Clearly acceptable	Just acceptable	Just unacceptable	Clearly unacceptable
Overall comfort (OC)					Comfortable	Slightly uncomfortable	Uncomfortable	Very uncomfortable

3.4.2.2. Surveyed subjects

Undergraduate and postgraduate students in science-based and art-based subjects participated in the surveys. The questionnaire surveys saw a total 3873 students. However, approximately 9% of the participants did not provide answers and were excluded from the data base. A small number of the questionnaires filled by the subjects sitting directly next to a heating or cooling source were also excluded. Overall, 3516 students, 2046 subjects in Coventry and 1460 in Edinburgh took part in the surveys. Participants were in both gender and age groups with an average age of 22.

3.4.2.3. Classification of the thermal history groups

One of the most widely used climate classification schemes, the updated Köppen-Geiger, was selected to categorise the students' climatic backgrounds (Kottek et al. 2006; Kelly and Parsons 2010). Each climate zone is based on the qualitative features of the Earth's vegetation (Strahler 1969). The updated versions by Kottek et al. (2006) and Peel et al. (2007) have been applied in various research problems ranging from climate change through to thermal comfort (Fraedrich, Gerstengarbe and Werner 2001; Crawley 2007; Mishra and Ramgopal 2015b). Table 3-4 presents the five main groups distinguished by Köppen-Geiger including zones A (tropical), B (arid), C (temperate), D (cold) and E (polar) (Peel, Finlayson and McMahon 2007). The second letter in the classifications indicates the precipitation level and the third letter refers to air temperature (Kottek et al. 2006) (e.g. Dfc for snow, fully humid with a cool summer).

Table 3-4. Description of Koppen climate symbols and criteria (Kottek et al. 2006)

1st	2nd	3rd	Description	Criteria
A			**Tropical**	$T_{cold} \geq 18$
	f		- Rainforest	$P_{dry} \geq 60$
	m		- Monsoon	Not (Af) & $P_{dry} \geq 100 – MAP/25$
	w		- Savannah	Not (Af) & $P_{dry} < 100 – MAP/25$
B			**Arid**	$MAP < 10 \times P_{threshold}$
	w		- Desert	$MAP < 5 \times P_{threshold}$
	s		- Steppe	$MAP \geq 5 \times P_{threshold}$
		h	- Hot	$MAT \geq 18$
		k	- Cold	$MAT < 18$
C			**Temperate**	$T_{hot} > 10$ & $0 < T_{cold} < 18$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Cs) or (Cw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a or b) & $1 \leq T_{mon10} < 4$
D			**Cold**	$T_{hot} > 10$ & $T_{cold} \leq 0$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Ds) or (Dw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a, b or d)
		d	- Very cold winter	Not (a or b) & $T_{cold} < –38$
E			**Polar**	$T_{hot} < 10$
	t		- Tundra	$T_{hot} > 0$
	f		- Frost	$T_{hot} \leq 0$

MAP = Mean Annual Precipitation, MAT = Mean Annual Temperature, T_{hot} = temperature of the hottest month, T_{cold} = temperature of the coldest month, T_{mon10} = number of months where the temperature is above 10, P_{dry} = precipitation of the driest month, P_{sdry} = precipitation of the driest month in summer, P_{wdry} = precipitation of the driest month in winter, P_{swet} = precipitation of the wettest month in summer, P_{wwet} = precipitation of the wettest month in winter, $P_{threshold}$ = varies according to the following rules (if 70% of MAP occurs in winter then $P_{threshold}$ = 2 x MAT, if 70% of MAP occurs in summer then $P_{threshold}$ = 2 x MAT + 28, otherwise $P_{threshold}$ = 2 x MAT + 14).

The students' hometowns and home countries were coded according to the Köppen-Geiger climate classification map (Figure 3-7). Considering Table 3-4, the main difference between groups A and B is precipitation level, while other thermal features were broadly similar. Moreover, the ANOVA tests indicated no statistically significant difference in the students' thermal comfort results between the A and B climates of origin, so they have been collapsed into a single group for the purposes of our analysis. As both locations of the field work, Coventry and Edinburgh, are in the temperate climate zone (group C), the cities in tropical or arid areas (zone A or B with a higher mean annual temperature than UK) and cold or polar areas (zones D or E with a lower mean annual temperature than UK) were considered as warmer and cooler climates compared to the UK, respectively.

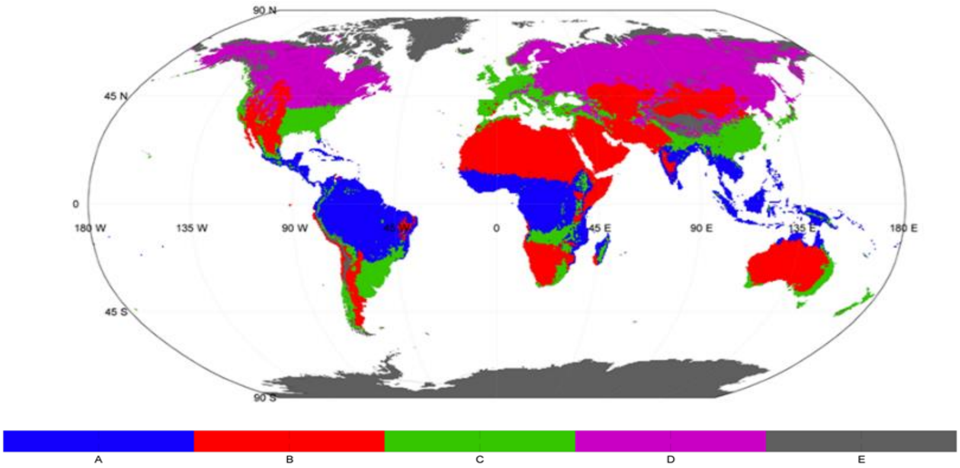


Figure 3-7.Koppen Geiger climate classification map- main climate types (Kottek et al. 2006)

Table 3-5 summarises the samples Köppen-Geiger climate origins and thermal history groups relative to the UK. For instance, students from Malaysia (zone A) and Norway (zone D) were categorised as "warmer" and "cooler" thermal history groups, respectively.

Table 3-5. Labelled thermal history groups in relation to Köppen-Geiger climate zones

Letter	Climate type	Climate zone origins
A & B	Tropical / dry	Warmer background
C	Mild temperate	Similar background
D & E	Snow/ polar	Cooler background

3.4.3. Observations

During the survey, an observation list was completed by the author to monitor the potential environmental factors which may have affected the thermal environment in each room. The students' education level, their activity, teaching style, curtain and window status (open or closed), the number of windows, existing opportunities for adaptive behaviours, HVAC operation mode, ventilation type and room dimensions in each room were registered.

The HVAC mode was registered based on the running mode within the survey period (when students were filling in the questionnaires), regardless of the outdoor air temperature. In some cases, the HVAC mode was changed by the occupants before the survey. For instance, HT mode was running at the beginning of the lecture while it changed to FR (or CL) in the middle or at the end of the lecture (before the survey started); therefore, FR (or CL) mode was registered.

3.5. Data analysis

Collected data were statistically analysed to estimate the thermally comfortable environments in which the majority of the students were thermally satisfied.

The probability value (p-value) was evaluated and statistical tests were applied to confirm the differences between the thermal comfort indices of each group of participants. A normality test was conducted to designate whether a set of data was normally or non-normally distributed. An independent t-test and one-way ANOVA were applied for the normally distributed set of data and the Mann-Whitney U test (non-parametric equivalent to the independent t-test) or Krauskal Wallis test (non-parametric equivalent to One way ANOVA) were applied to non-normal distributions or ordinal variables (Marshall 2016).

Furthermore, due to the big data set and the large number of outliers in the linear regression analysis, data were binned at a certain intervals (where applicable) to minimise the impact of residuals on the final result and improve the value of the regression coefficient, as suggested by de Dear et al. (1998). For instance, as there was a high variety of thermal sensation votes in each indoor air operative temperature in this work, (mainly due to the individual differences between the subjects (Shipworth et al. 2016; Schweiker et al. 2018)), in a linear evaluation of these two parameters, the operative temperature was binned at 1ºC (or 0.5ºC to increase the accuracy), similar to previous studies (e.g. Nakano, Tanabe and Kimura 2002; Wang 2006). In a regression analysis with binned data, the results including the constant, slope, etc. remain the same as working with raw data, but the regression coefficient increases, which consequently improves the statistical validity of the results (de Dear and Brager 1998; Gautam et al. 2019). According to de Dear et al. (1998), "'working with the bins' means response to, say thermal sensation vote, instead of individual subjects' thermal votes".

3.5.1. Calculation of operative temperature

Operative temperature is a thermal index applied for the assessment of an indoor environment in the existing standards and guidelines (*EN ISO 7730* 2005; *ASHRAE 55* 2010b; *CIBSE Guide A*. 7th ed. 2010; CEN 2007). Operative temperature (°C) combines the effect of indoor air temperature and the mean radiant temperature into a single value to express their joint effect. It is a weighted average of the two, the weights depend on the heat transfer coefficients by convection and by radiation at the clothed surface of the occupant (*CIBSE Guide A*. 7th ed. 2010). According to de Dear and Brager (1998), the indoor operative temperature can successfully combine features of both static and adaptive models and as a result, can be used as a sufficient index to predict thermal comfort in an environment. Operative temperature is calculated by the following equation (*CIBSE Guide A*. 7th ed. 2010):

$$T_{op} = \frac{T_{in}\sqrt{10v}+T_{mr}}{10+\sqrt{10v}} \qquad \textit{3-1)}$$

Where T_{op} is the operative temperature (°C), T_{in} the air temperature (°C), T_{mr} the mean radiant and v is the indoor air speed (m/s).

At an indoor air velocity equal or lower than 0.1 m/s, operative temperature may be taken as the average of the indoor air and mean radiant temperature, equation 3-2 (Nicol and Humphreys 2010).

$$T_{op} = \frac{1}{2}(T_{in} + T_{mr}) \qquad \textit{(3-2)}$$

In this study, both formulae were employed based on the indoor air velocity value.

3.5.2. Statistical tests

Relevant statistical tests were applied to confirm or reject the differences between the thermal comfort indices of each group of subjects. An independent t-test (for two subject groups) or a one-way ANOVA test (for three or more than three subject groups) was applied to the normally distributed data and a Mann-Whitney U test (for two groups) or Kruskal Wallis test (for three or more groups) was applied to the non-normal distributions or ordinal variables (Marshall 2016).

3.6. Threats to validity

Similar to the other field studies and surveys in the field of thermal comfort and the built environment, there are several possible random sources of errors in this work which need to be noted. Such errors can be listed as follows:

- Uncertainty in the measurement of the environmental variables such as inaccurate measurements and inappropriate locations of the probes and sensors can cause some errors in the recorded points. To minimise such errors, this study tried to use equipment with high accuracy and resolution (Figure 3-6) and to place the equipment in the proper location in each classroom. The indoor air and radiant temperature sensors were placed in the middle of each classroom, away from any heating/cooling source and direct sun penetration. Also, loggers for the indoor air temperature were in different parts of the classroom to fully reflect the students' thermal sensations, even if they were away from the central equipment (Figure 3-4). However, there was still the possibility of the inaccurate prediction the thermal environment perceived by the students away from the classroom's central zones. In this study, operative temperature was used as the thermal evaluation index (Nicol, Humphreys and Roaf 2012). As operative temperature is a function of the indoor air and mean radiant temperature (*CIBSE Guide A*. 7th ed. 2010), uncertainty in the measurement of the indoor air temperature can affect the calculated operative temperature and consequently may lead to some errors in the predicted environmental requirements.

- In terms of the personal errors, factors such as metabolic rates and clothing insulation are almost impossible to measure in real field surveys with a big sample size; it is normally estimated by the descriptors and we have to rely on the values measured in laboratories (Nicol, Humphreys and Roaf 2012). This means that the recommended values for clothing insulation and metabolic rates used in real field surveys are approximate. As an example, climatic conditions could affect the metabolic rate, the effect of which is overlooked by the descriptor (Nicol, Humphreys and Roaf 2012). Furthermore, in an uncomfortably warm or cold thermal condition, people may carry out a particular activity to restore their comfort, which cannot be recognised by the descriptors (Nicol, Humphreys and Roaf 2012). The clothing insulation value can also be affected by factors such as subjects sweating and wet skin, which can influence the insulation value of clothing.

- In this work, students' metabolic rates and clothing were predicted based on the recommended standards in the environmental guidelines. However, to improve the accuracy of this study, a comprehensive and detailed clothing checklist was provided in the questionnaire to obtain a description of the clothing items worn. The possible error in the considered metabolic rate was also minimised by conducting the survey after the students had been seated in the classroom for at least one hour.
- People tend to evaluate a thermal environment based on their thermal experiences as a result of their repeated exposure to an environment, such as their living or work spaces (Nicol, Humphreys and Roaf 2012). In this study, the thermal comfort votes might have been biased by the students' thermal comfort in their living environments, the influence of which could not have been taken into account in this study, due to the large sample size and ethical issues. Therefore, apart from the mentioned contextual and human characteristics affecting thermal comfort perceptions in this study, the thermal condition of the students' living spaces might have influenced the thermal comfort votes, which is recommended to be taken into account in future works.
- The field study was carried out during the academic semesters when students were available in the university classrooms (from October 2017 to March 2018). However, as presented in Figure 3-2, the outdoor air temperature difference in Coventry and Edinburgh was negligible during the survey period (summer and spring months). Therefore, the results of this study cannot be extended to the whole year as it is likely that higher differences would be observed between the thermal perceptions of the occupants in Coventry and Edinburgh during the summer months (as a result of the subjects' acclimatisation).

3.7. Ethics

The field studies started after receiving the research ethics certificate from both universities. Ethics approval was provided after a review of the survey protocol, the participants' consent form, the participant recruitment strategy, the questionnaire and the data management protocol by both universities' Ethics Committees.

Chapter 4

4. Acclimatisation and Thermal Comfort in England & Scotland

4.1. Introduction

The human body can physiologically adjust itself to a broad range of thermal environments as a result of “thermoregulation” (Humphreys, Nicol and Roaf 2015). Body thermoregulation happens to maintain core body temperature at around 37ºC, to provide human health, well-being and comfort against environmental fluctuations (Humphreys, Nicol and Roaf 2015; Schweiker et al. 2018). As elaborated in section 2.3.2.1, such thermal adaptations along with the individual’s age and gender-related differences have been introduced as three parameters under *physiological human characteristics* affecting thermal perceptions. This chapter aims to investigate the influence of acclimatisation and age and gender-related differences as physiological drivers of diverse thermal perceptions, on the thermal comfort of occupants in UK higher learning environments.

- ***Research questions***

Considering the different prevalent climatic conditions in the northern (Scotland, with very cool, damp, rainy and windy weather) and southern/midland regions of the UK (England, with temperate and cool weather) (World Climate Guide 2019), it is expected to observe different thermal perceptions for people exposed to these various local climates. Furthermore, statistics on UK higher learning environments show various gender and age groups of university students (from under 20 to above 40 years old) (Patterns and Trends in UK Higher Education 2018), who may or may not, have different thermal perceptions (Fanger 1970; Cena, Spotila and Ryan 1988; Karyono 2000; Karjalainen 2007; Choi, Aziz and Loftness 2010; Hwang and Chen 2010). Therefore, this chapter aims to address the research questions number 1 and 2 of this thesis:

RQ 1. *"Taking account of the different climatic conditions in the northern (Scotland) and southern (England) regions of the UK, are the same thermal comfort criteria applicable in higher educational buildings throughout the UK"*

RQ 2. *"How do age- and gender-related differences among students affect thermal perceptions in higher learning environments?"*

4.2. Environmental thermal comfort indices

Table 4-1 summarises the environmental thermal comfort indices during the survey. The mean outdoor air temperature was higher in Coventry than Edinburgh. However, the mean indoor operative temperature, indoor air and mean radiant temperatures were approximately 1°C lower in Coventry than Edinburgh. The indoor air velocity was low and the mean indoor RH was almost in a similar range in both locations.

Table 4-1. Environmental thermal comfort indices

Location	Variables	Number	Mean	S.D.
Coventry	T_{out}	2051	11.2	4.1
	T_{air}	2051	22.9	1.6
	T_{mr}	2051	22.6	1.6
	T_{op}	2051	22.8	1.6
	RH	2051	45	12
	V_i	2051	0.07	0.03
	Clothing	1963	0.88	0.32
	TSV	2046	–0.1	1.2
	TP	2041	−0.04	1.1
Edinburgh	T_{out}	1460	5.8	1.9
	T_{air}	1460	23.9	1.6
	T_{mr}	1460	23.5	1.1
	T_{op}	1460	23.7	1.3
	RH	1460	30	6
	V_i	1460	0.04	0.04
	Clothing	1421	0.86	0.32
	TSV	1460	0.4	1.2
	TP	1459	0.30	1.1

T_{out}: Outdoor air temperature (°C), T_{air}: Indoor air temperature (°C), T_{mr}: Indoor mean radiant temperature (°C), T_{op}: Operative temperature (°C), V_i: Indoor air velocity (m/s), TSV: thermal sensation vote, TP: thermal preferences, S.D.: Standard deviation

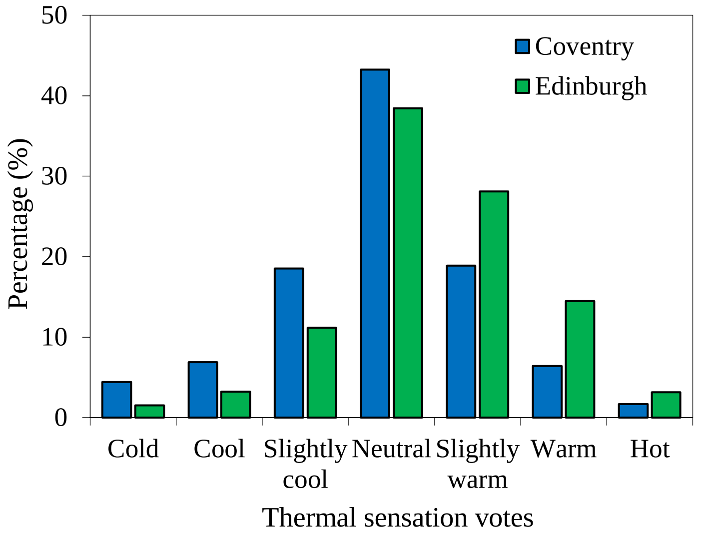
4.3. Subjective thermal comfort indices

The mean thermal sensation votes were equal to -0.1 and 0.4 in Coventry and Edinburgh respectively, showing that occupants in Coventry felt cooler than their counterparts in Edinburgh. This was confirmed by the warmer thermal preferences in Coventry and cooler preferences in Edinburgh (Table 4-1).

The distribution of the thermal sensation votes and thermal preferences in Coventry and Edinburgh is presented in Figure 4-1. Students in both locations felt thermally neutral and voted for ‘no change’ as their thermal preference. The thermal sensation votes were skewed more towards the colder than the neutral side in Coventry. However, an opposite pattern with a distinct skewing more towards the warmer than the neutral side was indicated in Edinburgh.

Regarding the thermal preference votes, a clear shift towards ‘want warmer’ votes can be observed for students in Coventry, whereas a shift toward cooler preferences is indicated for the students in Edinburgh, which is consistent with the thermal sensation votes in both locations.

(a)



(b)

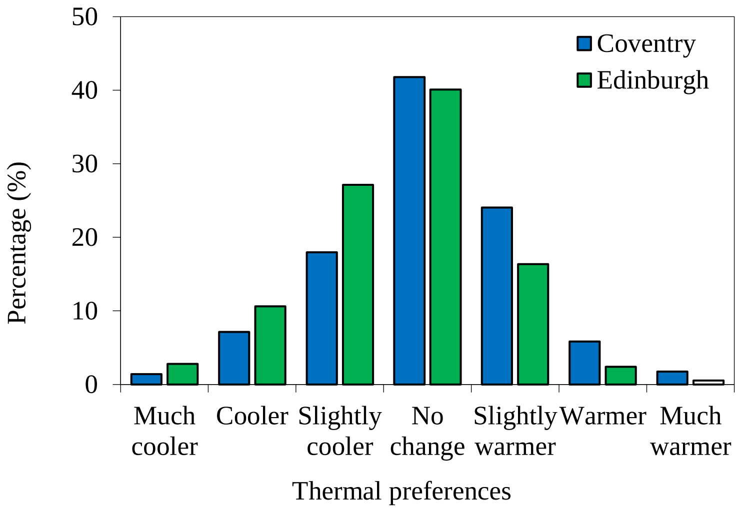


Figure 4-1. Distribution of thermal sensation (a) and preference (b) votes in Coventry and Edinburgh

This section explores the relation between thermal sensation and preference votes to investigate how the students perceived the currently-exposed thermal environment and how they would have liked to feel at the moment (Figure 4-2). The ‘want warmer’ includes ‘slightly warmer’, ‘warmer’ and ‘much warmer’ preference votes, whereas ‘want cooler’ includes ‘slightly cooler’, ‘cooler’ and ‘much cooler’ thermal preference votes. The ‘want warmer’ and ‘want cooler’ line is the cumulative percentage and ‘no change’ line is the actual percentage for each thermal sensation vote. As expected, by moving more towards warmer and cooler than neutral thermal sensation votes, the percentage of the ‘want cooler’ and ‘want warmer’ thermal preferences respectively increases. The highest proportion of the students with thermal sensation votes of ‘neutral’ preferred no change, showing their thermal satisfaction in the currently-exposed thermal condition.

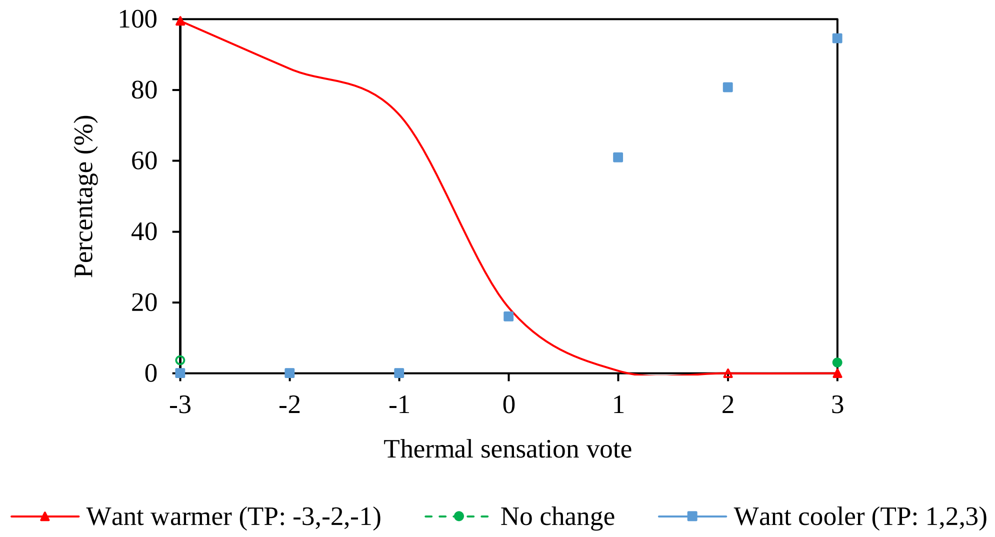


Figure 4-2. Relation between TSVs and TPs. The ‘want warmer’ or ‘want cooler’ line is the cumulative percentage and ‘no change’ line is the actual percentage for each thermal sensation vote.

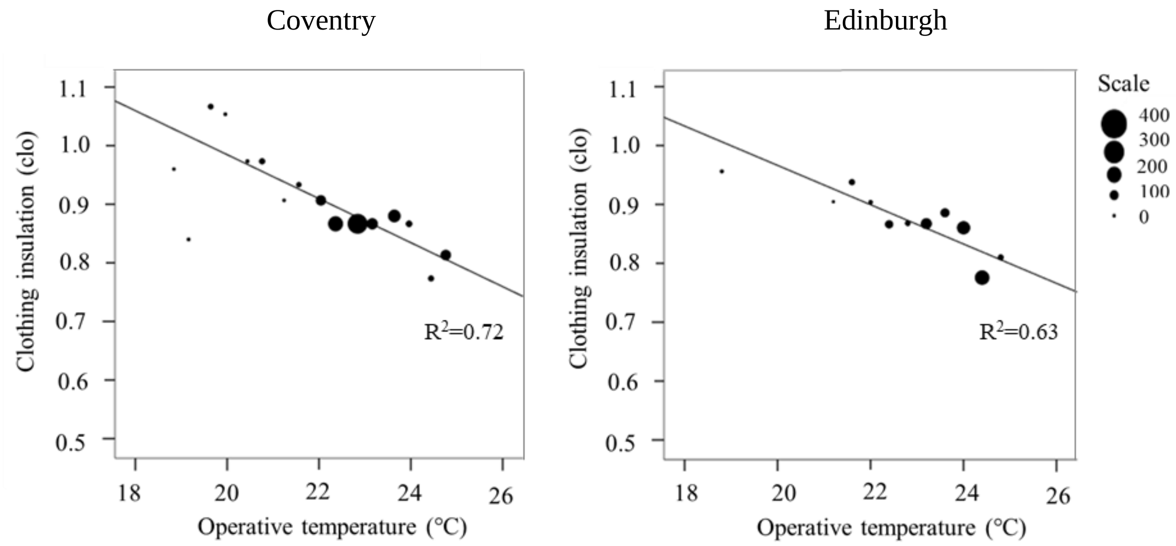


Figure 4-3. Relation between clothing insulation value and operative temperature

In terms of clothing insulation, a significant correlation between this parameter and the mean outdoor and indoor operative temperature was revealed in this study ($p<0.05$). Figure 4-3 and Table 4-2 show the negative correlation between clothing insulation value and operative temperature in both locations. This negative association between clothing insulation and mean indoor and outdoor temperature is also supported by previous studies in the field of thermal comfort and adaptive behaviour (Nicol et al. 1999; De Carli et al. 2007; Schiavon and Lee 2013; Liu et al. 2018).

Table 4-2. Relation between clothing insulation and operative temperature

Location	Equation	N	R^2	S.D.	S.E.
Coventry	$I_{cl} = -0.02\,T_{op} + 1.06$	1400	0.72	0.05	0.03
Edinburgh	$I_{cl} = -0.01\,T_{op} + 1.03$	1000	0.63	0.04	0.03

I_{cl}: Clothing insulation value, T_{op}: Operative temperature, N: Number, R2: Regression coefficient, S.D.: Standard deviation, S.E.: Standard error

4.4. Thermal neutrality

Linear regression between the thermal sensation votes (TSVs) and indoor operative temperature was used to determine the thermal neutrality (Figure 4-4). The resulting equations and coefficient of determination are presented in Table 4-2. In this work, similar to previous studies (e.g. Nakano, Tanabe and Kimura 2002; Wang 2006), there was a high variety of thermal sensation votes in each indoor air temperature, which was mainly due to the individual differences between the subjects (discussed in section 4.1, Introduction) (Shipworth et al. 2016; Schweiker et al. 2018). The raw data caused too low a coefficient of determination (R^2) between the thermal sensation votes and the prevalent indoor operative temperature, which can be considered acceptable for such types of studies (de Dear and Brager 1998).

Table 4-3. Equations from the linear regression between TSV and Operative temperature

Location	Equations	N	R^2	p-value	S.E.
Coventry	$TSV = 0.30\, T_{op} - 6.82$	2044	0.15	<0.001	1.11
Edinburgh	$TSV = 0.29\, T_{op} - 6.47$	1430	0.11	<0.001	1.08

TSV: thermal sensation vote, T_{op}: Operative temperature, N: Number, R2: Regression coefficient, p-value: probability, S.E.: Standard error

Neutral temperature (which was identified by the substitution of 0 for TSV in the equations presented in Table 4-3) was equal to 22.7°C in Coventry and 22.3°C in Edinburgh. Considering the regression gradient in the equations as an index showing how TSVs were dependent on the operative temperature, approximately each 3°C temperature change led to a variation of one unit in the thermal sensation votes in a 7-point sensation scale in both Coventry and Edinburgh, which shows a similar sensitivity of the occupants to the temperature changes inside the classrooms in both locations.

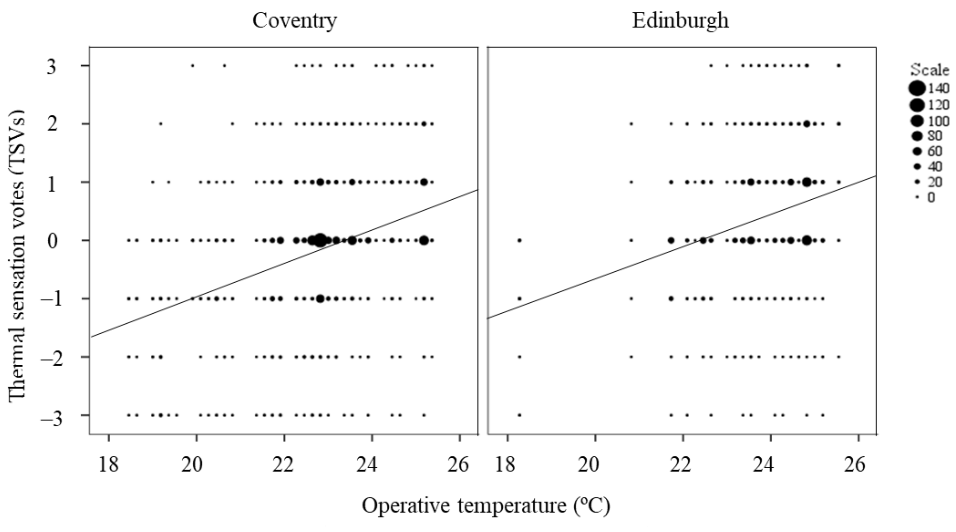


Figure 4-4. Linear regression of TSV and indoor operative temperature in Coventry and Edinburgh

4.5. Preferred temperature

To identify the occupants' preferred temperatures, thermal preference votes of 'much warmer', 'warmer', and 'slightly warmer' were classified as 'want warmer' and thermal preference votes of 'much cooler', 'cooler' and 'slightly cooler' were categorised as 'want cooler'. The proportions of warmer and cooler thermal preference votes in relation to the operative temperature were evaluated, as suggested in de Dear et al. (2015) and Jungsoo and de Dear's studies (2018). In Figure 4-5, the intersection points between warmer and cooler thermal preference votes is considered as the preferred temperature. Table 4-4 summarises the equations from the probit analysis. The mean temperature was calculated by dividing the constant value by the probit regression coefficient for each equation. The standard deviation was the inverse of the regression coefficient. All the equations were statistically significant ($p<0.001$).

