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The influence of acclimatisation, 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.

Keywords: *Thermal comfort, Higher learning environments, Thermal acceptability, Comfort temperature, Thermal satisfaction*

Nomenclature

T_{out}	Outdoor air temperature (ºC)
T_{pre}	Monthly mean outdoor air temperature within the summer season, before the survey
T_{air}	Indoor air temperature (ºC)
T_{mrt}	Indoor mean radiant temperature (ºC)
T_{op}	Operative temperature (ºC)
V_i	Indoor air velocity (m/s)
TSV	thermal sensation vote,
TP	thermal preferences
S.D.	Standard deviation
I_{cl}	Clothing insulation value (clo)
N	Sample size
R^2	Coefficient of determination
S.E.	Standard error of regression coefficient
p-value	Significance level of regression coefficient
T_C	Griffiths' comfort temperature (ºC)
$T_{accept.}$	Thermal acceptability (ºC)

1. Introduction

The rapidly growing worldwide use of energy raises concerns over supply difficulties, exhaustion of energy resources and heavy environmental impacts [1]. During the last two decades, worldwide energy use has grown with an average annual rate of 2%, and it is predicted to grow by 67% in the non-domestic sector in the next 20 years [1].

Given that educational buildings represent a significant part of public building stock around Europe [2], regulations and strategies have been developed in countries such as the UK [3], Denmark [4], Finland, the Netherlands, Italy and Portugal [5], Belgium, Slovakia and Austria [6] to mitigate energy use and related emissions in learning environments.

In the UK education sector, space heating is the largest and the most expensive part of energy consumption [7]. Typical annual energy use in educational buildings in this country is reported as 157 kWh/m^2, 58% of which is used for space heating [7]. Among the education sector in the UK, research and investigations are specifically required on thermal environments in the UK higher educational buildings due to the following reasons:

1. Large energy use and carbon emission in higher educational buildings:

   Higher learning environments 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 [8], which shows potential to make significant contributions to the global climate change effort [9]. High energy use along with the dramatic expansion of the UK higher education in scale and scope, put more pressure on this sector to formally develop and implement policies and practices to minimize energy consumption [10]. So far, carbon reduction targets and energy efficiency strategies have been developed for higher learning environments in England [11], Scotland, Wales and Northern Ireland [9].

2. Significance of thermal comfort and wellbeing in educational buildings:

   Given that the satisfaction with the surrounding space has a significant impact on the overall health and productivity [12], the occupants' wellbeing should not be overlooked. Considering the significant influence of thermal environment on academic productivity in educational buildings [13], students' thermal comfort should be considered as an essential factor when acting to improve energy efficiency or to reduce carbon footprint in such buildings. Considering the large energy consumption required for space heating/cooling in an environment [14,15], inaccurate prediction of the occupants' thermal comfort in a classroom leads to uncomfortably overheated or overcooled thermal environments at the same time as waste of energy and environmental impact. To improve the quality and lifetime added value generation of the space, early phase planning is essential [16].

The subjective nature of thermal comfort and differences between individuals in terms of thermal perceptions under the same indoor climatic conditions are well known [17,18]. Nicol et al. [19] 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. Shipworth et al. [20] and Schweiker et al. [21] described this variety of thermal comfort votes as a result of numerous factors affecting individuals' thermal perceptions. These parameters are grouped into 1) contextual factors (building related properties) and 2) human physiological and psychological properties that result from the contribution of skin temperature and core body heat generation and the subject’s state of mind, respectively.

In terms of the physiological human characteristics, this study is mainly focused on the human body physiological thermal adaptation, age- and gender-related differences.

- *Physiological thermal adaptation:* The human body can physiologically adapt to a thermal environment as a result of, so called, “thermoregulation” [22]. This physiological adjustment maintains individual’s comfort against thermal environmental fluctuations (e.g. over different seasons, a course of a day and night) [21]. As an example, repeated exposure to a cold or warm thermal environment can increase or decrease core body heat generation, and subsequently make a subject cold or heat adapted, respectively; and change the perception of a thermal environment accordingly [21]. Warmer thermal preferences of the university students in Malaysia compared to their counterparts in Japan [23], the direct relation between the monthly mean outdoor temperature and subjects’ neutral temperature in the hot climate of Indonesia [24] and the high sensitivity of subjects to cold in a hot-humid climate in China [25] confirm the role of climatic adaptation in subjects’ thermal perceptions.

  Regarding the seasonal adaptation, existing studies presented a shift in subjects thermal perceptions as a result of seasonal changes over a year [21]. The large seasonal differences in the neutral temperature can be attributed to the different seasonal clothing insulation [26]. However, in some other cases clothing difference is not enough to explain such diversity in thermal comfort votes [27,28]. The findings of these investigations suggest that people have considerable capability for adapting to seasonal weather changes [29].

  Overall, physiological thermal adaptation and changes of the subjective thermal perceptions as a result of acclimatization is confirmed in studies in university buildings in China , India [30,31], Indonesia [26], Malaysia [25] and Brazil [32,33], suggesting that the same environmental criteria cannot be applied for different climates [34].

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 [30]. During the winter months, the mean daily temperature drops to around 7.5 °C in England and 5.3 °C in Scotland, which does not differ much from each other. However, during summer higher differences are observed; the air temperature reaches around 17 °C in Scotland and 24.6 °C in England [31]. Considering that the academic semesters start in September/early November in the UK, students' thermal perceptions in higher learning environments tend to be affected by their thermal adaptation to the previous season, i.e. summer months.

- *Age and gender:* In addition to the climatic thermal adaptation, age- and gender-related differences can physiologically affect occupants' thermal perception in higher learning environments. Regarding the influence of age on thermal comfort, there are contradictory opinions. Some studies found age-related differences in the perception of thermal comfort while other found similar thermal perception for different age groups [21,32,33]. Indraganti et al. [34] 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 [35] 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), using to the PMV model. Likewise, age-related differences were shown in comfort and preferred temperatures and in thermal sensations in residential buildings [36,37], offices [38,39] and controlled chambers [40–42]. However, no significant differences were shown in thermal sensations [43,44], preferences [36,40,41,45] and neutrality [46–48] in different age groups in some other studies. Older adults' lower core body heat generation and consequently lower skin temperature is followed by less body heat loss to the surrounding environments compared to their younger counterparts. Therefore, they are still able to keep their body heat balance in a thermal environmental, which can explain their same thermal comfort votes as the younger adults [33,40,49].

Similar to the studies on thermal comfort of different age groups, there are conflicting results regarding the thermal comfort perception of each gender in the existing literature. The first set of investigations indicated cooler thermal sensation [11,52], lower thermal acceptability/satisfaction [38,51–53], warmer thermal preferences [52,54–56], and higher comfort temperature/neutrality [47,51,54–57] for women than men. In contrast, other studies showed no difference between the two genders' thermal comfort requirements [39,43,46]. 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 temperature preferences among females than males [49,60]. Statistics regarding the UK higher learning environments reveals the variation of student gender and age groups across different levels of study. In the last report from Universities UK [60], the percentage of the female and male students are reported to be 58 and 42%, respectively, in 2016−17. In terms of age groups, students are shown to be from under 20 to above 40 years old in 2016-17, with an upward trend for 18 to 24 year-olds in the last decade [60]. Thus, according to at least some of the research on the effect of age and gender-related differences on thermal comfort, such diversity may lead to conflict in the thermal perceptions in the UK higher learning environments.

