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Original citation & hyperlink:
Jowkar, M, de Dear, R & Brusey, J 2020, 'Influence of long-term thermal history on thermal comfort and preference', Energy and Buildings, vol. 210, 109685.
https://dx.doi.org/10.1016/j.enbuild.2019.109685

DOI 10.1016/j.enbuild.2019.109685
ISSN 0378-7788

Publisher: Elsevier

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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.

Key words: *Thermal comfort, Thermal history, Thermal expectation, Climatic background, Higher educational buildings*

1. Introduction

It is well documented that thermal comfort is an essential factor in learning environments to optimise the students' educational achievements and to enhance learning performance and mental tasks [1–5]. Exposure to indoor temperatures higher or lower than the comfort zone impairs students' performance and ability to grasp instructions, manual dexterity and speed of cognitive performance [7,8]. However, considering that HVAC services account for the largest end-use of energy in most non-residential buildings [7–9], providing students with thermally comfortable classrooms should not come at the cost of the environmental impact from energy and associated greenhouse gas emissions. This underscores the necessity of understanding what indoor climatic conditions are required to not only provide students with a thermally comfortable indoor environment, but also to minimise building energy consumption. Due to the considerable influence of thermal comfort on students' productivity, energy consumption and environment, this topic has attracted substantial attention among researchers in recent years [10–13].

The adaptive model of thermal comfort posits that occupants are not passive subjects, but instead they actively interact with the indoor environment through multiple feedback loops [14]. The context of this interaction includes not only environmental factors but also behavioural, cognitive and emotional parameters [15]. Previous studies indicate that psychological adaptation nudges the subjective thermal comfort temperature (i.e. neutrality) in the direction of the climatic conditions prevailing outdoors [16]. Psychological adaptation refers to the thermal perception and evaluation of a given indoor environment based on the subject's past thermal experiences and comfort expectations [17]. Consequently, perception of thermal comfort cannot be considered as a static condition [18] since it is affected by some psychological factors and differs from person to person [10, 12]. The concept of comfort is dynamic, depending on how people adapt, perceive and interact with the environment [20]. This fact is highlighted in university buildings which accommodate individuals from diverse cultural and climatic backgrounds.

Thermal history is a critical factor affecting thermal comfort perception in an environment [14]. Thermal history refers to the previous thermal conditions that were experienced by individuals. It exerts its influences on current thermal perceptions [9,10, 13] by providing a benchmark or experiential calibration frame of reference. Thermal sensation in a space is thought to result from a comparison between the current and previously experienced environmental conditions [22]. For further analysis we classify thermal history into two temporal scales [18]:

1. Short-term: Referring to the effects across timescales ranging from weeks, days, hours to seconds in day-to-day thermal exposures.
2. Long-term: Referring to the climatic influences of where people have been living for some years.

In terms of short-term thermal history, some studies have been conducted in transitional spaces in the UK higher educational buildings [20], office buildings in the hot and humid climate of Brazil [23], a university in the cold seasons in Pennsylvania, USA [24] and controlled chambers in different climate types [25–28]; with various exposure durations of 30 minutes [28], 1 day [25] and a 10-day period [29]. All these studies lead to a common conclusion that pre-exposure to cold thermal environments improves comfort votes in the cold, whereas people pre-exposed to warmth tend to evaluate cool environments as colder than they would otherwise have done in the absence of the previous warm exposure.

Regarding long-term thermal history, it is evident in previous studies that long-term pre-exposure to both indoor [30–34] and outdoor climatic conditions [33,35,36] affects subjects' in-the-moment thermal comfort perceptions.

Zhang et al. [30] conducted an experiment in a controlled chamber in a hot and humid area of China under naturally ventilated (NV) and cooling (CL) modes 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. The 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 [31], in climate chambers in Hungry (during the summer months with an indoor temperature of 30°C) [32] and in China (in an extremely cold climate under heating mode) [33]. Luo et al. [34] 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 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 occupants' thermal expectation, whereas experience of non-neutral thermal environments stimulates thermal adaptation. Collectively, these studies confirm the influence of pre-exposure to indoor thermal environments on in-the-moment thermal comfort perceptions [30–34]. However, it should be noted that these studies were conducted in extreme climatic conditions and mostly on subjects who were exposed to the same climate as the experiment, for at least more than three years [30–34].

The relation between climatic background and the subjects' thermal comfort ratings was examined in a hall of residence in the UK [35,36] and in outdoor spaces in Israel [37]. The participants were people from different climatic backgrounds. The results showed higher temperature preferences and cooler thermal sensations for the residents in the UK who had been living in a warmer climate for two years before moving there [35]. The indoor air comfort temperature was also shown to be higher for subjects from warmer climatic background compared to the UK native residents [36]. However, a warmer indoor air temperature was reported by the residents from cooler climates than the UK residents, which can be due to their thermal adaptation to high levels of central space heating [36]. It may be deduced here that people's exposure to warmth tends to play a more important role in thermal adaptation and as a result, in future thermal evaluations compared to exposure to cold. This finding was supported by Brychkov et al. [37], showing how people's different "climato-cultural" background may lead to different thermal perceptions. It is also concluded in this work that in stressful but not extreme thermal conditions, the warmer climatic background group has cooler thermal sensations in winter and higher levels of comfort in summer compared to their counterparts from cooler climates [37].