The preferred temperature was around 23.5°C in Coventry and 23°C in Edinburgh, which was similar in both locations. According to the results from the previous sections, the preferred temperature was apparently slightly affected by the students' thermal expectations as a result of acclimatisation.

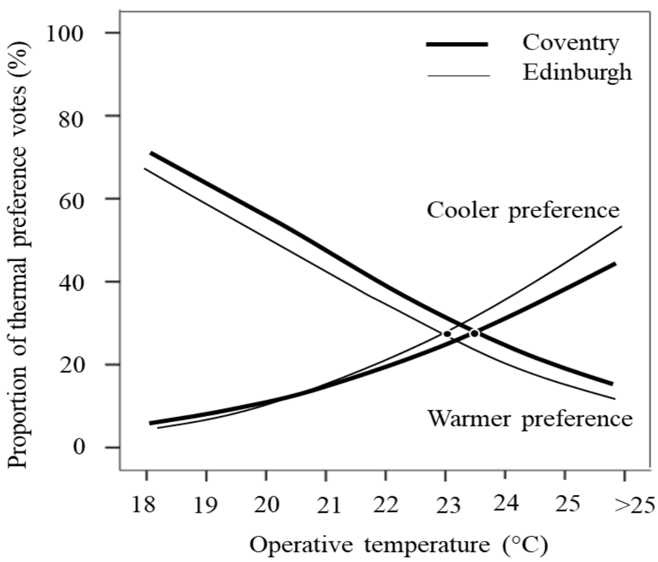


Figure 4-5. Preferred temperature in Coventry and Edinburgh

A comparison between the neutral and the preferred temperatures shows approximately a 1°C higher preferred than neutral temperature in Coventry and a less than 1°C higher preferred than neutral temperature in Edinburgh. This suggests that students in both Coventry and Edinburgh may have felt comfortable in slightly warmer than neutral thermal sensations. As discussed by Shahzad et al. (2018) and Shahzad and Rijal (2019), the neutral thermal sensation cannot guarantee the occupant's thermal comfort as the subjects may feel comfortable in thermal sensations other than neutral. Therefore, thermal preference is shown to be more likely to predict people's thermal comfort in a real world context.

Table 4-4. Equations from the probit analysis

Location	Thermal preference votes	Equations	P value	Mean	SD
Coventry	Warmer preference	$TP_{warmer} = -0.20\ Top + 0.95$	< 0.01	4.8	5.0
	Cooler preference	$TP_{cooler} = 0.18\ Top - 1.95$	< 0.01	10.9	5.6
Edinburgh	Warmer preference	$TP_{warmer} = -0.21\ Top + 0.85$	< 0.01	4.1	4.8
	Cooler preference	$TP_{cooler} = 0.22\ Top - 2.12$	< 0.01	9.6	4.6

The findings in this section have been confirmed in some studies that show the influence of acclimatisation on thermal preferences and preferred temperature (Teli, Jentsch and James 2012; Hwang 2018; Jungsoo and de Dear 2018). Results from studies conducted in the hot and humid climate of Taiwan (Hwang 2018), during the summer season in Australia (Jungsoo and de Dear 2018), during the heating period in the UK (Teli, Jentsch and James 2012) and in Japan, Norway and the UK (Shahzad and Rijal 2019) confirm the gap between thermal neutrality and preferences.

4.6. Thermal acceptability

The thermal acceptability level was evaluated with two approaches in this study: 1) an indirect approach considering the three central thermal sensation votes (TSV= ±1 and 0) on a 7-point sensation scale as a thermally acceptable range (recommended in *ASHRAE 55* 2010b) and applied in previous studies (Toe and Kubota 2013; Manu et al. 2016; Zaki et al. 2017); 2) a direct approach analysing the students' direct responses to the question of "How do you find the thermal condition of the classroom at this moment?" on the 4-point acceptability scale (Table 3-3) in the questionnaire (Andreasi, Lamberts and Cândido 2010; Mishra and Ramgopal 2014b, 2015a).

4.6.1. The indirect approach

Thermal dissatisfaction was considered as thermal sensation votes other than the acceptable zone of –1, 0 and +1 on the 7-point thermal sensation scale (*ASHRAE 55* 2017). Therefore, thermal sensation votes of −3 and −2 were recoded as '1, uncomfortably cold' and the other votes recoded as '0, other votes'. The same rule was applied to the warmer than neutral thermal sensation votes where TSVs equal to +2 and +3 were recoded as '1, uncomfortably warm' and the rest were recoded as '0, other votes'. A probit regression model was applied to categorise the proportion of thermal dissatisfaction in binned operative temperature in 0.5°C intervals (Figure 4-6). The mean temperature was calculated by dividing the constant value by the probit regression coefficient and the standard deviation was the inverse of the regression coefficient (Rijal, Humphreys and Nicol 2019).

Considering the standard of a minimum 80% acceptability and less than 20% thermal dissatisfaction as recommended in regulatory documents such as ASHRAE 2017 (*ASHRAE 55* 2017), the thermally acceptable zone was 21 to 24.5°C in Coventry and 19.5 to 23.5°C in Edinburgh. A more detailed look indicates that cold thermal dissatisfaction occurred at a 1.5°C higher operative temperature in Coventry (20.5°C) than in Edinburgh (19.0°C). In other words, at 19.0°C, where more than 20% of the participants in Coventry still felt uncomfortably cold, more than 80% of the subjects in Edinburgh than in Edinburgh. Warm thermal dissatisfaction started at 25.5°C and 24.5°C in Coventry and Edinburgh, respectively. The optimal acceptable temperature, at which the lowest percentage of students were thermally dissatisfied, was approximately 22.5°C in Coventry and 21.5°C in Edinburgh (Figure 4-6).

A lower acceptable temperature range, a lower optimal acceptable temperature and a higher sensitivity to warmth in Edinburgh than Coventry apparently happened due to the participants' lower thermal expectations and cooler thermal adaptation in Edinburgh.

Findings on the thermally acceptable range (through the indirect approach) have been supported by previous studies conducted in higher education buildings in similar climatic conditions in China (Nicol et al. 1999; Schiavon and Lee 2013) and Italy (Nakano, Tanabe and Kimura 2002; Shipworth et al. 2016).

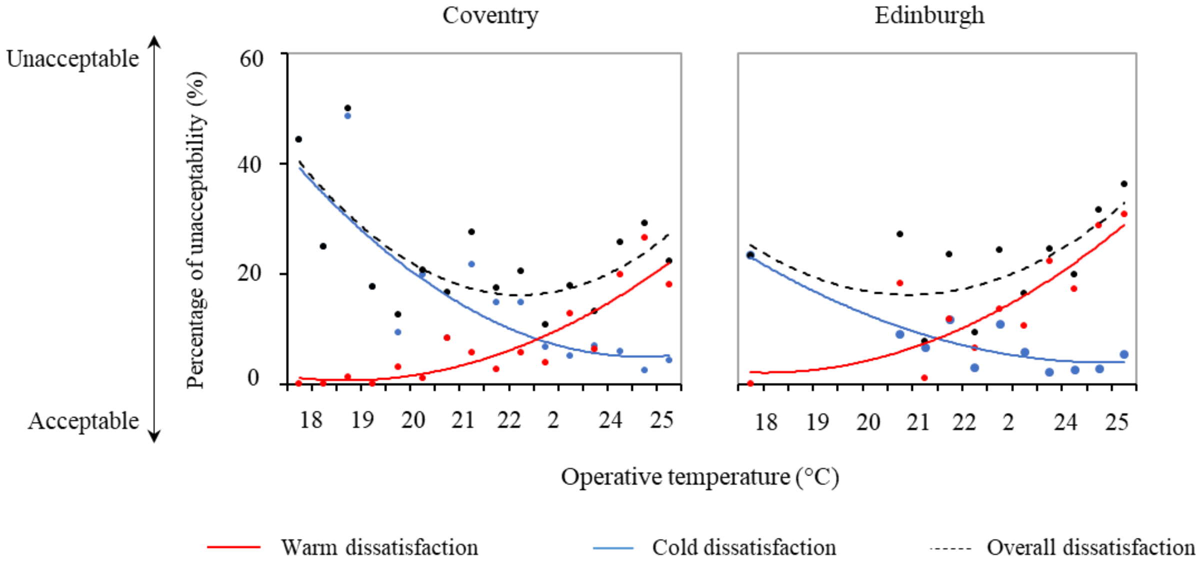


Figure 4-6. Uncomfortably warm and cold thermal dissatisfactions

4.6.2. The direct approach

Figure 4-7 shows the distribution of the participants' thermal acceptability votes in relation to their thermal sensation votes. The highest percentage of thermal acceptability occurred at TSVs of slightly cool (–1), neutral (0) and slightly warm (1), while moving towards 'hot' and 'cold' thermal sensation votes led to lower thermal acceptability levels.

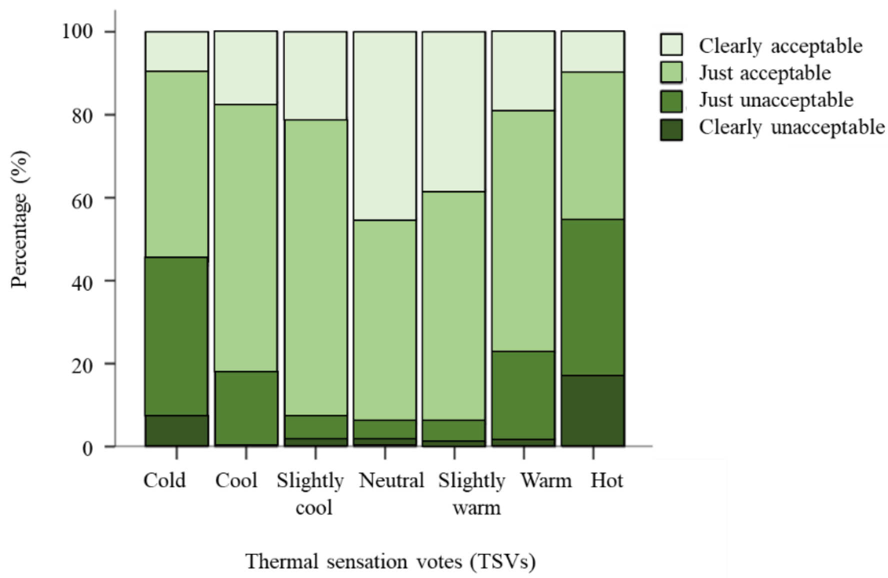


Figure 4-7. Distribution of thermal acceptability in relation to TSVs

Thermal acceptability in both evaluation methods in each 1ºC binned operative temperature is presented in Figure 4-8. An almost similar trend can be observed for both approaches with a slightly higher acceptability level and a wider range in the direct compared to the indirect approach. Students in higher learning environments tend to be more forgiving about their thermal environment when consciously evaluating and voting for it, compared to identifying their acceptable zone based on their thermal sensation votes, as recommended in regulatory documents (*ASHRAE 55* 2010b).

Two reasons may contribute to such a higher thermal acceptability level in the direct approach; one reason presumably was due to the students' perceptions of control in the classroom's thermal environment and its impact on their thermal acceptability level (Nicol et al. 1994; Brager, Paliaga and de Dear 2004; Rijal et al. 2008; Rijal, Yoshida and Umemiya 2010). Students in higher learning environments (depending on the classroom type and their activities) have freedom for adaptive behaviours, the perception of which can improve their thermal satisfaction (Brager, Paliaga and de Dear 2004) and lessen their feelings of thermal discomfort. The other reason can be due to the students' diverse physiological and psychological backgrounds (sections 2.3.2.1 and 2.3.2.2) resulting in a higher acceptability range, which could not have been predicted through thermal sensation votes (the indirect approach).

Overall, the similar trend in both the indirect and direct acceptability suggests that students in higher educational buildings tend to accept a wider range of thermal environments compared to those recommended in regulatory documents (*ASHRAE 55* 2010b). Therefore, fulfilling the occupants' thermal acceptability based on the three central TSVs (the indirect method) can be a better predictor of the thermally comfortable environment in higher educational buildings, as this method already covers the students' actual thermal satisfaction based on their direct thermal acceptability votes.

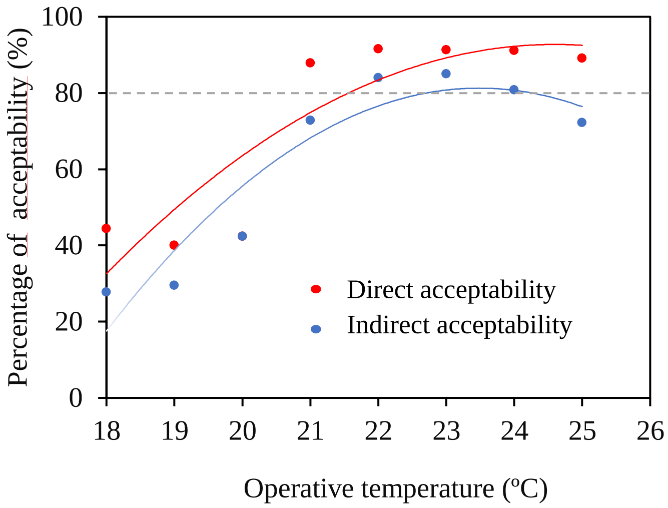


Figure 4-8. Thermal acceptability in each operative temperature

A detailed look at the subjects' thermal neutrality, preferred and optimal acceptable temperature confirms a more comparable value of the neutral and acceptable temperature but a slightly higher preferred temperature for students in both Coventry and Edinburgh. Although the students tended to prefer a warmer than neutral thermal environment, they still accepted an approximately 1ºC lower temperature than their preferred and neutral temperatures. From an energy point of view, considering temperatures of 22.5ºC and 21.5ºC as acceptable in university classrooms in Coventry and Edinburgh, respectively, could provide the occupants' comfort at the same time as saving energy for heating purposes.

4.7. Relation between gender and age with thermal comfort

Regarding the influence of age and gender on thermal comfort, the studies can be classified into two categories showing significant or no significant differences between thermal comfort perceptions of each gender and age group. In this work, the thermal comfort perceptions of both genders and different age groups were explored to identify their contribution to providing thermal comfort in higher learning environments. Table 4-5 presents the number of the participants in each gender and age group.

Table 4-5. Distribution of participants in each gender and age group

Gender						
	Male	Female				
Number	2308	1157				
Percentage (%)	66	33				
Age groups						
	Under 21	21-25	26-30	31-35	36-40	Above 40
Number	1785	1421	175	48	27	24
Percentage (%)	51	41	5	1	1	1

Table 4-6 summarises the indoor climatic conditions that each gender group was exposed to. With similar indoor operative temperature for both genders (≈23°C), women tended to have lower thermal sensation votes and higher thermal preferences compared to men. This comparison suggests that women evaluated the environment as cooler and wanted to be in warmer indoor climatic conditions than men, despite higher clothing insulation values for females than males. The comfort temperature was shown to be similar for both gender groups with identical operative temperatures and higher clothing insulation for females than males. To exclude the influence of the 1°C higher operative temperature in Edinburgh than Coventry on the thermal comfort results, evaluations for gender groups were considered separately in Coventry and Edinburgh.

Table 4-6. Thermal environmental condition to which each gender group was exposed

		Coventry			Edinburgh		
Gender	Variables	N	Mean	S.D.	N	Mean	S.D.
Female	TSVs	584	–0.26	1.27	571	0.27	1.13
	TP	582	−0.28	1.09	571	0.09	1.04
	Clothing (clo)	569	0.92	0.32	555	0.91	0.33
	T_c (ºC)	584	23.24	2.37	571	23.04	2.23
	T_{op} (ºC)	586	22.71	1.56	571	23.58	1.27
Male	TSVs	1436	−0.02	1.17	870	0.56	1.14
	TP	1434	−0.06	1.10	870	0.50	1.06
	Clothing (clo)	1369	0.86	0.31	848	0.82	0.31
	T_c (ºC)	1436	22.86	2.29	870	22.59	2.20
	T_{op} (ºC)	1438	22.81	1.54	870	23.72	1.30

TSV: thermal sensation votes, TP: thermal preferences, TC: Griffiths' comfort temperature, T_{op}: operative temperature, S.D.: Standard deviation

Considering the 100% of the subjects in each thermal sensation and preference vote, the proportion of the gender groups are demonstrated in Figure 4-9 and Figure 4-10, respectively. There are cooler thermal sensation votes for women than men in similar thermal environments in the classrooms. However, a distinct opposite trend can be observed for the thermal preference votes of both genders with cooler preferences for males and warmer preferences for females. An independent sample t-test and a Mann-Whitney U test (for normally and non-normally distributed votes, respectively) confirms the statistically significant difference between thermal sensation and preference votes between males and females in both Coventry and Edinburgh ($p<0.001$).

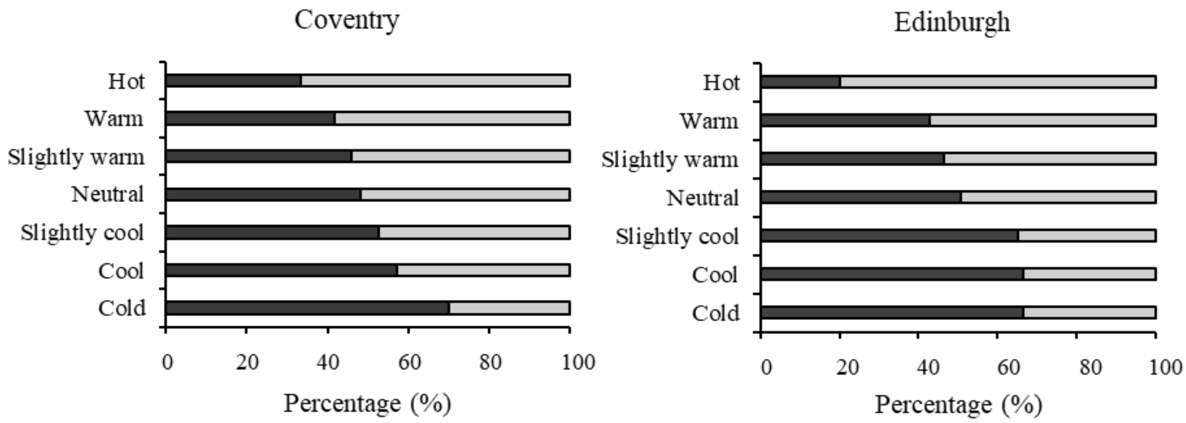


Figure 4-9. Thermal sensation votes in relation to genders

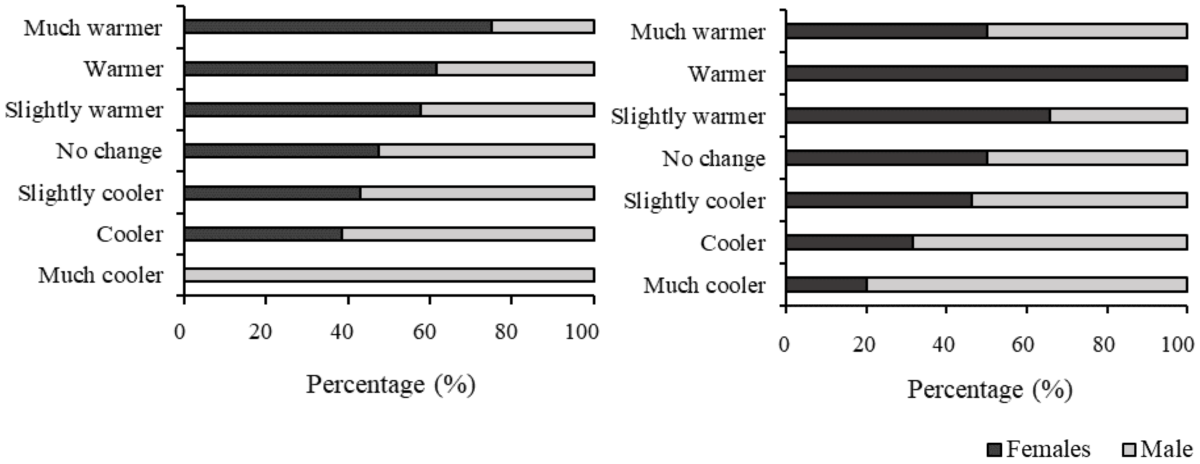


Figure 4-10. Thermal preference votes in relation to genders

Comfort temperatures were calculated using Griffiths' method for both genders in Coventry and Edinburgh. The comfort temperature for each of the thermal sensation votes was calculated using the following equation (Griffiths, 1991; Nicol et al. 1994; Rijal et al. 2008);

$$T_c = T_{op} + (TSV_n - TSV)/\alpha \quad \textit{(4-1)}$$

Where T_c is the comfort temperature by Griffiths' method (°C), T_{op} is the operative temperature (°C), TSV_n is the neutral thermal sensation vote (i.e. equal to 0 in this study), TSV is the thermal sensation vote and α is Griffiths' constant. The Griffiths' constant represents the change rate of the thermal sensation vote with the indoor temperature. Therefore, if the participants' thermal sensation vote was 0 (neutral), the comfort temperature would be the same as the operative temperature. According to the linear regression gradient between mean thermal sensation vote and operative temperature, approximately each 3°C temperature changes led to a variation of 1 unit in the thermal sensation votes in the ASHRAE 7-point sensation scale. Therefore, the value of 0.33 for the Griffiths' constant (α) was used (Rijal, Yoshida and Umemiya, 2010; Mustapa et al. 2016) to predict the students' comfort temperatures. An independent sample T-test confirmed the statistically significant difference between the mean comfort temperature between the gender groups with a slightly higher value for females (t-value: 4.809, F value: 0.755, Cohen's effect size: 0.175, p<0.001). However, there was a very similar comfort temperature for males and females with less than 0.5 ºC difference (Table 4-7). Although a similar comfort temperature for both genders was found, the heavier clothing worn by women (women's higher clothing insulation value) than men still confirms warmer thermal comfort requirements for females than males.

Table 4-7. Comfort temperature for each gender group

	Comfort temperature (ºC)					
	Coventry			Edinburgh		
Gender	N	Mean	S.D.	N	Mean	S.D.
Female	584	23.2	2.4	571	23.0	2.2
Male	1436	22.9	2.3	870	22.6	2.2

N: Number, S.D.: Standard deviation

Mean thermal acceptability was weighted in 1ºC binned operative temperature and a polynomial regression model was fitted to identify the acceptable temperature range of each gender group (Figure 4-11). The thermally acceptable zone (based on the 80% acceptability (*ASHRAE 55* 2010b)) for women was 21 to 25ºC, whereas this was between 20.5ºC and 24.5ºC for men, which may indicate higher and lower sensitivities of women than men to cool and warm thermal environments, respectively (Lan et al. 2008). The optimal acceptable temperature was 23.5ºC for females and 22.5ºC for males, showing a 1ºC warmer acceptable temperature for females than males.

Results in this work agree with the group of studies showing different thermal comfort for the gender groups, section 2.3.2.1 (Beshir and Ramsey 1981; Cena and de Dear 2001; Fato, Martellotta and Chiancarella 2004; Lan et al. 2008; Peng 2010). This study also shows a cooler thermal sensation, a warmer thermal preference, higher comfort temperature and a warmer thermal acceptability range for women than men.

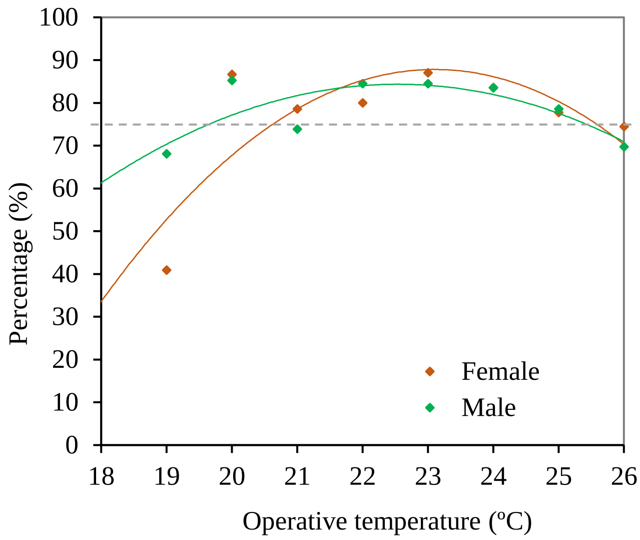


Figure 4-11. Thermal acceptability range (based on three central TSVs)

Regarding the influence of age-related differences on thermal comfort, Table 4-8 presents the thermal environment and thermal comfort votes of the different age groups in Coventry and Edinburgh. There was an almost similar outdoor and operative temperature for all age groups in Coventry (≈11ºC and ≈23ºC, respectively) and in Edinburgh (≈6ºC and 24ºC, respectively). Clothing insulation values were also similar for all age groups with mean values of 0.8-1.0 clo in Coventry and 0.7-0.9 clo in Edinburgh.

The normality test showed non-normal distribution of the thermal sensation votes, thermal preferences, acceptability and comfort temperature for each age group. Therefore, the Kruskal-Wallis test (the non-parametric alterative to the One-Way ANOVA) was run to examine the statistically significant difference between the thermal comfort of different age groups. The result of a Kruskal-Wallis test showed a statistically not significant difference between thermal sensation, preferences, acceptability and comfort temperature of different age groups in Coventry ($p>0.05$). Likewise, a statistically not significant difference was revealed between the thermal sensation and preference votes of the different age groups in Edinburgh ($p>0.05$). However, for those above 40 years old, a lower thermal acceptability was observed compared to those under 25 and a higher comfort temperature was observed compared to those under 35 years old in Edinburgh ($p<0.05$).

Table 4-8. Summary of thermal comfort indices for each age group

			T_{out} (ºC)	T_{op} (ºC)	Clothing *(clo)*	TSV	TP	T_c (ºC)	$T_{accept.}$
Under 21	N	Coventry	1200	1200	1159	1197	1196	1197	1195
		Edinburgh	585	585	573	585	585	585	585
	Mean	Coventry	11.4	22.8	0.9	−0.1	0.0	23.0	1.8
		Edinburgh	5.2	23.3	0.9	0.5	0.4	22.4	1.7
	SD	Coventry	4.3	1.5	0.3	1.2	1.1	2.4	0.7
		Edinburgh	1.5	1.3	0.3	1.2	1.1	2.3	1.7
21-25	N	Coventry	728	728	692	728	727	728	726
		Edinburgh	693	693	674	693	692	693	679
	Mean	Coventry	10.8	22.7	0.9	−0.1	−0.1	22.9	1.8
		Edinburgh	6.2	23.9	0.9	0.5	0.3	22.9	1.7
	SD	Coventry	3.8	1.6	0.3	1.2	1.1	1.3	0.7
		Edinburgh	6.2	23.8	0.9	0.5	-0.3	22.9	0.7
26-30	N	Coventry	55	55	54	55	55	55	55
		Edinburgh	120	120	117	120	120	120	109
	Mean	Coventry	11.2	22.9	0.9	−0.1	0.0	23.1	1.8
		Edinburgh	6.4	23.9	0.8	0.4	0.2	23.3	1.9
	SD	Coventry	3.0	1.3	0.3	1.1	1.0	2.1	0.7
		Edinburgh	1.6	1.1	0.3	1.2	1.1	2.0	0.7
31-35	N	Coventry	22	22	18	22	22	22	22
		Edinburgh	26	26	26	26	26	26	25
	Mean	Coventry	11.9	23.3	1.0	0.2	0.1	22.9	2.1
		Edinburgh	6.1	23.9	0.9	0.0	−0.2	23.9	1.9
	SD	Coventry	2.3	1.0	0.3	1.5	1.3	2.6	0.7
		Edinburgh	1.9	1.2	0.3	1.3	1.	2.4	1.0
36-40	N	Coventry	12	12	12	12	12	12	12
		Edinburgh	15	15	15	15	15	15	13
	Mean	Coventry	12.6	23.1	0.8	−0.6	−0.1	24.1	1.9
		Edinburgh	6.5	23.7	0.8	0.5	0.1	22.7	1.9
	SD	Coventry	2.2	1.0	0.3	1.3	1.0	2.7	0.7
		Edinburgh	1.7	1.2	0.4	1.0	1.0	2.2	0.6
Above 40	N	Coventry	12	12	12	12	12	12	12
		Edinburgh	12	12	11	12	12	12	12
	Mean	Coventry	11.3	22.3	0.8	0.0	0.1	22.3	2.0
		Edinburgh	6.4	23.4	0.7	1.0	0.8	23.3	2.0
	SD	Coventry	3.6	1.4	0.2	1.4	1.2	2.7	1.0
		Edinburgh	1.8	1.3	0.3	1.3	1.2	2.2	0.6

T_{out}: Outdoor air temperature, T_{op}: $operative\ temperature$, TSV: thermal sensation votes, TP: thermal preferences, T_c: Griffiths' comfort temperature, $T_{accept.}$: thermal acceptability , N: Number, S.D.: Standard deviation

4.8. Chapter summary

In this chapter, warmer thermal sensation votes, cooler preferences and higher comfort temperatures were revealed for the subjects in Coventry, England, compared to their counterparts in Edinburgh, Scotland, presumably as a result of acclimatisation. Regarding the influence of age and gender on perceptions of thermal comfort, a similar comfort temperature was found for both genders, with cooler sensations for females than males. However, no statistically significant difference between the thermal comfort of the different age groups was observed.

The key findings of this chapter are listed as follows:

- A negative correlation between the subjects' clothing insulation value and indoor operative temperature was found in both Coventry and Edinburgh (section 4.3).

- The thermal acceptability level was examined in two methods: a direct (considering the actual votes of the occupants on thermal acceptability) and an indirect approach (considering the thermal sensation votes between –1 and +1 as an acceptable range). A comparison between these two methods suggests that in designing a thermal environment in higher educational buildings, the indirect approach is a better predictor of the occupants' thermal acceptability as this method can provide comfort for a higher proportion of the students (section 4.6).
- Acclimatisation to the cold and temperate climates of Edinburgh and Coventry, respectively, caused cooler thermal sensation votes (mean TSV: –0.1) and warmer thermal preferences (mean TP: –0.04) for students in Coventry compared to their counterparts in Edinburgh (mean TSV: 0.4, mean TP: 0.3). Also, a higher comfort temperature in Coventry (23.5°C) than Edinburgh (22.1°C) was observed in this evaluation (section 4.6).
- The thermally acceptable zone was 21 to 24.5°C in Coventry and 19.5 to 23.5°C in Edinburgh. Cold thermal dissatisfaction started at a warmer temperature in Coventry than Edinburgh showing a higher sensitivity to cold in Coventry than Edinburgh. In contrast, a higher sensitivity to warmth in Edinburgh than Coventry was also revealed. The influence of acclimatisation on thermal sensitivity and acceptability in northern and southern regions of the UK can thus be inferred (section 4.6.1).
- A similar comfort temperature was found for both genders (≈23°C). However, heavier clothing insulation worn by women (≈0.92 clo) than men (≈ 0.83 clo) tends to support the warmer thermal comfort requirements of females than males. Regarding the thermal comfort of different age groups, there was no statistically significant difference between the thermal sensation and preference votes of the different age groups ($p>0.05$). However, for those above 40 years old, a lower thermal acceptability compared to those under 25 and a higher comfort temperature compared to those under 35 years old was observed in Edinburgh ($p<0.05$) (section 4.7).