1.1. Research aim and output

Overall, due to the huge power consumption for space heating in the UK educational buildings [8] combined with the considerable influence of thermal comfort on students' productivity in academic environments [13,61], several studies have been conducted to evaluate the thermal environment in the UK higher educational buildings [10,62–66]. However, none of these studies has taken into account the different climatic conditions over the UK.

From the perspective of physiological adaptation, weather variations between the northern and southern parts of the UK during the summer months (before the beginning of the academic year) suggest a potential diversity in the thermal expectation of the occupants in different regions of the UK. Therefore, this study aims to determine a thermally comfortable and acceptable range of the indoor air temperature for university classrooms in Coventry (England) and Edinburgh (Scotland). The influence of the occupant's climatic adaptation, age- and gender-related differences as the physiological drivers of diverse thermal perception, is mainly focused in this investigation.

The findings provide an insight into the comfortable and acceptable thermal environment for students in university classrooms in two different climatic regions of the UK. Thus, the output of this study can contribute towards the modification of the thermal environment settings, or to propose architectural design solutions towards providing thermal comfort at the same time as minimizing energy waste through over heating/overcooling in such spaces.

2. Methods

Field experiments took place in eight buildings at two university campuses in Coventry, England and Edinburgh, Scotland, United Kingdom (Figure 1). According to the Koppen Geiger climate classifications, England is categorized as temperate with warm summer without dry season (Cfb) and Scotland has a temperate climatic condition, with cold summer without dry season (Cfc) [67]. Outdoor air temperature, during the survey, fluctuated with the minimum, mean and maximum outdoor air temperatures being 1 °C, 7 °C and 15 °C, respectively, in Coventry and 2 °C, 6 °C and 13 °C in Edinburgh.

Figure 1. Location of the surveyed buildings, 1: Coventry, 2: Edinburgh, source: [68]

Figure 2 shows the monthly mean outdoor air temperature in Coventry (England) and Edinburgh (Scotland). As can be observed, differences are higher during the summer months (before the onset of the academic year in the UK) than the rest of the year in these two locations [31]. Data on the outdoor air temperature was obtained from the UK meteorological office [69]. The weather stations were less than 5 km from the study sites and thus likely to be representative.

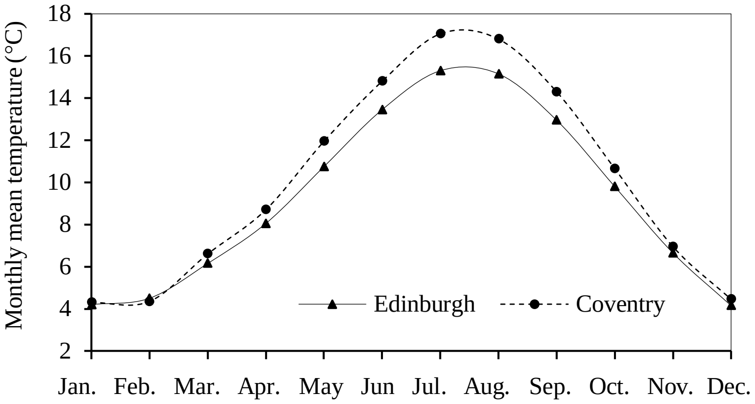


Figure 2. Monthly mean outdoor air temperature in Coventry and Edinburgh, source: [31]

Simultaneous questionnaire surveys and indoor environment measurements were conducted during the academic year of 2017 – 2018 (i.e. from October 2017 to March 2018). The studied buildings operated on changeover or concurrent mixed modes [70]. 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.

Field measurements included recording of four parameters: indoor air temperature (Tair), relative humidity (RH), air velocity (Vi) and mean radiant temperature (Tmrt). Environmental variables were recorded using a Multi purposes SWEMA 3000 instrument (conforming to EN ISO 7730 and incorporating built-in calculation features) [71] and seven temperature and RH loggers [72] (TRH USB, only Tair was recorded) with a 5-minute time logging interval (Table 1). The indoor air temperature and the mean radiant temperature probes were positioned at 1.1 m above the floor level on a vertical stand, as recommended by EN ISO 7726 [73]. The SWEMA kit and one TRH USB logger were placed in the middle of the room, away from the heating/cooling sources to register the ambient environment prevalent in the classrooms. The other TRH USB loggers were placed around the room close to the students to register the environmental conditions nearest to their sensations.

Figure 3 indicates the position of the probes and TRH loggers in some type of the classrooms.

Table 1. Description of the instruments used

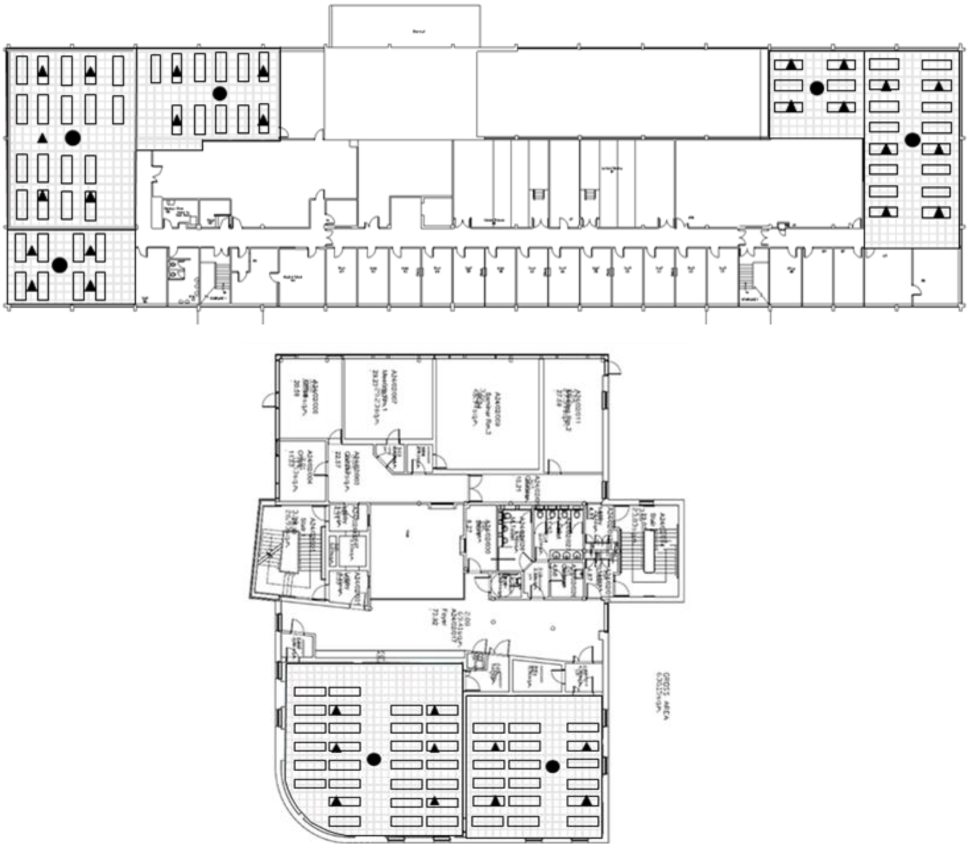
Measured parameter	Parameter nomenclature	Sensor type/logger	Resolution	Range	Accuracy
Mean radiant temperature (°C)	T_{mrt}	Black-bulb thermometer/SWEMA	0.1	0 - 50	±0.1
Air velocity (m/s)	V_i	Anemometer/SWEMA	0.03	0.05 - 3.00	±0.04
Relative humidity (%)	RH	Relative humidity probe/SWEMA	0.8	0 - 100	±0.8
Air temperature (°C)	T_{air}	TRH USB logger	0.1	−40 - 70	±1.0

