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

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**Abstract**

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

**Key words:** Thermal comfort, Higher education buildings, Lecture room, Studio, Comfort temperature, Adaptive behaviour.

## 1. Introduction

Trying to find an effective energy efficiency strategy is the basis of recent research in many developed and developing countries. The UK's commitment to reduce its greenhouse gas (GHG) emissions by 2050 [1] highlights the importance of reducing energy consumption in this country. Considering the 5.2 billion kWh of energy consumed annually by UK higher educational buildings [2], studying thermal comfort in such spaces that influence energy consumption plays an important role in saving energy and reducing the related GHG emissions. However, potential energy gains should not be achieved at the cost of reduced thermal comfort in educational buildings as thermal comfort is shown to be one of the influential parameters on students' intellectual performances [3,4]. It is confirmed in a number of studies that thermal discomfort creates dissatisfactory conditions which consequently causes distraction and reduction of the students' learning performance and mental tasks [2–6]. Both higher and lower temperatures than the comfort zone tend to reduce students' performance and their ability to grasp instructions. Warm environments affect students' productivity and cold temperatures reduce manual dexterity and speed [7,8].

Given the importance of thermal comfort in educational buildings, along with the influence of thermal environment on energy consumption and related emissions, this topic has attracted substantial attention among researchers in the recent years. So far, studies have been conducted on thermal comfort in educational buildings in *primary schools* in the UK [8–10], Italy [11], the Netherlands [6,8] and Taiwan [12], *secondary schools* in Italy [13,14], Portugal [15] and Cyprus [16] and *university buildings* in Italy [4,17], the Netherlands [18], Japan [19,20], Brazil [21], India [22,23] and UK [24–26]. Vargas [25,26] conducted two studies at Sheffield University in the UK that evaluated the impact of HVAC technologies on environmental diversity along with examining the role of transitional lobby spaces on occupants' thermal comfort. Lawrence and Keime [24] also examined how active and passive building design strategies provide comfortable and energy efficient workspaces at Sheffield University, UK.

Existing guidelines such as CIBSE [27] ASHRAE [28] and EN ISO 7730 [29] recommend general environmental criteria for classrooms or educational buildings with no discrimination based on educational level. This suggests applying the same environmental criteria for school buildings to universities and colleges without considering the potential differences between the occupants in each level. However, students in higher learning environments vary in terms of age, gender, thermal background, subjects studied, and the class type that they are exposed to. Therefore, the environmental standards recommended for primary to high school cannot be applied to such multidisciplinary environments. This shows the necessity of having a correct understanding about the occupants' thermal comfort requirements in university buildings in order to provide them with the thermal environment close to their comfort perceptions.

In a thermally uncomfortable setting, occupants tend to react to the 'discomfort sources' in order to restore their personal thermal comfort either unconsciously (by sweating, shivering, etc.) or consciously (via environmental or personal adaptive behaviours) [30]. Conscious behaviours may be through *environmental* or *personal* adjustments [30,31]. People's priorities for adaptive behaviours tend to vary according to their levels of control over the environment [32–34]. Students in higher learning environments are typically from different disciplines and studying various topics [35]. They are exposed to different classroom types with variable occupancy periods and different levels of freedom for adaptive behaviours. For example, students in art-based subjects may spend four or five hours in studios. They have great freedom for adaptive behaviour in the classrooms. Meanwhile, students in science-based subjects spend one to two hours in lecture rooms or PC labs with low or medium levels of freedom to control indoor environment.

Given the influence of occupancy period and thermal adaptation, and control over a space on thermal comfort, different thermal perceptions are expected for students in each classroom type. Therefore, applying similar comfort criteria in all class types may not thermally satisfy students in diverse disciplines.

The lack of an environmental standard for such spaces in the existing guidelines as well as limited studies in field of thermal comfort and energy efficiency to determine thermal comfort range in higher learning environments show the need for more investigations, in this regard.

This study aims to identify:

1. The comfort temperature ranges for students in different classroom types in higher learning environments (sections 3.3 and 3.4).
2. Students' priorities for adaptive behaviour in each classroom type and its influence on their thermal comfort perceptions (section 3.5).

## 2. Methods

Field experiments were conducted through simultaneous environmental measurements, questionnaire surveys, and observations in eight mixed-mode university buildings in Coventry (52.4068° N, 1.5197° W), England, and Edinburgh (55.9533° N, 3.1883° W), Scotland, in the United Kingdom (UK). The mean annual temperature in Coventry and Edinburgh is 12°C and 10°C, respectively [36]. Relative humidity is similar in both locations, at around 85%. The mean annual air velocity is 2 m/s higher in Edinburgh than Coventry. The locations were selected to represent two different climatic conditions in the north and south of the UK. Data collection took place between October and November 2017 in Coventry and between January and April 2018 in both Coventry and Edinburgh, during the first and second academic semesters when students attended the classrooms.

## 2.1. Case-study buildings

Experiments were conducted in eight different buildings (B1 to B4 in Coventry and B5 to B8 in Edinburgh). Classrooms were selected based on the availability of the lecturers' consent, classroom types and the number of students. Both morning and afternoon sessions were selected to cover outdoor temperature changes during the day and the impact on students' thermal comfort.

All classrooms were equipped with HVAC systems and operated on changeover or concurrent mixed-mode [37]. Space heating was provided through a square ceiling diffuser in all buildings, and radiators in some cases. Space cooling was provided through ceiling ducts in all buildings except B3, which were equipped with floor cooling outlets. Based on the indoor ambient environment, free-running (FR, neither heating nor cooling), cooling (CL) or heating (HT) modes were preferred by the occupants in these spaces. Ventilation was achieved through operable windows and fresh air supplier ducts controlled manually (except B3) or automatically and manually (B3). However, due to presence of top hung windows and the small extent of window openings because of safety issues, natural ventilation through the windows was not efficient enough. Overall, curtain and window status (open or closed), the number of windows, existing opportunities for adaptive behaviours, HVAC operation mode and ventilation type in each room were also registered.