Chapter 5

5. Thermal Comfort in Different Classroom Types

5.1. Introduction

As identified in the literature survey, section 2.3.2, students in higher learning environments come from a variety of disciplines and study a range of topics (Patterns and Trends in UK Higher Education 2018). Depending on the disciplines, students are exposed to different classroom types with variable occupancy periods, different activities and different levels of freedom for adaptive behaviours. Thus, different perceptions of thermal comfort in each classroom type follows, showing that the same environmental criteria may not be applicable in all types of classrooms to provide the occupants' thermal satisfaction. This chapter investigates students' thermal comfort in lecture rooms, studios and PC labs to determine the acceptable temperature range, comfort temperature and preferred adaptive behaviour in each type of teaching environment.

- ***Research question***

Given that students in studios are more active with making mock-ups and drawing, etc., it is expected to observe warmer thermal sensations, cooler thermal perceptions and lower comfort temperatures for the students in studio type classrooms compared to their counterparts in lecture rooms and PC labs. Thus, this chapter addresses the research question number 3 of this thesis:

<u>*RQ 3.*</u> *"What are the thermal comfort requirements of students in diverse disciplines exposed to various classroom types? / Can the same thermal comfort criteria be applicable in all classroom types in university buildings?"*

5.2. Outdoor and indoor environments

Results for the indoor and outdoor environmental parameters are presented in Table 5-1 The mean indoor air temperature, the mean radiant temperature and the operative temperature (in the survey period) were approximately 22.9°C, 22.6°C and 22.8°C in Coventry, respectively. In Edinburgh, these values (averaged over January to April 2018) were 21.7°C, 22.2°C and 22.0°C, respectively. According to Table 5-1, the mean outdoor air temperature for FR mode in Coventry was higher than Edinburgh within the survey period. However, the indoor operative temperature in all the classroom types under all operation modes in Edinburgh was higher than Coventry. The air velocity was low in both locations in all the operation modes. The mean indoor relative humidity was 24% higher in Coventry than Edinburgh under FR mode, but it was almost in a similar range in both locations under HT mode. Considering the classroom types and the HVAC operation modes in Coventry, the mean operative temperature in the studios was 1°C higher than the lecture rooms under FR mode and 2°C under HT mode (Table 5-1). In the PC labs, it was 1°C higher than the lecture rooms under both FR and CL modes. The operative temperature in all the classroom types was higher in Edinburgh than Coventry.

Table 5-1. Summary of the indoor and outdoor environmental parameters

Classroom type	Mode	Item	T_{out} (°C)		T_{air} (°C)		T_{mr} (°C)		T_{op} (°C)		V_i (m/s)		RH_{in} (%)		CO_2 (ppm)	
			Cov.	Edi	Cov.	Edi	Cov.	Edi	Cov.	Edi.	Cov.	Edi.	Cov.	Edi	Cov.	Edi.
Lecture room	FR	Mean	12.7	6.5	22.6	24.3	22.7	23.7	22.6	24.1	0.08	0.03	51	27	1359	1022
		SD	2.6	1.2	1.3	1.1	1.4	0.9	1.3	1.0	0.35	0.02	9	3	725	275
	CL	Mean	10.3	-	22.7	-	22.0	-	22.4	-	0.07	-	38	-	951	
		SD	4.8	-	2.1	-	1.7	-	1.9	-	0.24	-	9	-	157	
	HT	Mean	3.8	5.6	21.2	23.8	20.3	23.4	20.8	23.7	0.06	0.04	24	31	779	1020
		SD	2.7	2.1	1.5	1.3	1.2	0.9	1.2	1.1	0.29	0.03	5	6	34	263
Studio	FR	Mean	14.0	-	24.0	-	23.8	-	23.9	-	0.07	-	60	-	2624	-
		SD	2.2	-	1.0	-	1.1	-	0.9	-	0.04	-	7	-	1367	-
	HT	Mean	9.0	-	23.3	-	23.2	-	23.2	-	0.03	-	41	-	1847	-
		SD	0.0	-	0.6	-	0.7	-	0.6	-	0.01	-	4	-	327	-
PC lab	FR	Mean	11.3	-	23.3	-	23.5	-	23.4	-	0.03	-	44	-	1322	-
		SD	2.0	-	0.9	-	0.8	-	0.8	-	0.02	-	7	-	327	-
	CL	Mean	13.1	-	23.5	-	23.1	-	23.3	-	0.08	-	49	-	1651	-
		SD	1.8	-	0.5	-	0.7	-	0.6	-	0.05	-	5	-	771	-

T_{out}: Outdoor air temperature (°C), T_{air}: Indoor air temperature (°C), T_{mr}: Indoor mean radiant temperature (°C), T_{op}: Operative temperature (°C), V_i: Indoor air velocity (m/s), -: no data available, SD: standard deviation

5.3. Subjective thermal comfort indices

Figure 5-1 indicates the relation between the clothing insulation values and the thermal sensation votes vs. the operative temperature binned at 0.5°C intervals in Coventry and Edinburgh. A very similar trend can be observed for mean TSVs and mean clothing insulation values in both locations.

(a) (b)

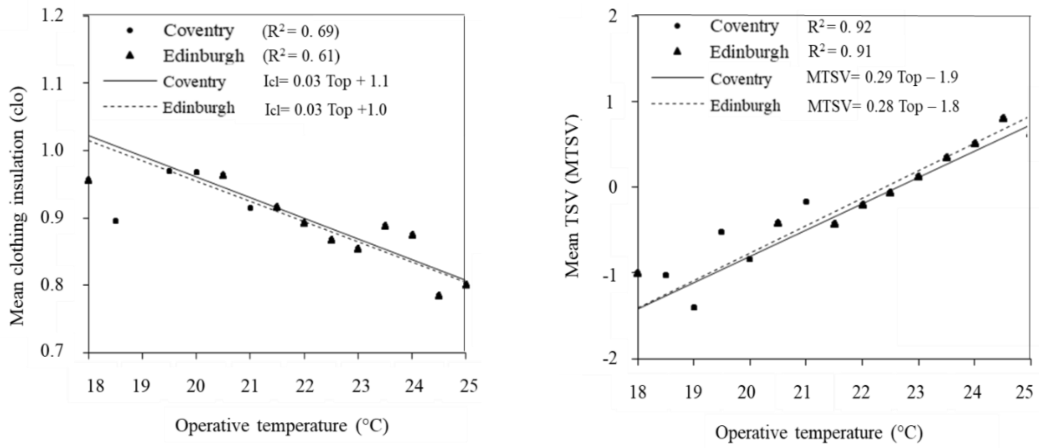


Figure 5-1. Relation between operative temperature and (a) mean clothing insulation, and (b) mean TSV

Table 5-2 presents a summary of the mean value of the subjective parameters collected during the survey. The mean thermal sensation votes (MTSVs) in all classroom types in both locations were in the comfort zone between –0.5 and +0.5. The negative value of MTSV in the lecture rooms in Coventry (−0.26) indicates the students' cold thermal sensations in such spaces. However, the MTSV in the studios and PC labs were 0.20 and 0.12, respectively, showing that students felt warmer than neutral in these environments. The thermal preference votes under all the operation modes showed the occupants' preferences towards a warmer thermal environment in lecture rooms and a cooler environment in studios and PC labs, which is consistent with their thermal sensation votes. The mean clothing value for all participants in all classroom types was in the range of 0.85 to 0.91 clo.

Table 5-2. Summary of subjective evaluations

Classroom type	Mode	Item	TSV		TP		Clothing (clo)		Overall comfort		Thermal acceptability	
			Cov.	Edin.	Cov.	Edin.	Cov.	Edin.	Cov.	Edin.	Cov.	Edin.
Lecture room	FR	Mean	−0.20	0.49	−0.13	0.38	0.87	0.84	1.54	1.53	1.86	1.83
		SD	1.22	1.22	1.11	1.12	0.32	0.32	0.80	0.75	0.67	0.74
	CL	Mean	−0.23		−0.11	-	0.85	-	1.56	-	1.83	-
		SD	1.20		1.12	-	0.31	-	0.78	-	0.67	-
	HT	Mean	−0.54	0.50	−0.32	0.39	0.96	0.85	1.45	1.48	1.75	1.8
		SD	1.17	1.10	1.14	1.03	0.32	0.31	0.68	0.70	0.64	0.78
Studio	FR	Mean	0.18	-	0.19	-	0.90	-	1.56	-	1.90	-
		SD	1.15	-	1.13	-	0.29	-	0.76	-	0.64	-
	CL	Mean	-	-	-	-	-	-	-	-	-	-
		SD	-	-	-	-	-	-	-	-	-	-
	HT	Mean	0.27	-	0.12	-	0.87	-	1.49	-	1.82	-
		SD	1.14	-	1.05	-	0.30	-	0.73	-	0.66	-
PC lab	FR	Mean	0.19	-	0.17	-	0.86	-	1.43	-	1.77	-
		SD	1.09	-	0.99	-	0.31	-	0.71	-	0.72	-
	CL	Mean	0.05	-	0.06	-	0.87	-	1.43	-	1.68	-
		SD	1.21	-	1.03	-	0.32	-	0.74	-	0.62	-
	HT	Mean	-	-	-	-	-	-	-	-	-	-
		SD	-	-	-	-	-	-	-	-	-	-

- : No data available, SD: standard deviation, Cov.: Coventry, Edin.: Edinburgh

Figure 5-2 shows the distribution of thermal sensation and thermal preference votes in Coventry and Edinburgh. TSVs are normally distributed centred in "neutral" with a negligible shift towards colder votes in Coventry. However, there is a tendency towards the warmer side in Edinburgh, showing students' warmer than neutral thermal sensations. As suggested by Fanger (1970), Humphreys and Nicol (1970), Humphreys, Nicol and Roaf (2015), Nicol et al. (1999) and the ASHRAE standard (*ASHRAE 55* 2017), thermal sensation votes between −1 and 1 can be considered as a subject's thermal satisfaction. Accordingly, in this study, approximately 78% and 80% of the students in Edinburgh and Coventry, respectively, were thermally satisfied. This shows that the classrooms in Coventry where the surveys were conducted were already in the thermal acceptable zone (80% acceptability) (Humphreys and Nicol 1970; *ASHRAE 55* 2013; Humphreys, Nicol and Roaf 2015), whereas the classrooms in Edinburgh were slightly below this acceptability reference value. As expected, there was an opposite trend between the students' TSVs and TPs in both locations. Around 40% of students in Edinburgh and Coventry voted for '0 no change'. 41 % of students in Edinburgh preferred to be cooler, while only 19% wanted a warmer environment. In Coventry, 27% and 32% of the participants preferred to be cooler and warmer, respectively.

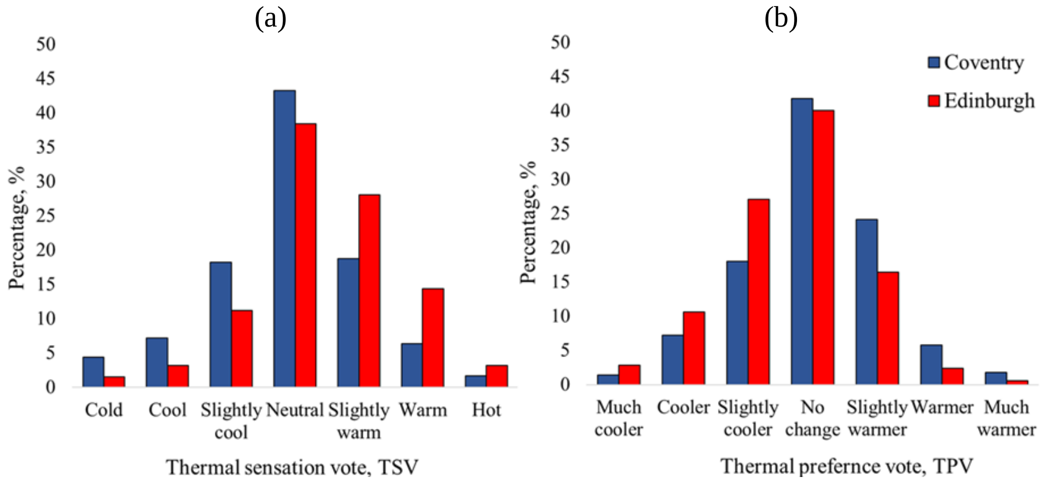


Figure 5-2. Distribution of thermal sensation (a) and preference votes (b) in Edinburgh and Coventry

5.4. Comfort zone

As suggested by Nicol et al (2012), Humphreys et al. (2015) and the ASHRAE standard (*ASHRAE 55* 2017), the thermal comfort zone was assumed as the range within which a subject would feel thermally comfortable or satisfied, which was taken as the three central categories on the ASHRAE sensation scale. The thermal acceptable zone was considered as the temperature range in which 80% of the occupants voted for thermal sensations between −1 to 1 (Nicol, Humphreys and Roaf 2012; Humphreys, Nicol and Roaf 2015).

To identify the students' thermal comfort zone under each operation mode, Probit regression analysis was applied to the thermal sensation votes and the operative temperatures. Probit analysis deals with binary responses to a variable. In the case of thermal sensation votes, the two responses are arranged as 1) TSV between −1 to 1 (on the subjective ASHRAE seven-point scale), which is considered as the 'comfort zone' (Fanger 1970; Nicol, Humphreys and Roaf 2012; *ASHRAE 55* 2017); and 2) TSVs beyond the comfort zone (TSV= ±2 and ±3). This analysis was conducted by applying Probit regression as a link function and the operative temperature as covariate (Rijal, Humphreys and Nicol 2017). To complete the process, all the equations were transformed to proportions in the CDF.NORMAL function using the SPSS statistical software package.

$$Probability = CDF.NORMAL\ (quant, mean, SD) \quad (5\text{-}1)$$

where CDF.NORMAL is the cumulative distribution function, quant is the operative temperature (°C); the mean is calculated by dividing the constant value by the Probit regression coefficient and standard deviation (SD) is the inverse of the regression coefficient in each equation (Rijal, Humphreys and Nicol 2017). Equations from the Probit regression analysis (statistically significant, $p < 0.001$) are presented in Table 5-3.

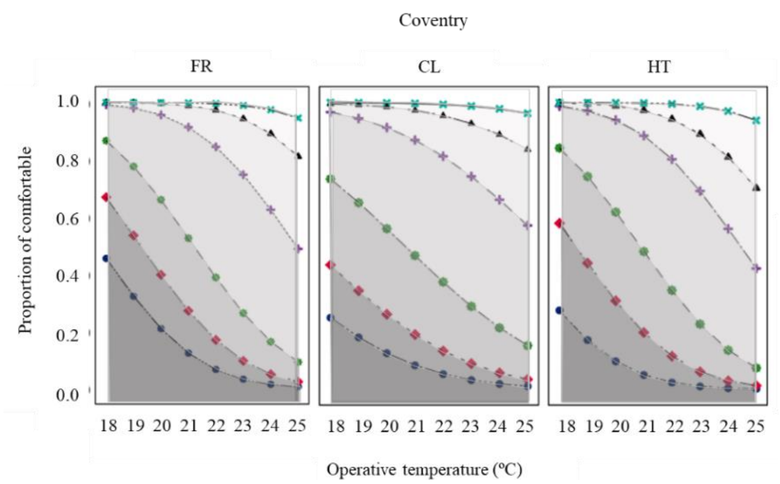
Table 5-3. Results of the Probit analysis

Location	Classroom type	Equation *	Median	SD
Coventry	FR	$P(\leq -3) = 0.35\ T_{op} - 6.14$	17.5	2.85
		$P(\leq -2) = 0.35\ T_{op} - 6.69$	19.1	
		$P(\leq -1) = 0.35\ T_{op} - 7.37$	21.0	
		$P(\leq 0) = 0.35\ T_{op} - 8.66$	24.8	
		$P(\leq 1) = 0.35\ T_{op} - 9.58$	27.4	
		$P(\leq 2) = 0.35\ T_{op} - 10.29$	29.4	
	CL	$P(\leq -3) = 23\ T_{op} - 3.57$	15.5	4.34
		$P(\leq -2) = 0.23\ T_{op} - 4.08$	17.7	
		$P(\leq -1) = 0.23\ T_{op} - 4.86$	21.1	
		$P(\leq 0) = 0.23\ T_{op} - 6.07$	26.4	
		$P(\leq 1) = 0.23\ T_{op} - 6.88$	29.9	
		$P(\leq 2) = 0.23\ T_{op} - 7.68$	33.4	
	HT	$P(\leq -3) = 0.35\ T_{op} - 5.69$	16.3	2.85
		$P(\leq -2) = 0.35\ T_{op} - 6.49$	18.6	
		$P(\leq -1) = 0.35\ T_{op} - 7.29$	20.1	
		$P(\leq 0) = 0.35\ T_{op} - 8.55$	24.4	
		$P(\leq 1) = 0.35\ T_{op} - 9.27$	26.5	
		$P(\leq 2) = 0.35\ T_{op} - 10.28$	29.4	
Edinburgh	FR	$P(\leq -3) = 0.25\ T_{op} - 3.86$	15.4	4.00
		$P(\leq -2) = 0.25\ T_{op} - 4.29$	17.2	
		$P(\leq -1) = 0.25\ T_{op} - 4.91$	19.6	
		$P(\leq 0) = 0.25\ T_{op} - 6.13$	24.5	
		$P(\leq 1) = 0.25\ T_{op} - 6.85$	27.4	
		$P(\leq 2) = 0.25\ T_{op} - 7.90$	31.6	
	HT	$P(\leq -3) = 0.31\ T_{op} - 4.87$	15.7	3.22
		$P(\leq -2) = 0.31\ T_{op} - 5.47$	17.6	
		$P(\leq -1) = 0.31\ T_{op} - 6.23$	20.1	
		$P(\leq 0) = 0.31\ T_{op} - 7.42$	23.9	
		$P(\leq 1) = 0.31\ T_{op} - 8.34$	26.9	
		$P(\leq 2) = 0.31\ T_{op} - 9.28$	29.9	

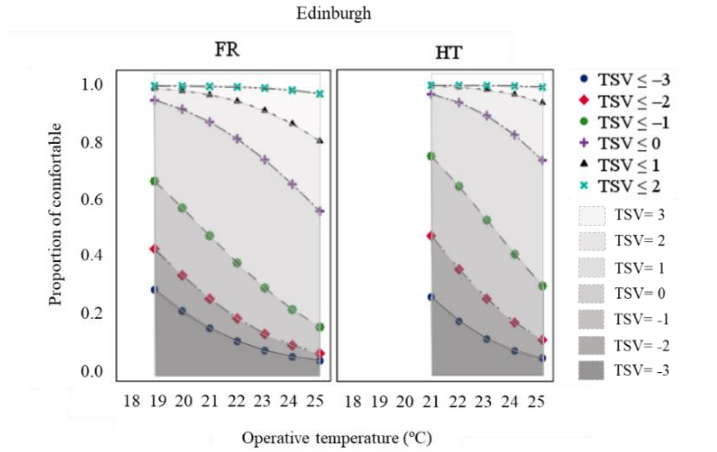
* All the equations are statistically significant ($p<0.001$)

In Figure 5-3 (a) and (b), each layer indicates the proportion of comfort votes equal to a particular vote (the lowest layer shows the actual proportion of vote –3) (Nicol, Humphreys and Roaf 2012). The mean neutral temperature, which can be identified with a probability of 0.5 in TSV between –1 and 1 was around 23°C in FR and HT modes and 24°C in CL mode in Coventry. In Edinburgh, it was around 22°C under both FR and HT modes. Figure 5-3 (c) indicates the optimal temperature at which the highest proportion of the occupants were thermally satisfied. In Coventry, this value was equal to 24°C under both FR and CL modes and 22°C under HT mode and in Edinburgh, 22°C under FR and HT modes. Considering the standard of minimum 80% acceptability as recommended in regulatory documents such as ASHRAE 55 (2017), the comfort zone in Coventry was equal to 22-25°C under FR and CL and 21-24°C under HT mode. In Edinburgh, it was 21-24°C under HT mode (Figure 5-3, c).

(a)



(b)



(c)

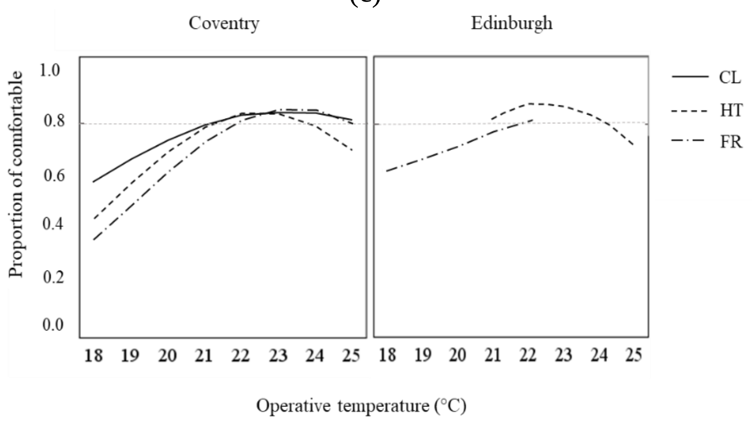


Figure 5-3. Proportion of thermal sensation votes vs. operative temperature (a,b) and proportion of comfortable vs. operative temperature (c)

5.5. Comfort temperature

Griffiths' method was applied to estimate the comfort temperature in each classroom type under FR, CL and HT modes. This approach can calculate the comfort temperature for each single thermal sensation vote and temperature. It is useful for small temperature ranges where linear regression is unreliable (Nicol, Humphreys and Roaf 2012). Griffiths' method uses a standard value for the linear relationship between comfort vote and operative temperature: 'Griffiths slope', which is equivalent to the regression coefficient. This method assumes a constant rate of comfort temperature change per variation of thermal sensation scale by considering the sensation vote of 'neutral' as comfortable (Nicol, Humphreys and Roaf 2012). The comfort temperature was calculated using the following equation (Griffiths, 1991; Nicol et al. 1994; Rijal et al. 2008);

$$T_c = T_{op} + (0 - TSV) / \alpha \quad (5\text{-}2)$$

T_c: comfort temperature – Griffiths' method (°C)
T_{op}: operative temperature (°C)
TSV: thermal sensation vote
α : Griffiths' constant (K^{-1})

Therefore, if the participants' thermal sensation vote was 0 (neutral), the comfort temperature would be the same as the operative temperature.

Table 5-4. Comfort temperature estimated by Griffiths' method

Location	Classroom	Mode	N	Comfort temperature (°C)					
				α = 0.25	S.D.	α = 0.33	S.D.	α = 0.50	S.D.
Coventry	Lecture room	FR	513	23.4	4.4	23.2	3.3	23.0	2.1
		CL	580	23.3	4.5	23.1	3.5	22.9	2.5
		HT	154	22.9	4.4	22.4	3.3	21.8	2.1
	Studio	FR	261	23.2	4.5	23.4	3.4	23.8	2.3
		HT	147	22.2	4.4	22.4	3.3	22.7	2.1
	PC lab	FR	192	22.6	4.3	22.8	3.2	23.0	2.2
		CL	199	23.2	4.6	23.2	3.5	23.2	2.3
Edinburg	Lecture room	FR	353	22.1	4.7	22.6	3.5	23.1	2.4
		HT	1013	21.6	4.2	22.2	3.2	22.7	2.1

α: Griffiths' constant, SD: standard deviation

Similar to the previous studies conducted by Nicol et al. (1994), Rijal et al. (2010) and Mustapa et al. (2016), three values for the Griffiths' constant (0.25, 0.33 and 0.50) were adopted to find the most reasonable comfort temperature (Table 5-4). A negligible difference was indicated between the obtained comfort temperatures. As the assumption behind Griffiths' method is no presence of the occupants' thermal adaptation (Nicol, Humphreys and Roaf 2012), the value of 0.5 for the Griffiths' constant (α) was considered in order to compensate for the influence of thermal adaptation. This shows that each 2°C change in the operative temperature leads to a 1 scale unit increase or decrease of the thermal sensation votes. According to the Griffiths' method assumption, the comfort temperature was calculated for each data record. The mean of the comfort temperature in the lecture rooms was similar; 23°C in both Coventry and Edinburgh under FR mode, but Edinburgh had a 1°C higher comfort temperature than Coventry under HT mode (Figure 5-4).

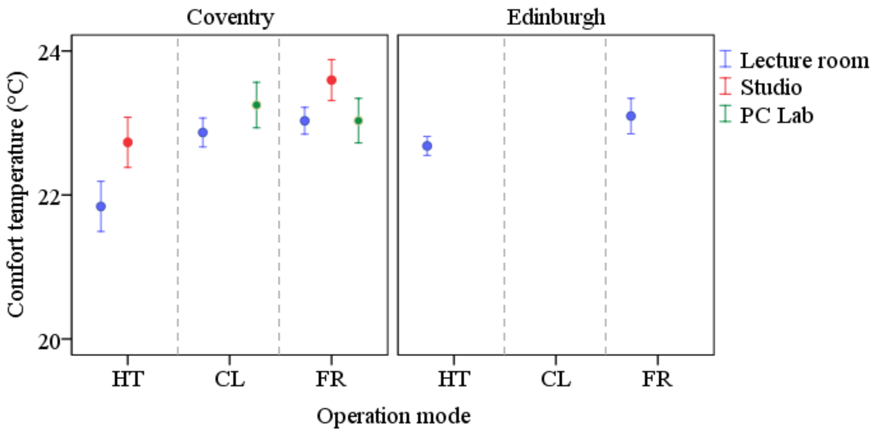


Figure 5-4. Comfort temperature in the classrooms in each mode

A one-way ANOVA test confirmed that there was no statistically significant difference between comfort temperatures in the lecture rooms and the PC labs in Coventry. However, a statistically significant difference was illustrated between the comfort temperature in the studios and the other classroom types (F value: 15.174, $p<0.05$). The comfort temperature was approximately 1°C higher in the studios compared to the lecture rooms and PC labs under FR and HT modes. The higher comfort temperature in the studios could have been due to the higher operative temperature in such classrooms than the lecture rooms and the PC labs. Figure 5-5 indicates a direct association between mean comfort and operative temperature in all classroom types, showing an increase of the comfort temperature as a result of the growth of the operative temperature.

According to Shahzad et al. (2019) and Shahzad and Rijal (2019), the essential information regarding the thermal comfort of a group of occupants is whether they prefer any change in the environment, as subjects may feel warm or cold but still find it acceptable; therefore, they prefer no change. Apart from the impact of this consideration on the subjects' comfort, it can save energy over the space as changing the thermal environment may increase the space energy demand (Shahzad et al. 2019). Although the comfort temperature was shown to be higher in the studios than the lecture rooms and PC labs, students in the studios and PC labs preferred to be cooler than their in-the-moment thermal sensations. This can be due to their higher levels of physical activities in studios and PC labs (drawing, PC modelling, making mock ups, etc.) than in the lecture rooms.

As shown in Table 5-1 and Table 5-4, proximity to the comfort temperature and prevailing operative temperatures is greater in the studios compared to the other classroom types. Similar comfort and operative temperatures in the studios can be explained by considering two influential factors: thermal adaptation and the students' control over the space.

1. *Thermal adaptation:* people physically adapt to a thermal environment to maintain a constant internal body temperature against environmental fluctuations. Long occupancy periods in the studios gives enough time for the occupants' physiological and psychological thermal adaptation to the environment. From a psychological point of view, occupants' thermal assessments during their initial occupancy of a space results from their thermal history, not the currently exposed thermal environment (Humphreys and Hancock 2007; Vargas and Stevenson 2014; Shahzad and Rijal 2019). However, after an extended period of occupancy, they change this set mental benchmark according to their experience of the indoor climatic condition (Fadeyi 2014). Therefore, a higher operative temperature along with a longer occupancy period in the studios than the other classroom types led to the occupants' warmer thermal adaptation and higher comfort temperature in the studios than the lecture rooms and PC labs.
2. *Control over the space:* due to the students' greater freedom and consequently higher levels of control over the space in the studios, they can take on proper environmental or personal adaptive behaviours to improve their physiological thermal adaptation and to maintain their thermal comfort. Psychologically, the perception of control over an environment reduces the occupants' thermal sensitivity and improves their thermal comfort perceptions (Liu, Yao and McCloy 2014). According to Brager et al. (2004), the availability of control opportunities in an environment leads to the proximity of the occupants' neutral temperature and the prevalent mean operative

temperature. This would obviously explain the similar comfort temperature to the operative temperature in the studios.

Results in this section are supported by previous studies showing that optimal comfort and neutral temperature of the occupants with a high level of environmental control is very close to the actual experienced temperature (Nicol et al. 1994; Rijal et al. 2008). It is also shown that control over a space leads to an improvement in the occupants' thermal comfort (Nicol et al. 1999; *CIBSE Guide A*. 7th ed. 2010), neutral temperature (Zagreus et al. 2004) and thermal acceptability (Humphreys and Nicol 1970; Nicol et al. 1994, 1999; Rijal et al. 2008; Rijal, Yoshida and Umemiya 2010).