Paper-based cross-sectional questionnaire surveys were conducted in the last 15 minutes of each class after at least 1-hour of students sitting in the classrooms, to maximise the exposure of the students to the classroom environmental conditions, to minimize the influence of metabolic rate on students' thermal evaluations, and to lessen the lecture disturbance. A summary of the investigated buildings, including the number of surveyed subjects, classrooms, etc. is presented in Table 2.

Table 2. Summary of the investigated buildings

Location	Buildings	No. of participants	No. of surveyed rooms	No. of survey repetitions in each building	Average occupancy density (m^2/person)
Coventry	B1	293	6	6	3.5
	B2	707	5	18	2.2
	B3	900	14	31	2.5
	B4	147	4	5	5.0
Edinburgh	B5	382	3	8	1.2
	B6	155	1	4	1.2
	B7	200	1	4	1.2
	B8	728	3	15	1.2

Questionnaires contained background questions (such as the subject's age and gender), thermal comfort votes and clothing garment checklist. Thermal sensation vote (TSV) and thermal preferences (TP) were examined in the questionnaire, based on the ASHRAE 7-point scale (Figure 4). 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 that is shown in Figure 4. Clothing insulation value was evaluated using a checklist covering both underwear and outer garments as per in EN ISO 7730 [74]. Participants were asked to select the clothes they worn in the survey time.



● Black bulb thermometer, RH and air velocity probs and a TRH USB logger

▲ TRH USB logger

Figure 3. Position of the instruments in the classrooms of two buildings, as an example

In total, 3507 students, 2049 in Coventry and 1458 in Edinburgh, participated in the surveys but approximately 8% of the participants (27 persons) did not provide answer on their age. All the participants were sitting and listening to the lecturers during the measurements (metabolic rate of 1.1 met [75]). They were of both genders with an average age of 22 years in both locations (

Table 3).

Table 3. Distribution of the participants in each gender and age groups

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

Collected data were statistically analysed to estimate the acceptability, neutrality and preferred temperature in which the majority of students were thermally satisfied. The mean values of the recorded environmental variables in the last 15 minutes of each class (during the questionnaire survey) were considered for data analysis.

How do you feel right now?						
Cold –3	Cool –2	Slightly cold –1	Neutral 0	Slightly warm 1	Warm 2	Hot 3
At this moment, would you prefer to be…?						
Much warmer –3	Warmer –2	Slightly warmer –1	No change 0	Slightly cooler 1	Cooler 2	Much cooler 3
At this moment, do you find this climatic environment…?						
Clearly acceptable 1	Just acceptable 2	Just unacceptable 3	Clearly unacceptable 4			

Figure 4. Thermal comfort scales in the survey questionnaire

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 higher air velocity [75]:

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

Where T_{op} is the operative temperature, A is a constant value introduced as 0.6 [75], T_{air} is the indoor air temperature and T_{mrt} is the mean radiant temperature. Relevant statistical tests were applied, to examine the statistical significance of possible differences between the thermal comfort indices of each group of subjects. Considering the large sample size in this study, an independent t-test or One-way ANOVA was applied where the means of data were normally distributed and a Mann-Whitney U test or Kruskal Wallis test (non-parametric equivalent to the independent t-test and One-way ANOVA) was applied to the non-normally distributed means of data or ordinal variables [76].

3. Results and discussion

3.1. Environmental thermal comfort indices

Table 4 summarises the environmental thermal comfort indices during the survey. The mean outdoor air temperature in the survey period and the season before the beginning of the survey was higher by 5.4 °C and 1.5 °C, respectively 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 mean indoor RH was higher in Coventry (45%) than Edinburgh (30%) and the indoor air velocity was low (below 0.10 m/s) in a similar range in both locations.

Table 4. Environmental thermal comfort indices

Location	Variables	Number of readings	Mean	S.D.
Coventry	T_{out}	240	11.2	4.1
	$T_{pre.}$	-	14.2	1.0
	T_{air}	349	22.9	1.6
	T_{mrt}	349	22.6	1.6
	T_{op}	349	22.8	1.6
	RH	349	45	12
	V_i	349	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}	152	5.8	1.9
	$T_{pre.}$	-	15.7	0.7
	T_{air}	218	23.9	1.6
	T_{mrt}	218	23.5	1.1
	T_{op}	218	23.7	1.3
	RH	218	30	6
	V_i	218	0.04	0.04
	Clothing	1421	0.86	0.32
	TSV	1460	0.4	1.2
	TP	1459	0.30	1.1

3.2. 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). The distribution of the thermal sensation votes and thermal preferences in Coventry and Edinburgh is presented in Figure 5. Students in both locations tended to feel thermally neutral and preferred ‘no change’ in the thermal environment. The skewness value for the TSVs in Coventry (–0.23) and

Edinburgh (–0.22), shows a shift toward the warmer than neutral side in both locations. However, the thermal preferences were skewed towards ‘want cooler’ in Coventry and Edinburgh (Skewness value = 0.09 and 0.14, respectively).