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 (most were conducted in extreme climatic conditions), the impact of pre-exposure to indoor thermal environments on thermal comfort perception was indicated, however, a negligible relation between pre-exposure to outdoor climates and current thermal expectation was shown [30–34]. According to Brychkov et al. [37], 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. Nonetheless, these conclusions cannot be generalised to non-extreme climatic conditions. The research carried out in the temperate climate of the UK [35,36] was based on online post-occupancy evaluations, considering only two years pre-exposure of the subjects to a climatic condition [35,36]. None of the studies in this literature review demonstrated clear impacts of thermal history and expectations on thermal comfort in buildings that are shared by multiple occupants who have grown up in diverse climatic conditions. The present study addresses the research questions: “Is there any relation between thermal comfort perception and long-term thermal history in environments accommodating occupants with diverse climatic backgrounds?” and “How does the occupant’s climatic background (long-term thermal history) influence their in-the-moment thermal comfort assessments inside classrooms in higher education institutions?” This work supposes that warmer thermal expectations and cooler thermal sensations will be observed among the subjects from warmer climates than the UK, compared to their counterparts from a cooler climatic background than the UK native residents.

The output of this work can contribute to identify the thermally comfortable and energy efficient environmental criteria for UK universities as multidisciplinary buildings. Furthermore, information on the thermal comfort requirements of different climatic background groups can help to suggest appropriate environmental and design solutions which can offer a comfortable and satisfactory thermal environment.

2. Methods

The data collection took place in eight mixed-mode ventilation university buildings in Coventry, England (buildings 1 to 4) and Edinburgh, Scotland (buildings 5 to 8), in the United Kingdom. All the buildings were equipped with HVAC systems and operated on changeover or concurrent mixed-mode [38]. The summary of the investigated buildings is presented in Table 1.

The climate of Edinburgh is cool and moist, cloudy and rainy, reflecting its maritime setting. The average daily temperature ranges from 4 °C in January to 15 °C in July and August. In Coventry, the climate is temperate and cool for most of the year. Winter is cold but above zero, while summer is cool. The average Coventry temperatures changes from 4 °C in January to 18°C to June, July and August [39].

Comfort surveys were conducted in three different types of classrooms: lecture theatres, studios and PC labs. Classrooms were selected if the lecturers consented and all the students were involved in comparable activities. Each room was equipped with ceiling diffusers or radiators for heating and supply ducts or floor outlets for cooling. Three operation modes were available in the classrooms: free running (FR, neither heating nor cooling), cooling (CL) and heating (HT). Natural or mechanical ventilation was achieved through operable windows or fresh air supply ducts respectively, controlled manually or automatically, based on the CO_2 level monitored in some classrooms. Data collection occurred between October and November 2017 in Coventry; and between January and April 2018 in both Coventry and Edinburgh.

Table 1. Summary of the investigated buildings

Location	Building (B)	Construction type	Types of classrooms	Average area (m^2)	No. of surveyed rooms	No. of survey repeat	Ave. occupancy density (person/m^2)
Coventry	1	A	Lec.	100	2	2	2.5
			Stu.	150	4	4	5.0
	2	C	Lec.	120	1	8	1.2
			Stu.	130	1	3	3.0
			Pc.	90	3	7	3.5
	3	B	Lec.	100	8	21	2.0
			Pc.	80	6	10	3.0
	4	A	Stu.	150	4	5	5.0
Edinburgh	5	A	Lec.	80	3	8	1.2
	6	A	Lec.	80	1	4	1.2
	7	A	Lec.	120	1	4	1.2
	8	C	Lec.	120	3	15	1.2

A: Heavy weight, B: Medium weight, C: Low weight

Lec.: Lecture room, Stu.: Studio, PC.: PC lab

2.1. Field study procedure

The field studies started after receiving research ethics certificates 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. Data was collected through simultaneous and contiguous *instrumental environmental evaluation*, *questionnaire survey*, and *observation*. Figure 1 summarises the methods of data collection and classification.

Indoor air temperature (T_{in}), relative humidity (RH), air velocity (air_V) and mean radiant temperature (T_{mr}) were recorded at 5 minutes interval continuously throughout the study. Each variable was measured from the beginning to the end of the class. For the analysis however, the recorded points averaged through the same time interval as the questionnaire survey were considered (the last 15 minutes of each class). The black globe thermometer was placed 1.1m above the floor level, as recommended by EN ISO 7726 [40], on a vertical stand. The anemometer and humidity probe were placed above and below the thermometer in the middle of the room, away from any heating or cooling sources (Figure 2).