## 2.2. Thermal environmental measurement

Field measurements included the recording of four parameters in each classroom: indoor air temperature ($T_{in}$), relative humidity ($RH$), air velocity ($V_i$) and mean radiant temperature ($T_{mr}$). Relative humidity, air velocity and mean radiant temperature were recorded using the Multi-purpose SWEMA 3000 [38] instrument, working based on ISO 7730 with a time interval of 5 minutes (Table 1

*Description of the instruments*

| Measured parameter | Resolution | Range | Accuracy |
|---|---|---|---|
| Mean radiant temperature | 0.1°C | 0 - 50°C | ±0.1°C |
| Air velocity | 0.03m/s | 0.05 - 3m/s | ±0.04m/s |
| Relative humidity | 0.8% | 0 - 100% | ±0.8% |
| Air temperature | 0.1°C | −40 - 70°C | ±1.0°C |

As shown in Figure 1 (b), the thermometer was placed 1.1 m above the floor level, as recommended by EN ISO 7726 [39] and the anemometer and humidity probe were placed above and below the thermometer. The SWEMA kit and one temperature and RH logger were placed in the middle of the room, away from heating or cooling sources. The rooms were divided into 4 or 5 zones, based on their physical shape (Figure 1 (a)). Each temperature and RH logger was placed in each zone to gain the nearest environmental data on the students' sensations.

The majority of cases, measurements started from the beginning to the end of the class to register all the changes of the environmental variables during each session. However, for the data analysis, averages of the recorded points in the last 15 minutes of each class (when the students were filling in the questionnaires) were considered. The operative temperature, which is generally worked with in this study, was calculated as the mean of the radiant temperature and indoor air temperature for air velocity below 0.2 m/s and through the following formula for higher air velocity [40].

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

Where $T_{op}$ is operative temperature, A is the constant value introduced as 0.6 [40] and $T_{mr}$ is mean radiant temperature.

Outdoor air temperature data was obtained from the UK meteorological office [36]. The weather station which represented ambient temperatures in the vicinity of the university was less than 5 km from the study site.

). The probes included in the SWEMA kit were positioned at the occupants' head heights on a vertical stand to reflect all the subjects' thermal sensations.

***Table 1***
*Description of the instruments*

| Measured parameter | Resolution | Range | Accuracy |
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| Mean radiant temperature | 0.1°C | 0 - 50°C | ±0.1°C |
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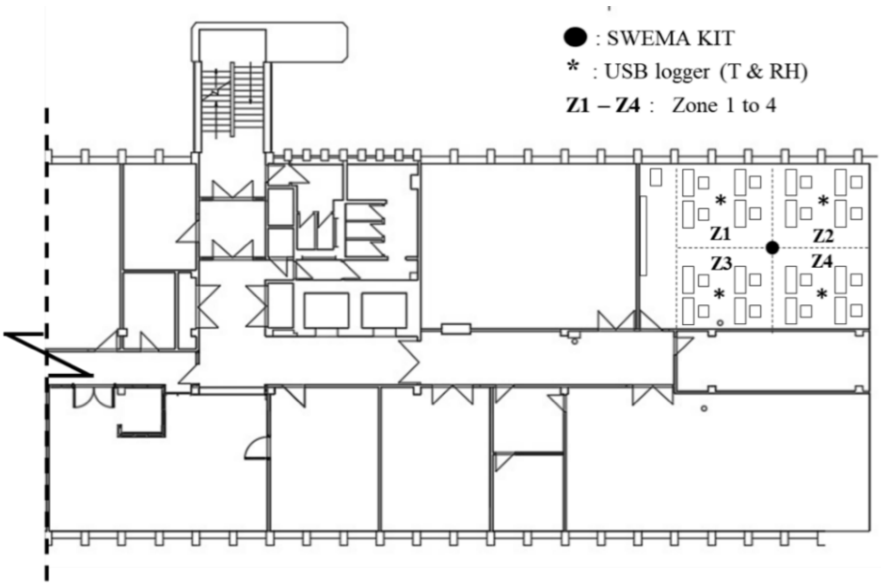
(a)




(b)

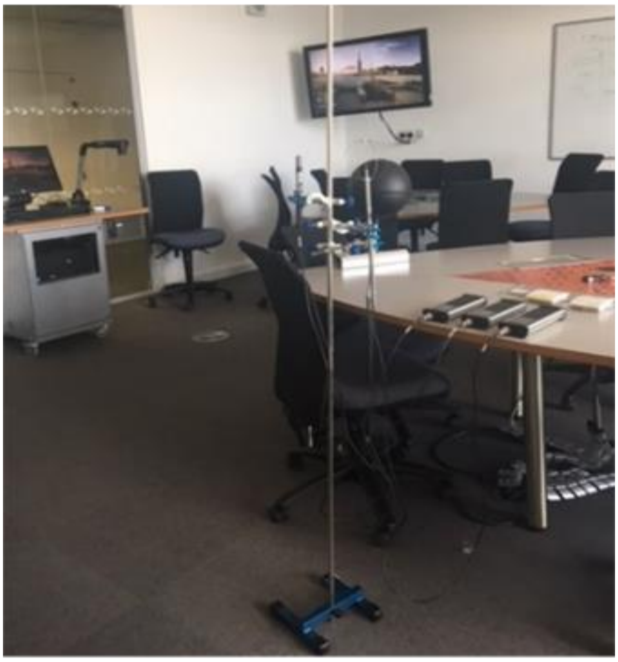


*Figure 1. Location of instruments in one of the lecture rooms. a: architectural plan, b: photo of instruments*

## 2.3. Questionnaire survey and participants

Cross-sectional questionnaire surveys were conducted with students in both art- and science-based subjects in studios, PC labs and lecture rooms. The average area of the classrooms, occupancy density, the number of surveys and the number of participants in each room are summarized in Table 2. In Coventry, the survey was repeated 31 times in eleven lecture rooms, 12 times in nine studios and 17 times in nine PC labs and in Edinburgh, 31 times in eight lecture rooms.

Students in the lecture rooms and PC labs were involved in sedentary activities such as listening to the lecturer, and computer modelling during the measurements. However, in the studios, they were involved in activities such as creating mock ups, drawing and computer modelling. According to the classrooms' timetable at both universities and author's observation, the duration of each lecture was around 1 or 2 hours, including a fifteen-minute break in between, while, studio sessions took almost half a day with a couple of breaks in between. Metabolic rate was assumed to be 1.1 met [40] for the students in all classroom types based on their activity levels. Clothing values were evaluated using a checklist (provided in the questionnaire) including upper- and lower-body underwear and outwear items. Participants were asked to select the worn clothes at the survey time. The insulation value for each worn item was obtained from the introduced clo values in EN ISO 7730 [41], sum of which were considered as the total clothing insulation for each subject. The HVAC mode was selected based on the running mode within the survey period, (when students were filling in the questionnaires), regardless of the outdoor air temperature. In some cases, HVAC mode was changed by the occupants before the survey. For instance, HT mode was running at the beginning of the lecture while it changed to FR (or CL) in the middle or at the end of the lecture, (before the survey started); therefore, FR (or CL) mode was registered.