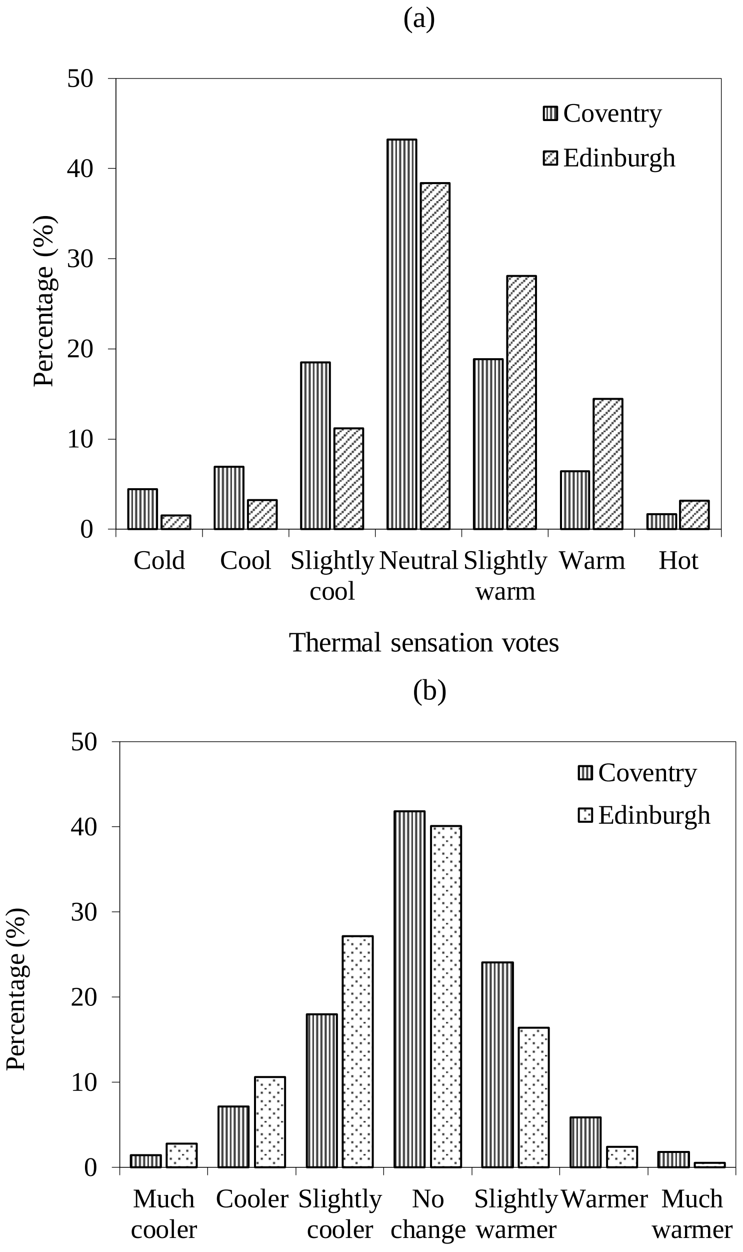


Figure 5. Distribution of thermal sensation (a) and preference(b) votes in Coventry and Edinburgh

This section explores the relation between thermal sensation and preference votes to investigate how the students perceived their current thermal environment and how they would have liked to feel at the moment (Figure 6). 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, increase. The highest proportion of the students with thermal sensation votes of 'neutral' preferred no change, in the thermal environment. This presumably confirms thermal satisfaction of the majority of the students in the currently exposed thermal condition.

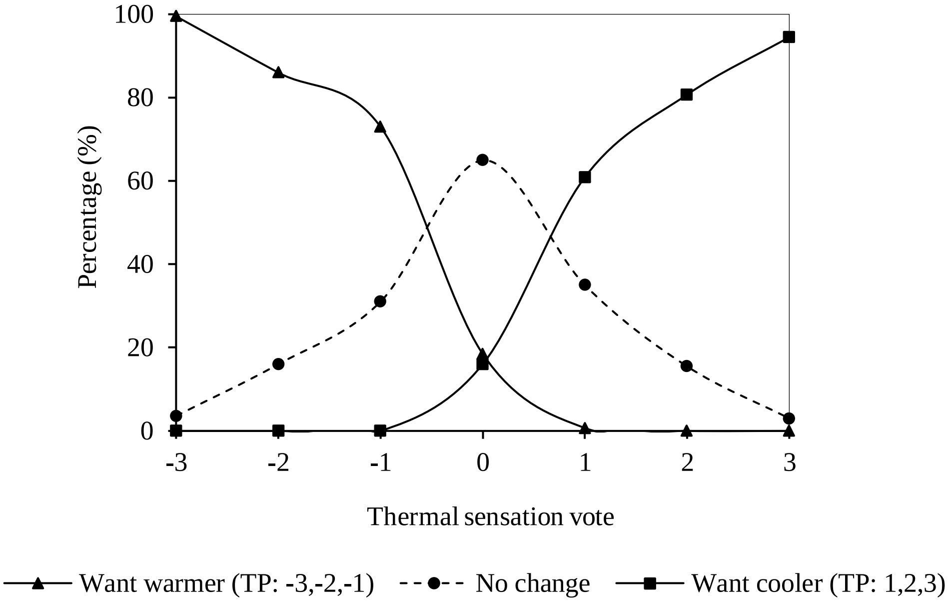


Figure 6. Relation between TSVs and TPs. The 'want warmer' or 'want cooler' line is the cumulative percentage and 'no change' line is the actual percentage for each thermal sensation vote.

In terms of clothing insulation, Figure 7 and Table 5 show the linear relation between clothing insulation value and operative temperature. A significant correlation between this parameter and the mean outdoor air and indoor operative temperature was found in this study ($p<0.05$). The p-value and S.E of the regression coefficient is also presented in Table 5. The negative correlation between clothing insulation value and operative temperature in both locations. This negative relationship is also supported by previous studies in the field of thermal comfort and adaptive behaviour [82–85]. For instance, a study conducted by De Carlie et al. [80] shows that the outdoor temperature (in the morning in particular) affects people's choice of clothes. Whereas, indoor air temperature does not influence the occupants' daily clothing choice, but it does affect their clothing adjustment in the building, assuming they are allowed to. The same result is indicated in Schiavon's study [79] showing a statistically significant correlation between clothing insulation, and both outdoor (morning) and indoor air temperature. Results from other studies conducted by Liu et al. [77] and Nicol et al. [78] in office buildings, in China and Pakistan, respectively, also confirm the negative relationship between clothing insulation, and outdoor running mean and indoor air temperature [77,78]. However, in this study the relation between the clothing insulation value and the outdoor air temperature was not considered. According to Jowkar et al. [82], clothing adjustment is a priority of the university students in a thermally uncomfortable classroom. Given that the surveys in this work were conducted at the end of each class (after a one- or two-hour lecture) it is much likely that the students had adjusted their cloths based on the indoor operative temperature, not outdoor weather conditions.

Considering clothing adjustment as an adaptive response to the changes of operative temperature [19,78,80], The regression Coefficient (RC) in Figure 7 shows the sensitivity of the subjects and the speed of their clothing adjustments by variation of the operative temperature. The higher RC in the Coventry's than Edinburgh's Equation (Table 5), suggests the occupants' higher sensitivity to the temperature fluctuations in Coventry than Edinburgh, that reflects a faster change of clothing by the occupants in Coventry than Edinburgh. Results of this section are comparable with previous studies in university classrooms in China [83] (RC: – 0.03), office buildings in 28 cities around the world (RC: – 0.05) [78] and office buildings in China (RC: – 0.02) [84].