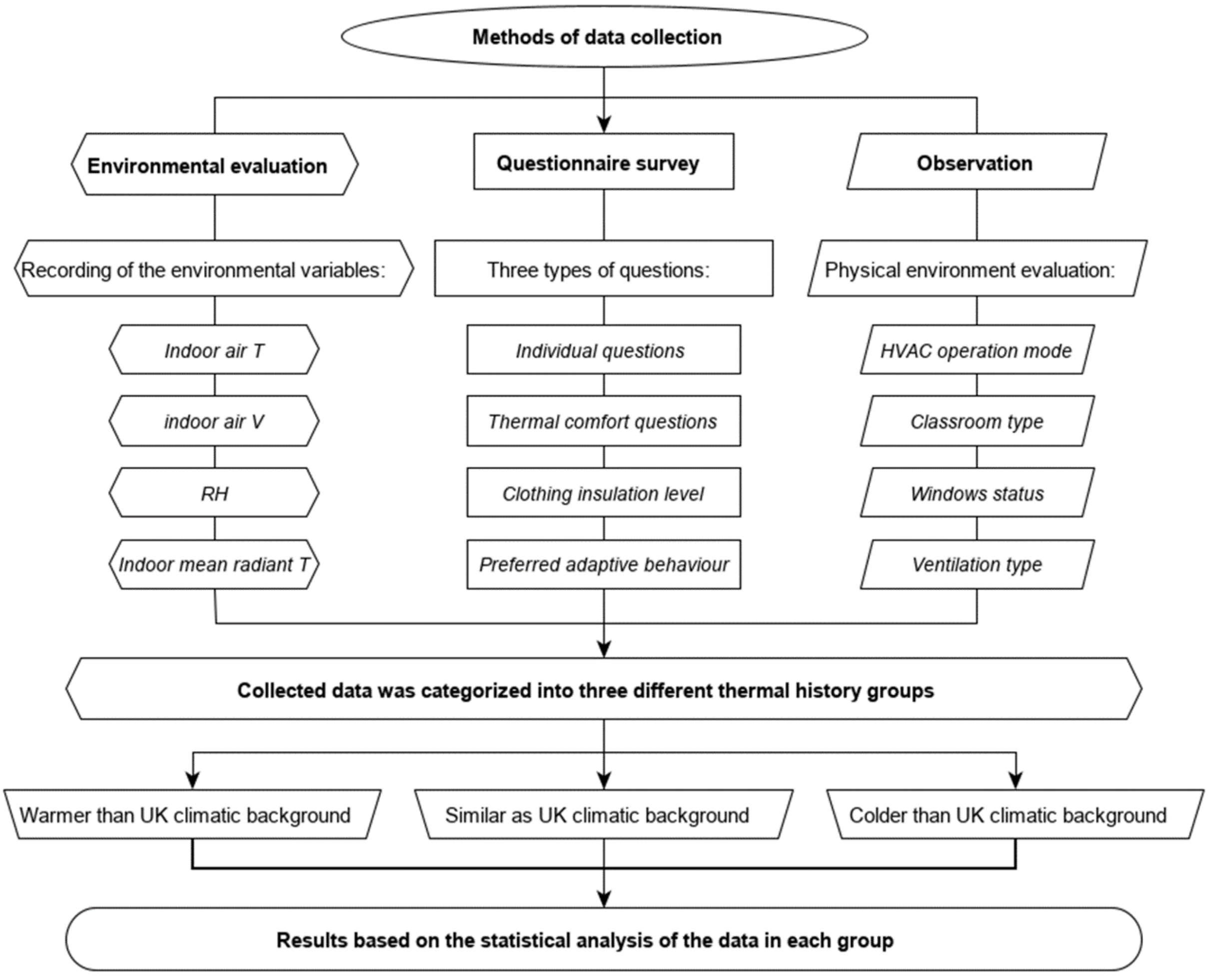

Figure 1. Summary of the research methods

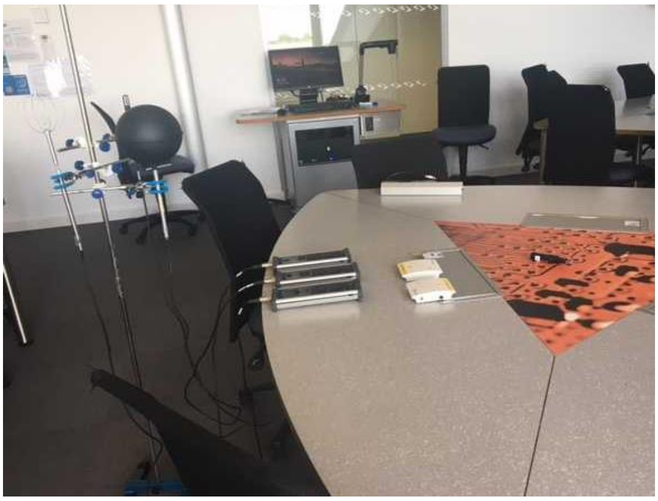

Figure 2. Measurement instruments installed in a surveyed classroom

A summary of the measurement instruments is presented in Table 2. Outdoor air temperature data was obtained from the UK Meteorological Office [41] whose weather station was less than 5km from the comfort field study site.

Table 2. Description of the instruments

Measured parameter	Instrument	Resolution	Range	Accuracy
Mean radiant temperature	Multi purposes SWEMA 3000	0.1 ºC	0 –50 ºC	±0.1 ºC
Air velocity	Multi purposes SWEMA 3000	0.03 m/s	0.05 –3 m/s	±0.04 m/s
Relative humidity	Multi purposes SWEMA 3000	1 %	0 –100%	±0.8 %
Air temperature	RH10 USB data logger	0.1 ºC	−40 –70 ºC	±1.0 ºC

The cross-sectional research design saw a total 3,873 students. However, approximately 9% of the students did not provide answers and were excluded from the data base. A small number of the questionnaires filled by the students sitting directly next to the heating or cooling sources were also excluded. Overall, 3,516 students, 2,046 in Coventry and 1,460 in Edinburgh took part in the surveys.

Information regarding the students' residence period in the UK was only available for "less than 1 year", "1 to 3 years" and "more than 3 years". To exclude the influence of acclimatisation in the UK, only students with less than 3 years of residence in the UK were considered for inclusion in the analysis. Results from a one-way ANOVA test confirmed the statistically insignificant difference between the mean thermal sensation votes (TSV), thermal preferences (TP), comfort temperature (neutrality) of the students with "less than 1 year" and "1 to 3 years" residence duration ($p>0.05$). A statistically significant difference in the mean TSV, TP and comfort temperature between these two groups and participants with more than 3 years residence in the UK was however observed ($p<0.001$). Furthermore, the potential confounding factors for each residence period group in the UK (including gender, age and clothing insulation levels in each group) were examined and the results presented in Table 3. The distribution of the participants in terms of gender, age, and mean clothing insulation value were comparable for these three categories. Therefore, data for students who had been in the UK for more than 3 years were excluded. In total, 1,225 subjects (729 in Coventry and 496 in Edinburgh) of both genders and average ages between 18 and 25 years were retained for analysis.