*Table 2*
*Summary of the investigated buildings*

| Location | Building | No. of participants | Classroom type | Mode | Average area ($m^2$) | No. of surveyed rooms | No. of survey repeat | Average occupancy density ($m^2$/person) |
|---|---|---|---|---|---|---|---|---|
| Coventry | B1 | 293 | Lecture room | FR | 100 | 2 | 2 | 2.5 |
| | | | Studio | FR | 150 | 4 | 4 | 5.0 |
| | B2 | 707 | Lecture room | CL, HT | 120 | 1 | 8 | 1.2 |
| | | | Studio | FR | 130 | 1 | 3 | 3.0 |
| | | | PC lab | CL, FR | 90 | 3 | 7 | 3.5 |
| | B3 | 900 | Lecture room | CL, FR, HT | 100 | 8 | 21 | 2.0 |
| | | | PC lab | CL, FR | 80 | 6 | 10 | 3.0 |
| | B4 | 147 | Studio | HT | 150 | 4 | 5 | 5.0 |
| Edinburgh | B5 | 382 | Lecture room | HT | 80 | 3 | 8 | 1.2 |
| | B6 | 155 | Lecture room | HT, FR | 80 | 1 | 4 | 1.2 |
| | B7 | 200 | Lecture room | HT | 120 | 1 | 4 | 1.2 |
| | B8 | 728 | Lecture room | HT, FR | 120 | 3 | 15 | 1.2 |

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

The thermal sensation votes (TSV) were examined based on the ASHRAE 7-point thermal sensation scale. A similar 7-point scale was used for thermal preferences (TP). Thermal acceptability and overall comfort were also assessed on 4 point scale, as Zhang's study [42] (Table 3).

Hard copy versions of the questionnaires were distributed in the last 15 minutes of each class, after the students had sat in the classrooms for at least 1 hour. It is mentioned in the previous studies that 15 minutes  was enough to eliminate the influence of metabolism on the thermal sensation votes [10,43]. However, in this study, 1 hour is considered for the safe margins of a settled metabolic rate and to minimise the disturbance of the class activity. All participants were asked to complete the questionnaires at the same time to make sure the recorded environmental variables corresponded to all the collected thermal sensation votes. Almost 10% of the students did not provide responses, but overall, 3,511 students (1,247 in lecture rooms, 408 in studios and 391 in PC labs) participated in Coventry. 1,406 questionnaires were collected in lecture rooms in Edinburgh. Participants in both locations were of both genders with an average age of 22 years old.

*Table 3*
*Thermal sensation, preference, comfort and acceptability scales*

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

### 2.4. Data analysis

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

As suggested by Humphreys et al. [30,44] and ASHRAE standard [40] thermal comfort zone was assumed as the range within which a subject feel thermally comfortable or satisfied, which was taken as the three central categories on the ASHRAE sensation scale. Thermal acceptable zone was considered as the temperature range in which 80% of the occupants voted for thermal sensations between −1 to 1 [30,44]. To identify the students' thermal comfort zone under each operation mode, Probit regression analysis was applied to the thermal sensation votes and operative temperatures. Probit analysis deals with binary responses to a variable. In the case of thermal sensation votes, the two responses are arranged as: 1) TSV between −1 to 1 (on the subjective ASHRAE seven-point scale) which is considered as "comfort zone" [30,40,45]; and 2) TSVs beyond the comfort zone (TSV= ±2 and ±3). This analysis was conducted by applying Probit regression as a link function and operative temperature as covariate [46]. To complete the process, all the equations were transformed to proportions in the CDF.NORMAL function using SPSS, statistical software package.

$$\text{Probability= CDF.NORMAL (quant, mean, SD)} \quad (2)$$

Where CDF.NORMAL is the cumulative distribution function, quant is the operative temperature (°C). Mean were calculated by dividing the constant value by the Probit regression coefficient; and standard deviation (SD) is the inverse of the regression coefficient in each equation [46].

Griffiths' method was applied to estimate comfort temperature in each classroom type under FR, CL and HT modes. This approach can calculate the comfort temperature for each single thermal sensation vote and temperature. It is useful for small temperature ranges where linear regression is unreliable [30]. Griffiths' method uses a standard value for the linear relationship between comfort vote and operative temperature: 'Griffiths slope' which is equivalent to the regression coefficient. This method assumes a constant rate of comfort temperature change per variation of thermal sensation scale by considering the sensation vote of 'neutral' as comfortable [30].

The comfort temperature was calculated using the following equation [47–49];

$$T_c = T_{op} + (0 - \mathrm{TSV}) / \alpha \quad (3)$$

Where $T_c$ is comfort temperature by Griffiths' method (°C), $T_{op}$ is operative temperature (°C), TSV is thermal sensation vote and α is Griffiths' constant ($K^{-1}$). Therefore, if the participants' thermal sensation vote is 0 (neutral), the comfort temperature would be the same as the operative temperature. Similar to previous studies conducted by Nicol et al. [48], Rijal et al. [50] and Mustapa et al. [20], three values for the Griffiths‘ constant (0.25, 0.33 and 0.50) were adopted to find the most reasonable comfort temperature.

## 3. Results and discussion

In the following sections, an overview of the indoor and outdoor environmental data and results from subjective evaluations are illustrated.

### 3.1. Outdoor and indoor environments

Figure 2 shows the outdoor air fluctuations in 2017 - 2018, and within the survey period in Coventry and Edinburgh. There is a higher temperature difference between these two locations during the summer compared to the winter months. Regarding the survey period, there is a minimum, average and maximum air temperature of 1°C, 7°C and 15°C in Coventry and 2°C, 6°C and 13°C in Edinburgh, respectively.