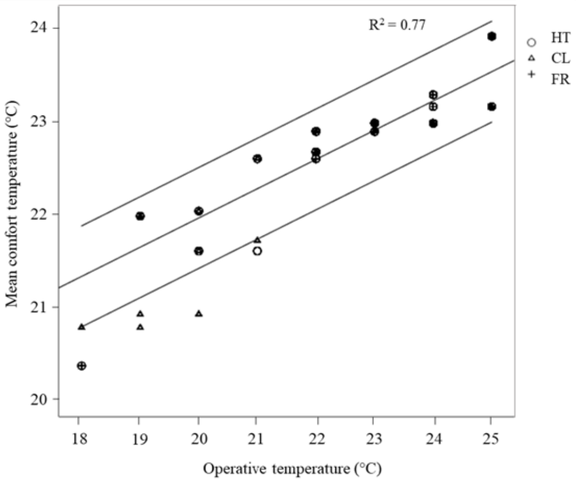


Figure 5-5. Relation between indoor operative and comfort temperature under each operation mode

5.5.1. Comparison of comfort temperature with other studies

Table 5-5 summarises the findings from other studies regarding comfort temperatures in higher educational buildings. As there is no study of the studio type of classrooms in university buildings, the comparison between the current and previous studies is mainly focused on the results from the lecture rooms. The most outstanding feature in Table 5-5 is the proximity of the operative and comfort temperatures in all the mentioned studies, reinforcing the results from the current work. Students tend to feel comfortable in a thermal environment they have been exposed to for a period of time. This finding was also confirmed by other researchers (Fanger 1970; Brager, Paliaga and de Dear 2004; Rijal et al. 2008; Ji et al. 2017), declaring that people's comfort temperatures are close to the mean temperatures they have experienced over a period of time. This confirms the influence of thermal adaptation on thermal comfort in classrooms. The comfort temperature obtained in this work is very close to studies conducted in European countries such as Italy (Nico, Liuzzi and Stefanizzi 2015) and the Netherlands (Mishra et al. 2017). The comfort temperature introduced in Italy (Nico, Liuzzi and Stefanizzi 2015) is equal to 21.8°C under FR mode, showing an almost 1°C lower comfort temperature than the UK. Also, the comfort temperature of 22°C and the comfort zone of 21–25°C in lecture rooms under HT mode in the UK is close to the comfort temperature range in the Netherlands at 22–24°C (Mishra et al. 2017), but with a wider range in the UK than the Netherlands showing an approximately similar thermal comfort for students in both locations under HT mode. However, a higher comfort temperature compared to the UK has been illustrated in other studies conducted in warm and tropical climates such as Malaysia, Singapore, Japan and India (Mustapa et al. 2016; Rijal, Humphreys and Nicol 2017; Zaki et al. 2017; Singh et al. 2018). Higher operative temperatures and occupants' warmer thermal adaptation and expectations could be the main reasons for the distinctions between these countries and the UK.

Table 5-5. Comparison of comfort temperature with previous studies in higher educational buildings

Ref.	Year	Location	Season	Analysis method	Sample size	T_{out} (°C)	T_{op} (°C)	T_c (°C)		
								FR	CL	HT
(Cao et al. 2011)	2011	China	Summer, Winter	Linear regression	206	Summer:24.5-30 Winter: 2.5-12.5	CL: 25.1 HT: 21.6		26.8	20.7
(Mishra and Ramgopal 2015a)	2013-2014	India	Autumn, Spring	Griffiths' method	357	14.5-32.5	29.8	29.5		
(Z. Wang et al. 2014)	2014	China	Summer	Linear regression	488	20.4-25	22.5 - 22.8		22.6, 21.7	
(Nico, Liuzzi and Stefanizzi 2015)	2015	Italy	Spring	Linear and Probit regression Adaptive model Rational model	126	13.5-14.6	22.6	21.8		
(Mishra et al. 2017)	2016	Netherland	Spring	Linear regression	384	3.5-8	21.3 - 23.5			20-24
(Mustapa et al. 2016)	2016	Japan	Summer	Griffiths' method	660	28-32	26.6			
(Zaki et al. 2017)	2017	Malaysia	Summer	Linear and Probit regression Griffiths' method	561	25.3-33.4	25.6			
(Zaki et al. 2017)	2017	Japan	Summer	Linear and Probit regression Griffiths' method	449	25.5	CL: 25.5 FR: 25.3	25.1	26.2	
(Lau, Zhang and Tao 2019)	2019	Singapore		Linear regression & Griffiths' method	1043	20-30	25			
Current study	2017-2018	UK	Autumn, winter, summer	Probit regression Griffiths' method	3511	Coventry: 1-15 Edinburgh: 2-13	23.4	23	22.9	22.3

5.6. Preferred adaptive behaviour for thermal comfort

5.6.1. Priorities of personal and environmental behaviours

Students' priorities for either personal or environmental adaptive behaviours in uncomfortably warm or cold environments (TSV beyond −1 to 1) were evaluated in all types of classrooms using the students' answers to the question "what would you prefer to do in uncomfortably warm and cold thermal conditions when you are in the classroom?" The available adaptive opportunities in the classrooms were listed in the questionnaire, including adjusting clothing, operating windows and doors, having a hot or cold drink, changing position and operating the HVAC system. The students were asked to choose three of them based on their priorities in uncomfortably warm and cold thermal environments. Approximately 9 % of the students did not provide answers; therefore, their votes were removed from the data.

Results in Figure 5-6 show that adjusting clothing and operating windows were the most common actions among students in both uncomfortably warm and cold conditions. In uncomfortably warm thermal condition, nearly half of the students in both lecture rooms (48 %) and PC labs (47 %) preferred to adopt personal behaviours (adjust clothing) to restore their thermal comfort, whereas half of the students in the studios (48%) preferred to adopt an environmental behaviour (operating windows) before any personal action. This indicates the students' priorities for personal behaviours before environmental actions in lecture rooms and PC labs. However, they preferred environmental behaviours in the studios.

The main reason for such priorities is the different levels of freedom in each classroom type. Occupants in the lecture rooms do not have enough freedom to take environmental actions such as operating windows or doors and changing the HVAC set points. They may not feel comfortable about walking in the classroom to access the windows, doors or the HVAC control point while a lecture is running. This happens due to the nature of teaching in such spaces. However, there are less strict rules in the studios than the lecture rooms. Students in studios tend to have greater freedom to move around and adjust the environment based on their comfort levels.

Operating HVAC systems was shown as the third priority for the students either because working with HVAC systems was not very clear for them, or that the thermal environment was centrally operated by the university building management system.

It should be noted that even if the HVAC control point was accessible, the majority of students in all the classrooms in uncomfortably cold thermal conditions were expected to prefer adjusting clothing first, operating windows second and changing the HVAC set point third. Operating windows was not the priority as windows are rarely open in cold thermal conditions. Even if there are open windows, closing them cannot improve thermal comfort in cold conditions as it does in uncomfortably warm environments. Heating systems, either through supply ducts or radiators, were also not a main priority, as mentioned above. As a result, the easiest option may be adjusting clothing to gain comfort in thermally cold conditions. Common personal adaptive behaviours in lecture rooms can be another reason for the wider comfort zone in such spaces compared to the studios. According to the existing literature (Brager, Paliaga and de Dear 2004), personal behaviour provides a high level of thermal comfort for occupants in an environment. Occupants tend to change the thermal conditions through different available ways, which may differ from person to person. It may be difficult to provide a comfortable and satisfactory thermal environment for all the occupants. Therefore, individual control leads to far greater thermal comfort in comparison to centrally controlled systems (Huizenga et al. 2006; Fadeyi 2014). Environmental behaviours, such as opening/closing windows and doors or operating HVAC in lecture rooms may thermally satisfy one group of occupants but may cause thermal discomfort for the others. Personal behaviours, such as adjusting clothing or changing position, provide comfort for each occupant based on their own preferences.

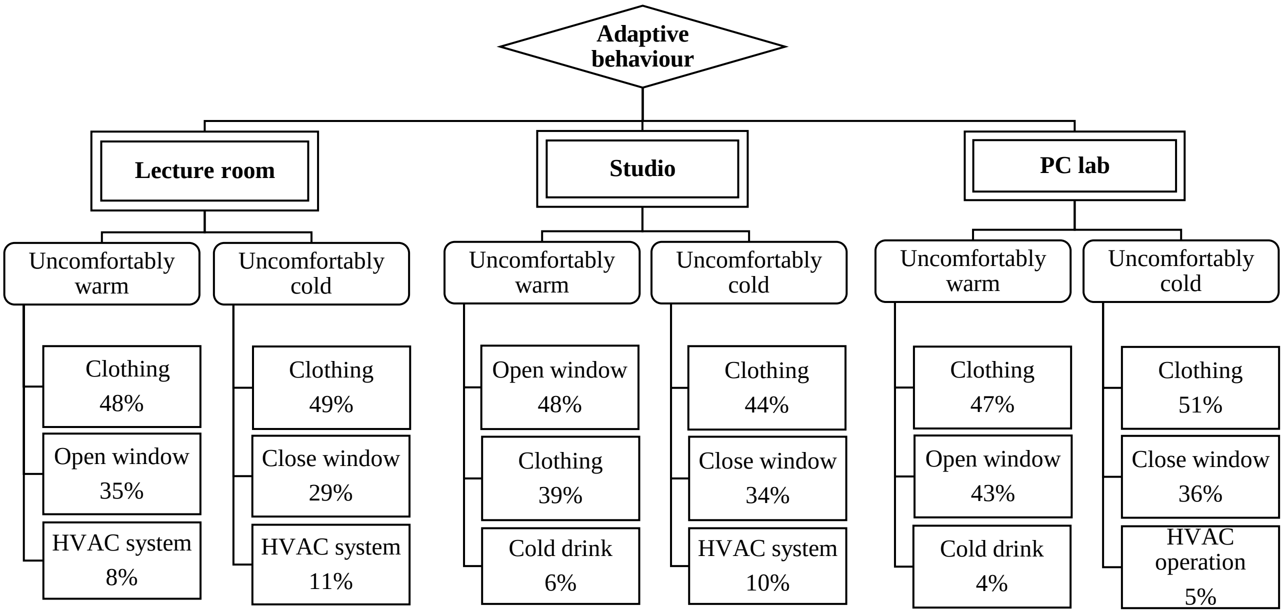


Figure 5-6. Priority of students for adaptive behaviours in uncomfortably warm or cold environments

5.6.2. Comparison of adaptive behaviour with other studies

The results in section 5.6.1 are supported by previous studies showing the influence of occupants' freedom levels on preferred adaptive behaviours. Some investigations in university buildings confirmed the students' priorities for personal adaptive behaviours before environmental actions inside the classrooms (*EN ISO 7730* 2005; *CIBSE Guide A*. 7th ed. 2010; Patterns and Trends in UK Higher Education 2018).

Drinking a beverage has priority in Japanese universities with a mean indoor air temperature of 25°C and 27°C (Zagreus et al. 2004; Mishra et al. 2017; Ricciardi and Buratti 2018). Likewise, employees in mixed mode office buildings in the UK prefer personal adaptive behaviours before any environmental actions in thermally uncomfortable conditions, with a mean indoor air temperature of 22°C (Liu, Yao and McCloy 2014). Among the environmental behaviours, HVAC operation was preferred by occupants in higher educational spaces in the hot climates of Malaysia (Zaki et al. 2017) and Indonesia (Damiati et al. 2016) with mean indoor air temperatures of 27°C and 30°C, respectively. Operating windows is also the most common action in a school building in Taiwan with a mean indoor air temperature of 35°C (Chen, Hwang and Shih 2014).

In contrast, studies conducted in residential buildings in the hot climate of Indonesia (Huizenga et al. 2006; Tao and Li 2014) and the warm and tropical climate of Singapore (Wong et al. 2002), with a mean indoor air temperature of 27°C and 29°C, respectively, suggest that people usually prefer to gain comfort through environmental actions before any personal adjustments. Creating higher air movement through applying air conditioning systems, fans and opening windows are the most preferred actions during the day in residential buildings in both locations (Huizenga et al. 2006; Tao and Li 2014).

Occupants in classrooms and offices tend towards personal behaviours before any environmental adjustments. Similar to the current study, adding or removing clothes, taking hot/cold drinks or changing position are common behaviours in such spaces. However, in residential buildings where the occupants have enough freedom, environmental adjustments such as HVAC and operating windows have priority over personal ones, despite their financial costs.

A main reason for this can be that in public spaces like classrooms and offices, occupants may not feel fully allowed to change the thermal environment as these changes could cause thermal discomfort for the others. Limited access to environmental opportunities like windows or HVAC systems for some of the occupants and low levels of freedom to adjust the thermal environment are other reasons why personal behaviour is more preferred in such spaces. Nevertheless, the influence of climatic conditions and indoor air temperature on the selection of adaptive behaviours should not be overlooked. As mentioned above, in educational buildings with indoor air temperatures between 22°C and 30°C, personal behaviours are preferred over environmental ones (Yao, Liu and Li, 2010; Zhang et al. 2010; Damiati et al. 2016; Mustapa et al. 2016; Zaki et al. 2017), while in extreme conditions with indoor air temperatures from 27°C to 35°C, environmental actions are more common (Bauman et al. 1998; Zagreus et al. 2004; Ricciardi and Buratti 2018). In other words, in extreme thermal conditions, environmental behaviours are more preferred because the personal adjustments may not properly provide comfort for the occupants (Frontczak and Wargocki 2011). Such information on the prediction of occupants' adaptive behaviours helps to provide the proper adaptive opportunities in teaching and learning spaces, which not only provide the subjects with thermal comfort, but also helps to save energy and minimise the buildings' running costs.

5.7. Chapter summary

In this section, it was hypothesised to observe a warmer thermal sensation, cooler thermal preference and lower comfort temperature in studio type classrooms compared to lecture rooms and PC labs. Thermal sensation and thermal preference were shown to be warmer and cooler, respectively, in studios due to the subjects' higher levels of physical activities there. However, a 1°C higher comfort temperature was observed in the studios than the other classroom types because of the higher operative temperature in the studios and the students' adaptation to the prevailing thermal environment, which was a result of a longer occupancy period in studios than lecture rooms and PC labs.

- A similar comfort temperature was observed under FR and CL modes inside the classrooms. However, a 2ºC lower comfort temperature was shown under HT mode, which suggests that the operation mode may affect the comfort temperature inside the classrooms. A potential reason for the lower comfort temperature under HT mode compared to the FR and CL modes could be due to the lower outdoor air temperature in HT periods and, consequently, the students' adaptation to the colder environment outside. The similar comfort zone under FR and CL mode and the different value under HT mode shows that this finding can also be extended to the comfort zone (section 5.4).
- Although the comfort temperature (Griffiths' method) was shown to be approximately 1°C higher in the studios than the lecture rooms and PC labs under HT and FR modes (section 5.5), the cooler thermal preferences and warmer thermal sensations in the studios than the lecture rooms suggests that students in the studios may feel thermally comfortable in cooler than neutral thermal sensations. The higher comfort temperature in the studios was apparently resulted from the higher prevailing operative temperature there, compared to the other classroom types, followed by the students' physiological and psychological thermal adaptation to the environment. The similar comfort and operative temperatures in the studios under all operation modes confirms the students' thermal adaptation to the thermal environment as a result of their long occupancy period in the studios.

- In terms of adaptive behaviour, students' freedom levels in classrooms (depending on the classroom type and class activity) affect their preferred adaptive behaviours (section 5.6).

Finally, in this work, a dissimilar thermal comfort perception was observed in the investigated classroom types (lecture rooms, studios and PC labs) at higher learning environments. Therefore, the same thermal environment cannot provide comfort in all teaching environments which can cause a waste of energy through over-heating or over-cooling in some spaces.

6. Diverse Climatic Background and Thermal Perception: Influence of Thermal History

6.1. Introduction

The influence of the thermal environments experienced as thermal history on the subjects' in-the-moment thermal comfort evaluation was explained in section 2.3.2.2. Previous thermal experiences create a thermal benchmark or experiential calibration frame of reference for subjects that affect their thermal comfort perception in a new environment (Chun et al. 2008; van der Lans et al. 2013; Vargas, Lawrence and Stevenson 2017). Students in higher learning environments are from different climatic backgrounds. Therefore, they tend to evaluate the learning environments differently depending on their past climatic exposures and thermal experiences (their long-term thermal history).

In this chapter, the students' thermal sensations and preference votes, thermal acceptability, sensitivity, neutrality, comfort and preferred temperatures are investigated in relation to their thermal histories. Furthermore, an architectural design solution is suggested to provide thermal comfort for occupants with various thermal comfort perceptions in the classrooms.

It is hypothesised in this work to observe warmer thermal expectations and cooler thermal sensations among the subjects coming from warmer climates than the UK, compared to their counterparts with cooler climatic background than the UK native residents.

- ***Research questions:***

  To investigate the students' thermal comfort perceptions in relation to their climatic background/thermal history, this chapter addresses research question number 4 of this thesis:

<u>RQ 4.</u> *"How does climatic background/long-term thermal history influence students' in-the-moment thermal perceptions inside the classrooms?"*

6.2. Distribution of the operative temperature

Figure 6-1 shows the distribution of operative temperatures (T_{op}) recorded inside the classrooms during the survey period. Almost 90% of the observations fell between 22°C and 25°C.

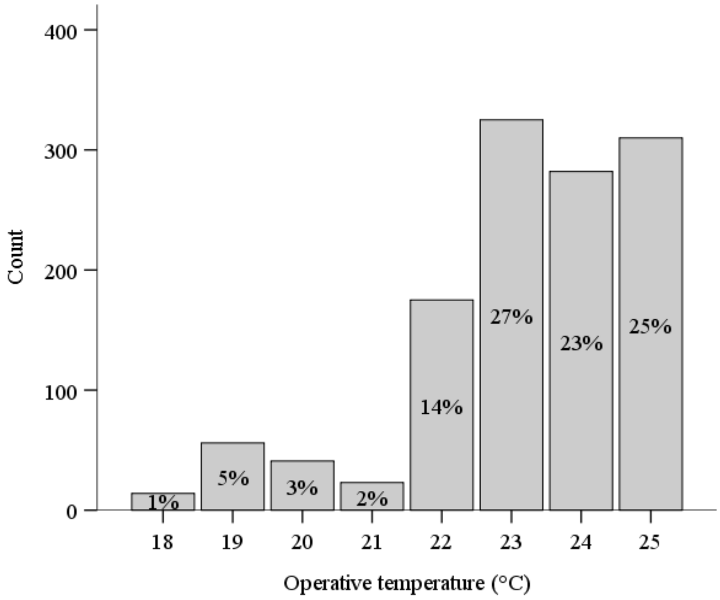


Figure 6-1. Distribution of indoor air operative temperatures in the surveyed classrooms

A summary of the thermal comfort indices for each thermal history group is given in Table 6-1. In terms of indoor thermal environments, all the climatic background groups were generally exposed to comparable indoor conditions. Subjects with similar backgrounds and cooler backgrounds were exposed to comparable indoor thermal environments in terms of operative temperature (T_{op}), air velocity and relative humidity (RH). With mean thermal sensation votes of 0.23 and 0.05 respectively, similar and cooler background groups were just on the very slightly warm side, which was consistent with their thermal preference votes. The warmer climatic background group was exposed to slightly lower (<0.5°C) operative temperatures, but similar RH and Air_V compared to the similar and cooler background groups. The Mean Thermal Sensation Vote (TSV) at −0.28 and the mean Thermal Preference Vote (TPV) of –0.10 indicate that the warmer background group experienced a marginally cooler perception compared to the other two groups.

Table 6-1. Thermal comfort indices for each thermal history group

	Sample size*	Mean T_{op} (°C)	Mean Air_V (m/s)	Mean RH (%)	Mean TSV (7-pt scale)	Mean TPV (7-pt scale)	Clothing (clo)
Warmer background	340	22.8	0.06	38	−0.28	−0.10	0.95
Similar background	345	23.2	0.06	36	0.23	0.18	0.85
Cooler background	210	23.0	0.06	36	0.05	0.06	0.84

* The climatic background of 331 subjects could not be classified – missing values on the questionnaire

6.3. Clothing insulation value for different thermal history groups

Figure 6-2 shows the mean clothing insulation estimates for each thermal history group. Students with warmer backgrounds wore more clothing insulation (0.95 clo) compared to their counterparts in the other two groups (≈0.85 clo). As the assumption of a normal distribution was not met for an independent t-test, a non-parametric Mann-Whitney U test was conducted between each pair of groups as suggested in previous studies for such a type of data (Chan 2003; McCrum-Gardner 2008; Scheff 2016). Results indicated a significant difference between the clothing value of the warmer background compared with both cooler and similar climatic background groups ($p<0.001$, effect size: 0.33), but no significant difference was detected between the clothing insulation levels of the similar and cooler groups ($p>0.05$).

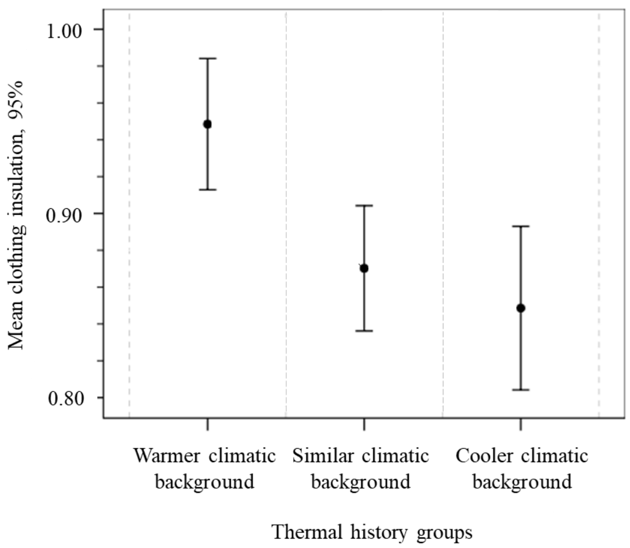


Figure 6-2. Mean of clothing insulation estimates for the three thermal history groups

6.4. Thermal sensations

The thermal sensation votes (TSV) of the students sorted into the three thermal background groups are presented in Figure 6-3. The thermal sensation votes of similar and cooler thermal history groups are comparable, being skewed towards the warmer-than-neutral side of the scale. However, a completely opposite pattern can be observed in the votes of those from warmer backgrounds. Despite wearing significantly heavier clothing insulation, the warmer thermal history group's thermal sensations were displaced cooler than their counterparts in the other two groups. From a statistical point of view, using an ANOVA test, a not significant difference was shown in the TSVs of the cooler and similar climatic background groups. However, a statistically significant difference was observed in the TSVs of the warmer thermal history group with both similar (F value: 24.94, df1: 1, df2: 418.956, $p<0.001$, effect size: 0.26) and cooler climatic backgrounds ($p<0.05$, effect size: 0.32).

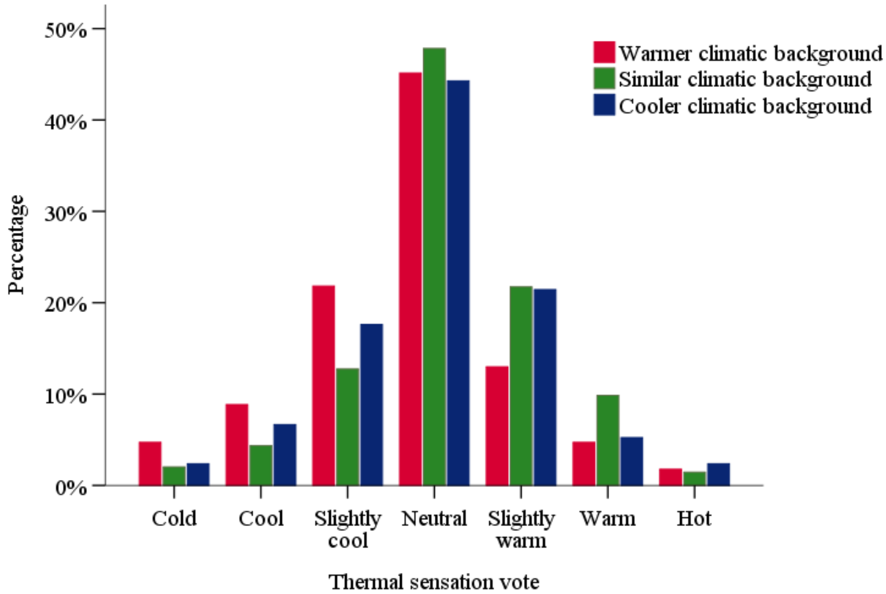


Figure 6-3. Thermal sensation votes of the warmer, similar and cooler thermal history groups

The results so far and in the following sections show the same trend for similar and cooler thermal history groups in terms of environmental variables, clothing insulation, thermal sensation votes, thermal acceptability, preferences, neutrality and sensitivity. Furthermore, the statistical tests (independent t-test and one-way ANOVA) indicated no significant differences between the votes on all the thermal comfort scales of the similar and cooler thermal history groups ($p>0.05$). Therefore, to make them subsequently more intelligible, the results for the similar and cooler thermal background groups were collapsed into one group, so the two remaining thermal history groups were; Warmer background (group 1) and Similar/cooler background (group 2).

6.5. Thermally acceptability

According to ASHRAE 2017 (*ASHRAE 55* 2017), thermal dissatisfaction is considered as thermal sensation votes beyond the acceptable zone of –1, 0 and +1 on the 7 point thermal sensation scale. To find the acceptable temperature zone, thermal sensation votes were binary recoded as acceptable (TSV= 0 and ±1) and unacceptable votes (TSV= ±2 and ±3). Operative temperature was binned at 1°C intervals and the proportion of thermally acceptable votes in each bin is indicated in Figure 6-4. Probit regression was employed to identify mean the thermal acceptability and thermal comfort ranges for each climatic background group, as applied in previous studies (Hwang et al. 2009; Yan et al. 2016; Jungsoo and de Dear 2018). The Probit model is a statistical method that relates the proportion/probability of a binary qualitative variable to a continuous explanatory variable (Ballantyne, Hill and Spencer 1977; Nicol, Humphreys and Roaf 2012). The advantage of probit regression analysis is that it does not require the equal-intervals property, encouraging researchers to apply this method to the intervals between thermal comfort descriptors to see how well they fulfil the ‘equal interval’ assumption (Nicol, Humphreys and Roaf 2012). In this work, thermal acceptability is the dependent binary outcome and operative temperature is considered as the independent variable.

Considering the standard minimum 80% acceptability as recommended in regulatory documents such as ASHRAE 2017 (*ASHRAE 55* 2017), the thermally acceptable zone extends from 23°C to above 25°C for the warmer climatic background (group 1), and from around 18°C to 25°C for the similar/cooler climatic background (group 2). The optimal acceptable temperature was 25°C and 22°C for groups 1 and 2, respectively. The thermally acceptable zone started at 18°C for group 2, which was 5°C cooler than the lower acceptable margin for group 1 (23°C). In contrast, in the higher margin, in an operative temperature of above 25°C, more than 80% of the participants in group 1 were still thermally satisfied, while this temperature fell beyond the comfort zone for the participants in group 2.

The higher optimal acceptable temperatures along with the heightened thermal acceptability observed in higher operative temperatures for warmer climatic background group 1 compared to similar/cooler climatic background group 2 is consistent with group 1's thermal comfort expectations being warmer than group 2's. Students in group 1, with a warmer climatic background, were better adapted to warmth as evidenced by their thermal sensation and acceptability results. Likewise, a wider thermal comfort range in lower operative temperatures for group 2 compared to group 1 confirms the influence of long-term thermal history on in-the-moment thermal comfort evaluations.

Higher levels of thermal acceptability, tolerance of, and even enjoyment of warm thermal sensations resulting from familiarity and adaptation to warmth, plus higher acceptance and tolerance of cool exposures due to acclimatisation in cold thermal environments have been also observed in previous studies (Han et al. 2009; Aljawabra and Nikolopoulou 2010; Yu et al. 2013; Mishra and Ramgopal 2015b).

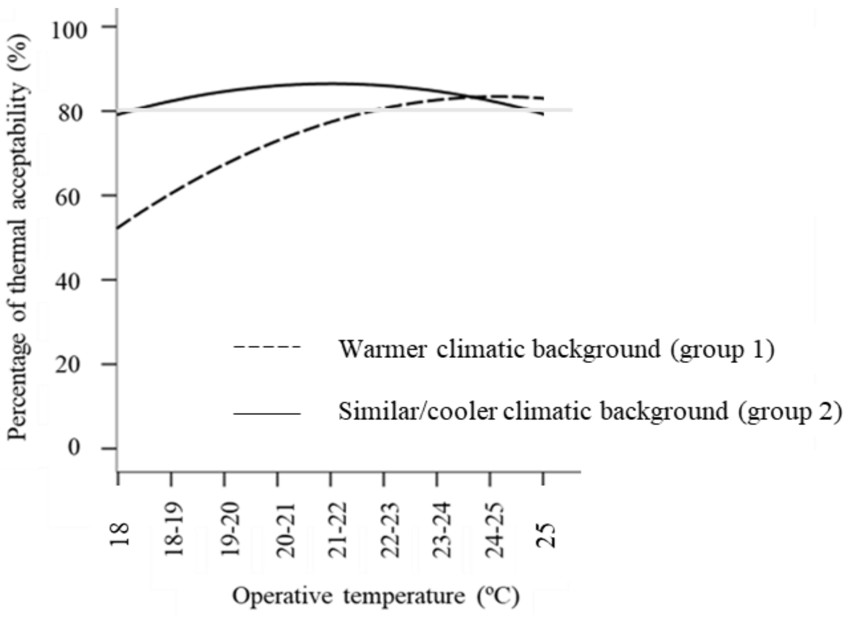


Figure 6-4. Percentage of acceptable thermal sensation votes for warmer and similar/ cooler thermal history groups

Warm and cool thermal dissatisfaction levels of each group are presented in Figure 6-5. According to the minimum 80% acceptability recommended by ASHRAE 2017 (*ASHRAE 55* 2017), cold thermal dissatisfaction starts at 21°C for the warm climatic background group 1 and 20°C for the similar/cooler climatic background group 2. Warm dissatisfaction for group 1 could not be precisely identified as there were no operative temperatures registered above 25°C in this study. More than 80% of the participants in group 1 remained thermally comfortable at 25°C and presumably a couple of degrees above that. However, warm dissatisfaction for group 2 occurred at 24°C.

Results in this section indicate the high sensitivity of the participants in group 1 compared to group 2 in cool exposures and the lower tolerance of group 2 than 1 in warm exposures. The optimum temperatures at which thermal dissatisfaction was minimised were 24°C and 22.5°C for groups 1 and 2 respectively, which is consistent with the previous findings.

Taken together, this evidence supports the subjective nature of thermal comfort, reinforcing the view that a purely physiological model of absolute comfort is an inadequate representation of human thermal perceptions.