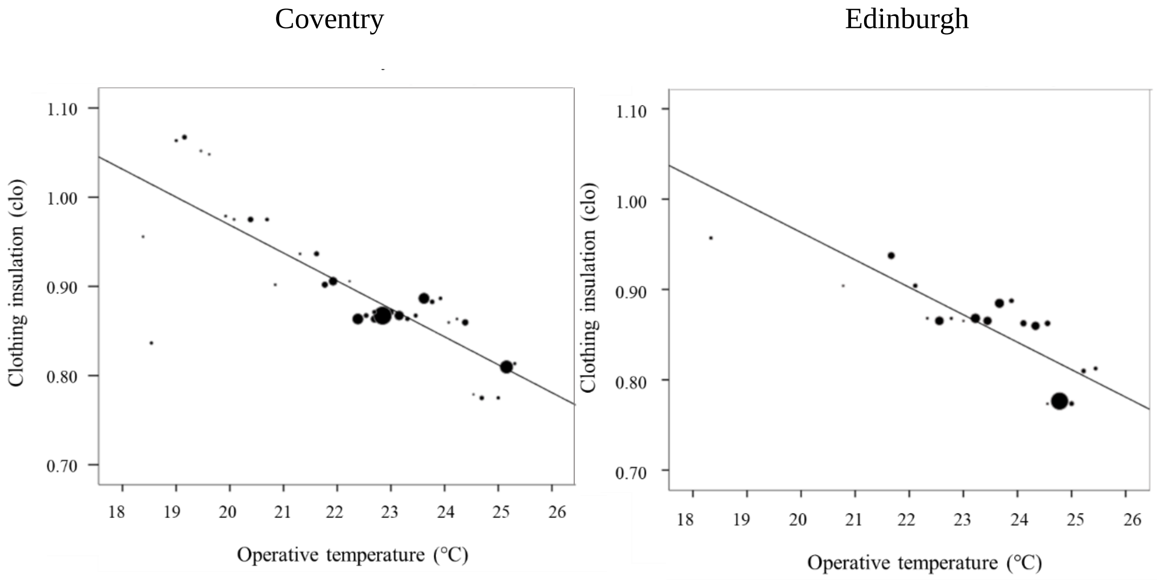


Figure 7. Relation between clothing insulation value and operative temperature

Table 5. Relation between clothing insulation and operative temperature

Location	Equation	p-value	N	R^2	S.E.
Coventry	$\boldsymbol{I_{cl} = -0.034\,T_{op} + 1.7}$	<0.01	1963	0.6	0.0.005
Edinburgh	$\boldsymbol{I_{cl} = -0.026\,T_{op} + 1.5}$	<0.01	1421	0.5	0.0.006

3.3. 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 as recommended in ANSI/ASHRAE standard 55 [75] and applied in similar studies [23,85–87]; 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 (Figure 4) in the questionnaire [88–90].

3.3.1. The indirect approach

In 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 [75]. 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, as applied in previous studies (e.g. [91,92]).

Figure 8 shows the results of this probit analysis. Considering the standard of a minimum 80% acceptability level, as recommended in ASHRAE 2017 [75], the thermally acceptable zone was 21.0 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 started feeling thermally satisfied. In contrast, a lower sensitivity to warmth was indicated in Coventry 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 8).

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 [93,94], Italy [95,96] and the UK [97].

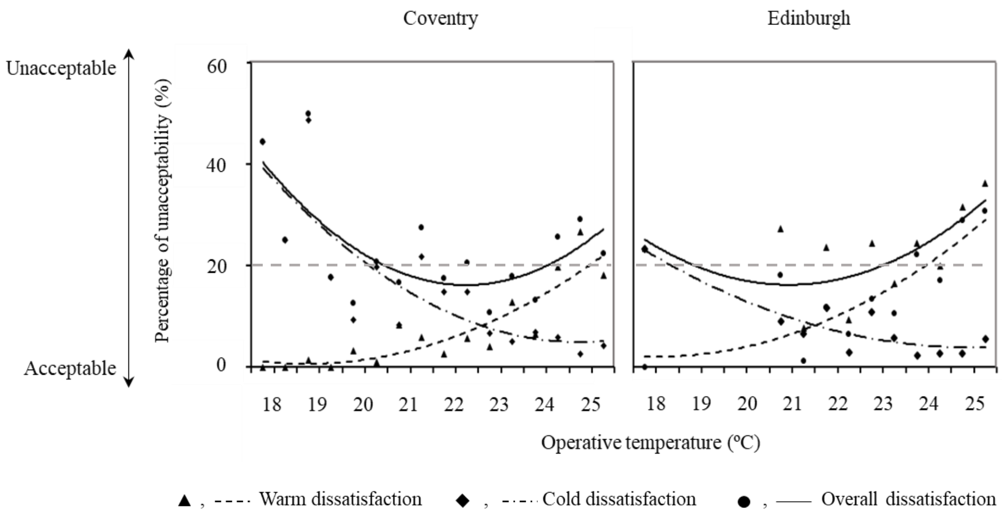


Figure 8. Uncomfortably warm and cold thermal dissatisfactions

3.3.2. The direct approach

Figure 9 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. This supports the selection of the acceptable TSVs for the above-mentioned indirect approach.

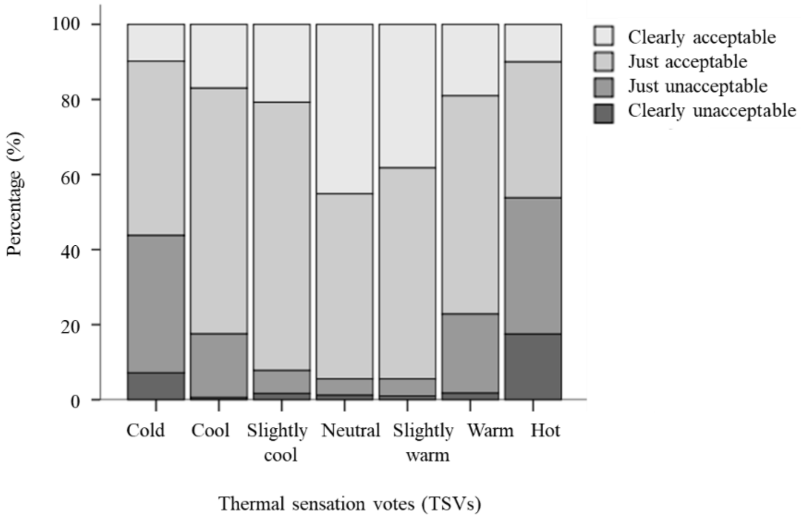


Figure 9. Distribution of thermal acceptability in relation to TSVs

Thermal acceptability level in each 0.5 binned operative temperature for both evaluation methods are presented in Figure 10.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 comfort when consciously evaluating and voting for it, compared to when their acceptability is identified based on thermal sensation votes (TSV between –1 to 1) [75].

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 [26,100–102]. 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 and lessen their feelings of thermal discomfort [102]. The other reason can be due to the students' various physiological and psychological backgrounds resulting in a higher acceptability range, which could not have been predicted through thermal sensation votes (the indirect approach).

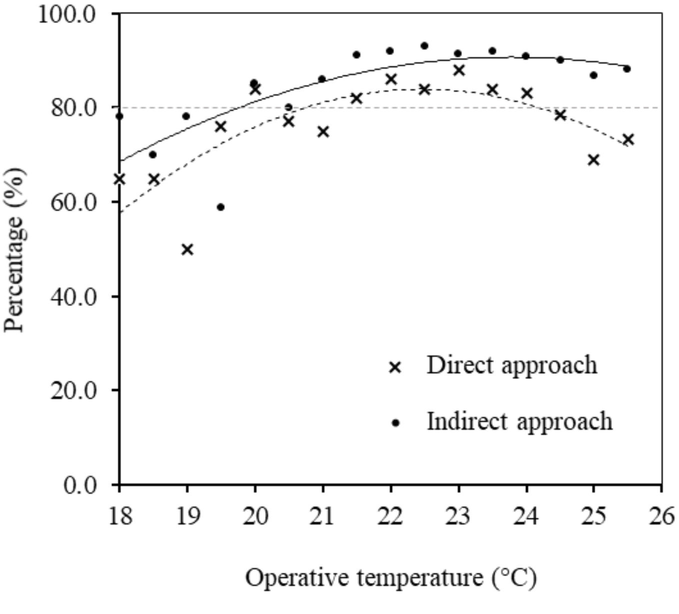


Figure 10. Thermal acceptability in each operative temperature

3.4. Thermal neutrality

Linear regression between the thermal sensation votes (TSVs) and indoor operative temperature was used to determine thermal neutrality (Figure 11). The resulting equations and coefficient of determination for both raw and binned data are presented in Table 6. As can be observed the regression coefficient of the raw and binned data are the same in Edinburgh and it is very close in Coventry. However, the coefficient of determination (R^2) of binned data is much higher than that of raw data. This trend is supported in some previous studies (e.g. Gautam et al. 2019 [98]).