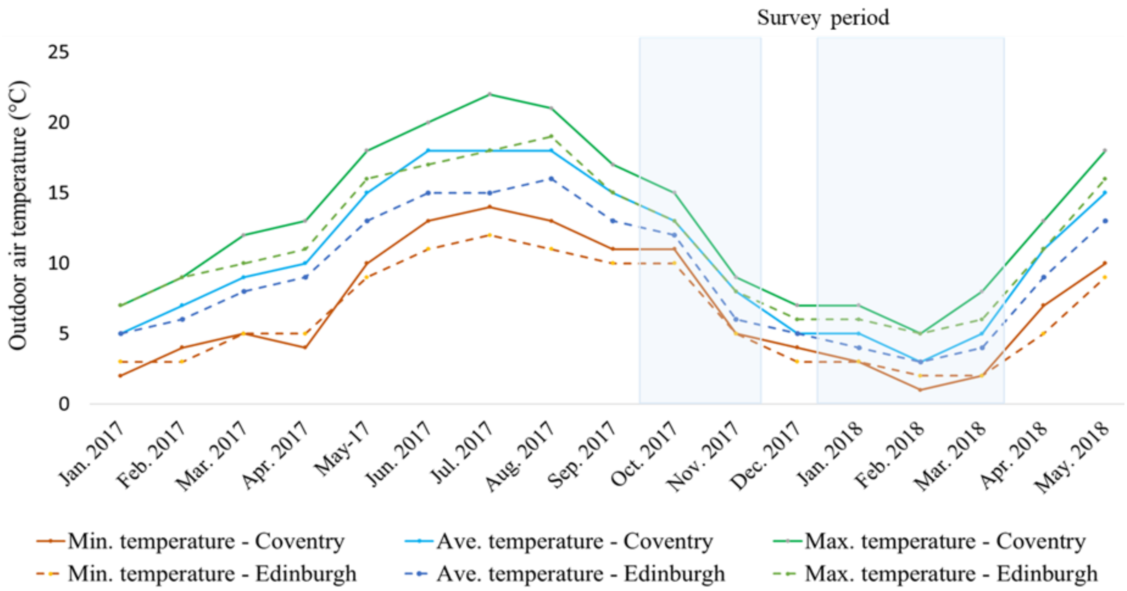



*Figure 2. Monthly mean outdoor air temperature in Coventry and Edinburgh, (source:* [36]*)*

Results for the indoor and outdoor environmental parameters are presented in Table 4. Mean indoor air temperature, mean radiant temperature and operative temperature (in the survey period) were approximately equal to 22.9°C, 22.6°C and 22.8°C in Coventry, respectively. These values (averaged over January to April 2018) changed to 21.7°C, 22.2°C and 22.0°C in Edinburgh.

***Table 4***
*Summary of the indoor and outdoor environmental parameters*

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

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

According to Table 4, the mean outdoor air temperature for FR mode in Coventry was higher than Edinburgh within the survey period. However, the indoor operative temperature in all the classroom types and operation modes in Edinburgh were higher than Coventry. The air velocity was low in both locations in all operation modes. The mean indoor relative humidity was 24% higher in Coventry than Edinburgh under free running mode, but it is almost in a similar range in both locations under HT mode.

Considering the classroom types and HVAC operation modes in Coventry, the mean operative temperature in the studios was 1°C higher than the lecture rooms under FR mode and 2°C under HT mode. In the PC labs, it was 1°C higher than the lecture rooms under both FR and CL modes. The operative temperature in all the classroom types was higher in Edinburgh than Coventry.

### 3.2. Subjective evaluation

Figure 3 indicates the relation between the clothing insulation values, and thermal sensation votes vs operative temperature binned at 0.5°C intervals in Coventry and Edinburgh. Very similar trend can be observed for mean TSVs and mean clothing insulation values in both locations.

(a) (b)

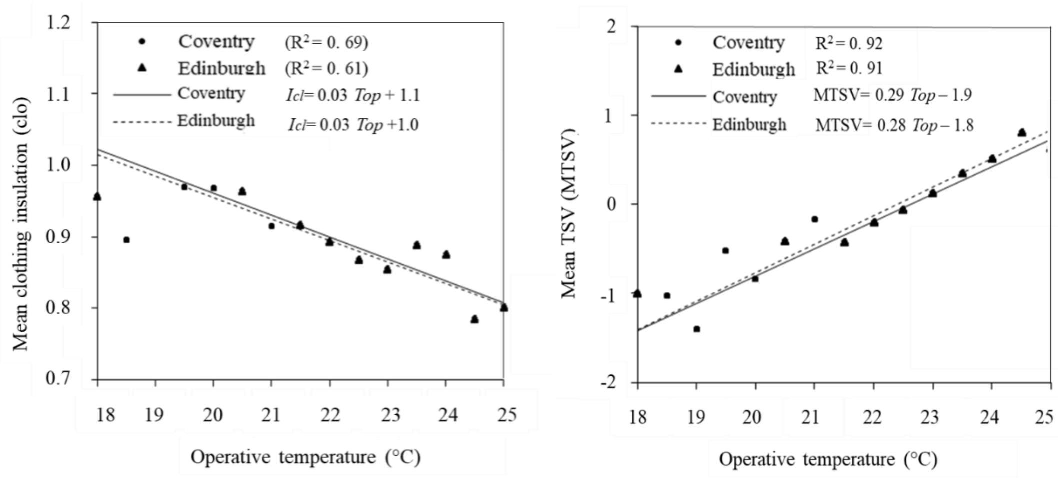



*Figure 3. Relation between: (a) mean clothing insulation and operative temperature, and (b) mean TSV and operative temperature*

Table 5 presents a summary of the mean value of the subjective parameters collected during the survey. The mean thermal sensation votes (MTSVs) in all classroom types in both locations tend to fell between ±0.5. The negative value of MTSV in the lecture rooms in Coventry (−0.26) indicates the cold thermal sensation of students in such spaces. However, the MTSV in the studios and PC labs were equal to 0.20 and 0.12, respectively showing that students felt warmer than neutral in these environments.

Considering all the modes, the mean values of the thermal preference votes in Coventry were approximately equal to 0.14, −0.2 and −0.05 in the lecture rooms, studios and PC labs, respectively. This shows the occupants' preferences towards a warmer thermal environment in lecture rooms and a cooler environment in studios and PC labs, which is consistent with their thermal sensation votes. The mean clothing value for all participants in all classroom types was in the range of 0.85 to 0.91 clo.

*__Table 5.__*
*Summary of subjective evaluations*

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

- : No data available, SD: standard deviation

Figure 4 shows the distribution of thermal sensation and thermal preference votes in Coventry and Edinburgh. TSVs are normally distributed centred in ‘neutral’ with a negligible shift toward colder votes in Coventry. However, there is a tendency towards the warmer side in Edinburgh, showing students’ warmer than neutral thermal sensations. As suggested by Fanger [45], Humphreys and Nicol [44,51], Nicol et al. [52] and ASHRAE standard [40], thermal sensation votes between −1 and 1 shows subject’s thermal satisfaction. Accordingly, in this study, approximately 78% and 80 % of the students in Edinburgh and Coventry, respectively, are thermally satisfied. This shows that the classrooms in Coventry, where the surveys were conducted, were already in the thermal acceptable zone [44,51,53]. In contrast, the classrooms in Edinburgh were slightly below this acceptability reference value. As expected, there was an opposite trend between students’ TSVs and TPs in both locations. Around 40 % of students in Edinburgh and Coventry voted for ‘0 no change’. 41 % of students in Edinburgh preferred to be cooler, while only 19% wanted a warmer environment. In Coventry, 27 % and 32 % of the participants preferred to be cooler and warmer, respectively.