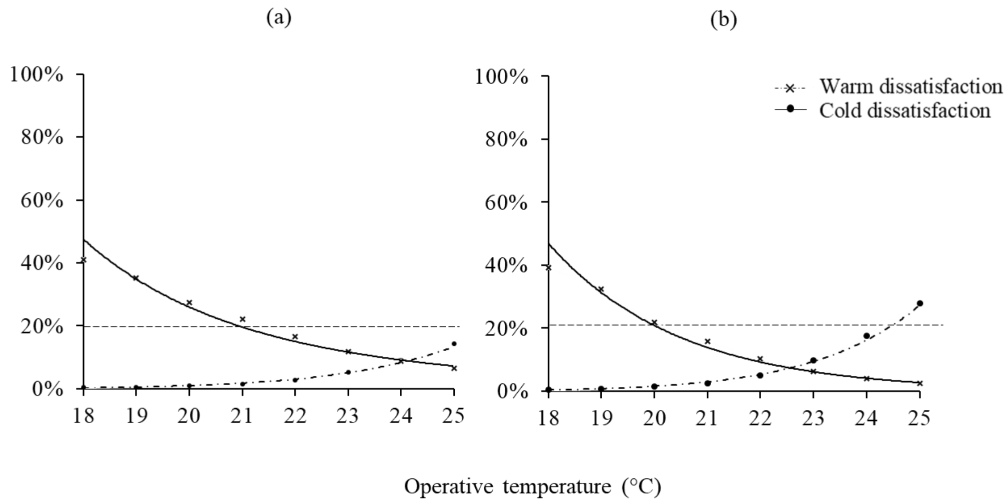


Figure 6-5. warm and cold thermal dissatisfaction of warmer background group 1 (a) and similar/cooler background group 2 (b)

6.6. Comfort temperature

Griffiths' method was applied to the thermal sensation votes of each participant to estimate the mean comfort temperature. Griffiths constant considered as 0.5, as suggested by Humphreys et al. (Humphreys, Rijal and Nicol 2013).

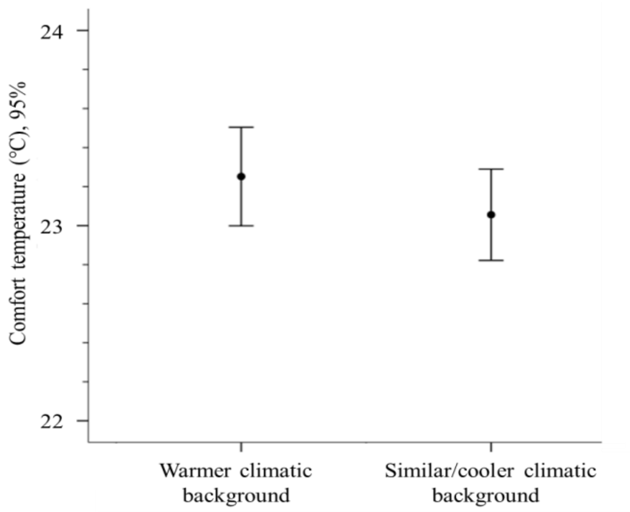


Figure 6-6. Comfort temperature of the warmer and similar/cooler thermal history groups (95% confidence interval)

Figure 6-6 indicates the mean comfort temperature of the warmer background group 1 (mean = 23.3, SD= 2.4) and similar/cooler background group 2 (mean= 23.01, SD= 2.22). The result of an independent t-test indicates no significant difference between the mean comfort temperatures of the thermal history groups. (t value: 6.818, F value: 0.099, p>0.05). However, the subjects in the warmer climatic background group 1 still registered slightly higher comfort temperatures than their counterparts in the similar/ cooler climatic background group 2, despite the former's higher clothing insulation level (Figure 6-2).

6.7. Preferred temperature

To evaluate each climatic group's preferred temperature, probit regression models were fitted to the relationship between the operative temperature and thermal preference votes, as described in de Dear et al. (2015). In Figure 6-7, the intersection points between the 'want warmer' and 'want cooler' probit curves for each thermal history group is assumed to correspond with the group's optimum preferred temperature (Yang, Wong and Jusuf 2013; Jungsoo and de Dear 2018).

Regardless of the students' thermal backgrounds, as expected, the operative temperature had a negative correlation with warmer thermal preferences (Spearman's r: –0.47) and a positive association with the cooler preference votes (Spearman's r: 0.35). The preferred temperature was 24.5° C for group 1, which is about 1°C higher than group 2's preferred temperature. The result of an independent t-test confirmed the difference between the preference votes of the climatic background groups (t value: 5.850, F value: 1.273, Cohen's effect size: 1.065901, $p<0.05$). According to Cohen's classification (Cohen 1998), the effect size of 0.21 is 'small' but, as mentioned in section 2.3, the effect size in social/soft science research may interpret differently. Therefore, the resulted small effect size in this work may not necessarily mean the small power of the statistical results (Cohen 1962; Schäfer and Schwarz,2019). Probit regression p-values and the Pearson goodness also indicated that the fitted curve for these two thermal history groups was significantly different ($p<0.001$).

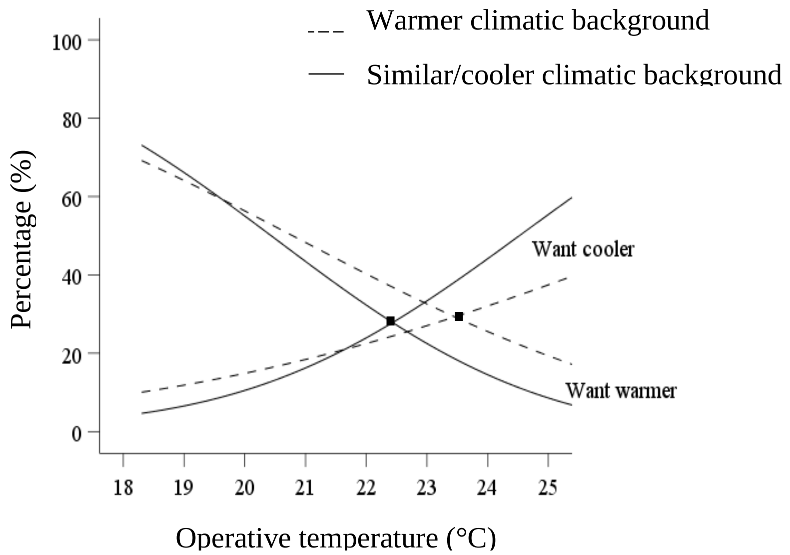


Figure 6-7. The proportion of the thermal preference votes for the warmer and similar/cooler thermal history groups

A more detailed look at the 'want warmer' thermal preferences reveals that in operative temperatures above 19.5°C, a higher percentage of the students in the warmer background group 1 preferred the room temperature to be warmer compared to their counterparts in the similar/cooler background group 2. Regarding the 'want cooler' thermal preference votes, a higher percentage of the similar/cooler background group 2 preferred to be cooler compared to the warmer background group 1 above 21.5°C. The sharper growth of the cooler thermal preference votes by increasing the operative temperature for the similar/cooler background group 2 compared to the warmer background group1 emphasises the higher sensitivity to warmth for group 2 than group 1.

The higher preferred temperature and lower thermal sensitivity to warmth for the warmer climatic background group 1 than the similar/cooler climatic background group 2 indicates the influence of long-term thermal history on the participants' thermal preferences and preferred temperature. Evidence showing the influence of thermal history and past experiences of thermal conditions on people's current thermal preferences and perceptions has also been reported in the earlier thermal comfort research literature (Goto et al. 2000; Nicol, Humphreys and Roaf 2012; S.L. Wong et al. 2012; Teli, Jentsch and James 2012; Mishra and Ramgopal 2015b).

According to Figure 6-4 through to Figure 6-7, the acceptable temperature range (thermal comfort zone), comfort temperature (neutrality), and preferred temperature were consistently lower for the cooler climatic background group 2 compared to the warmer background group 1. The group 2 subjects had a wider range of thermal acceptability and comfort and a reduced thermal sensitivity to cool indoor temperatures compared to the warmer background group 1, when exposed to the same indoor climatic conditions. The opposite trend was evident for the warmer background group 1 subjects, with a higher acceptable temperature range, a lower sensitivity to warmth and higher comfort and preferred temperatures, despite wearing heavier clothing compared to the other climatic background group.

6.8. Chapter summary

In this study it was hypothesised that subjects with warmer climatic backgrounds than the UK native residents would have warmer thermal expectations and feel cooler compared to the subjects from climates that were cooler than UK. The analyses reported in this chapter broadly agreed with this prediction. Therefore, an environmental or architectural design strategy can be developed for higher learning environments which are shared by occupants from various backgrounds with diverse thermal comfort perceptions.

The following key findings also emerged from the analysis:

1. Climatic background and long-term thermal exposure to a thermal condition apparently affects the thermal sensation, thermal comfort zone, thermal acceptability and temperature preferences in buildings accommodating occupants with diverse climatic backgrounds, such as higher learning environments (section 6.2).

2. There was generally no statistically significant difference in the subjective comfort responses (thermal sensation, preference, neutrality and thermal acceptability) of students from colder climates than the UK and the native UK residences. However, significant differences emerged in the thermal comfort evaluations of the students with a warmer thermal history than the UK (section 6.4).

3. Considering the operative temperature between 18°C and 25°C in this work, thermal acceptability ranged from 23°C to 25°C for warmer climatic background subjects and approximately 18°C to 25°C for similar/cooler climatic background subjects. Optimal acceptable temperatures were 24°C and 22°C for these two groups, respectively (section 6.5).

4. Overall, when exposed to the same thermal environment, participants with warmer thermal histories felt cooler compared to their counterparts in the similar-to and colder-than-the-UK thermal history groups. They also had lower thermal sensation votes, higher optimal acceptable temperatures, warmer thermal neutralities and preferred temperatures compared to the subjects in similar-to and colder-than-the-UK thermal history groups (sections 6.5, 6.6 and 6.7).

Chapter 7

7. Discussion and Conclusion

7.1. Introduction

Given the significant influence of thermal environment on students' productivity and well-being in academic environments, this thesis investigated thermal comfort requirements in UK university classrooms, which are shared by different group of students, in terms of physiological and psychological human characteristics.

Considering the influencing factors affecting the occupants' thermal perceptions in higher learning environments, the human characteristics affecting thermal comfort have been categorised into two groups including the *physiological* and *psychological* parameters.

In order to investigate the potential influencing physiological drivers of diverse thermal comfort in university classrooms, the following research questions have been addressed:

RQ 1. ***Taking account of the different climatic conditions in the northern (Scotland) and southern (England) regions of the UK, are the same thermal comfort criteria applicable in higher educational buildings throughout the UK?***

Results show that the same environmental criteria cannot provide thermally comfortable classrooms in higher learning environments in England and Scotland. Colder climatic conditions prevailing in Scotland (Edinburgh) compared to England (Coventry) and the students' acclimatisation cause cooler thermal sensations, warmer preferences, warmer thermal acceptability zones (21°C to 24.5°C in Coventry and 19.5° to 23.5°C in Edinburgh) and higher comfort temperature in England, 23.5°C in Coventry, compared to Scotland, 22.1°C in Edinburgh, (Chapter 4).

Although the differences in the observed comfort temperatures in these two locations are small, providing a cooler set point in the university buildings in Edinburgh than Coventry can save up to 10% energy at the same time as avoiding overheated environments for students. According to Nicol et al. (2012), in the UK, reduction of the indoor air temperature for only 1ºC can save 10% of energy used for heating purposes. Considering the number of campuses and learning environments in higher educational buildings, 10% reduction of energy consumption in each building can lead to a considerable energy saving in this sector.

Furthermore, as the outdoor air temperature was almost similar in both locations during the survey period, the influence of the subjects' climatic thermal adaptation might have been eliminated, which can be a reason for the similar comfort temperatures in Coventry and Edinburgh. Therefore, the results of this study do not necessarily apply to the whole a year.

RQ 2. ***How do age- and gender-related differences among students affect thermal perceptions in higher learning environments?***

The result of this study shows no significant difference in the thermal comfort votes of the different age groups in the university classrooms. In terms of gender-related differences, despite the heavier clothing insulation worn by women (≈ 0.92 clo) than men (≈ 0.83 clo), cooler thermal sensations and warmer thermal comfort requirements were observed for women. However, the comfort temperature was shown to be around 23°C for both genders (Chapter 4).

RQ 3. ***What are the thermal comfort requirements of students in diverse disciplines exposed to various classroom types? / Can the same thermal comfort criteria be applicable in all classroom types in university buildings?***

Results on the students' thermal comfort in different classroom types showed a similar comfort temperature of 23°C in the lecture rooms and the PC labs under Free Running (FR) and Cooling modes (CL) and 22°C under Heating (HT) mode in the lecture rooms. However, a 1°C higher temperature was shown in the studios than in the other classroom types under all operation modes (24°C under FR and

23°C under HT mode). Nevertheless, 1) the longer occupancy period in the studios and 2) the greater freedom for adaptive behaviours and a higher perception of control over the space in the studios than in the other classroom types presumably led to the students' respective physiological and psychological thermal adaptation in such spaces. This was followed by the lower thermal sensitivity and improved comfort perceptions of the students in the exposed environmental condition in the studios.

In this work, the operative temperature was 1°C higher in the studios than the lecture rooms and PC labs during the survey period, which might have led to the thermal adaptation of the students to a warmer condition and could be a reason for the higher comfort temperature in the studios than the other classrooms (Chapter 5).

Thus, it is likely that the same thermal environment (23°C) could be applicable in all the classroom types as the students can thermally adapt to the climatic condition of the studios. However, as there is not enough evidence in this regard in this study, further investigation is recommended in future works to evaluate whether the same temperature set point could provide thermal comfort for the occupants in the lecture rooms, studios and PC labs in higher educational buildings.

In terms of adaptive behaviours, personal behaviours (i.e. clothing adjustment) were shown to be the priority for students in the lecture rooms and PC labs in both uncomfortably warm and cold thermal conditions. However, in the studios, both personal and environmental behaviours were preferred by the students to restore their comfort. Therefore, providing the occupants with more opportunities for personal behaviours in the lecture rooms and PC labs should be considered in the future refurbishment or environmental design strategies in university classrooms.

RQ 4. ***How does climatic background/long-term thermal history influence students' in-the-moment thermal perceptions inside the classrooms?***

Findings in this study show a similar thermal comfort perception for the students native to the UK and the group of students from cooler climates than the UK. However, significant differences were observed between the thermal comfort votes of the subjects with warmer backgrounds compared to their counterparts from the UK and cooler climates.

A warmer thermal acceptability zone for the students from warmer backgrounds than the UK (23 to 25°C) compared to their counterparts with colder climatic backgrounds (18-25°C) confirms the lower thermal sensitivity of the occupants with colder backgrounds to cold temperatures. Therefore, it is clearly confirmed that the same thermal environment in a classroom shared by students with diverse climatic backgrounds could be perceived differently based on their thermal history and expectations (Chapter 6). This suggests that providing thermally comfortable classrooms for all students may not be possible in such multidisciplinary environments. Thus, some architectural design/refurbishment strategies can be offered by designers to provide different thermal zones in the classrooms so that each student could choose a thermally comfortable place based on their in-the-moment thermal perceptions. As an example, subjects seated next to the windows may be cooler than the others in the central parts of a classroom, or students in the central areas or close to the heating outlets may be warmer than the others. These zones can be designated with a different colour or floor covering to let the students choose their desired thermal zone which would be more compatible with their in-the-moment thermal perceptions.

In this study, due to the time limit, only two case studies in England and Scotland were studied. For future works, it is recommended to conduct a similar investigation in other regions/climatic conditions of the UK (Wales and Northern Ireland). In this way, a better understanding of the thermal comfort requirements in higher learning environments over the UK can be achieved. In a broader perspective, it is recommended to study the students' comfort in relation to all the ambient environmental variables (including the indoor air temperature, air velocity, radiant temperature, relative humidity) and CO_2 level in classrooms. Through a simultaneous environmental monitoring and questionnaire surveys the comfortable range of each variable can be identified. Expanding this investigation to all the climatic conditions/regions of the UK (Scotland, England, Wales and Northern Ireland) may lead to determining a comprehensive environmental design criterion for university buildings across the UK.

Regarding the thermal comfort in different classroom types the students' thermal perceptions in the PC labs and studios type classrooms in Edinburgh could not be studied in this work. The main reason was that 1) there was no studio type classroom at Heriot-Watt University (the case study building in

Edinburgh) and 2) the indoor ambient environmental conditions in the PC labs in Edinburgh was incomparable to Coventry. Therefore, further research in the studio types classrooms and PC labs in Edinburgh is encouraged to have a better understanding of the thermal comfort criteria in the UK higher educational buildings. Furthermore, it is recommended to conduct the survey on the same group of students in different classroom types, to exclude the influence of personal parameters affecting thermal comfort such as climatic background, age and gender. To do so, students can provide their name, or they may be given a number on top of the questionnaires so that they are trackable in the other classroom types.

In addition, considering the influence of student's activities (in terms of group or individual) on perception of thermal comfort and overall satisfaction can lead to more accurate results. Students in studios and PC labs can be involved in group (e.g. creating mock-ups, group discussion) or individual activities (e.g. drawing, modelling in computers). As shown by Aljawabra and Nikopoulou (2018) from a psychological/social point of view, involvement of people in group activities tends to distract them from the sources of thermal discomfort, and consequently improve their satisfaction with the exposed ambient environment. As mentioned above, to consider this factor, students can provide their name or a number on top of the questionnaires in a way that they are surveyed once while involved in group and once in individual activities. Then comparison of the results can reveal the influence of the activity type on perception of thermal comfort.

Finally, the result of this thesis combined with the findings from these recommendations in the future works can provide more detailed understanding about the thermal comfort requirements in the UK higher educational buildings. Thus, these results can contribute to develop a comprehensive environmental design criterion or alternatively can help to update/modify the existing environmental guidelines for the UK higher learning environments. Apart from that, the outcome of these recommendations can help to develop some environmentally friendly architectural or refurbishment design strategies to support occupants' comfort and well-being in university buildings in the UK.

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Appendix 1

Journal and Conference articles

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Comfort temperature and preferred adaptive behaviour in various classroom types in the UK higher learning environments

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A B S T R A C T

Maintaining the thermal comfort of occupants along with minimising the related energy consumption is necessary in educational buildings in the UK. Thermal comfort is particularly important in this context as it affects how well students learn in the classroom. This study aims to identify comfort temperature ranges in different classroom types, lecture rooms, studios and PC labs in UK higher learning environments. Overall, more than 3,000 university students in Coventry and Edinburgh were observed and surveyed simultaneously with the monitoring of environmental measurements under free-running, cooling and heating modes, in October and November 2017 and January to March 2018. Thermal comfort zones and comfort temperatures were identified in each classroom type under these three operation modes. The thermal comfort zone was shown to be significantly dependant on the operative temperature in the studios and PC labs. In terms of the students' priorities for adaptive behaviour inside the classrooms, students in the lecture rooms and PC labs with lower levels of freedom, preferred to restore their thermal comfort through personal adaptive behaviour. However, environmental behaviour was shown to be preferred in the studios where the occupants have a greater freedom level. Results indicate a higher level of physiological and psychological thermal adaptation for the occupants of the studios and PC labs compared to those in the lecture rooms. Consequently, the type of classroom and the students' freedom levels should be considered in environmental design of higher education buildings.

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(a)

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Influence of long-term thermal history on thermal comfort and preference

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ABSTRACT

This study explores how climatic background or long-term thermal history influences individuals' in-the-moment thermal comfort experiences. This investigation was conducted at eight mixed-mode university buildings in United Kingdom whose occupants had diverse thermal histories. The research design consisted of simultaneous environmental measurements, a questionnaire survey and observation on 3,452 students performing sedentary activities in the classrooms. To eliminate the influence of acclimatisation in the UK, a subset of 1,225 students with less than 3 years of residence in the UK were selected as the survey sample. Students' thermal comfort responses were categorised into three main groups based on their climatic background compared to the UK (warmer, similar and cooler climatic background groups). Data was statistically analysed to derive the thermal comfort requirements of each climatic group based on reported thermal sensations, preferences, acceptability and comfort votes. The findings confirm the influence of long-term thermal history on thermal sensation, thermal comfort zone, acceptability, preference and comfort temperature (neutrality). There was generally no difference in the subjective thermal comfort of the students with similar climatic backgrounds to the UK and those from cooler climates than the UK. However, significant differences appeared between the warmer thermal history group and the other two groups. It was also demonstrated that the participants with a warmer thermal history had cooler thermal sensations compared to their counterparts in the similar-to and colder-than-UK thermal history groups, when exposed to the same environments. The optimal acceptable temperature was higher for the warmer climatic background (24 °C) than the similar/cooler climatic background groups (22 °C). Likewise, heightened values of preference and comfort temperatures were observed for the warmer thermal history group than the other two groups, despite their heavier clothing insulation than the other groups.

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The influence of acclimatization, age and gender-related differences on thermal perception in university buildings: Case studies in Scotland and England

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ABSTRACT

The higher education sector in the UK is responsible for large amount of the country's energy consumption. Space heating, which is the largest and most expensive part of the energy used in the UK educational buildings is a potential target for improving energy efficiency. However, the role of thermal comfort in students' productivity in academic environments cannot be overlooked. Considering the prevalence of two different climatic conditions in Northern and Southern/Midland regions of the UK, this study investigated thermal comfort in two university campuses in Scotland and England. environmental measurements combined with a simultaneous questionnaire survey were conducted in eight university buildings in Edinburgh and Coventry. The field study was carried out during the academic year of 2017-18 on 3507 students. The results confirmed influence of students' acclimatization, showing a warmer than neutral mean Thermal Sensation Vote (TSV) and cooler thermal preference in Edinburgh than Coventry. The higher acceptable temperature in Coventry (23.5 °C) than Edinburgh (22.1 °C) reinforced the results on the influence of climatic adaptation. Thermal acceptability was examined in a direct (analysing the actual votes on thermal acceptability) and an indirect approach (considering the TSV between 1 and 1 as acceptable). The indirect approach was shown to be a better predictor of the thermal acceptability as this method extends beyond the acceptable range suggested by the direct method. Thermal perceptions of females were shown to be colder than males in university classrooms. However, no statistically significant difference was observed in the thermal comfort of different age groups.

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TheEnvironmental design criteria for the university buildings in the Northern and Southern regions of the UK

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Abstract:
Considering the prevalence of the different climatic conditions in Northern and Midland regions of the UK, this study investigated the occupants' thermal comfort requirements in two university campuses in Scotland and England, UK. The aim of this investigation is to develop a practical, energy-efficient, and thermally comfortable environmental guideline for university classrooms. Indoor environmental measurements were combined with a simultaneous subjective monitoring through a questionnaire survey and observation in two university buildings in Edinburgh (Scotland) and Coventry (England), UK. Field study conducted during academic year of 2017-18 on 3511 university students in the classrooms involved in sedentary activities. Results confirm the influence of students' acclimatization to Scotland and England climates indicating warmer than neutral thermal sensation, cooler thermal preferences, and higher neutral temperatures in England compared to Scotland. In terms of thermal acceptability, an indirect approach (considering the central three thermal sensation votes) is a better predictor of the thermally acceptable zone compared to the direct evaluation approach (analysis of acceptability votes in the questionnaires).
Keywords: Thermal comfort, Higher learning environments, Thermal acceptability, Comfort temperature, Thermal satisfaction

1. Introduction

European educational buildings are responsible for a considerable part of energy use for heating purposes. In the UK, space heating is reported as the largest and the most expensive source of energy consumer (58% of total energy) in education sector (Carbon Trust, 2010). Higher learning environments in the UK demonstrated a strong commitment to global efforts to combat climate change over the last decade through reducing harmful emissions (Paul and Patton, 2018). Therefore, carbon reduction targets and strategies have been developed for higher learning environments in England (UK Universities, 2013), Scotland, Wales and Northern Ireland (Paul and Patton, 2018), to move towards healthier indoor environments (Clarke et al., 2008). However, given the significant influence of the thermal environment on students' well-being and productivity in educational buildings (Pepler and Warner, 1968; Wyon, Andersen and Lundqvist, 1979; Witterseh, Wyon and Clausen, 2002), occupants' comfort requirements should not be overlooked in such environmental considerations. This suggests a strong understanding of the occupants' thermal requirements to design a practical, thermally comfortable and energy efficient environmental criteria for university buildings.

The subjective nature of thermal comfort perception is well known in the existing literature (de Dear and Brager, 1998; McCartney and Nicol, 2001, 2002; Nicol, Humphreys and Roaf, 2012). Shipworth et al. (Shipworth et al., 2016) and Schweiker et al. (Schweiker et al., 2018) categorized the influencing human characteristics on perception of thermal comfort into the physiological and psychological properties resulting from contribution of the core body heat generation and state of mind, respectively.

Human body can physiologically adapt to a thermal environment as a result of, so called, "thermoregulation" (Humphreys, Nicol and Roaf, 2015), which maintains individual's comfort against thermal environmental fluctuations (Schweiker et al., 2018). As an example, repeated exposure to cold or warmth can decrease or increase core body heat generation, and subsequently make a subject cold or heat adapted, respectively; and change the perception of a thermal environment accordingly (Schweiker et al., 2018). Warmer thermal expectations of the subjects in warmer climate of Malaysia than Japan (Zaki et al., 2017), the relation between the outdoor temperature and neutral temperature in hot climate of Indonesia (Karyono, 2008) and thermal sensitivity of the subjects to cold in hot-humid climate of China (Zhang et al., 2010) confirm the role of climatic adaptation in thermal comfort evaluations. Overall, acclimatization and its impact on thermal perception is already confirmed in university buildings in China (Yao, Liu and Li, 2010; Zhang et al., 2010; Wang et al., 2014), India (Mishra and Ramgopal, 2014a, 2014b), Indonesia (Karyono, 2008), Malaysia (Zaki et al., 2017) and Brazil (C. Cândido et al., 2010; Christhina Cândido et al., 2010), suggesting that the same comfort environmental criteria cannot be applied for different climates (Rupp, Vásquez and Lamberts, 2015).

In the UK, climatic condition differs from region to region. In the Northern areas the weather is cold, damp, windy and rainy for most of the year. Mean daily temperature drops to 4–5°C in winter and goes up to 14–19°C in winter and summer months, respectively. In the Southern parts it is normally temperate, cloudy and sometimes windy in winters. Mean daily temperature is approximately 3–6°C during winter and 19–23°C during summer in the Northern areas (World climate guide, 2019).

Given the human body thermoregulations and physiological thermal adaptation, such climatic differences may lead to diverse thermal perceptions and heating energy demands in different regions of the UK. Thus, this study aims to investigate the thermally comfort and acceptable temperature ranges in university classrooms in the Northern (Scotland) and Southern/Midland (England) regions of the UK.

2. Methods

Field experiments took place during the academic year of 2017 – 2018 (i.e. from October 2017 to March 2018) in classrooms in two university campuses in Coventry, England (52.4068° N, 1.5197° W) and Edinburgh, Scotland (55.9533° N, 3.1883° W), United Kingdom (UK). Case study buildings operated on changeover or concurrent mixed modes (Brager, Borgeson and Lee, 2007). Space heating was available through ceiling diffusers or radiators and space cooling was provided through ceiling ducts or floor cooling outlets. Operable windows and fresh air supply ducts were available for ventilation purposes.

Indoor air temperature (Tin), relative humidity (RH), air velocity (Vi) and mean radiant temperature (Tmr) were measured using Multi purposes SWEMA 3000 (Universal instrument, 2019) instrument (working based on ISO 7730) (Table 1). Indoor air temperature and mean radiant temperature probes were positioned at 1.1 m above the floor level, as recommended by EN ISO 7726 (EN ISO 7726, 2001) on a vertical stand. SWEMA kit and one temperature and

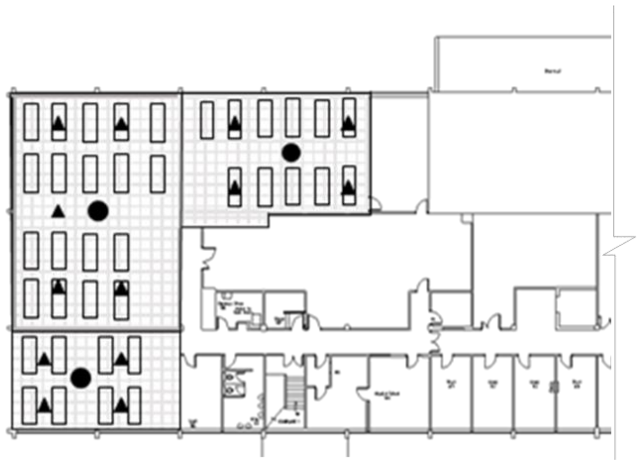
RH logger were placed in the middle of the room, away from the heat/cool sources to register the prevalent ambient environment in the classrooms. Also, six temperature and RH loggers were placed around the room close to the students to register the nearest environmental data to their sensations. Figure 1 indicates the position of the probes and temperature/RH loggers in some type of the classrooms.

Table 1. Description of the instruments

Measured parameter	Resolution	Range	Accuracy
Mean radiant temperature (°C)	**0.1**	**0 - 50**	**±0.1**
Air velocity (m/s)	**0.03**	**0.05 – 3.00**	**±0.04**
Relative humidity (%)	**0.8**	**0 - 100**	**±0.8**
Air temperature (°C)	**0.1**	**−40 - 70**	**±1.0**

Paper-based questionnaire surveys were conducted on 3511 students (2049 in Coventry and 1458 in Edinburgh) after at least 1-hour of students sitting in the classrooms. All the participants were sitting and listening to the lecturers during the measurements (metabolic rate of 1.1 met (ASHRAE 55, 2017)). They were of both genders with average age of 22 years old in both locations.

Thermal sensation vote (TSV) and thermal preferences (TP) were examined in the questionnaire, based on the ASHRAE 7-point scale (Table 2). Thermal acceptability was also assessed through the direct question of "How do you find the thermal condition of the classroom at this moment?" with the 4-point scale shown in Table 2. Clothing insulation value was evaluated using a checklist covering both underwear and outer garments as per in EN ISO 7730 (EN ISO 7730, 2005). Participants were asked to select the worn clothes at the survey time.



● Black bulb thermometer, RH and air velocity probs

▲ Temperature and RH logger

Figure 1. Position of the instruments in the classrooms of two buildings, as an example

Collected data were statistically analysed to estimate the acceptability, neutrality and preferred temperature in which the majority of students were thermally satisfied. Mean value of the recorded environmental variables in the last 15 minutes of each class (during the period of questionnaire survey) was considered for data analysis. Outdoor air temperature data was obtained from the UK meteorological office (WOW Met-Office, 2019). The weather station was less than 5 km from the study site and thus likely to be representative.