Table 3. Distribution of gender, age and clothing insulation values in groups of residence period in the UK

	Gender		Age group							Mean clothing value (clo)
Residence period in the UK	Males (%)	Females (%)	<21 (%)	2–25 (%)	26–30 (%)	31–35 (%)	36–40 (%)	>40 (%)	Do not wish to specify	
< 1 year			44	45	7	1	1	1	1	0.88
1–3 years			41	51	5	1	1	0	1	0.90
>3 years			54	38	4	1	1	1	0	0.87

The questionnaire included four sections: 1) background questions such as age, gender, hometown and home country, 2) thermal comfort including thermal sensation, preference, acceptability and overall comfort votes, 3) clothing garment checklist and 4) preferred adaptive behaviours in the classrooms during uncomfortably warm and cold thermal conditions. The thermal sensation vote (TSV) was based on the ASHRAE 7-point scale. A similar 7-point scale was used for thermal preferences (TP) as indicated in Table 4. Clothing insulation levels were evaluated based on the tabulated garment clo values in EN ISO 7730 [42]. Students filled in the paper-based questionnaires during the last 15 minutes of each class. Although 15 minutes is generally regarded as enough to eliminate the influence of prior activities on thermal sensation votes [53, 54], in this study, 1 hour of sitting in the 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 [27] and to minimise disruption to the class activity.

Table 4. 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 (TPV)	Much warmer	Warmer	Slightly warmer	No change	Slightly cooler	Cooler	Much cooler

2.2. 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 [28, 10]. Each climate zone is based on the qualitative features of the Earth's vegetation [47]. The updated versions by Kottek et al. [10] and Peel et al. [11] have been applied in various research problems ranging from climate change through to thermal comfort [49–51]. Table 5 presents the five main groups distinguished by Köppen-Geiger including zones A (tropical), B (arid), C (temperate), D (cold) and E (polar) [48]. The second letter in the classifications indicates the precipitation level and the third letter refers to air temperature [46] (e.g. Dfc for snow, fully humid with cool summer).

Table 5. Description of Koppen climate symbols and criteria [46]

1st	2nd	3rd	Description	Criteria
A			**Tropical**	Tcold≥18
	f		- Rainforest	$P_{dry} \geq 60$
	m		- Monsoon	Not (Af) & Pdry≥100–MAP/25
	w		- Savannah	Not (Af) & Pdry <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≥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* $P_{threshold} = 2 \times MAT$*, if 70% of MAP occurs in summer then* $P_{threshold} = 2 \times MAT + 28$*, otherwise* $P_{threshold} = 2 \times MAT + 14$*).*

The students' hometowns and home countries were coded according to the Köppen-Geiger climate classification map (Figure 3). Considering Table 5, the main difference between groups A and B is precipitation level, while other thermal features are broadly similar. Moreover, the ANOVA tests indicated no statistically significant difference in the students' thermal comfort results between 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 higher mean annual temperature than UK) and cold or polar areas (zones D or E with lower mean annual temperature than UK) are considered as warmer and cooler climates compared to the UK, respectively. Table 6 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) are categorised as "warmer" and "cooler" thermal history groups, respectively.

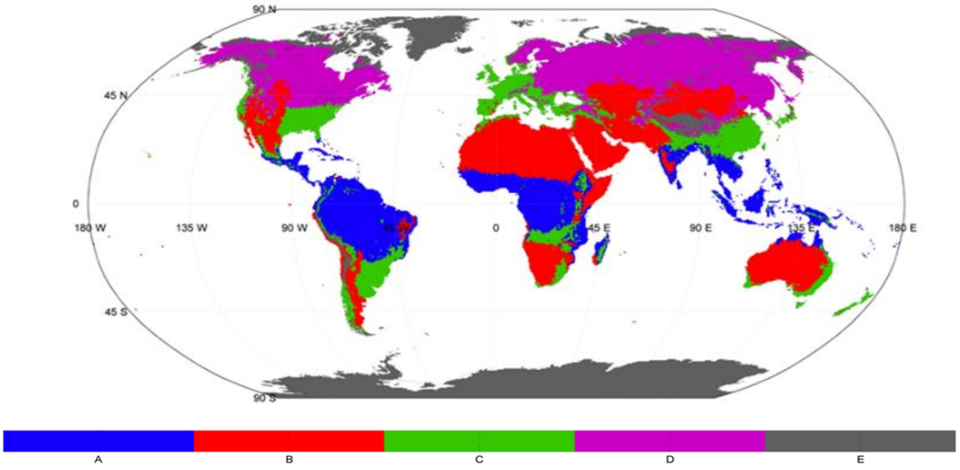

Figure 3. Koppen Geiger climate classification map- main climate types [46]

Table 6. 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

2.3. Data analysis

The collected data was statistically analysed to estimate the acceptable thermal zone, comfort and preferred temperatures for each thermal history group. Statistical tests were applied to confirm the difference between the thermal comfort indices of each thermal history group. An independent t-test and one-way ANOVA test were applied to the normally distributed data and a Mann-Whitney U test (non-parametric equivalent to the independent t-test) was applied to the non-normal distributions or ordinal variables [52]. The probability vale (p-value) and Cohen's effect size were also calculated [53] to confirm statistical differences between the thermal comfort of the climatic background groups. According to Cohen's standard [53], an effect size of 0.2 is considered as small, 0.5 as medium, and 0.8 as a large difference between groups. A medium effect of 0.5 is visible to the naked eye of an observer; mathematically/statistically, a small effect of 0.2 is smaller than medium but it is not so small as to be trivial, while a large effect of 0.8 is above medium and shows larger differences [53, 54]. However, for social science research or general 'soft' science research, interpretation of effect size is challenging as researchers tend to quantify the subjective factors in ways that are often deemed arbitrary [55]. Therefore, effect size for such soft studies may be interpreted differently to purely mathematical studies [55].

3. Results and Discussion

Figure 4 shows the outdoor temperatures through 2017 – 2018 within the survey periods in Coventry and Edinburgh. There was a larger temperature difference between these two locations during summer compared to the winter months. Regarding the survey period, there were minimum, average 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.