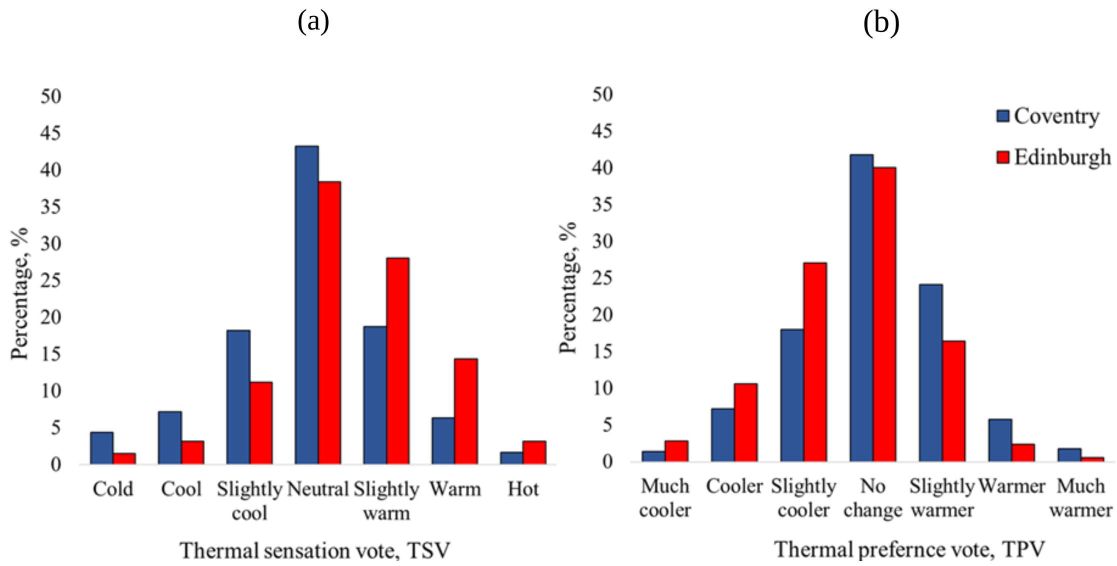



*Figure 4. Distribution of thermal sensation (a) and preference votes (b) in Edinburgh and Coventry*

According to Figure 5, the majority of the respondents with a TSV of ‘cold’ preferred to be ‘warmer’, but not ‘much warmer’. The highest proportion of students with a ‘cool’ TSV preferred to be ‘slightly warmer’, one scale unit lower than ‘warmer’. Also, the majority of the occupants with ‘hot’ and ‘warm’ TSVs wanted to be ‘cooler’ and ‘slightly cooler’, respectively. This shows that students mainly do not prefer extreme changes when dissatisfied to the warm or cold thermal environments. Occupants who felt warm or cold, with a TSV of 3, 2 or −3, −2, preferred to be 2, 1 or −2, −1, respectively, showing a one unit move toward ‘0 no change’ from the corresponding TSV value (Figure 4). However, the respondents with a TSV of ‘1 slightly warm’ or ‘−1 slightly cool’ preferred to be ‘1 slightly cooler’ and ‘−1 slightly warmer’, respectively. The existing inconsistency between TSVs of ±3 and ±2 and the same TPs can be a result of subjects’ various thermal preferences which does not necessarily match their neutrality. It is indicated in previous studies that people with non-neutral thermal sensations may prefer to be warmer or cooler not toward their neutrality [54,55]. For instance, people with warm thermal sensation votes, may still want to be warmer.

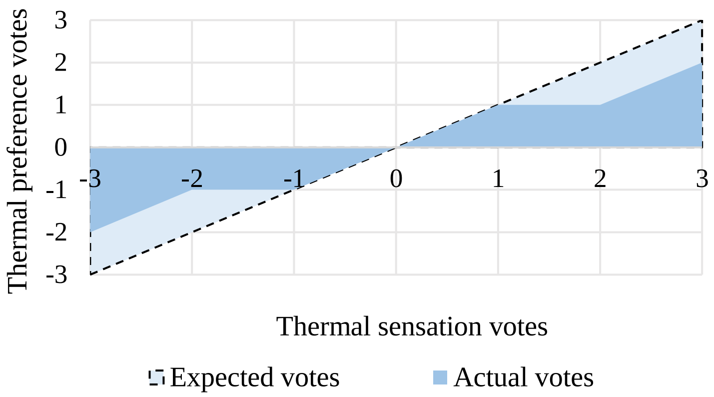



*Figure 5. Prevalent thermal preferences in each thermal sensation vote*

## 3.3. Comfort zone

Equations from Probit regression analysis (statistically significant, $p$ < 0.001) are presented in Table 6.

***Table 6.***
*Results of the Probit analysis*

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

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

In Figure 6 (a) and (b), each layer indicates the proportion of comfort votes equal to a particular vote (the lowest layer shows the actual proportion of vote –3) [30]. The mean neutral temperature, which can be identified with a probability of 0.5 in TSV between –1 and 1 is around 23°C in FR and HT modes and 24°C in CL mode in Coventry. In Edinburgh, it was around 22°C under both FR and HT modes. Figure 6 (c) indicate the optimal temperature at which the highest proportion of the occupants are thermally satisfied. In Coventry, this value is equal to 24°C under both FR and CL modes and 22°C under HT mode and in Edinburgh, 22°C under FR and HT modes. Considering the standard of minimum 80% acceptability as recommended in regulatory documents such as ASHRAE 55 [40], the comfort zone in Coventry is equal to 22-25°C under FR and CL and 21-24°C under HT mode and in Edinburgh, 21-24°C under HT mode (Figure 6, c).

### 3.4. Comfort temperature

Results regarding the comfort temperature (calculated by Griffiths' method) using three different constant values are presented in Table 7. A negligible difference is indicated between the obtained comfort temperatures. As the assumption behind Griffiths' method is no presence of occupants' thermal adaptation [30], the value of 0.5 for the Griffiths' constant (α) is considered in order to compensate the influence of thermal adaptation. This shows that each 2°C change in the operative temperature leads to 1 scale unit increase or decrease of the thermal sensation votes.