Table 2. Thermal comfort scales in the survey questionnaire

Scale	−3	−2	−1	0	1	2	3	4
Thermal sensation (TSV)	**Cold**	**Cool**	**Slightly cool**	**Neutral**	**Slightly warm**	**Warm**	**Hot**	
Thermal preference (TP)	**Much warmer**	**Warmer**	**Slightly warmer**	**No change**	**Slightly cooler**	**Cooler**	**Much cooler**	
Thermal acceptability (TA)					**Clearly acceptable**	**Just acceptable**	**Just unacceptable**	**Clearly unacceptable**

Operative temperature was calculated as the mean of radiant temperature and indoor air temperature for air velocity below 0.2 m/s and through the following formula for the higher air velocity (ASHRAE 55, 2010a). Where T_{op} is operative temperature, A is the constant value introduced as 0.6 (ASHRAE 55, 2010a), T_{air} is indoor air temperature and T_{mr} is the mean radiant temperature.

$$T_{op} = \mathrm{A} \cdot T_{air} + (1 - \mathrm{A})T_{mr} \quad (1)$$

3. Results and discussion

The environmental thermal comfort indices during the survey is summarizes in Table 3. Mean outdoor air temperature was higher in Coventry than Edinburgh. However, mean indoor operative temperature, indoor air and mean radiant temperatures are approximately 1°C lower in Coventry than Edinburgh. Indoor air velocity was low and mean indoor RH is almost in a similar range in both locations. Mean thermal sensation votes of -0.1 and 0.4 in Coventry and Edinburgh, respectively shows that occupants in Coventry feel cooler than their counterparts in Edinburgh. This is confirmed by the warmer thermal preferences in Coventry and cooler preferences in Edinburgh (Table 3).

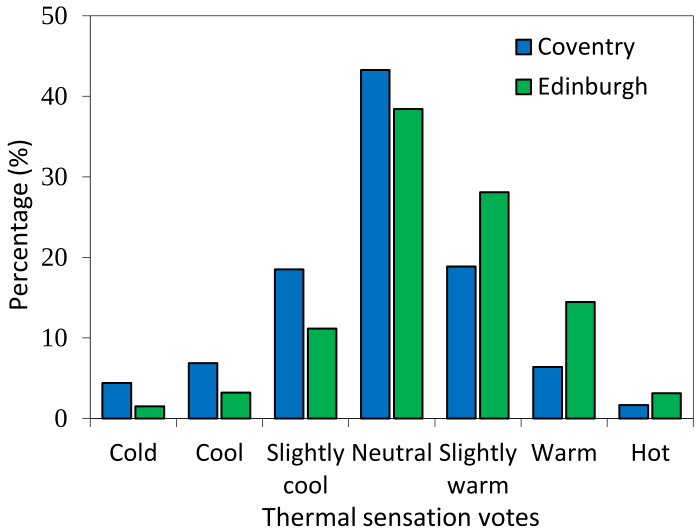
Table 3. thermal comfort indices

Location	Variables	Number	Mean	S.D.
Coventry	T_{out}	2051	11.2	4.1
	T_{air}	2051	22.9	1.6
	T_{mr}	2051	22.6	1.6
	T_{op}	2051	22.8	1.6
	RH	2051	45	12
	V_i	2051	0.07	0.03
	Clothing	1963	0.88	0.32
	TSV	2046	–0.1	1.2
	TP	2041	−0.04	1.1
Edinburgh	T_{out}	1460	5.8	1.9
	T_{air}	1460	23.9	1.6
	T_{mr}	1460	23.5	1.1
	T_{op}	1460	23.7	1.3
	RH	1460	30	6
	V_i	1460	0.04	0.04
	Clothing	1421	0.86	0.32
	TSV	1460	0.4	1.2
	TP	1459	0.30	1.1

T_{out}: Outdoor air temperature (°C), T_{air}: Indoor air temperature (°C), T_{mr}: Indoor mean radiant temperature (°C), T_{op}: Operative temperature (°C), V_i: Indoor air velocity (m/s), TSV: thermal sensation vote, TP: thermal preferences, S.D.: Standard deviation

Regarding the distribution of the thermal sensation and thermal preference votes, Figure 2 presents a skewed thermal sensation votes towards colder than neutral side in Coventry and a distinct skewing toward warmer than neutral side in Edinburgh. However, a clear shift toward 'want warmer' and 'want cooler' preference votes can be observed for students in Coventry and Edinburgh, respectively.

(a)



(b)

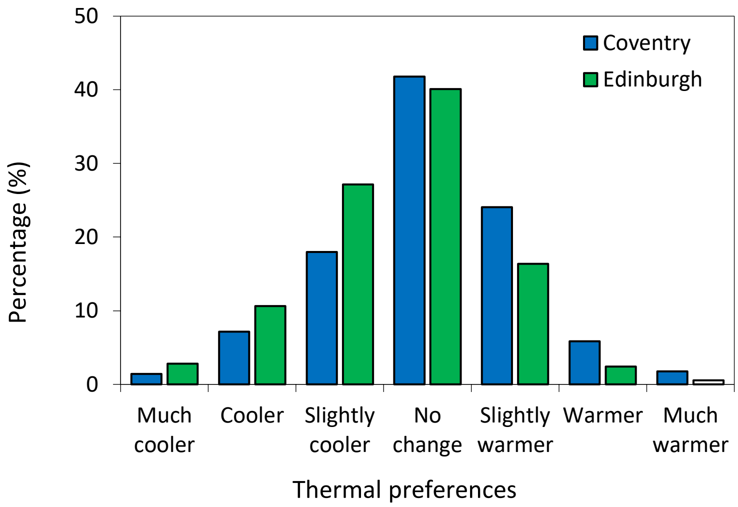


Figure 2. Distribution of thermal sensation (a) and preference(b) votes in Coventry and Edinburgh

3.1. Thermal neutrality

Thermal neutrality is determined using a linear regression between the thermal sensation votes (TSVs) and indoor operative temperature, Figure 3. In this work, similar to the previous studies (e.g. Nakano, Tanabe and Kimura, 2002; Wang, 2006), there was a high variety of thermal sensation votes in each indoor air temperature, which is mainly due to the individual differences between the subjects (Shipworth et al., 2016; Schweiker et al., 2018). The raw data caused too low coefficient of determination (R2) between thermal sensation votes and indoor operative temperature, which can be considered acceptable for such type of studies (de Dear and Brager, 1998). Neutral temperature, identified by substitution of 0 for TSV in the equations, is 22.7°C in Coventry and 22.3°C in Edinburgh. Considering regression gradient in the equations, as an index showing how TSVs are dependent on the operative temperature, approximately each 3°C temperature change, leads to variation of one unit thermal sensation vote in a 7-point sensation scale in both Coventry and Edinburgh, which shows similar sensitivity of the occupants to the temperature changes inside the classrooms in both locations.

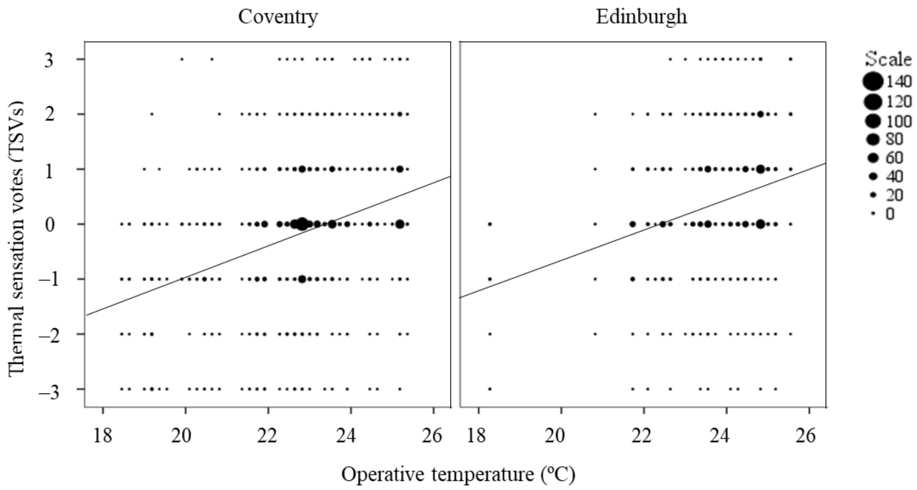


Figure 3. Linea regression of TSV and indoor operative temperature in Coventry (N=2044, $TSV = 0.30\ T_{op} - 6.82$, R2=0.15) and Edinburgh (N=1430, $TSV = 0.29\ T_{op} - 6.47$, R2=0.11)

3.2. Preferred temperature

To identify the occupants' preferred temperature, thermal preference votes of 'much warmer', 'warmer', and 'slightly warmer' were classified as 'want warmer' and thermal preference votes of 'much cooler', 'cooler' and 'slightly cooler' were categorized as 'want cooler'. The proportions of warmer and cooler thermal preference votes in relation to the operative temperature was evaluated, as suggested in Jungsoo's and de Dear's studies (de Dear et al., 2015; Jungsoo and de Dear, 2018). In Figure 4, the intersection points between warmer and cooler thermal preference votes is considered as preferred temperature.

The findings in this section is confirmed in some studies showing the influence of acclimatisation on thermal preferences and preferred temperature (Teli, Jentsch and James, 2012; Hwang, 2018; Jungsoo and de Dear, 2018). Results from studies conducted in hot and humid climate of Taiwan (Hwang, 2018), in Australian during summer season (Jungsoo and de Dear, 2018), in the UK during the heating period (Teli, Jentsch and James, 2012) and in Japan, Norway and UK (Shahzad and Rijal, 2019) confirm the gap between the thermal neutrality and preferences.

Table 4 summarizes the equations from probit analysis. Mean temperature is calculated by dividing the constant value by the probit regression coefficient for each equation. Standard deviation is inverse of the regression coefficient. All the equations are statistically significant ($p < 0.001$). Preferred temperature is around 23.5°C in Coventry and 23°C in Edinburgh which is similar in both locations. According to the results from previous sections, preferred temperature is apparently slightly affected by the students' thermal expectation as a result of acclimatisation.

A comparison between the neutral and preferred temperatures shows approximately 1°C higher preferred than neutral temperature in Coventry and less than 1°C higher preferred than neutral temperature in Edinburgh. This suggests that students in both Coventry and Edinburgh may feel comfortable in slightly warmer than neutral thermal sensations. As it is discussed by Shahzad et al. (Shahzad et al., 2018; Shahzad and Rijal, 2019), neutral thermal sensation cannot guarantee thermal comfort of the occupant as the subjects may feel comfortable in thermal sensations rather than neutral. Therefore, thermal preference is shown to be more likely to predict thermal comfort of people in the real world context (Shahzad et al., 2018; Shahzad and Rijal, 2019).

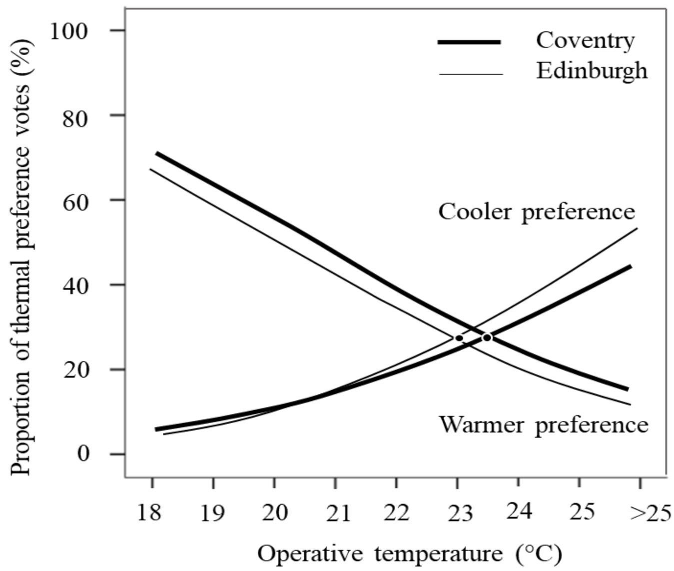


Figure 4. Preferred temperature in Coventry and Edinburgh

The findings in this section is confirmed in some studies showing the influence of acclimatisation on thermal preferences and preferred temperature (Teli, Jentsch and James, 2012; Hwang, 2018; Jungsoo and de Dear, 2018). Results from studies conducted in hot and humid climate of Taiwan (Hwang, 2018), in Australian during summer season (Jungsoo and de Dear, 2018), in the UK during the heating period (Teli, Jentsch and James, 2012) and in Japan, Norway and UK (Shahzad and Rijal, 2019) confirm the gap between the thermal neutrality and preferences.

Table 4. Equations from probit analysis

Location	Thermal preference votes	Equations	P value	Mean	SD
Coventry	**Warmer preference**	$TP_{warmer} = -0.20\ Top + 0.95$	**< 0.01**	**4.8**	**5.0**
	Cooler preference	$TP_{cooler} = 0.18\ Top - 1.95$	**< 0.01**	**10.9**	**5.6**
Edinburgh	**Warmer preference**	$TP_{warmer} = -0.21\ Top + 0.85$	**< 0.01**	**4.1**	**4.8**
	Cooler preference	$TP_{cooler} = 0.22\ Top - 2.12$	**< 0.01**	**9.6**	**4.6**

3.3. Thermal acceptability

Thermal acceptability level is evaluated with two approaches in this study: 1) an indirect approach: considering the three central thermal sensation votes (TSV= ±1 and 0) on 7-point sensation scale as thermally acceptable range, recommended in (ASHRAE 55, 2010b) and applied in previous studies (Toe and Kubota, 2013; Manu et al., 2016; Zaki et al., 2017); 2) a direct approach: analysing the students' direct responses to the question of "How do you find the thermal condition of the classroom at this moment?" on the 4-point acceptability scale in the questionnaire, Table 2 (Andreasi, Lamberts and Cândido, 2010; Mishra and Ramgopal, 2014b, 2015). In the indirect method, thermal dissatisfaction is considered as thermal sensation votes other than the acceptable zone of –1, 0 and +1 on the 7-point thermal sensation scale (ASHRAE 55, 2017). Therefore, thermal sensation votes of −3 and −2 are recoded as '1, uncomfortably cold' and the other votes recoded as '0, other votes'. The same rule is applied to the warmer than neutral thermal sensation votes where TSVs equal to +2 and +3 are recoded as '1, uncomfortably warm' and the rest are recoded as '0, other votes'. In the direct approach, students vote for "1, clearly acceptable" and "2, just acceptable" are recoded as "1, Acceptable" and the votes for "3, just unacceptable" and "4, clearly unacceptable" are considered as "0, Unacceptable".

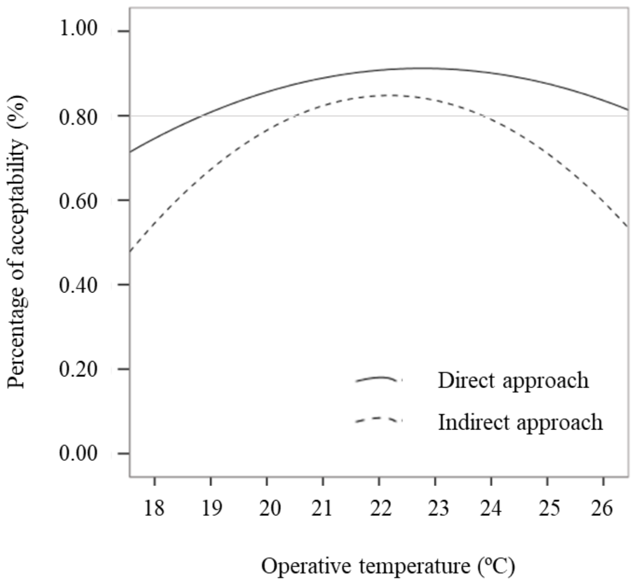


Figure 5. Thermal acceptability in each operative temperature

Thermal acceptability in both methods of evaluation in each 1ºC binned operative temperature is presented in Figure 5. A similar trend can be observed for both approaches with slightly higher acceptability level and a wider range in direct compared to indirect approach. Students in higher learning environments tend to be more forgiving about their thermal environments when consciously evaluating and voting for it, compared to identifying their acceptable zone based on their thermal sensation votes, as recommended in regulatory documents (ASHRAE 55, 2010b). As can be observed, determining the thermal acceptability through indirect approach can already cover the occupants' actual thermal acceptability votes. Therefore, setting the thermal environment based on the indirect method can provide occupants actual satisfaction. However, form an environmental point of view, thermally acceptable temperature range starts from 1.5°C lower indoor air temperature with direct than indirect approach. Thus, setting the classrooms thermal environment based on the results from direct approach may provide a thermally acceptable environment at the same time as saving energy for heating purposes.

Two reasons may contribute to the higher thermal acceptability level in the direct approach; one presumably is due to the students' perception of control on the classroom thermal environment, the impact of which can improve the level of thermal acceptability and lessen their thermal sensitivities in the exposed environment (Nicol et al., 1994; Brager, Paliaga and de Dear, 2004; Rijal et al., 2008; Rijal, Yoshida and Umemiya, 2010). The other reason can be due to the students' diverse physiological and psychological backgrounds resulting in a wide variety of thermal acceptability levels, which could not be predicted through thermal sensation votes in indirect approach.

4. Conclusion

This study is part of a comprehensive investigation on thermal performance and the occupants' comfort in the UK higher educational buildings. The potential influencing factors on thermal perception of the occupants in university classrooms are identified and the impact of each is studied. So far, thermal comfort perception of the students in different disciplines in exposure to the various classroom types (Jowkar et al., 2020), thermal comfort of the gender and age groups and the diverse perception of thermal comfort resulted from the students' climatic background, as long-term thermal history, have been investigated by similar authors in the previous works.

Considering the different climatic conditions prevailing in different regions of the UK, this work investigates whether the same thermal environmental criteria can provide comfort in higher learning environments in Southern (Scotland) and Northern regions (England) of the UK. The investigation was conducted in two university campuses in Scotland (Edinburgh) and England (Coventry) in the UK. Simultaneous questionnaire surveys with environmental measurements were conducted in eight mixed-mode university buildings in Edinburgh and Coventry. Overall, 3352 university students were surveyed while being involved in sedentary activities inside the classrooms.

It is concluded in this study that the same environmental criteria for higher learning environments cannot be applicable in Scotland and England. The findings recommend investigating the thermal comfort requirements of the occupants in higher learning environments in different regions of the UK with diverse climatic conditions, which not only provides students comfort and improves their productivity, but also reduces the space energy waste and running cost for heating/cooling purposes.

Furthermore, A comparison between the two methods of thermal acceptability assessments, a direct approach (considering the actual votes of the occupants on thermal acceptability) and an indirect approach (considering the thermal sensation votes between –1 and +1 as acceptable range) shows that in designing the thermal environmental criteria for higher educational buildings, indirect approach is a better predictor of the occupants' thermal acceptability as this method can already cover the students' actual thermal acceptability votes. However, the direct method shows a potential for higher energy saving in university classrooms. Therefore, further investigations on thermal acceptability, occupants' comfort and energy demand is recommended to find the optimum thermal environmental design criteria for the UK university buildings.

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Thermal Comfort in Higher Educational Buildings: Different Classroom Types

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Abstract: Thermal comfort in learning environments influences the students' attention, concentration and learning productivity. Due to the impact of the thermal environment on students' thermal comfort and consequently their productivity in line with the impact on energy consumption, this topic has attracted substantial attention among researchers in the recent years. This study aims to evaluate thermal comfort of the students in different classroom types in the UK higher learning environments. Thermal comfort zone, comfort temperature and thermal acceptance are evaluated under Free running, Cooling and Heating modes. Simultaneous environmental measurements and questionnaire survey were conducted in the classrooms under each mode. 2046 students participated in the surveys in a university building in Coventry, United Kingdom, between October 2017 and March 2018. Results present thermal comfort zone between 21°C and 25°C and comfort temperature of around 23°C in the classrooms under each operation mode. The research output helps to expand the existing environmental guidelines for higher educational buildings to have more reliable and energy efficient standards.

Keywords: Thermal comfort, Higher education buildings, Comfort temperature, Energy efficiency

1. Introduction

Thermal comfort in learning environments influences the students' attention, concentration and learning productivity [1–4]. Both higher and lower temperatures than the comfort zone tend to reduce students' performance and ability to grasp instruction. Warm environment affects students' productivity and cold temperatures reduces manual dexterity and speed [7, 8]. Due to the influence of the thermal environment on students' thermal comfort and productivity in line with the impact on energy consumption, this topic has attracted huge attention among researchers in the recent years. So far, studies have been conducted on thermal comfort in educational buildings in *primary schools* in the UK [7, 8, 11, 12], Italy [11], Netherlands [7, 14] and Taiwan [13], *secondary schools* in Italy [16, 17], Portugal [16] and Cyprus [17] and *university buildings* in Italy [5, 20], Netherlands [19], Japan [22, 23], Brazil [22] and India [25, 26]. Vargas [27, 28] conducted two studies in Sheffield University in the UK evaluating the impact of HVAC technologies on environmental diversity along with examining the role of transitional lobby spaces on the occupants' thermal comfort in interior spaces. However, there are only limited studies carried out to investigate thermal comfort in the UK higher educational buildings [30, 31]. Existing guidelines such as CIBSE-A [29] and ASHRAE 55 [30] recommend general environmental standards for educational buildings, however, no detail information provided based on the educational levels. There is no specific standard for the higher learning environments where providing comfort for the occupants is quite challenging mainly due to the students' different climatic background, various subjects and exposed classroom types. Students in higher learning environments are typically from different disciplines and studying in disparate topics. They are exposed to dissimilar environmental conditions, in different classroom types, with variable occupancy periods and different levels of freedom for adaptive behaviour. For example, students in art-based subjects may spend four or five hours in studios with high levels of freedom for adaptive behaviour. While, students, mostly in science-based subjects, tend to occupy the lecture rooms for one to two hours or PC labs for two to three hours with low or medium levels of freedom. This study aims to evaluate the comfort temperature for students in different disciplines, art- based and science- based subjects, attending the studios and lecture rooms/ PC labs classroom types respectively.

2. Methodology

Field experiments were conducted through simultaneous environmental evaluation, questionnaire survey and observation in the four university buildings in Coventry, England. Mean annual temperature in Coventry is 12°C [31]. Relative humidity and mean annual air velocity is around 85% and 2 m/s respectively. Data collection took place between October and November 2017; and between January and April 2018. Experiments were conducted in the classrooms in four different mixed- mode buildings. All classrooms were equipped with HVAC systems and operated on changeover or concurrent mixed-mode [32]. Based on the indoor ambient environment, free running (FR, neither heating nor cooling), cooling (CL) or heating (HT) mode were preferred by occupants in those spaces.

Field measurements included recording of indoor air temperature (T_{in}), relative humidity (RH), air velocity (V_i) and mean radiant temperature (T_{mr}) in each classroom. Relative humidity, air velocity and mean radiant temperature were recorded using Multi purposes SWEMA 3000 instrument working based on ISO 7730 with time interval of 5 minutes. Probes included in SWEMA kit were positioned at the occupants' head height to reflect all subjects' thermal sensation. Thermometer placed on 1.1m above the floor level, as recommended by EN ISO 7726 [33], anemometer and humidity probe were placed above and below the thermometer.

SWEMA kit and one temperature and RH logger were placed in the middle of the room, away from heat or cool sources.

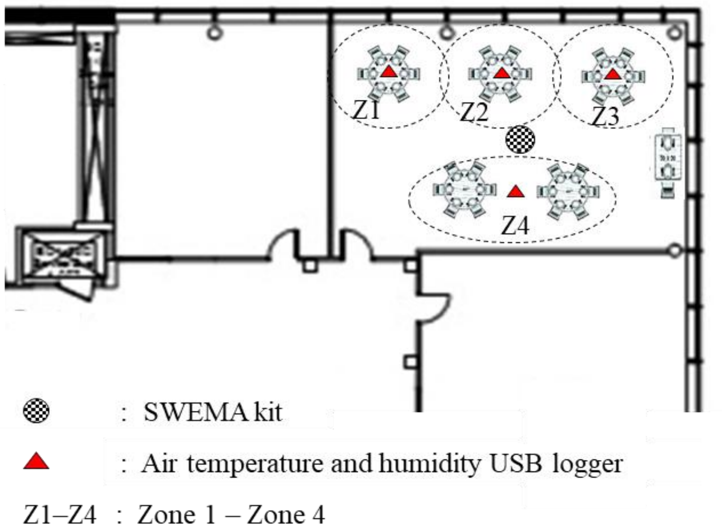


Figure 1. architectural plan of one of the surveyed classrooms

Classrooms were divided into 4 or 5 zones (Figure 1), based on the physical shape, and each temperature and RH logger were located in each zone to have nearest environmental data on the students' sensations. Operative temperature, which is generally worked within this study, was calculated as the mean of radiant temperature and indoor air temperature [34]. Outdoor air temperature data was obtained from the UK meteorological office [31]. Cross- sectional questionnaire survey was conducted on students in studios, PC labs and lecture rooms after obtaining ethical approval from both universities.

The duration of each lecture was around 1 or 2 hours while the students were seated listening to the lecturer. However, in studios they were involved in activities such as making samples and drawing which took almost half a day with couple of breaks in between. According to CIBSE-A [35], metabolic rate was considered 1.4 met for students in lecture rooms and PC labs and 1.8 in studios (workshop). Occupants' clothing level were evaluated based on the introduced clo value in EN ISO 7730 [36].

Table 1. Thermal comfort scales

Scale	−3	−2	−1	0	1	2	3
Thermal sensation (TSV)	Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
Thermal preference (TP)	Much warmer	warmer	Slightly warmer	No change	Slightly cooler	Cooler	Much cooler

Thermal sensation vote (TSV) was examined based on the ASHRAE 7 point scale. A similar 7-point scale was used for thermal preferences (TP), Table 1. The questionnaires were distributed in the last 15 minutes of each class, after at least 1-hour that students had sat in the classrooms. It is mentioned in the previous studies that 15 minutes is enough to eliminate the influence of metabolism on thermal sensation votes [53, 54]. All participants were asked to complete the questionnaires at the same time to make sure the recorded environmental variables correspond to all the collected thermal sensation votes. Overall, 2046 students, 1247 in lecture rooms, 408 in studios and 391 in PC labs participated in the survey. Each student participated once in the survey. Participants were in both genders and in average aged between 18 and 25 years. Collected data were statistically analysed to estimate the comfort temperature in which majority of students are thermally satisfied.

3. Results

3.1. Outdoor and indoor environment

Figure 2 shows the outdoor air fluctuations in 2017 – 2018 in Coventry. Minimum, average and maximum air temperature equals to 1, 7 and 15°C respectively within the survey period (October 2017- March 2018).

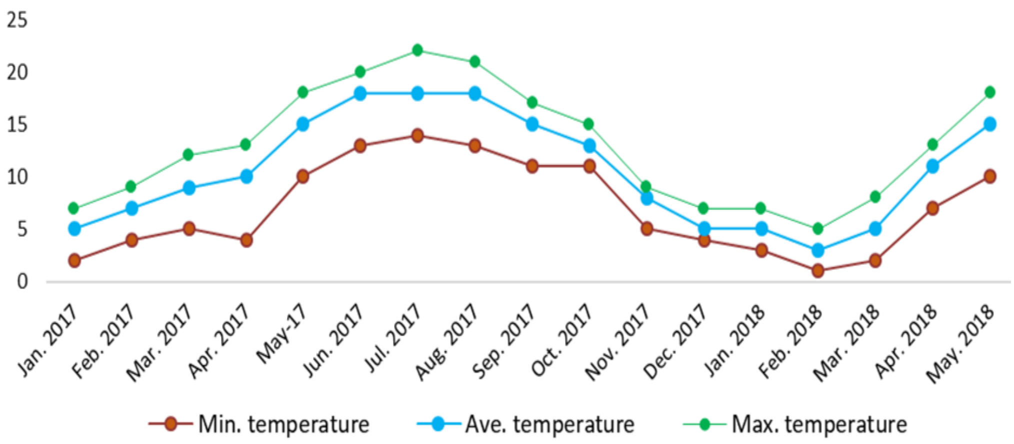


Figure 2. Monthly mean outdoor air temperature in Coventry

Results for the indoor and outdoor environmental parameters are presented in Table 2. Mean indoor air temperature, mean radiant temperature and operative temperature approximately equals to 22.9°C, 22.6 °C and 22.8°C respectively. Mean operative temperature is higher in studios than the other classrooms by 1°C under FR mode and 2°C under HT mode. In the PC labs, it is 1°C higher than lecture rooms under both FR and CL modes.

Table 2. Summary of the indoor and outdoor environmental parameters

Classroom type	Mode	Items	T_{out} (°C)	T_{air} (°C)	T_{mr} (°C)	T_{op} (°C)	V_i (m/s)	RH_{in} (%)
Lecture room	FR	Mean	12.7	22.6	22.7	22.6	0.08	51
		SD	2.6	1.3	1.4	1.3	0.35	9
	CL	Mean	10.3	22.7	22.0	22.4	0.07	38
		SD	4.8	2.1	1.7	1.9	0.24	9
	HT	Mean	3.8	21.2	20.3	20.8	0.06	24
		SD	2.7	1.5	1.2	1.2	0.29	5
Studio	FR	Mean	14.0	24.0	23.8	23.9	0.07	60
		SD	2.2	1.0	1.1	0.9	0.04	7
	CL	Mean	-	-	-	-	-	-
		SD	-	-	-	-	-	-
	HT	Mean	9	23.3	23.2	23.2	0.03	41
		SD	0	0.6	0.7	0.6	0.01	4
PC lab	FR	Mean	11.3	23.3	23.5	23.4	0.03	44
		SD	2.0	0.9	0.8	0.8	0.02	7
	CL	Mean	13.1	23.5	23.1	23.3	0.08	49
		SD	1.8	0.5	0.7	0.6	0.05	5
	HT	Mean	-	-	-	-	-	-
		SD	-	-	-	-	-	-

T_{out} : Outdoor air temperature (°C), T_{air}: Indoor air temperature (°C), T_{mr}: Indoor mean radiant temperature (°C) , T_{op}: Operative temperature (°C), Vi: Indoor air velocity (m/s)

3.2. Subjective evaluation

Table 3 presents the summary of the subjective parameters collected during the survey. Mean thermal sensation votes (MTSVs) in all classroom types in both locations fell between -1 and 1. The negative value of MTSV in lecture rooms, -0.26, indicate cold thermal sensation of students in such spaces. However, MTSV in studios and PC labs equals to 0.20 and 0.12 respectively showing that students feel warmer than neutral in these environments. Thermal preference votes are toward warmer thermal environment in the lecture rooms and cooler environment in studios and PC labs, which is consistent with thermal sensation votes. Mean clothing value is in the range of 0.85 to 0.91 clo in all classroom types.