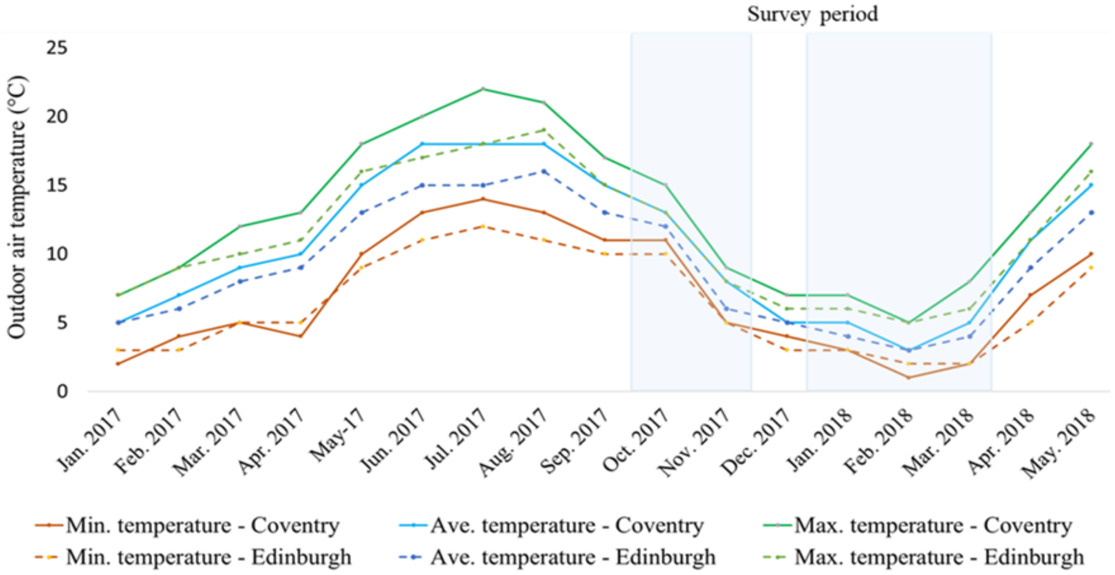

Figure 4. Monthly mean outdoor air temperature in Coventry and Edinburgh during survey periods (source: [41]*)*

Figure 5 illustrates the distribution of operative temperatures (T_{op}) recorded inside classrooms during the survey period. Around 90% of the observations fell between 22°C and 25°C. A summary of the thermal comfort indices for each thermal history group is given in Table 7. 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 (Air_V) 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 is 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. Mean Thermal Sensation Votes (TSV) at −0.28 and mean Thermal Preference Votes (TPV) of +0.10 idicate the warmer background group experienced marginally cooler perceptions compared to the other two groups.

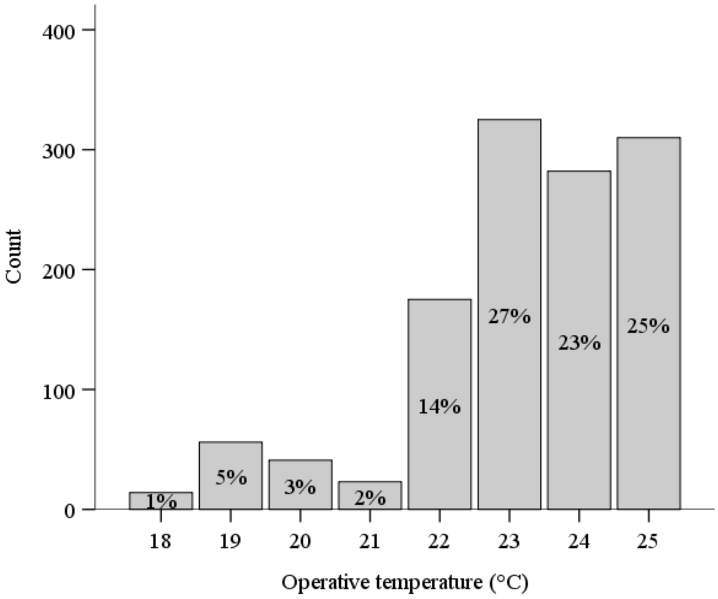

Figure 5. Distribution of indoor air operative temperature in the surveyed classrooms

Figure 6 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 the independent t-test, a non-parametric Mann-Whitney U test was conducted between each pair of groups, as suggeted in previous studies for such types of data [56–58]. Results indicated a significant difference between the clothing value of the warmer background group compared with both the cooler and similar climatic background groups ($p<0.001$, effect size: 0.33), but an insignificant difference was detected between the clothing insulation levels of the similar and cooler groups ($p>0.05$).

Table 7. 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

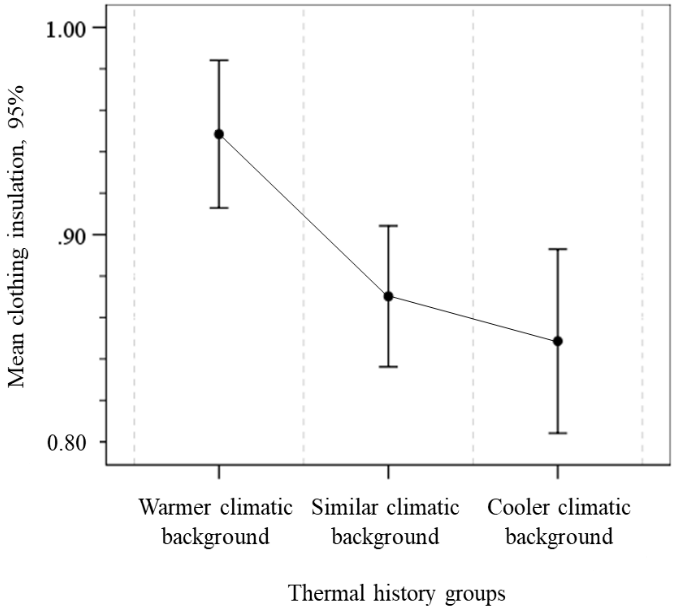

Figure 6. Mean of clothing insulation estimates for the three thermal history groups

In the following sections, the influences of long-term thermal history and climatic background on thermal sensation votes, thermal acceptability, comfort temperature and neutrality, thermal preferences and sensitivity are examined.