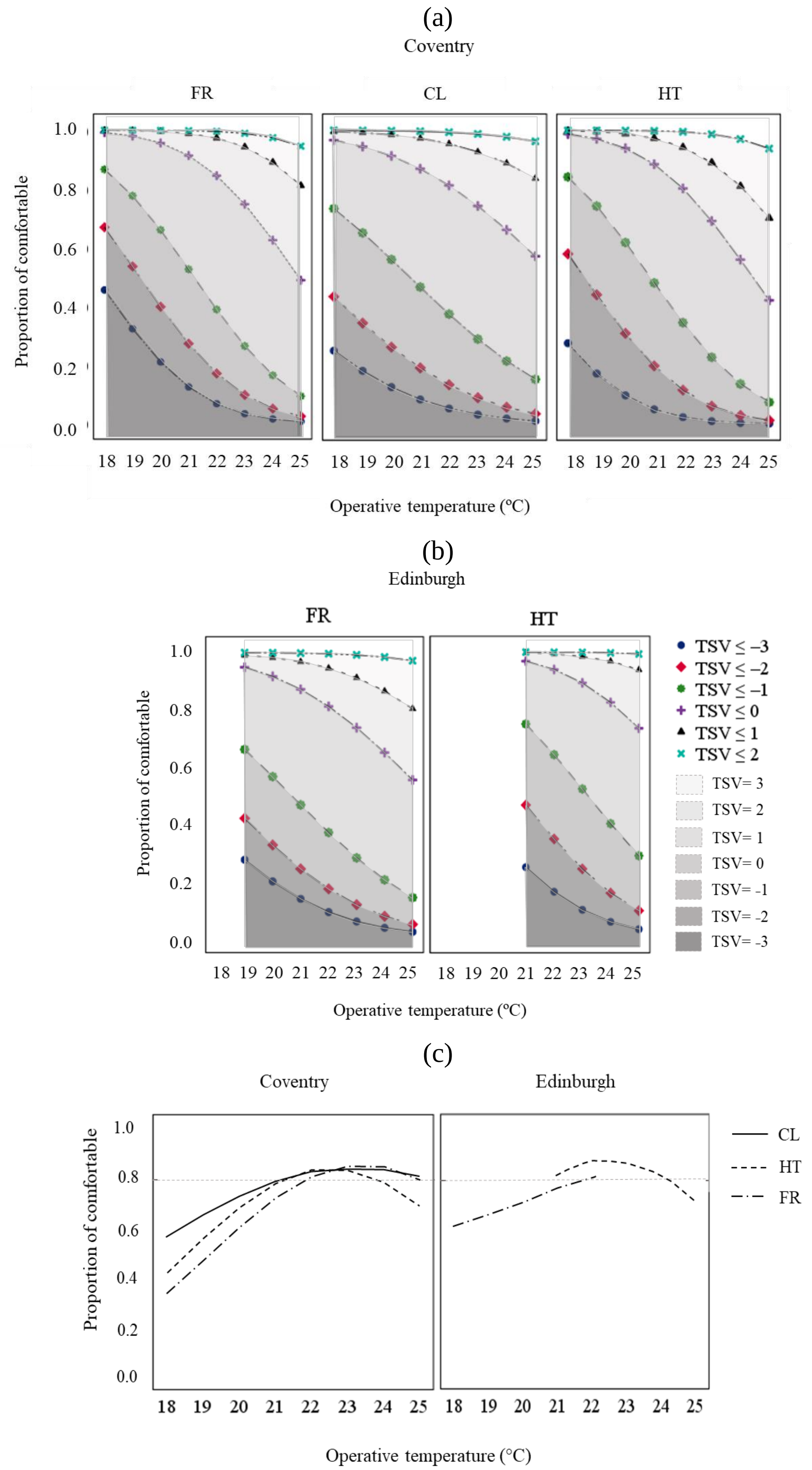



*Figure 6. Proportion of thermal sensation votes vs operative temperature (a,b) and proportion of comfortable vs operative temperature (c)*

*Table 7.*
*Comfort temperature estimated by Griffiths' method*

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

α: Griffiths' constant, SD: standard deviation

According to the Griffiths' method assumption, the comfort temperature was calculated for each data record. The mean of the comfort temperature in the lecture rooms was similar; 23°C in both Coventry and Edinburgh under FR mode, but Edinburgh has a 1°C higher comfort temperature than Coventry under HT mode (Figure 7).

Regarding the influence of diurnal cycle on thermal comfort perception, results show insignificant difference in the thermal sensation, preferences and comfort temperature zone of the students in the morning and afternoon classes.

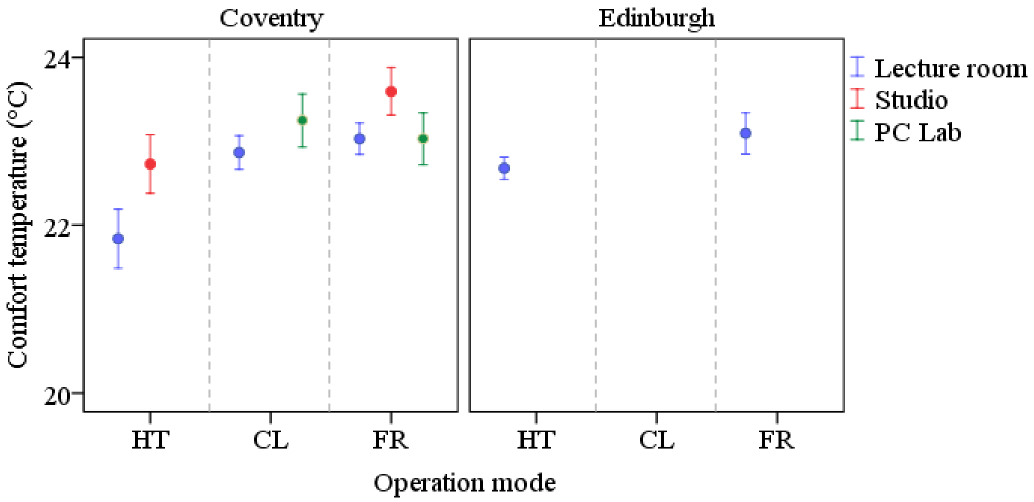



*Figure 7. Comfort temperature in the classrooms in each mode*

A one-way ANOVA test confirmed that there was no statistically significant difference between comfort temperatures in the lecture rooms and PC labs in Coventry. However, a statistically significant difference is illustrated between the comfort temperature in the studios and the other classroom types ($p < 0.05$). Comfort temperature was approximately 1°C higher in the studios compared to the lecture rooms and PC labs under FR and HT modes. Considering the warmer thermal sensation and cooler preference of the students in studios compared to the lecture rooms and PC labs (Table 5), this higher comfort temperature can be due to the higher operative temperature in studios than the other classroom types, followed by the students' physiological and psychological adaptation to the exposed thermal environment. Figure 8 indicates a direct association between mean comfort and operative temperature, in all classroom types showing an increase of the comfort temperature as a result of growth of the operative temperature. According to Table 4 and Table 7, proximity of the comfort temperature and prevailing operative temperatures is greater in studios compared to the other classroom types. Similar comfort and operative temperatures in studios can be explained by considering the occupants' physiological and psychological thermal adaptation to the studios as a result of two influential factors; thermal adaptation and students' control over the space:

1. *Thermal adaptation:* People physically adapt to a thermal environment to maintain a constant internal body temperature against environmental fluctuations. Long occupancy periods in the studios gives enough time for occupants' physiological and psychological thermal adaptation to the environment. From psychological point of view, occupants' thermal assessments during the initial occupancy in a space results from their thermal history, not the currently exposed thermal environment [25,54–56]. However, after extended period of occupancy, they change the set mental benchmark according to the experiencing indoor climatic condition [58]. Therefore, higher operative temperature along with the longer occupancy period in studios than the other classroom types leads to the occupants' warmer thermal adaptation and higher comfort temperature in studios than lecture rooms and PC labs.

2. *Control over the space:* due to the students' great freedom and consequently higher levels of control over the space in the studios, they can take proper environmental or personal adaptive behaviour to improve their physiological thermal adaptation and to maintain their thermal comfort. Psychologically, perception of control over an environment reduces the occupants' thermal sensitivity and improves their thermal comfort perceptions [34]. According to Brager et al. [59], the availability of control opportunities in an environment leads to proximity of the occupants' neutral temperature and the prevalent mean operative temperature. This obviously explained the similar comfort temperature to the operative temperature in the studios.

   Results in this section are supported by previous studies showing that optimal comfort and neutral temperature for occupants with a high level of environmental control is very close to the actual experiencing temperature [48,49]. It is also proved in the existing literature that control over a space leads to an improvement in the occupants' thermal comfort [27,52], neutral temperature [61] and thermal acceptability [48-52].

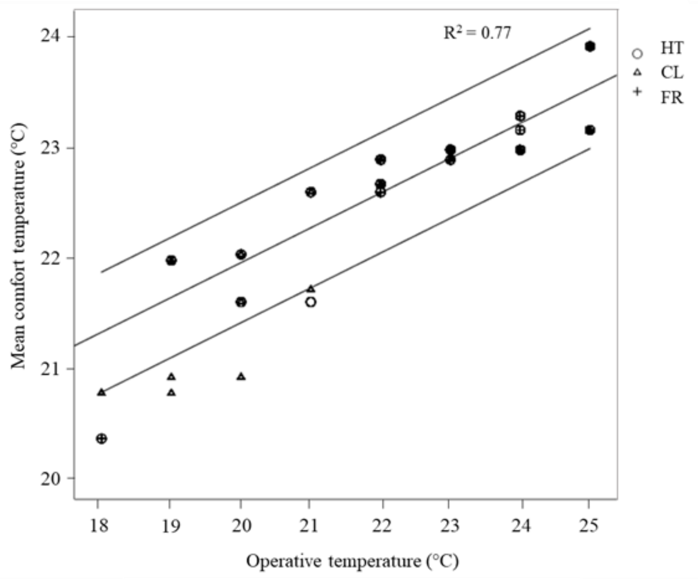



*Figure 8. Relation between indoor operative and comfort temperature under each operation mode*

### 3.4.1. Comparison of comfort temperature with other studies

Table 8 summarises the findings from other studies regarding the comfort temperatures in higher educational buildings. As there is no study of the studio type of classrooms in university buildings, comparison between the current and previous studies is mainly focused on the results from lecture rooms.

***Table 8.***
*Comparison of comfort temperature with previous studies in higher educational buildings*

| Ref. | Year | Location | Season | Analysis method | Sample size | $T_{out}$ (°C) | $T_{op}$ (°C) | $T_c$ (°C) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | FR | CL | HT |
| [62] | 2011 | China | Summer & winter | Linear regression | 206 | Summer:24.5-30<br>Winter: 2.5-12.5 | CL: 25.1<br>HT: 21.6 | | 26.8 | 20.7 |
| [22] | 2013-2014 | India | Autumn & spring | Griffiths' method | 357 | 14.5-32.5 | 29.8 | 29.5 | | |
| [63] | 2014 | China | Summer | Linear regression | 488 | 20.4-25 | 22.5 - 22.8 | | 22.6, 21.7 | |
| [17] | 2015 | Italy | Spring | Linear and Probit regression<br>Adaptive model<br>Rational model | 126 | 13.5-14.6 | 22.6 | 21.8 | | |
| [18] | 2016 | Netherland | Spring | Linear regression | 384 | 3.5-8 | 21.3 - 23.5 | | | 20- 24 |
| [20] | 2016 | Japan | Summer | Griffiths' method | 660 | 28-32 | 26.6 | | | |
| [19] | 2017 | Malaysia | Summer | Linear and Probit regression<br>Griffiths' method | 561 | 25.3-33.4 | 25.6 | | | |
| [19] | 2017 | Japan | Summer | Linear and Probit regression<br>Griffiths' method | 449 | 25.5 | CL: 25.5<br>FR: 25.3 | 25.1 | 26.2 | |
| [64] | 2019 | Singapore | | Linear regression & Griffiths' method | 1043 | 20-30 | 25 | | | |
| Current study | 2017-2018 | UK | Autumn, winter, summer | Probit regression<br>Griffiths' method | 3511 | Coventry: 1-15<br>Edinburgh : 2-13 | 23.4 | 23 | 22.9 | 22.3 |

The most outstanding feature in Table 8 is the proximity of the operative and comfort temperatures in all the mentioned studies, reinforcing the results from the current work. Students tend to feel comfortable in a thermal environment they have been exposed to for a period of time. This finding is also confirmed by other researchers [45,49,59,60], declaring that people's comfort temperatures are close to the mean temperatures they have experienced over a period of time. This confirms the influence of thermal adaptation on thermal comfort in classrooms. The comfort temperature obtained in this work is very close to studies conducted in European countries such as Italy [17] and the Netherlands [18]. The comfort temperature introduced in Italy [17], is equal to 21.8°C under FR mode, showing an almost

1°C lower comfort temperature than the UK. Also, the comfort temperature of 22°C and the comfort zone of 21–25°C in lecture rooms under HT mode in the UK is close to the comfort temperature range in the Netherlands, 22–24°C [18], with wider range in the UK than the Netherland showing approximately similar thermal comfort for students in both locations under HT mode. However, a higher comfort temperature compared to the UK is illustrated in other studies conducted in warm and tropical climates such as Malaysia, Singapore, Japan and India [19,20,23,46]. Higher operative temperatures and occupants' warmer thermal adaptation and expectations can be the main reasons for the distinctions between these countries and the UK.