In this work, similar to previous studies (e.g. [55,103]), there was a high variability of thermal sensation votes in each indoor air temperature, which was mainly due to the individual differences between the subjects (discussed in section 1, Introduction) [20,21]. The raw data caused a low coefficient of determination (R^2) between the thermal sensation votes and the prevalent indoor operative temperature, which is considered acceptable for such types of studies [18].

Table 6. Equations from the linear regression between TSV and Operative temperature

Location	Data	Equations	N	R^2	p-value	S.E.
Coventry	Raw	$TSV = 0.30\ T_{op} - 6.8$	2046	0.15	<0.001	0.016
	Binned	$TSV = 0.30\ T_{op} - 6.8$	15	0.95	<0.001	0.020
Edinburgh	Raw	$TSV = 0.30\ T_{op} - 6.5$	1460	0.11	<0.001	0.022
	Binned	$TSV = 0.28\ T_{op} - 6.2$	11	0.89	<0.001	0.033

The neutral temperature (which was identified by the substitution of 0 for TSV in the equations presented in Table 6) was comparable in Coventry (22.7 °C) and Edinburgh (22.3 °C). A detailed look at the mean operative temperature, clothing insulation value, the thermal sensation and preference votes in Coventry and Edinburgh (Table 4) shows that with similar clothing insulation value, students in Coventry were cooler than neutral and they preferred to be warmer (TSV= –0.1, TP= –0.04) but in Edinburgh occupants tended to be warmer than neutral with cooler thermal preferences (TSV= 0.4, TP=0.3). In Edinburgh, the mean prevailing operative temperature was approximately 1 °C higher than the neutral temperature, justifying the occupants' warmer thermal sensations and cooler preferences, in spite of colder outdoor air temperature than Coventry. However, in Coventry, despite the similar mean operative (22.8 °C) and neutral temperature (22.7 °C), the occupants still were cold. Higher outdoor air temperature and occupant's warmer thermal expectations in Coventry was apparently a reason for their cooler thermal sensation.

Considering the regression coefficient in the equations as an index showing how TSVs were dependent on the operative temperature, approximately each 3 °C temperature change, led to variation of one unit in the thermal sensation votes in a 7-point sensation scale in both Coventry and Edinburgh. This demonstrates a similar sensitivity of the occupants to the temperature changes inside the classrooms in both locations.

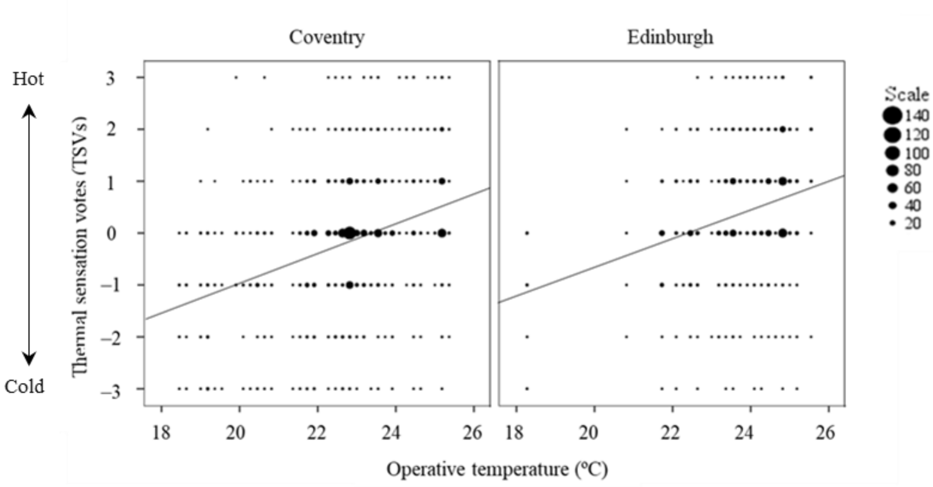


Figure 11. Linear regression of TSV on indoor operative temperature in Coventry and Edinburgh

3.5. Relation between gender and age with thermal comfort

Regarding the influence of age and gender on the perception of thermal comfort, contradictory opinions were found in the existing literature, showing statistically significant or no significant differences between thermal comfort perceptions of each gender or age group. In this work, the thermal comfort perceptions of both genders and different age groups were explored to identify whether age- and gender-related differences can affect thermal comfort requirements of the occupants in higher learning environments.

Table 7 summarises the indoor climatic conditions that each gender group was exposed to and Figure 12 shows the comparison between the clothing insulation, thermal sensation and preference votes of each gender. With a 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 the statistically significant higher clothing insulation value for females than males ($p<0.001$). Figure 12 also shows a wider distribution of the thermal sensation and thermal preference votes for women than men. The comfort temperature was shown to be similar ($p>0.05$) for both genders with identical operative temperatures and higher clothing insulation for females than males (Table 7).

Table 7. Thermal environmental condition for each gender group in Coventry and Edinburgh

		Coventry			Edinburgh		
Gender	Variables	N	Mean	S.D.	N	Mean	S.D.
Female	TSVs	586	–0.26	1.27	571	0.28	1.13
	TP	582	–0.28	1.09	571	0.10	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	1438	–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

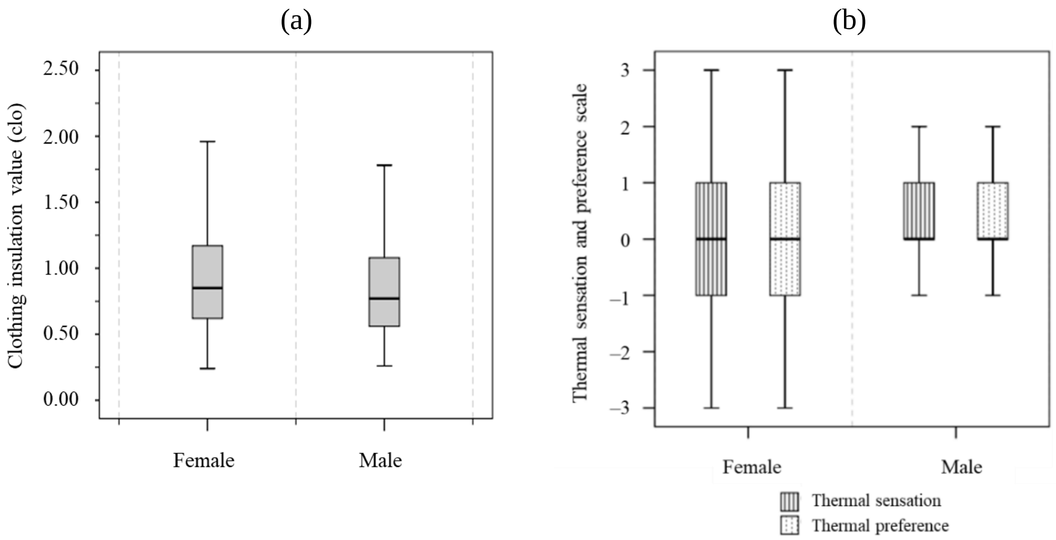


Figure 12. Clothing insulation (a), thermal sensation and preference (b) of each gender group

Considering the 100% of the subjects in each thermal sensation and preference vote, the proportion of the gender groups is shown in Figure 13. 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 samples t-test and a Mann-Whitney U test confirm the statistically significant difference between thermal sensation and preference votes between males and females in both Coventry and Edinburgh (p<0.001).