3.1. Thermal sensation votes

The thermal sensation votes (TSV) of the students sorted into the three thermal background groups are presented in Figure 7. 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 the warmer background group. 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, an insignificant difference was shown in 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 (p<0.001, effect size: 0.26) and cooler climatic backgrounds (p=0.020, effect size: 0.32).

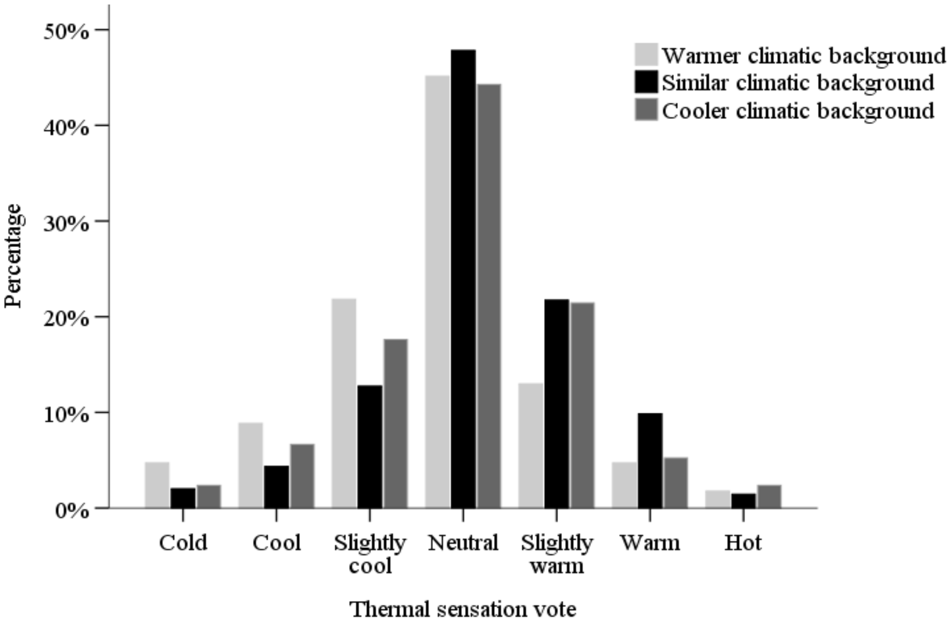

Figure 7. Thermal sensation votes of the warmer, similar, and cooler thermal history groups

The results so far and those 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 insignificant differences between 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, 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).

3.2. Thermally acceptable range

According to ASHRAE 2017 [59], 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, the thermal sensation votes were binary recoded as acceptable (TSV= 0 and ±1) and unacceptable votes (TSV= ±2 and ±3). Operative temperatures were binned at 1°C intervals and the proportion of thermally acceptable votes in each bin is indicated in Figure 8. Probit regression was employed to identify mean thermal acceptability and thermal comfort ranges for each climatic background group as applied in previous studies [60–62]. probit model is a statistical method that relates the proportion/probability of a binary qualitative variable to a continuous explanatory variable [63,64]. 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 the thermal comfort descriptors to see how well they fulfil the ‘equal interval’ assumption [64]. In this work, thermal acceptability is the dependent binary outcome and operative temperature is considered as the independent variable.

Considering the standard of a minimum 80% acceptability as recommended in regulatory documents such as ASHRAE 2017 [59], 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 starts at 18°C for group 2, which is 5°C cooler than the lower acceptable margin for group 1 (23°C). In contrast, in the higher margin in 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.

Higher optimal acceptable temperatures along with heightened thermal acceptability were observed in higher operative temperatures for the warmer climatic background group 1 compared to similar/cooler climatic background group 2, which 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 also been observed in previous studies [26,50,65,66].

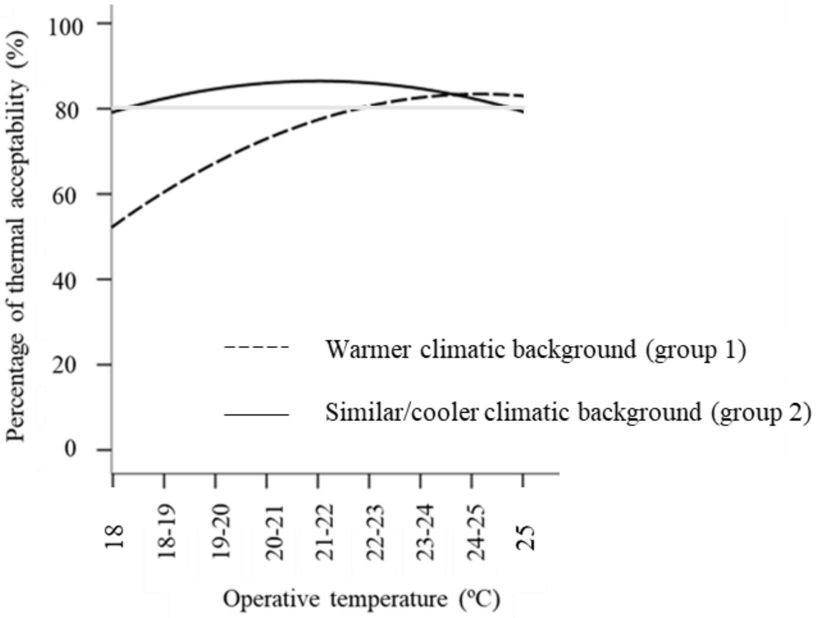

Figure 8. Percentage of acceptable thermal sensation votes for warmer and similar/ cooler thermal history groups

The warm and cool thermal dissatisfaction levels of each group are presented in Figure 9. According to the minimum 80% acceptability recommended by ASHRAE 2017 [59], 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 (Figure 8 to Figure 10).