Table 3. Summary of subjective evaluations

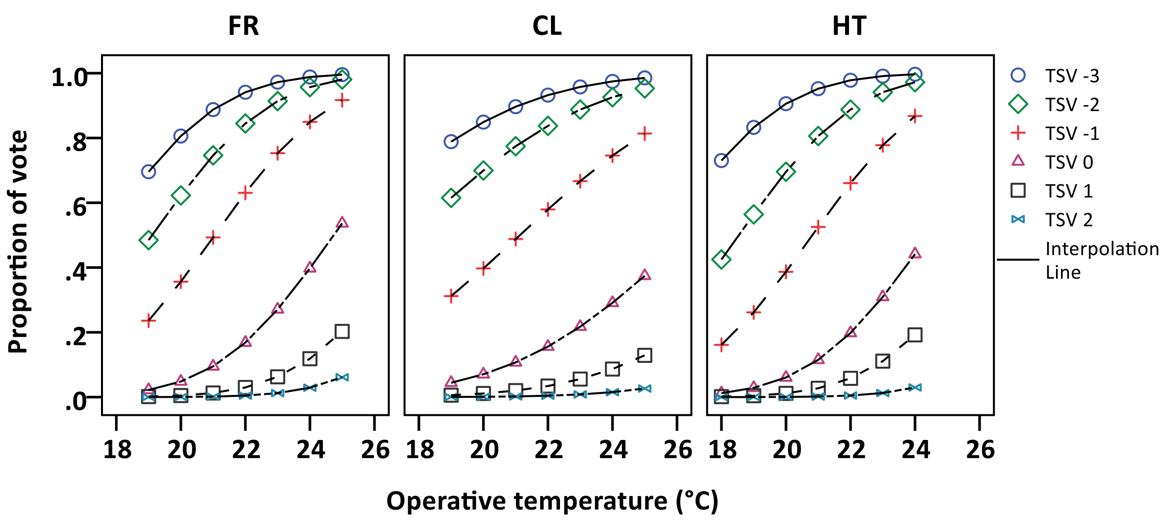
Classroom types	Modes	Items	TSV	TP	Clothing (clo)
Lecture room	FR	Mean	-0.20	0.13	0.87
		SD	1.22	1.11	0.32
	CL	Mean	-0.23	0.11	0.85
		SD	1.20	1.12	0.31
	HT	Mean	-0.54	0.32	0.96
		SD	1.17	1.14	0.32
Studio	FR	Mean	0.18	-0.19	0.90
		SD	1.15	1.13	0.29
	CL	Mean	-	-	-
		SD	-	-	-
	HT	Mean	0.27	-0.12	0.87
		SD	1.14	1.05	0.30
PC lab	FR	Mean	0.19	-0.17	0.86
		SD	1.09	0.99	0.31
	CL	Mean	0.05	0.06	0.87
		SD	1.21	1.03	0.32
	HT	Mean	-	-	-
		SD	-	-	-

- : No data available

3.3. Comfort zone

To identify the comfort zone for the students under each operation mode, probit regression analysis is applied for thermal sensation votes and operative temperature. This analysis was conducted by applying probit regression as the link function and operative temperature as covariate [39].

(a)



(b)

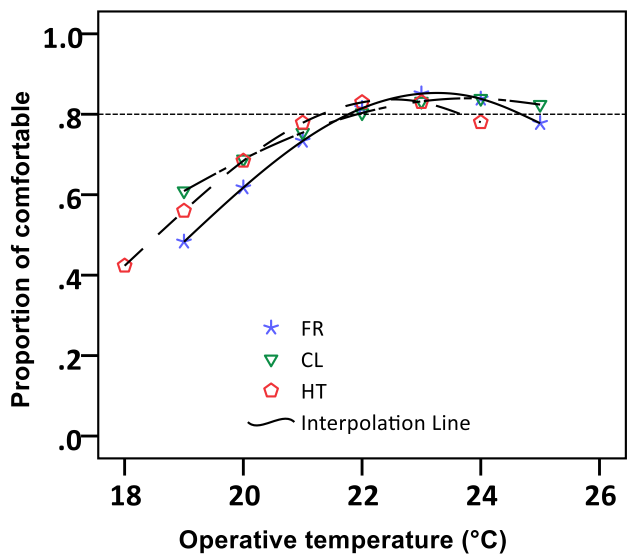


Figure 3. Comfort temperature in the classrooms in each mode

The first line (highest) in Figures 3 (a) shows the proportion of TSVs of “-3 cold” and last line (lowest) indicates the proportion of TSV of “2 warm”. The neutral temperature, between line TSV -1 and TSV 1, with probability of 0.5 is around 23°C in FR and HT modes and 24°C in CL mode. Optimum temperature with high proportion of occupants’ satisfaction equals to 24°C under FR and CL and 22°C under HT mode. Considering standard of minimum 80% acceptability as recommended in regulatory documents such as ASHRAE - 55 [34], comfort zone equals to 22- 25°C under FR and CL and 21- 24°C under HT mode (Figure 3b).

3.4. Comfort temperature

Griffiths’ method is applied to estimate comfort temperature in each classroom type under FR, CL and HT modes. Results presented in Figure 4, shows statistically significant difference between comfort temperature in studios and lecture rooms under FR and HT modes in Coventry. There is approximately 1°C higher comfort temperature in studios compared to the lecture rooms in both operation modes. However, it is similar in the lecture rooms and PC labs under FR and CL modes.

According to Gail, et.al. [47], high levels of freedom and control over the space can lead to 1.5°C higher comfort temperature for the occupants compared to a group with limited control in a same environment. Therefore, higher comfort temperature in the studios is resulted from the students’ higher levels of freedom and control in such spaces than the other classroom types.

Furthermore, according to Tables 2 and Figure 4, students’ comfort temperature is very close to the actual experienced operative temperature in the studios. This similarity happens due to the students’ thermal adaptation to the studios as they spend long enough time there to thermally adapt to the environment. Apart from physiological thermal adaptation which happens to maintain the constant internal body temperature and proved in some previous studies [34, 60, 61], psychological thermal adaptation plays an important role on students' thermal comfort in studios. Occupants' thermal assessment and mental benchmark during initial occupancy results from their thermal history, not current environmental condition [28, 31, 55, 56]. However, after extended period of occupancy they change the set benchmark according to the current thermal experience not previous environments [46].

Consequently, higher levels of freedom and control over the space as well as long occupancy period and thermal adaptation in the studios, is the main reason for higher comfort temperature in such spaces than the lecture rooms and PC labs.

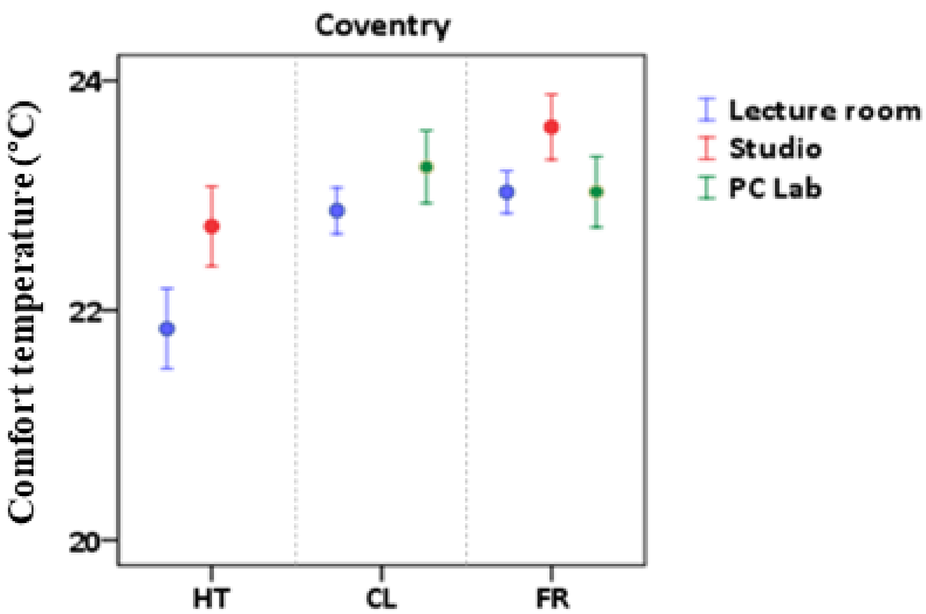


Figure 4. Comfort temperature in each classroom type

3.5. Thermal acceptability in the lecture rooms, studios and PC labs

Figure 5 shows the thermal acceptability votes in the lecture rooms, studios and PC labs. As the common operative temperature range in all classroom types is from 22°C to 25°C, the evaluation of thermal acceptability is completed in this temperature range to get more reliable comparison results. Overall, 90% of the students voted for acceptable thermal environment and only 10% of them thermally evaluate the classrooms as unacceptable.

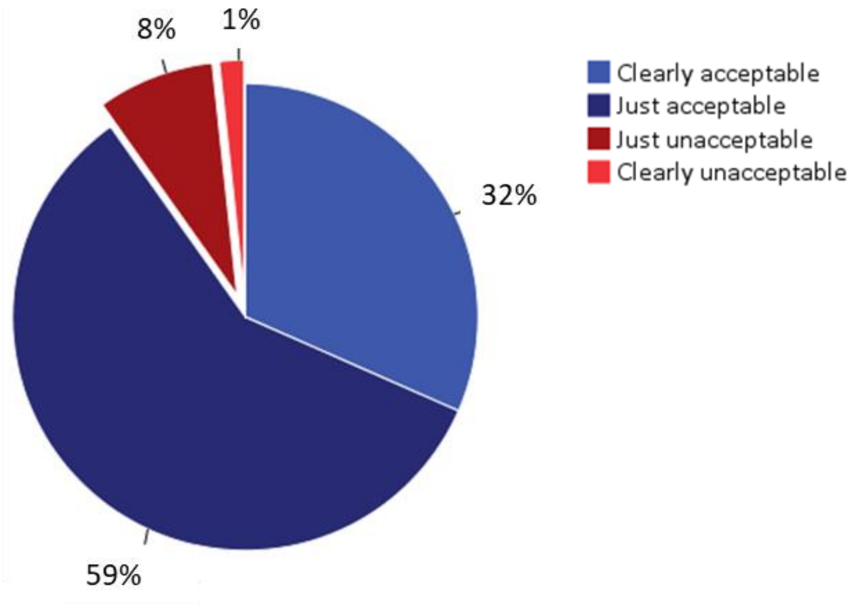


Figure 5. Thermal acceptance in the classrooms

Figure 6 illustrates the percentage of thermal unacceptable votes in each classroom type. As there is a similar environmental conditions and teaching style in the surveyed lecture rooms and PC labs, thermal acceptability votes in these two spaces are considered as the same group. Among all the students in the lecture rooms/ PC labs and studios, only around 10% of them vote for unacceptable thermal conditions. A detailed look at the thermal unacceptable and preferred votes at the same time to some extent shows a reason of the unacceptable votes. Students in the lecture rooms and PC labs prefer *warmer* thermal environments, while in the studios *colder* thermal environment is preferred by almost half of the students. Despite the higher comfort temperature in studios than lecture rooms and PC labs, cooler thermal condition is preferred in studios. In fact, higher level of activity in the studios (making samples and drawing) than lecture rooms and PC labs, may not directly affect the comfort temperature but affects the occupants' thermal preferences and, as a result, their thermal acceptability.

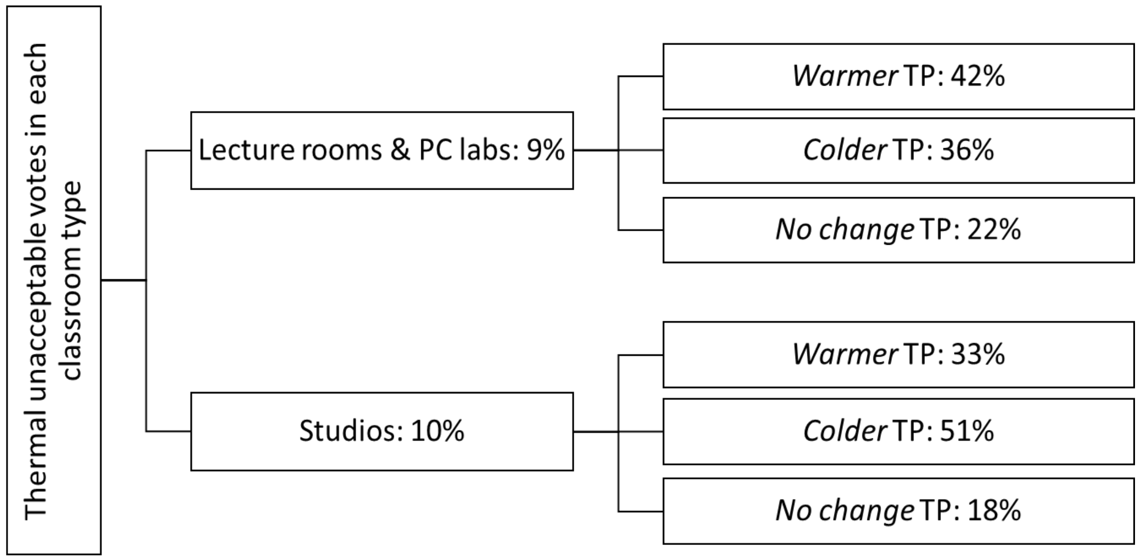


Figure 6. Thermal acceptance and preference votes in each classroom type – TP: Thermal Preference

4. Conclusion

This study evaluates thermal comfort in the lecture rooms, studios and PC labs in higher learning environments in Coventry, United Kingdom. Investigation was conducted through environmental measurements, questionnaire surveys and observations. Total, 2046 undergraduate and postgraduate students participated in this study inside the classrooms.

Considering standard of minimum 80% acceptability as recommended in regulatory documents, thermal comfort zone, evaluated by probit regression analysis, is wider in the lecture rooms than studios and PC labs. The main reason is due to the students' wider exposure temperature range in the lecture rooms than studios and PC labs.

Also, it is revealed that the comfort temperature calculated by Griffiths' method tends to be 1°C higher in the studios than the lecture rooms and PC labs as a result of higher operative temperature in the studios that the other classroom types.

Proximity of the comfort and operative temperature in the studios shows the occupants' thermal adaptation to the thermal environments due to the long occupancy period and high level of freedom/control over the space. In fact, thermal adaptation tends to both physiologically and psychologically overcome the influence of higher metabolism on the occupants' thermal comfort in the studios.

The output of this work helps to expand the existing environmental guidelines for higher educational buildings to not only improve the students' thermal comfortable and consequently productivity, but also minimize energy consumption and such buildings running costs.

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Thermal Comfort in the UK Higher Educational Buildings: The Influence of Thermal History on Students' Thermal Comfort

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Abstract: Statistics regarding the number of international students in the UK higher educational buildings show an upward trend in the recent years. These students coming from different cultural and climatic backgrounds have various thermal perceptions inside the classrooms. According to the significant influence of thermal quality of learning environments on students' productivity and wellbeing, it is essential to develop specific environmental guidelines for the UK higher educational buildings based on the students' backgrounds. Developed standards not only can provide occupants' thermal comfort in such multicultural spaces, but also can minimize energy consumption and running costs within the higher educational buildings in this country.
This study evaluated the students' thermal perception in three different types of learning environments including fifteen Naturally Ventilated lecture rooms, studios and PC Labs from three different buildings of Coventry University. Indoor air temperature, humidity level, air velocity and mean radiant temperature were monitored in different times of a day. A questionnaire survey was conducted on approximately 1000 undergraduate and postgraduate students at the same time of recording operative temperature. This study is completed based on thermal comfort votes of 650 students.
Results reveal the influence of short and long-term thermal history including climatic background, thermal condition of current accommodation and thermal adaptation to the UK weather on students' thermal comfort perception inside a classroom. The outcome of this study can be applied to develop the reliable and practical guidelines for the multicultural higher educational buildings within the UK.

Keywords: thermal comfort, higher educational buildings, classrooms, climatic background

1. Introduction

Thermal comfort can be defined as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ASHRAE 55, 2004). This clearly shows that people's thermal comfort is a subjective response (Singh, 2015), therefore, an identified value cannot thermally satisfy all the occupants in a space. Occupants' "condition of mind", in terms of thermal comfort, can be different due to various thermal perceptions, expectations, cultures, moods and some other personal or social factors (Katafygiotou and Serghides 2014, Nicol and Humphreys 2002, Singh et al. 2011).

Thermal history and adaptation is one of the major factors affecting people's thermal comfort in an environment. Occupants' thermal sensation in a space resulted from the contrast between the current and previous environmental experiences (Ji et al. 2017, Cândido et al. 2010). In general, the impact of thermal history on thermal comfort can be divided into two main groups of *short- term* and *long- term* based on the occupants' exposure duration to a thermal condition. The influence of *short-term* thermal history on people's thermal sensation, in both Naturally Ventilated (NV) and Air Conditioned (AC) environments, is evaluated in spaces such as transitional spaces in the UK higher educational buildings (Gloria A Vargasa 2014), office buildings in the hot and humid climate of Brazil (Cândido et al. 2010), universities in Pennsylvania, USA, in cold seasons (Fadeyi 2014) and controlled chambers in different climates (Chun et al. 2008, Ken Parsons Lisa Kelly 2010, Nagano et al. 2005, Barrett et al. 2015, Du et al. 2014, Ji et al. 2017, Yu et al. 2013). *Long- term* thermal history and its impact on thermal sensation is also assessed in residential buildings in north and south China by Luo et al. 2016a. It is concluded in these studies that people's thermal sensation and comfort level not only depends on the thermal condition of their current environment, but also previous thermal experiences have a significant influence on their thermal comfort votes.

Adaptive behaviour and control possibilities in an environment can also play important roles on people's thermal perception. Occupants with higher level of control within a space tend to feel more thermally comfortable than their counterparts with lower level or no control in the same environment. Evaluating the occupants' sources of dissatisfaction in the office buildings in winter months in the USA, Finland and Canada reveal that the most frequent problems with employees' thermal comfort is due to lack of control over the space such as no access to thermostat, heater, and operable windows (Huizenga et al. 2006). The improvement of the occupants' thermal comfort (Huizenga et al. 2006, Langevin et al. 2012) and thermal acceptability (Brager et al. 2004, Bauman et al. 1998, Zagreus et al. 2004, Langevin et al. 2012) in NV/ AC office buildings in warm climate, with almost 1.5 °C increase in acceptable temperature range (Brager et al. 2004), clearly shows the significant influence of control possibility on people's thermal comfort within a space. From psychological point of view, occupants who are aware of their control in an environment feel less irritable by uncomfortable thermal conditions (Liu et al. 2014).

According to the mentioned influential factors on people's thermal sensation, providing thermal comfort in the multicultural spaces such as higher learning environments tends to be quite challenging, due to the occupants' various physiological and psychological backgrounds.

Thermal quality of learning environments influences occupants' physical, mental and psychological health; which can affect the teaching and learning performance within the space (Mendell and Heath, 2005, Zomorodian et.al, 2016, Hassanian and Iftikhar, 2015, Schiavon and Zecchin, 2008) and as a result affects the outcome of the education system in each level. Developing the outcome of educational system is an important issue in the UK higher learning environments to attract the international students for studying in this country (Ursula, 2014). Considering the mentioned factors along with the UK commitment to reduce its energy consumption and greenhouse gas emission by 2050 (Committee on Climate Change, 2016, Committee on Climate Change, 2017), attracts more attention to provide thermally comfortable and energy efficient higher educational buildings in this country.

The currently existing environmental guidelines, such as CIBSE-A and EN 15251, introduce the same environmental standards in the UK educational buildings in all levels. In other words, similar thermal requirements are considered for students in all educational stages, from school level to higher learning environments. However, these environmental guidelines cannot be applied in higher learning environments the same as other educational buildings such as primary, secondary and high schools due to the following reasons;

- *Occupants' age and gender:* aging causes increasing the people's comfort temperature (Indraganti and K.D. Rao, 2010, Cena and R. de Dear, 2001, Hwang and C.P. Chen, 2010) and lowering their thermal sensation vote for almost 0.5 scale units (on the 7-point ASHRAE scale) for elderly people (Schellen et.al, 2010). Regarding gender, females tend to have higher neutral temperature (Cena and de Dear, 2001, Morgan, 2003, Karjalainen, 2007). As students in higher educational buildings are in different ages and both genders, they may have various thermal requirements to feel comfortable in an environment.
- *Cultural and background diversity:* personal characteristics (thermal history, culture and social factors) can play an important role on people's thermal sensation in a space (Knez and S. Thorsson, 2006, Kenawy, 2013, Luo et. al. 2016). Therefore, students in the UK higher learning environments, who are from different cultures and nationalities with different thermal experiences and backgrounds, may have various thermal requirements inside the classrooms.
- *Occupants' freedom to do adaptive behaviour:* students in the university classrooms usually have sufficient freedom to choose the appropriate environmental (e.g. opening or closing windows, using the interior blinds) or personal (e.g. changing position, clothing and having a hot or cold drink) adaptive behaviour (Nicol et.al. 2012). Prediction of the students and lecturers' adaptive behaviour in thermally uncomfortable conditions is another factor which should be taken into account in developing proper environmental guidelines.

Due to these reasons, it is required to introduce new environmental standards for higher educational level based on the building function and the occupants' type. Thermal comfort in higher learning environments is evaluated in different climates by considering students' thermal sensation and preferences votes. For instance, the acceptable temperature range and adaptive behaviour for students in university buildings are evaluated in China by Zhang et.al. 2007 and Yao and Lio, 2010; Buratti, 2006 examined the students' comfort temperature in Italy; Hwang, 2006 studied the acceptable temperature range for pupils' in Taiwan, based on the impact of thermal adaptation and adaptive behaviour. In the UK, the influence of thermal history on thermal sensation in transitional lobby spaces, and impact of air quality on occupants' overall comfort is evaluated in Sheffield and Loughborough University (Vargasa, and F.S, 2014, Barbhuiya, 2013). However, none of these investigations considered the influence of personal and environmental factors on students' thermal comfort inside the classrooms in this country. Therefore, a revision and modification on the existing comfort criteria based on the personal factors are essential to create the thermally comfortable and satisfactory environmental condition in higher educational buildings.

The current survey is part of a research project assessing the students' thermal comfort in the UK higher learning environments based on the influential environmental, physiological and psychological human characteristics. In this paper the influence of the students' thermal long and short-term history on thermal comfort perception in Coventry University, UK is evaluated.

2. Methodology

This survey was conducted through a physical evaluation, objective and subjective measurements in three different buildings in Coventry University showing in figure 1.

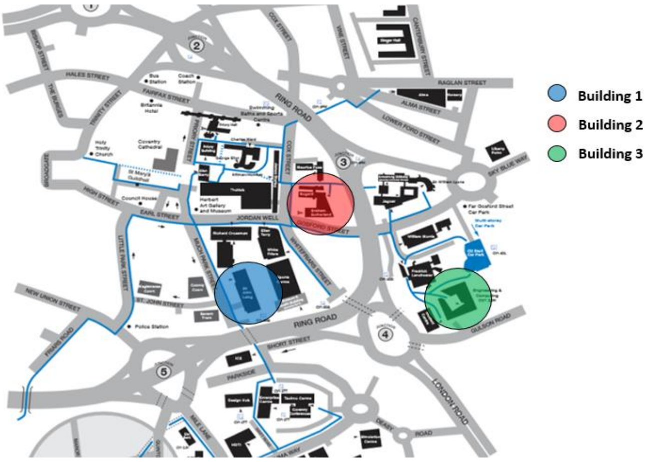

Figure 1, The location of the investigated buildings in Coventry University campus

2.1. Investigated Buildings

The evaluation was conducted in lecture rooms, studios and PC labs in three different buildings at Coventry University in October 2017. Type of the classrooms in each building in which the evaluation was carried out is presented in figure 2. Survey was conducted for 19 times in 6 lecture rooms, where students spend almost 2 or 3 hours with low level of freedom for adaptive behaviour and sedentary activity (1.2 met), 4 PC labs, occupied for 2 or 3 hours tutorial with medium level of freedom, and 3 art studios, where students spend more than 4 hours with high freedom and light activity level (1.6 met) (ISO 7730, 2005). Surveys were conducted in the mornings and afternoon sessions in the free running (FR) modes. Figures 3 to 5 shows a sample of a lecture room, studio and PC lab in buildings 1, 2 and 3 respectively. Also, the description of the investigated buildings 1, 2 and 3 is presented in table 1. Ventilation mode, location of the cooling outlets, windows and door situation, time of the day, sky condition and possible adaptive opportunities were also monitored in each classroom.

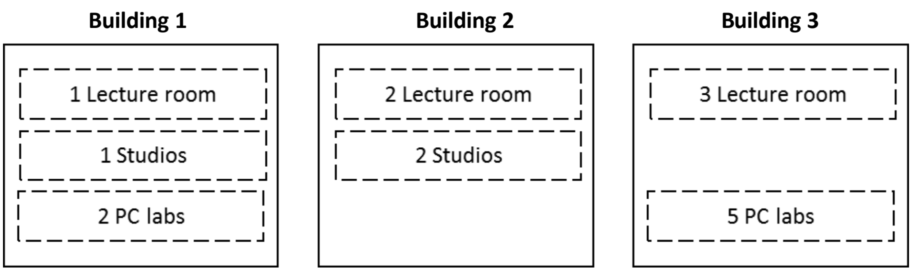

Figure 2, Type and the number of classrooms in each building

Table 1, description of investigated buildings

Building	Construction type	Mode	Number of floors	Investigated floor	Windows
1	Low thermal mass	FR	2	Ground, 1	No window/ operable
2	Heavy thermal mass	FR	4	Ground, 3, 4	Fixed/ operable
3	Medium thermal mass	FR	4	Ground, 1, 2	Fixed/ operable

2.2. Environmental Evaluations

Environmental variables including interior mean radiant temperature, air velocity, relative humidity was recorded during the surveys using SWEMA measurement instrument according to the ISO 7730 with time interval of 5 minutes and accuracy of ±0.1^{o}C, ±0.04 m/s and ±1.6 % respectively. Indoor air temperature, humidity and CO_2 level were also measured using four/ two loggers with accuracy of ± 40 ppm for CO_2 concentration, ± 0.8 ˚c for air temperature and ± 4% for air RH. Loggers placed on approximately 1.1 m above the fixed floor level at the occupants' head height, on a vertical stand, to reflect all subjects' thermal sensation. the CO_2 meters also positioned next to the loggers on a table. Outdoor air temperature was obtained from the nearest meteorological station.

2.3. Questionnaire Survey

To evaluate students' thermal comfort a cross-sectional questionnaire survey was conducted in each classroom. The questionnaire was divided into four main sections including individual questions (such as age, gender, nationality and worn clothes), thermal history and experiences (i.e. climate condition of hometown, thermal condition of family home and current accommodation), thermal comfort votes, (i.e. thermal sensation votes (TSV), thermal preferences votes (TPV) and thermal acceptability) and possibility and preferred adaptive behaviour in the classroom. TSVs were assessed based on the American Society of Heating, Refrigerating and Air- Conditioning Engineers rating scale, cold, cool, slightly cool, neutral, slightly warm, warm and hot. A similar trend was applied to evaluate occupants' TPV, much cooler, cooler, and slightly cooler, without change, slightly warmer, warmer and much warmer. Evaluation of students' thermal history and its impact on TSVs was carried out by analysis of their responses to the questions "How do you describe the climate condition of your hometown compared to Coventry's weather?" and "How long have been in the UK?". Questions for clothing were developed based on ISO 7730 guideline (2005). Almost 8% of the students did not provide the responses due to their busy schedule, but overall data form approximately 650 students in both genders aged from under 21 to 40 was evaluated in this survey. The number of approximately 180, 150 and 320 students participated in the survey in studios, PC labs and lecture rooms respectively. Questionnaires were filled out by students in the last 15 minutes of each class, after at least 1-hour seating in the classroom. The main reason for this is to reduce the disturbance of the class activity and minimize influence of unsettled metabolic rate on TSVs as a result of occupants' previous activities (Goto, et.al. 2000, Haddad, et.al. 2014, Montazami, et.al. 2016). The collected data were statistically analysed using the SPSS statistical package. Correlation between TSVs and students' short and long-term thermal history were evaluated based on the achieved p value and corresponding R^2. This helps to find out which of these factors has the greatest impact on the students' thermal perception in learning environments.

Figure 3, Lecture room in building 1

Figure 4, Studio in building 2

Figure 5, PC lab in building 3

3. Results and Discussion

This section presents the analysis of the students' questionnaire responses and recorded environmental variables. The psychological parameters affecting students' thermal sensation inside the classrooms are introduced based on the achieved results from this statistical evaluation. The influence of students' climatic background (long-term thermal history) and impact of their thermal adaption to the UK climate and influence of current accommodation (short-term thermal history) on students' thermal comfort perception inside the classrooms have been evaluated in the following sections.

3.1. Distribution of Indoor and Outdoor Air Temperature

According to figure 6, outdoor air temperature fluctuates in the range of 7 ^{o}C to 14 ^{o}C during running the survey. Data for indoor air condition is divided into three main sections for buildings 1, 2 and 3 in figure 7. Indoor operative temperature during voting changes from 23 to 25^{o}C in building 1, 19 to 26^{o}C in building 2 and 22 to 24^{o}C in building 3. Comparison of the temperature ranges in buildings 1, 2 and 3 shows smaller variation in building 1 compared to building 2 and 3.

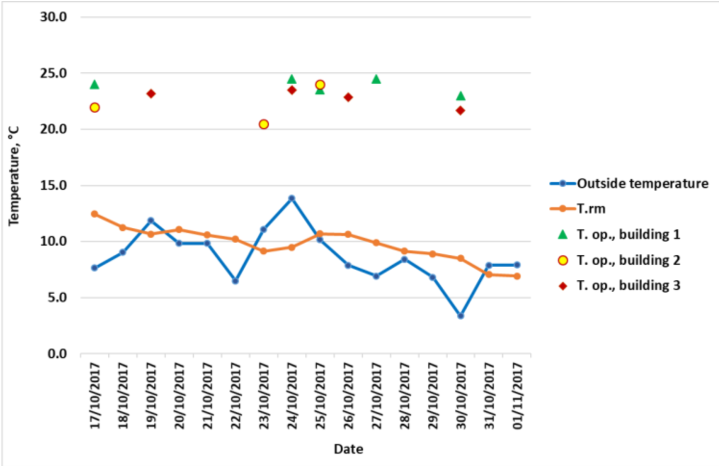

Figure 6, Mean outdoor air temperature (T_{out}) and mean running temperature (T_{rm})

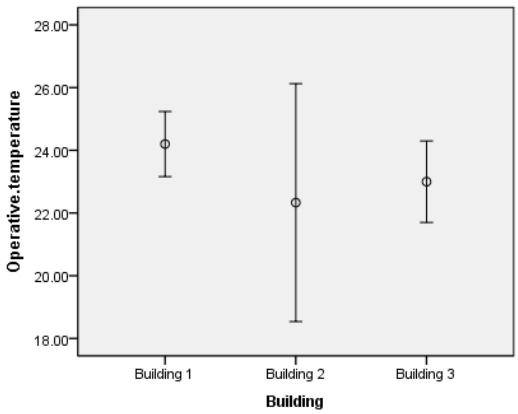

Figure 7, Indoor operative temperature range in building 1,2 and 3

3.2. Distribution of Thermal Sensation Votes

Results for the questionnaire survey show that approximately 153 students in building 1, 201 in building 2 and 294 in building 3 are participated in this survey. In general, 66% of the participants are in the first year, 18% in the second year and 16 % are in the last years of study (table 2).