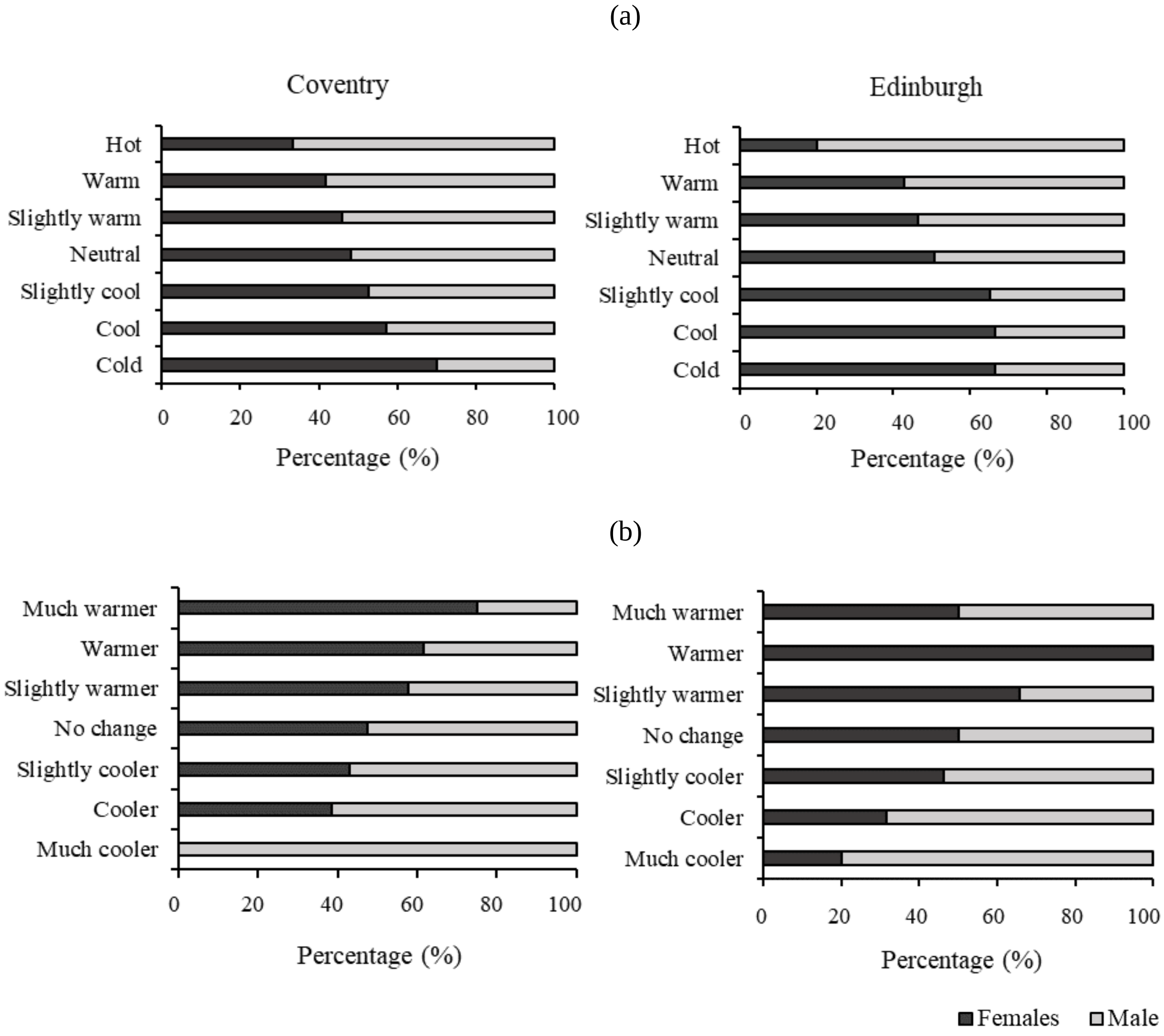


Figure 13. Thermal sensation (a) and preference votes (b) in relation to genders

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 [100,101,104];

$$T_c = T_{op} + (\mathrm{TSV}_n - \mathrm{TSV}) / \alpha \qquad (2)$$

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. equals 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 coefficient between mean thermal sensation vote and operative temperature, approximately each 3 °C temperature changes led to variation of one 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 [26,105] 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 ($p<0.001$). However, there were a very similar comfort temperature for males and females with less than 0.5 ºC difference (Table 8). Although a similar comfort temperature for both genders was found, the heavier clothing worn by women than men still confirms warmer thermal comfort requirements for females than males.

Table 8. Comfort temperature for each gender group

Gender	Comfort temperature (ºC)					
	Coventry			Edinburgh		
	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

Mean thermal acceptability was evaluated in 0.5 ºC binned operative temperature and a polynomial regression model was fitted to identify the acceptable temperature range of each gender group (Figure 14). The thermally acceptable zone (based on the 80% acceptability [75]) for women was 21.5 to 24.5ºC, whereas, this was between 19.5ºC and 24 ºC for men, which may indicate higher and lower sensitivities of women than men to cool and warm thermal environments, respectively [56]. The optimal acceptable temperature was 23.5ºC for females and around 22ºC for males, showing a 1.5ºC warmer acceptable temperature for females than males. Results in this work agree with the group of studies that showed dissimilar thermal comfort perceptions for males and females [43,51,53,56,106]. 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.