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.

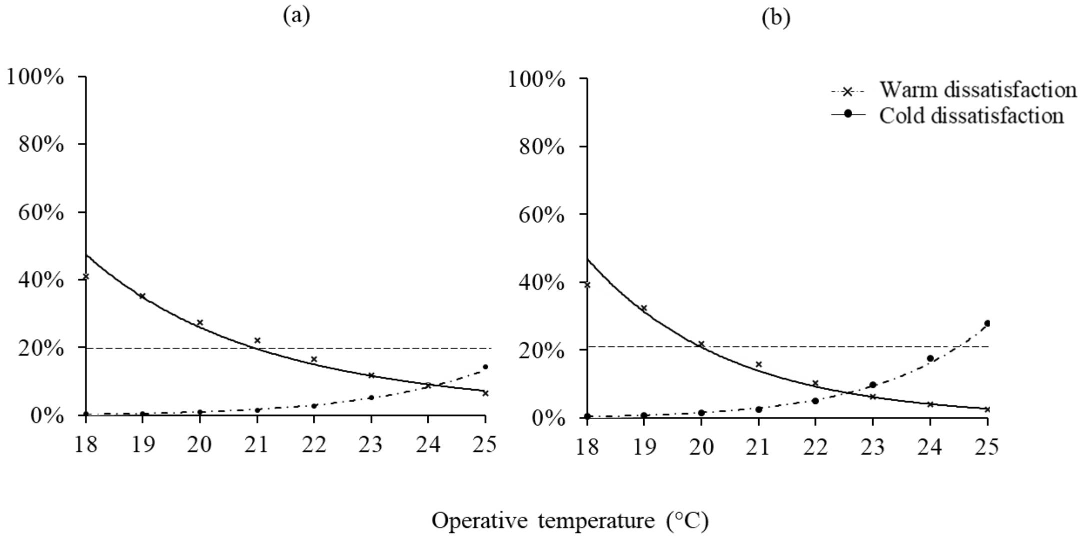

Figure 9. warm and cold thermal dissatisfaction of warmer background group 1 (a) and similar/cooler background group 2 (b)

3.3. Thermal neutrality (comfort temperature)

Griffiths' method was applied to the thermal sensation vote of each participant to estimate the mean comfort temperatures for the thermal history groups. This approach works based on an assumed constant rate of thermal sensation vote change per unit of temperature change. Comfort temperatures were calculated using Griffiths' method, equation (1) [67–69];

$$T_c = T_{op} + (TSV_{neutral} - TSV)/\ \alpha \tag{1}$$

Where T_c is comfort temperature or neutrality (°C), T_{op} is operative temperature (°C), $TSV_{neutral}$ is the neutral thermal sensation vote (zero in this project), TSV is the thermal sensation vote and α is the so-called Griffiths constant. Therefore, if the participants' thermal sensation vote is equal to "0, Neutral" for example, their comfort temperature would simply be the same as the operative temperature registered when they cast that vote. The value of 0.50 is assumed for the Griffiths' constant as suggested by Humphreys et al. [70], estimated from a field-survey database, meaning that a 2°C change of operative temperature leads to a single unit change on the 7-pt thermal sensation scale, all else being held constant.

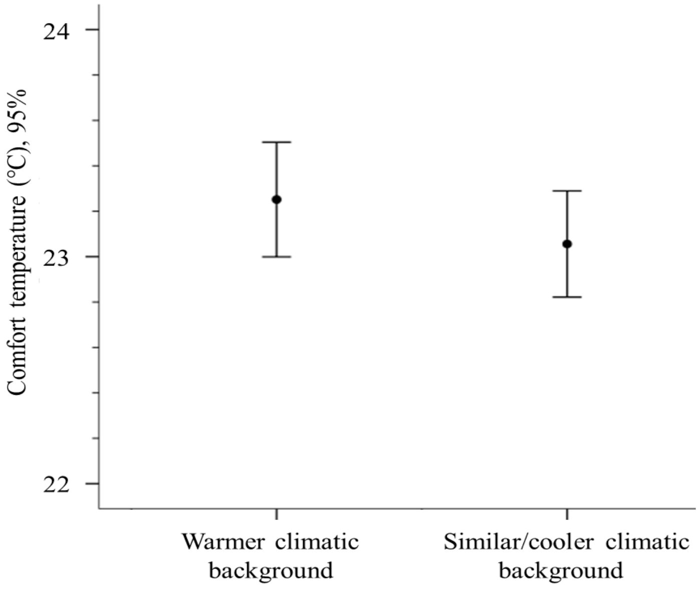

Figure 10. Comfort temperature of the warmer and similar/cooler thermal history groups (95% confidence interval)

Figure 10 indicates the mean comfort temperature of the warmer background group 1 (mean = 23.3, SD= 2.4) and the similar/cooler background group 2 (mean= 23.01, SD= 2.22). The results of an independent t-test indicate an insignificant difference between the mean comfort temperatures of the thermal history groups. ($p>0.05$, df=892, t=1.41). However, 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).

3.4. Preferred temperature

To evaluate each climatic group's preferred temperature, probit regression models were fitted to the relationship between the operative temperature and the thermal preference votes, as described in [71]. In Figure 11, the intersection points between "want warmer" and "want cooler" probit curves for each thermal history group are assumed to correspond with the group's optimum preferred temperature [61,72].