Table 2, Students' level of study

Students' level	Percentage [%]
1	66
2	18
3 and 4	16

The distribution of TSVs for entire sample in buildings 1, 2 and 3, with average operative temperature of 24 ^{o}C, 22 ^{o}C and 23 ^{o}C respectively. As it can be seen Figure 8-10, Thermal Sensation Vote in Building 1, has a Skew toward the warmer votes while Thermal Sensation vote in Building 2, has a Skew to the colder votes., Thermal Sensation Vote is almost normally distributed compare to the other buildings.

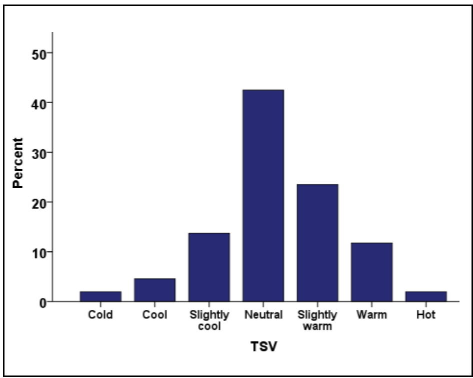

Figure 8, Students' TSV, building 1

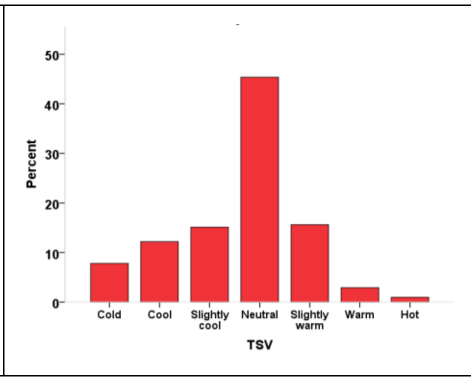

Figure 9, Students' TSV, building 2

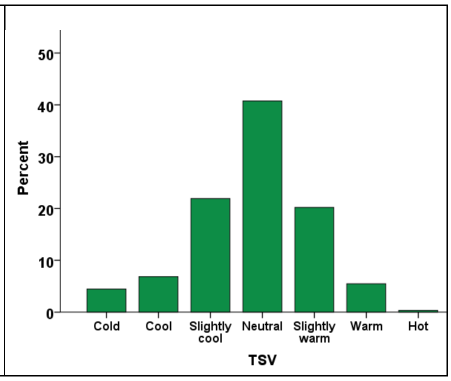

Figure 10, Students' TSV, building 3

3.3. Climatic background and Thermal Sensation Vote

In order to evaluate how climatic background may influence on students' thermal perception, students asked to report if they come from the regions that have similar, warmer and colder compare to the Coventry Climate. The result shows that nearly half of the students are from similar climatic conditions compare to Coventry climate, 35% are from warmer and much warmer and only 16% of them are from colder and much colder climate, figure 11. The result presents a significant correlation between students Thermal Sensation Votes (TSVs) and their climatic background ($p=0.00 <0.05$, $R^2=0.009$). This is a weak correlation; however, the influence of other factors should be investigated.

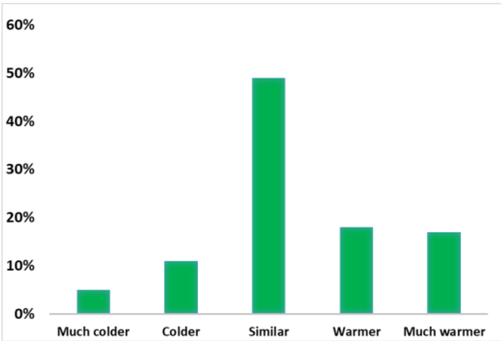

Figure 11, Students' thermal perceptions about their classrooms based on their climatic background

3.4. Students' year of Study and Thermal Sensation Vote

In order to assess the impact of students' thermal adaptation to the UK climate on their thermal comfort in the classroom, thermal sensation votes for the students in the first year, who just moved to Coventry, were compared with students' votes in the higher years. The result shows that there is a significant positive correlation between students' level of study and their Thermal Sensation Vote ($p = 0.00$, $R^2 = 0.02$). According to the influence of thermal history on thermal sensation, there are two main possibilities to justify this correlation; firstly, it is likely that students in higher levels have been in the UK for longer duration and therefore their thermal adaptation to the UK climate influences their Thermal Sensation Votes (TSVs) inside the classrooms. Secondly, it is likely that students in higher years are more familiar with adaptive opportunities exist within their classrooms environment and select an appropriate behaviour to achieve thermal comfort.

3.5. Current Accommodation Thermal Condition and Thermal Sensation Vote

Another major factor which influences the students' TSVs in the classroom is thermal experiences and the level of thermal comfort in their current accommodation which has been measured by analysis of students' responses to the question "How do you describe thermal condition of your current accommodation compared to this classroom?". Table 3, shows the proportion of students votes regarding the thermal condition of their accommodations. The result shows that there is a significant correlation between students' thermal perception at their current accommodation and their thermal sensation votes ($p < 0.05$, $R^2 = 0.1$).

Table 3, Proportion of the students' vote about thermal condition of their accommodations, %

Much colder	**5**
Colder	**24**
Similar	**38**
Warmer	**27**
Much warmer	**7**

Considering the correlation significance and the corresponding R^2 for the evaluated factors in table 4, shows the stronger impact on the students' thermal comfort level in their current accommodation compared to the other factors on TSVs. Students' level of the study showing the duration of being in the UK, is another dominant parameter on the occupants' TSVs inside the classrooms. A comparison between these three factors reveals the stronger impact of the students' short-term thermal history than the long-term thermal experiences on their TSVs inside a classroom.

As this evaluation is a small part of a bigger ongoing project, only small part of collected data is evaluated. The other effective parameters on students' TSVs and TPVs will be studied on larger sample size in the next phase of this research project. Also, the state of the correlations between the revealed physical, physiological and psychological factors on students' TSV will be examined in the next steps.

Table 4, Correlation significance and R^2 for influential factors on TSV

Thermal History	Correlated factor to TSV	Sig.	R^2
Long- term	**Climatic background**	**0.00**	**0.009**
Short- term	**Level of study**	**0.00**	**0.02**
	Thermal condition of current accommodation	**0.00**	**0.1**

4. Conclusion

Thermal comfort is proven to be a crucial parameter affecting students' performance in learning g environments. This parameter is affected by some environmental and personal factors. This paper aimed to address some influential personal factors such as climatic background, level of study and duration of being in the UK and thermal condition of the accommodations on students' thermal comfort at Coventry University, UK. The result reveals that students' long and short-term thermal history can affect their TSVs inside the classrooms. However, the latter effect seems to be more significant.

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Design to Thrive

Investigation the impact of students background on their thermal perception at higher education building

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Abstract: The quality of educational buildings can considerably affect teaching and learning processes. Literature shows that there is a significant relationship between students' thermal perception and their performance. The UK higher education buildings host many students from all over the world who have diverse backgrounds, perceptions and preferences toward their learning environment. The existing standards for optimum internal thermal condition in higher education learning environments consider students thermal sensation and requirement in a typical learning environment without addressing the impact of students' background.
This study aims to evaluate students' thermal sensation and preferences in an architecture studio at Coventry University during heating season of 2016 with reflation to their background. The result from 110 questionnaires, which are filled by students at the same time with temperature measurement inside the space, reveals that students' background and cultural differences can influence on students thermal sensation.
The outcome of this research provides better understanding about students' thermal requirement in higher learning environments with relation to their background. This result will help the Building Management System (BMS) to control the learning environment with relation to students' perceptions which results in improving students' productivity and wellbeing.

Keywords: Thermal comfort, Background, Learning environment, Higher education building

Introduction

Thermal quality of learning environments directly affects students and lecturers' productivity, health and wellbeing. The excellence of interior condition in such spaces not only affects occupants' physical health, but also influences their mental and psychological activities which in turn may affect the teaching and learning performance. (Tanabe et al. 2007). Inappropriate thermal condition in educational spaces can cause considerable reduction in students learning process and productivity (Zomorodian et al. 2016, Barrett et al. 2015, Hassanain and Iftikhar 2015).

UK is committed to reduce its greenhouse gases emissions by at least 80% by 2050, relative to 1990 levels (climate change act, 2008) which has implication on the amount of energy that should be consumed for providing thermal comfort within learning environment. For this reason, a practical thermal guideline for adult learning environment is required which not only can support students' productivity and well-being, but also can save energy within the space and considerably reduce the building running costs. Statistics show that UK every year hosts a large number of students from other countries, both European and non-European. Almost 20% of the students studying in the UK higher levels are from out of this country, 6% EU and 14% non- EU (HESA, 2017). Students' various geographical, climatic and cultural backgrounds may lead to differences in their clothes, behaviour, cognitive and finally thermal perception which cause a serious challenge in proving their thermal comfort in such multicultural spaces. Dissimilarity in their ages and genders can be another reason of their different thermal requirements (De Carli et.al. 2007, Kwon et.al, 2012). Digitalization and increasing the application of technological devices increase indoor air temperature (Jenkins, et.al. 2009) and may disrupt the space thermal balance.

Culture is defined by Reber (1985) as "The system of information that codes the manner in which people in an organized group, society or nation interact with their social and physical environment." (Reber, 1985, p. 170) people from a culture learn some standards, rules and regulations affecting their act, communication, belief, perception and evaluation. (Eisler et al. 2003). Culture origins which includes climatic background can affect students' thermal perception as well (Kenawy, 2013). In addition to the mentioned factors, occupants' thermal history and expectation influence their thermal comfort in an environment. Thermal experiences can establish a memory, named habit, psychological adaption that influence individual sensation in a new environment, by comparison the space with the past experiences (Ji et al. 2017). People thermal comfort is highly related to their long term thermal history (Chun et. al, 2008, Luo et. al, 2016). According to importance of students' thermal comfort, their various thermal requirements should be considered in developing appropriate standards, which helps to have more satisfactory thermal condition in line with having energy efficient spaces. Existing literature in this field, mostly, focus on influence of environmental factors and occupants' physiological differences on thermal comfort and there are limited studies about the impact of psychological parameters on people thermal sensation. In this study the influence of students' climatic background, thermal condition of their living environments, clothing factor and location within the room on students' thermal sensation are investigated.

Methodology

This survey was conducted in a naturally ventilated architecture studio at Coventry University in September 2016. 44 architecture undergraduate students, 20 males and 24 females, aged between 18 and 23 years old attended the studio in a weekday 10:30 am to 11:30 am. Students were from different countries, both European and non- European countries. Details for participants' climatic background can be seen in table 1. There was no heating or cooling HVAC mode in the studio. There were 5 top hung windows (open for almost 10 cm) which allowed students to adjust the environment to restore their comfort.

Environmental monitoring consisted of recording indoor air temperature, relative humidity and CO_2 concentration by using two 'Extech SD800 CO_2' loggers with time steps of 1 minute and accuracy of ± 40 ppm (<1000 ppm) and ± 5% rdg (> 1000 ppm) for CO_2 concentration, ± 0.8 ˚c for temperature and ± 4% for air RH. Loggers placed on carts 90cm above Fixed Floor Level (FFL), a CO_2 meter positioned in the higher and another in the lower level of trolley. Most equipment was at the rear of the room to avoid influence of windows. Classroom was divided into 4 different zones; a simple map is represented in figure 1, to assess impact of room layout on occupants' thermal perception. To prevent influence of clothing, students with almost similar clothing value are considered in this evaluation. To consider the impact of climatic background and thermal condition of living environments (before moving to Coventry) on students' current thermal comfort in the classroom, their Thermal Sensation Vote (TSV) in the studio, climate of their hometown and thermal condition of their previous accommodation were collected through a questionnaire.

Questionnaire were filled at the same time of environmental monitoring. The questionnaire were divided into three sections including individual questions (such as age, gender, worn clothes), thermal comfort (thermal sensation vote in the studio, thermal condition of their home and climatic background) and overall thermal experience in the space. The questions are designed based on ISO 7730, (2005) guideline. Answer is provided by using a 5 points thermal sensation scale from 1 (Too cold) to 5 (Too warm). Questions for clothing are developed based on the mentioned guideline as well.

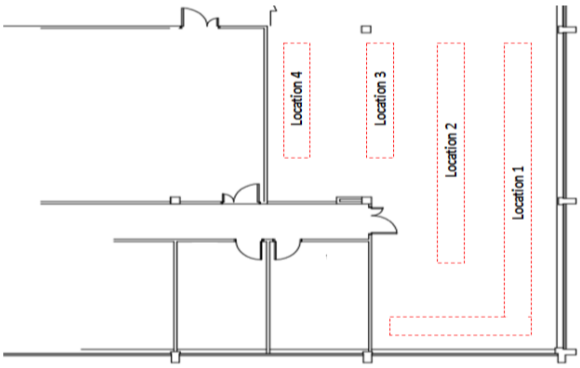

Figure 1, Studio layout during the experiment

Result analysis and discussion:

The final results for the measured variables and conducted survey are divided into two main sections; Environmental factors and Students' thermal comfort votes.

Environmental factors measurements

Result for outdoor air evaluation on the day of the experiment shows the minimum, maximum and average temperature for 10˚C, 18˚C and nearly 15˚C respectively. During the experiment outdoor temperature started at 15.00˚C and increased to 15.6˚C by the end of the period. Outdoor air humidity level started at 75% and decreased to 68% by the end of the test. Regarding the indoor air condition, recorded temperature and humidity are illustrated in figure 2 and 3. Indoor air temperature faced a negligible increase during the experiment and its value stays in the acceptable range 19˚C- 21˚C according to CIBSE A (2015). Indoor air relative humidity can be considered mostly in the acceptable range, 40%-70% according to ASHRAE (2007), during the survey.

Students' thermal comfort votes

Most of the participants in this survey are from UK, almost 68%, and about 32% of them are from other countries. There are international students from Romania, Italy, UAE, Bulgaria, Moldova, Zimbabwe, Indonesia and Nigeria with both colder and warmer climate compared to Coventry. Table 1 shows subjects' thermal background; majority of them (47.5%) are from warmer, 40% of them are from the same and 12.5% of them are from colder background compared to Coventry.

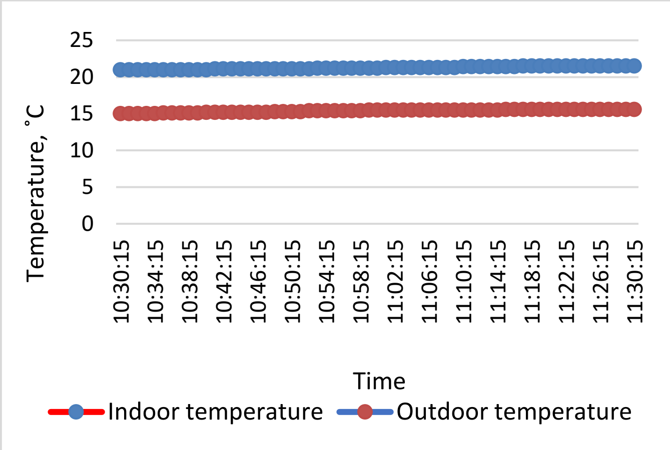

Figure 2, Indoor and outdoor air temperature during the experiment

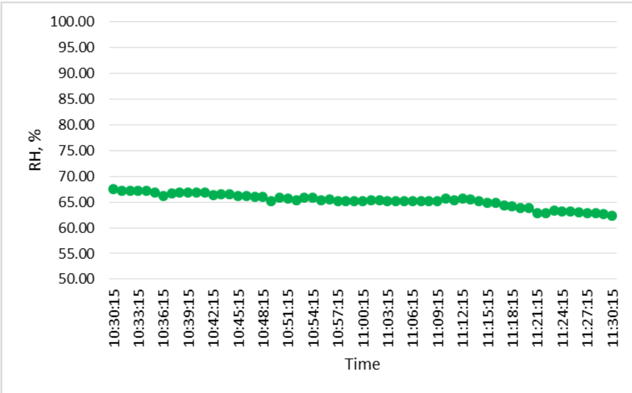

Figure 3, indoor air relative humidity during the experiment

Table 1, Subjects thermal background details

Country	Number of respondents	Climate	Summer temperature range	Winter temperature range
UK	30	Temperate	7_18 ˚C	-1_9 ˚C
Romania	6	Continental	18_22 ˚C	-2_5 ˚C
Nigeria	1	Tropical hot	25_28 ˚C	24_26 ˚C
Italy	1	Mediterranean	21_26 ˚C	6_10 ˚C
Zimbabwe	1	Tropical	32_38 ˚C	12_24 ˚C
Moldova	1	moderately continental	22_26 ˚C	-6_3 ˚C
UAE	1	Hot	35_43	20_27 ˚C
Bulgaria	2	temperate-continental	16_26 ˚C	-2_4 ˚C
Indonesia	1	Tropical	22_31 ˚C	22_29 ˚C

Students' TSVs based their climatic background

Figure 4 represents students' TSV in the classroom based on their climatic background. Considering students from warmer background compared to Coventry shows that 25.6 % of them feel warm in the classroom, 5.1 % feel neutral and 15.4 % feel cold in the studio. Students from colder climate than Coventry, 7.7 % feel cold, 5.1 % feel warm.

Students TSVs based on their home country

Thermal background and TSV in the studio for the UK students are illustrated in figure 5. Most of students have similar thermal sensation in the classroom and their hometown. 14% of students with colder background feel cold and 4% feel warm in the studio. 28.5% of students with warmer background feel warm and 9.5% feel cold in the studio.

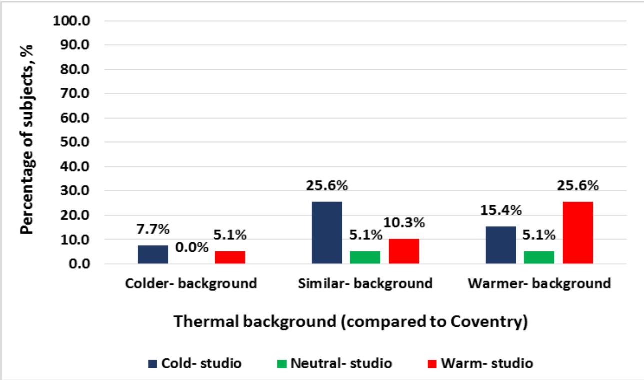

Figure 4, students TSV at studio based on their climatic background

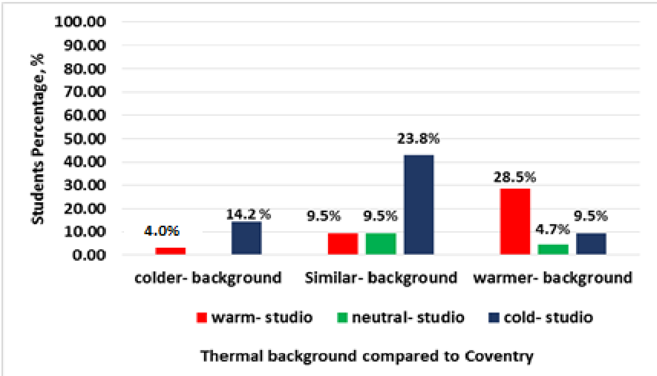

Figure 5, UK students TSV at studio based on their climatic background

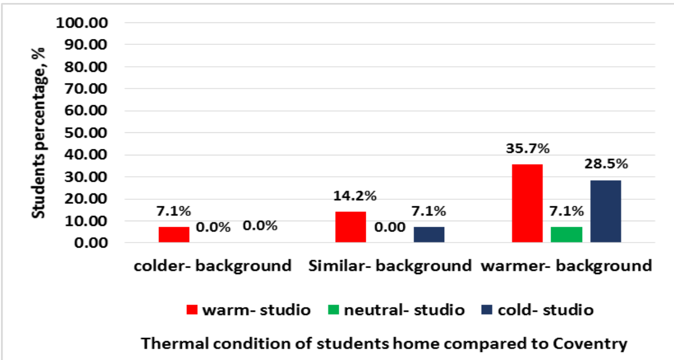

Figure 6, International students TSV at studio based on their climatic background

According to thermal history and expectation theory it is expected to find a reliable trend for the students' climatic background and TSV in the classroom. Statistical analyses show that there is a positive correlation between the UK students' thermal sensation in the classroom and thermal background. In other words, students with warmer background feel warm and others with colder background feel cold in the university studio (N= 21, P= 0.011 <0.05, correlation coefficient= 0.52). Figure 6 indicates thermal sensation vote for international students coming from various climatic, geographical and cultural backgrounds. Most of participants from warmer climates feel warm in the university (35.7%), 28.5% of them feel cold and 7.1% feel neutral. All the students from colder background feel warm in the university. The statistical analysis of results for this section does not show a clear correlation between participants thermal background and TSV in the studio (N= 14, P= 0.42 >0.05, correlation coefficient = - 0.2). The main reason for the poor correlation can be low number of collected data for this evaluation (N= 14).

Subjects clothing value and thermal sensation in the studio

Results for the UK and international students clothing value is summarized in table 2. Mean of clothing value is calculated for each group. This figure for students with neutral thermal sensation in the classroom (for either colder or warmer background) is considered as the benchmark. Comparing the students clothing value with the identified benchmark shows the reason of subjects' cold or warm thermal sensation in the studio. As there is no one with cold thermal background, neither from UK nor other countries, and neutral TSV in the classroom, no reasonable benchmark could be introduced for this group. Also, due to the low number of subjects with colder thermal background and cold thermal sensation in the current location (only 2 people) influence of clothing factor for them cannot be compared with other groups.

Table 2, UK and international students mean clothing value, thermal background and TSV at studio

	UK students	
Thermal background compared to Coventry	**Students TSV in the studio**	**Mean clothing value**
Warmer	Warm	0.82
Warmer	Neutral	0.48
Warmer	Cold	0.6
	International students	
Warmer	Warm	1.37
Warmer	Neutral	0.4
Warmer	Cold	0.85

Most of students in both UK and International groups are from warmer background and warm thermal sensation in the studio. UK students with warmer background and *warm* TSV in the classroom, in average have garments with 0.82 clo value. While, this figure for students with the same background and *neutral* and *cold* thermal sensation in the studio equals to 0.48 and 0.21 clo respectively. Clothing value for the UK students with both *cold* and *warm* thermal sensation votes in the studio is higher than the identified index.

Regarding the international students, mean clothing value for subjects with warm background and *warm* TSV in the classroom equals to 1.37 clo. This shows a much higher value compared to others from the same background with *neutral* or *cold* TSV in the classroom, 0.40 and 0.85 clo respectively. A reason for high level of clothing among the UK and international students with warm TSV and warm background can be due to their cold thermal perception in Coventry in the previous days. As most of students have moved to Coventry for less than 1 week, they may not be adapted to the weather and still may be affected by climate condition of their hometown. Therefore, the result in this section can support the theory of thermal history and expectation implying that cold or warm thermal background causes warmer or colder thermal perception in the new environments respectively. Students with cold thermal sensation have higher clothing value than the benchmark, but they still feel cold in the classroom. This again can be due to their warmer thermal history and cold sensation in current location. Higher clothing value for both UK and international students from warm background shows their cold thermal sensation in Coventry. It can be concluded that participants' with warmer thermal history feel colder compared to others with colder or similar backgrounds in a new environments. Higher level of clothing for this group is to adjust themselves to restore comfort.

Influence of interior thermal experiences on students TSV

Climatic background cannot be the only factor affecting people thermal history and TSV in a building. Statistics show that people in developed country spend approximately 90% of their time inside a building (Harrison,et.al. 2002). Therefore, thermal condition of interior environments people exposed to may influence their thermal sensation in the new locations. Furthermore, it is proved by Yu (2013) that interior thermal experiences affects occupants' thermal sensation and tolerant in the new environments more than their climatic background. A reason is due to their longer exposure time to interior spaces than outdoor air. In this experiment TSV for students in both groups are evaluated by considering their interior thermal experiences and thermal condition of their living environments before moving to Coventry. This evaluation can justify another reason of the positive correlation between students TSV in the classroom and their climatic background. Figure 7 represents percentage of students with warm or cold TSV in the classroom based on thermal condition of their previous living environment. Overall, 62% of students feel cold in the studio and 29% of these students (almost half of them) experienced mechanically heated buildings before. 38% of participants feel warm in the studio and 10% of them were exposed to mechanically cool living environments before moving to Coventry.

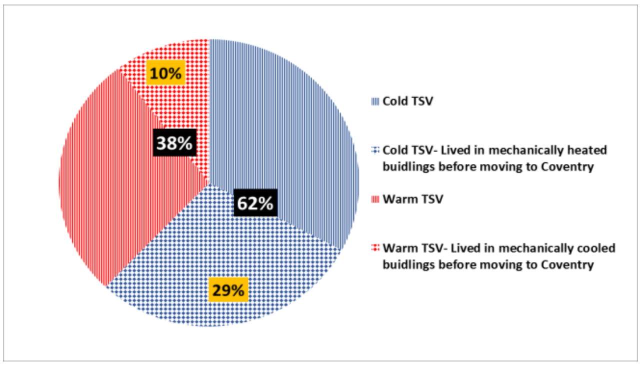

Figure 7, Students; TSV in the classroom and thermal condition of their previous living environments

This consideration, regardless of subjects' climatic background, indicates the significant impact of interior thermal experiences on students TSV in the classroom. Even, in this study, it is shown that interior thermal condition may affect subjects TSV in the new environments much more than their climatic backgrounds.

Table 3, percentage of students with warm, neutral and cold TSV in each zone

Zone	Students with warm TSV	Students with neutral TSV	Students with cold TSV
1 (next to windows)	37 %	45 %	18 %
2 (middle)	33 %	67 %	0 %
3 (middle)	80 %	0 %	20 %
4 (far from window)	25 %	63 %	12 %

Influence of room layout on subjects TSV

Result for analysing students' TSV in each zone in the classroom is summarized in table 3. In general the majority of students seating in zone 3 feel warmer compared to other locations of the classroom. Zone 2 seems to be slightly warmer than others as there are all the students seating here feel warm or neutral. This part of study shows the impact of location within a learning environment on students' thermal sensation.

Conclusion and recommendation

This study investigates the influence of climatic background on students' thermal sensation in an architecture studio at Coventry University. Results show that occupant's thermal history including both interior thermal experiences (heated or cooled living environments) and climatic background can influence their thermal sensation in the new environments. Also, a negative correlation between subjects' thermal experiences and current thermal sensation inside the university studio is indicated. This findings can support the theory of thermal history, expectation and thermal adaption. The other output from this investigation is the impact of a space layout and occupants' location on their thermal sensation inside a building. It is illustrated that students seating in the middle of the room tend to feel warmer than others next to the wall.

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Appendix 2

Survey Questionnaire

This survey is part of a study to evaluate students' thermal comfort in this classroom. We appreciate your contribution in this evaluation.
There is no right or wrong answer. Please do not think too long about your answers, just put down whatever comes first to mind. Your participation is entirely voluntary.

Researcher: Mina Jowkar

Informed consent **Sign here**

I confirm that I have read the information above and agreed to take part in this study __________

Questionnaire

Please answer the following questions and tick the box that best corresponds to your answer, where applicable.

1) Are you

◯ Female ◯ Male ◯ Do not wish to specify

2) How old are you? (Please tick one of the options)

◯ <21 ◯ 21-25 ◯ 26-30 ◯ 31-35 ◯ 36-40 ◯ >40 ◯ Do not wish to specify

3) How long have you been living in the UK?

◯ < 1 year ◯ 1 – 2 years ◯ 2- 3 years ◯ > 3 years

4) Please write down the country and city in which you were mainly living before moving to Coventry.

Country …………………… City ………………….

5) Please write down the country and city in which you mainly grew up.

Country …………………… City ………………….

6) How do you describe the climate condition of your hometown compared to Coventry's weather?

◯ Much colder ◯ Colder ◯ Similar ◯ Warmer ◯ Much warmer ◯ Warmer in summer and colder in winter

7) At your home before moving to Coventry (if you are from Coventry, please answer this question based on your family home thermal condition)**,**

◯ Heating system was used more than cooling system in a year
◯ Cooling system was used more than heating system in a year
◯ Heating and cooling system was used for the same months of a year
◯There is not mechanical heating/ cooling systems at home

8) How do you describe thermal condition of your current accommodation compared to this classroom?

My accommodation is:

◯ Much colder than this classroom ◯ Colder than this classroom ◯ Similar to this classroom ◯ Warmer than this classroom ◯ Much warmer than this classroom

9) Do you have control on the heating/cooling system at your current accommodation? ◯ Yes ◯ No

10) Do you have control on the heating/cooling system at your current classroom? ◯ Yes ◯ No

11) What do you prefer to do in uncomfortably warm or cold thermal conditions <u>when you are in this classroom</u>? You can select the actions from options A to F based on your priority. Please write it down in the boxes provided below.

A. Opening/ Close the windows
B. Reducing/ Increasing my clothing
C. Opening/ Closing the door
D. Having cold/ hot drink
E. Changing my position in the classroom
F. Adjust the heater/ air conditioner thermostat

In **warm** condition

First: ☐
Second: ☐
Third ☐

In **cold** condition

First ☐
Second ☐
Third ☐

12) How do you feel right now?

◯ Cold ◯ Cool ◯ Slightly cool ◯ Neutral ◯ Slightly warm ◯ Warm ◯ Hot

13) Do you find this…?

◯ Comfortable ◯ Slightly **un**comfortable ◯ **Un**comfortable ◯ Very **un**comfortable

14) At this moment, would you prefer to be…?

◯ Much cooler ◯ Cooler ◯ Slightly cooler ◯ Without change ◯ Slightly warmer ◯ Warmer ◯ Much warmer

15) At this moment, do you find the classroom thermal condition …?

◯ Clearly acceptable ◯ Just acceptable ◯ Just **un**acceptable ◯ Clearly **un**acceptable

16) Please tick the circle for each item of clothing that you are wearing right now.

Example

17) How tired you are?

Very tired **Very fresh**

1	2	3	4	5

18) Any additional comments?……………………………………………………

Thank you for taking part in this study