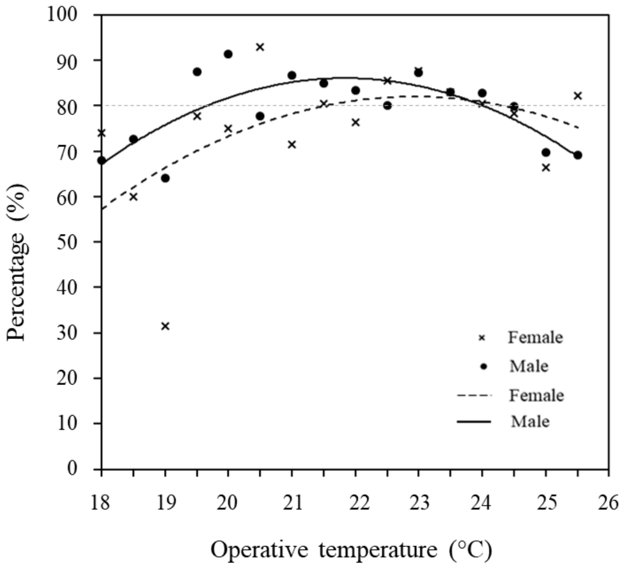


Figure 14. Thermal acceptability range (based on the central three TSVs)

Regarding the influence of age-related differences on thermal comfort, Table 9 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 value of 0.9 clo in Coventry and 0.8 clo in Edinburgh. As the assumption for normal distribution of the mean data was not met for the thermal sensation votes, thermal preferences, acceptability and comfort temperature of each age group, the Kruskal-Wallis test (the non-parametric alterative of the One-Way ANOVA) was run to examine the statistically significant difference between the thermal comfort of different age groups. The results 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). Nevertheless, as the number of above-40-years-old-subjects is not large enough compared to the number of subjects in the other age groups, results of such comparison may not be very dependable.

Table 9. Summary of thermal comfort indices for each age group

			T_{out} (ºC)	T_{op} (ºC)	Clothing *(clo)*	TSV	TP	T_c (ºC)	$T_{acc.}$
Under 21	Mean	Coventry	11.4 (4.3)	22.8 (1.5)	0.9 (0.3)	–0.1 (1.2)	0.0 (1.1)	23.0 (2.4)	1.8 (0.7)
		Edinburgh	5.2 (1.5)	23.3 (1.3)	0.9 (0.3)	0.5 (1.2)	-0.4 (1.1)	22.4 (2.3)	1.7 (1.7)
21-25	Mean	Coventry	10.8 (3.8)	22.7 (1.6)	0.9 (0.3)	–0.1 (1.2)	0.1 (1.1)	22.9 (1.3)	1.8 (0.7)
		Edinburgh	6.2 (6.2)	23.9 (1.3)	0.9 (0.9)	0.5 (0.5)	–0.3(–0.3)	22.9 (1.9)	1.7 (0.7)
26-30	Mean	Coventry	11.2 (3.0)	22.9 (1.3)	0.9 (0.3)	–0.1 (1.1)	–0.0 (1.0)	23.1 (2.1)	1.8 (0.7)
		Edinburgh	6.4 (1.6)	23.9 (1.1)	0.8 (0.3)	0.4 (1.2)	–0.2 (1.1)	23.3 (2.0)	1.9 (0.7)
31-35	Mean	Coventry	11.9 (2.3)	23.3 (1.0)	1.0 (0.3)	0.2 (1.5)	0.1 (1.3)	22.9 (2.6)	2.1 (0.7)
		Edinburgh	6.1 (1.9)	23.9 (1.2)	0.9 (0.3)	0.0 (1.3)	–0.2 (1.0)	23.9 (2.4)	1.9 (1.0)
36-40	Mean	Coventry	12.6 (2.2)	23.1 (1.0)	0.8 (0.3)	–0.6 (1.3)	–0.1 (1.0)	24.1 (2.7)	1.9 (0.7)
		Edinburgh	6.5 (1.7)	23.7 (1.2)	0.8 (0.4)	0.5 (1.0)	–0.1 (1.0)	22.7 (2.2)	1.9 (0.6)
Above 40	Mean	Coventry	11.3 (3.6)	22.3 (1.4)	0.8 (0.2)	0.0 (1.4)	0.1 (1.2)	22.3 (2.7)	2.0 (1.0)
		Edinburgh	6.4 (1.8)	23.4 (1.3)	0.7 (0.3)	1.0 (1.3)	–0.8 (1.2)	23.3 (2.2)	2.0 (0.6)

4. Discussion

The results of this study confirmed the role of physiological thermal adaptation, age- and gender-related parameters (as physiological human characteristics) on the perception of thermal comfort in the UK higher learning environments. Colder climatic conditions prevailing in Edinburgh (Scotland) compared to Coventry (England) and consequently thermal adaptation to the exposed climatic conditions led to warmer thermal sensations and cooler preference in Edinburgh than Coventry. This is supported by the cooler thermal acceptability zone (section 3.3), 0.4 °C lower neutral temperature (section 3.4) and 1 °C lower acceptable temperature (section 3.3) in Edinburgh than Coventry.

Although the difference in the observed thermal comfort requirements in these two locations is not very significant, it is worthwhile mentioning that providing even 1 °C cooler temperature set point in

Edinburgh than Coventry can potentially reduce up to 10% the related energy use [19] while at the same time avoiding overheated classrooms in Edinburgh.

Furthermore, extending this finding to all the higher learning environments in Scotland and England can potentially lead to a higher energy saving in the UK. Further investigation is suggested to determine comprehensive, thermally comfortable and energy efficient environmental criteria for the UK university buildings.

5. Conclusion

This study evaluated thermal comfort requirements of the students in university buildings in the Scotland (Edinburgh) and England (Coventry) in the UK. The influence of acclimatization, age- and gender-related differences (as the physiological drivers of diverse thermal comfort) on thermal perception is mainly focused in this study. Through conducting the simultaneous questionnaire surveys and thermal environmental measurements on 3507 university students in eight mixed mode university buildings, the following conclusions have been drawn:

- A negative correlation between the clothing insulation value and indoor operative temperature was found in both Coventry and Edinburgh. Students in Coventry reacted faster to the indoor temperature changes by clothing adjustment showing their higher sensitivity to the fluctuations of the indoor air temperature compared to their counterparts in Edinburgh. (section 3.2).
- The thermal acceptability was examined in two ways: 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 acceptable range). The indirect approach was shown to be a better predictor of the thermal acceptability as this method overextends the level of thermal acceptability achieved by direct approach. (section 3.3).
- Acclimatisation to the temperate and cold climates of Coventry and Edinburgh, 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 optimal acceptable temperature in Coventry (23.5 °C) than Edinburgh (22.1 °C) was observed in this evaluation (section 3.3).

- The thermally acceptable zone was 21.0 to 24.5 °C in Coventry and 19.5 to 23.5 °C in Edinburgh. A higher sensitivity to cold in Coventry and a higher sensitivity to warmth in Edinburgh was also revealed as a result of the subjects' acclimatisation. (section 3.3 and 3.4).
- Despite the similar comfort temperature for both genders (≈23 °C), heavier clothing insulation worn by women (≈0.92 clo) than men (≈ 0.83 clo) and the higher optimum acceptable temperature of females (23.5 °C) than males (22.0 °C) support the warmer thermal requirements of women compared to men (section 0).
- Although there is no statistically significant difference in the thermal comfort of the different age groups ($p>0.05$), for those above 40 years old, a potential lower thermal acceptability compared to those under 25, and a higher comfort temperature compared to those under 35 years old was observed in Edinburgh ($p<0.05$). However, due to the low number of subjects in some age groups, more investigation is required to validate this finding (section 0).

The outcome will result in an understanding of the potential thermally comfortable environment in the classrooms of the UK university buildings. Having found the comfort requirements in such spaces, sustainable environmental or architectural/refurbishment design strategies can be applied to provide acceptable thermal environments with minimum energy demand in the UK higher learning environments.

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