Regardless of the students' thermal background, operative temperature has a negative correlation with warmer thermal preferences and a positive association with the cooler preference votes, as expected. 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 confirms the difference between the preference votes of the climatic background groups ($p=0.01$, effect size: 0.21, t=2.58). According to Cohen's classification [53], the effect size of 0.21 is 'small', but as mentioned in section 2.3, effect size in social/soft science research may interpret differently. Therefore, the resulted small effect size in this work may not necessarily mean small power of the statistical results [73,74]. Probit regression p-values and the Pearson goodness also indicate that the fitted curve for these two thermal history groups is significantly different ($p=0.01$).

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 similar/cooler background group 2 preferred to be cooler compared to warmer background group 1 above 21.5°C. The sharper growth of the cooler thermal preference votes by increasing the operative temperature for similar/cooler background group 2 compared to warmer background group1, emphasises group 2’s higher sensitivity to warmth than group 1.

The higher preferred temperature and lower thermal sensitivity to warmth for warmer climatic background group 1 than similar/cooler climatic background group 2 indicates the influence of long-term thermal history on the participants’ thermal preferences and preferred temperatures. 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 [12,43- 45,50].

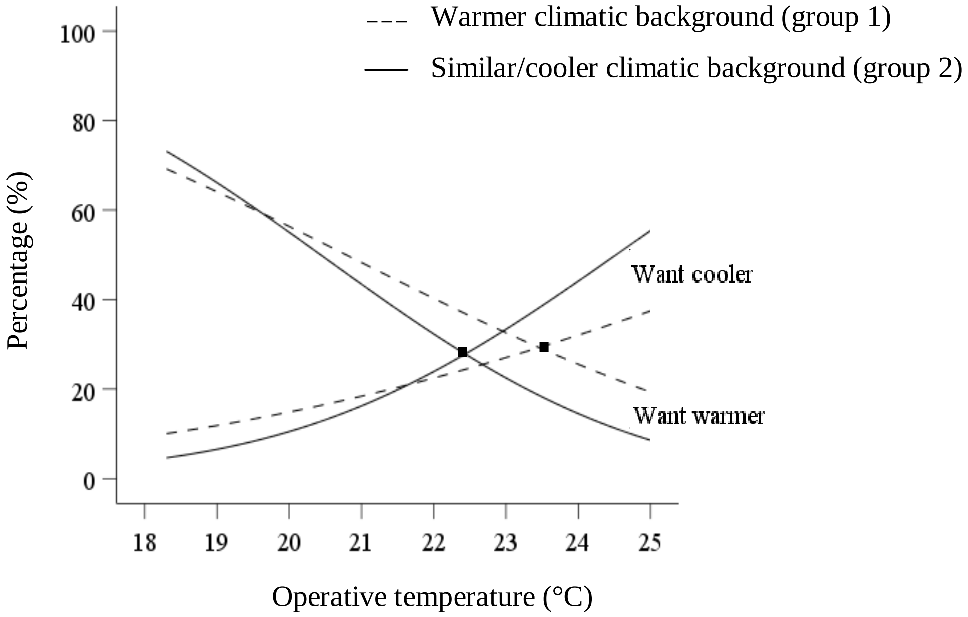

Figure 11. The proportion of the thermal preference votes for the warmer and similar/cooler thermal history groups

According to Figure 7 through to Figure 11, the acceptable temperature ranges (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 condition. 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.

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 the UK. The analyses reported in this paper broadly agreed with this prediction. Therefore, it is crucial to find an environmental or design solution which not only can provide thermal comfort for all climatic background groups of students in higher educational buildings, but also minimise the buildings' energy consumption and related emissions.

4. Conclusions

This study investigated influences of climatic background and long-term thermal history on in-the-moment thermal comfort experiences in eight mixed-mode university buildings located in the United Kingdom. Evaluations were conducted through environmental measurements, questionnaire surveys and observations. In total 3,452 students performing sedentary tasks inside classrooms were subjects in this study. Data from a subset of 1,225 students with less than 3 years of residence in the UK were categorised into three main groups based on their climatic background (climate of origin). The following key findings emerged from the analysis:

1. Climatic background and long-term thermal exposure to a thermal condition apparently affects thermal sensation, thermal comfort zone, thermal acceptability and temperature preferences in buildings accommodating occupants with diverse climatic backgrounds, such as higher learning environments.
2. There was generally no statistically significant difference in the subjective comfort responses (thermal sensation, preference, neutrality and thermal acceptability) of students with backgrounds in similar climates to the UK's and those from climates cooler than the UK. However, significant differences emerged in the results for the students with a warmer thermal history.
3. The thermally acceptable zone was defined using the minimum 80% acceptability criterion. Considering the operative temperature between 18°C and 25°C in this work, thermal acceptability ranged from 23°C to 25°C for the warmer climatic background subjects, and approximately 18°C to 25°C for the similar/cooler climatic background subjects. The optimal acceptable temperatures were 24°C and 22°C for these two groups, respectively.
4. Overall, when exposed to the same thermal environment, participants with a warmer thermal history felt cooler compared to their counterparts in the similar-to and colder-than-UK thermal history groups. They also had lower thermal sensation votes, higher optimal acceptable temperatures, warmer thermal neutralities and preferred temperatures compared to subjects in the similar-to and colder-than-UK thermal history groups.
5. Cold thermal dissatisfaction was experienced at lower indoor operative temperatures for the similar/cooler climatic background group compared to the warmer climatic background subjects. Furthermore, there was a wider acceptable temperature range in warmth for the warmer thermal history group compared to their counterparts in the

similar/cooler thermal history group. Heightened sensitivity to cool and warm conditions was also confirmed in this work for the warmer and similar/cooler climatic background groups, respectively.

Acknowledgments

The authors gratefully acknowledge the lecturers at Coventry and Heriot-Watt Universities for their assistance in conducting the field survey within their teaching sessions. This work was supported by Coventry University, UK and we would like to thank this institution for the funding provided to complete this research.

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