### 3.5. Preferred adaptive behaviour for thermal comfort

#### 3.5.1. Priorities of personal and environmental behaviours

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

Results in Figure 9 show that adjusting clothing and operating windows were the most common actions among students in both uncomfortably warm and cold conditions. In uncomfortably warm thermal condition, nearly half of the students in both lecture rooms (48 %) and PC labs (47 %) preferred to adopt personal behaviours (adjust clothing) to restore their thermal comfort, whereas half of the students in the studios (48 %) preferred to adopt an environmental behaviour (operating windows) before any personal action. This indicates students' priorities for personal behaviours before environmental actions in lecture rooms and PC labs. However, they preferred environmental behaviours in the studios.

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

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

It should be noted that even if the HVAC control point is accessible, the majority of students in all the classrooms in uncomfortably cold thermal conditions were expected to prefer adjusting clothing first, operating windows second and changing the HVAC set point third. Operating windows was not the first priority as windows are rarely open in cold thermal conditions. Even if there are open windows, operating them cannot improve thermal comfort in cold conditions as it does in uncomfortably warm environments. Heating systems, either through supplier ducts or radiators, were also not a main priority, as mentioned above. As a result, the easiest option may be adjusting clothing to gain comfort in thermally cold conditions. Common personal adaptive behaviours in lecture rooms can be another reason for the wider comfort zone in such spaces compared to the studios. According to the existing literature [59], personal behaviour provides a high level of thermal comfort for occupants in an environment. Occupants tend to change the thermal conditions in different patterns which can differ from person to person. It may be difficult to provide a comfortable and satisfactory thermal environment for all the occupants. Therefore, individual control, in comparison to centrally controlled systems, leads to far greater thermal comfort [58,66]. Environmental behaviours such as opening/closing windows and doors or operating HVAC in lecture rooms may thermally satisfy one group of occupants but may cause thermal discomfort for the others. Personal behaviours such as adjusting clothing, changing position, etc. provides comfort conditions for each student based on their own preferences.

### 3.5.2. Comparison of adaptive behaviour with other studies

The results in this section are supported by previous studies showing the influence of occupants' freedom levels on preferred adaptive behaviours. Results from the study conducted in the university buildings showed that students usually prefer personal adaptive behaviours before environmental actions in classrooms [4,18,59,61,63]. Adjusting clothing is the first preferred behaviour by occupants in university buildings in China [59,63], with a mean indoor air temperature of 22°C and 30°C.

Drinking a beverage has priority in Japanese universities with a mean indoor air temperature of 25°C and 27°C [4,18,61]. Likewise, employees in mixed mode office buildings in the UK prefer personal adaptive behaviours before any environmental actions in thermally uncomfortable conditions, with a mean indoor air temperature of 22°C [34]. Among the environmental behaviours, HVAC operation was preferred by occupants in higher educational spaces in the hot climates of Malaysia [19] and Indonesia [67] with mean indoor air temperatures of 27°C and 30°C, respectively. Operating windows is also the most common action in a school building in Taiwan with a mean indoor air temperature of 35°C [68].

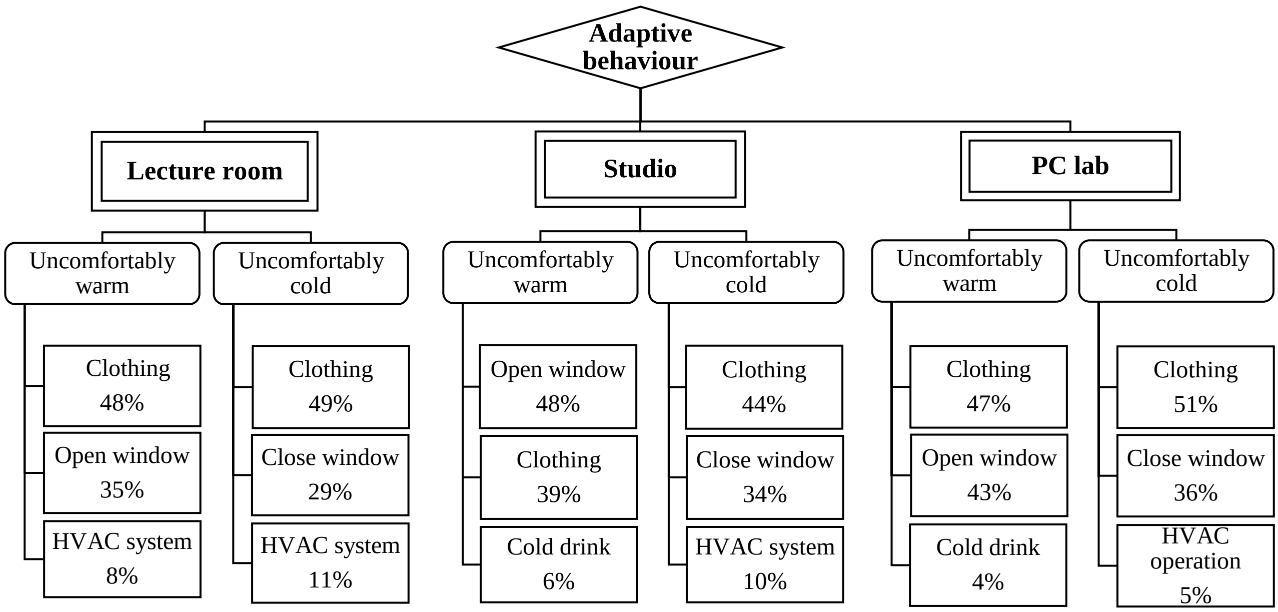



*Figure 9. Priority of students for adaptive behaviour in uncomfortably warm or cold environment*

In contrast, studies conducted in residential buildings in the hot climate of Indonesia [66,69] and the warm and tropical climate of Singapore [33]**,** with a mean indoor air temperature of 27°C and 29°C, respectively, evidence that people usually prefer to gain comfort through environmental actions before any personal adjustments. Creating higher air movement through applying air conditioning systems, fans and opening windows are the most preferred actions during the day in residential buildings in both locations [66,69].

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

A main reason for this can be that in public spaces like classrooms and offices, occupants may not feel fully allowed to change the thermal environment as these changes could cause thermal discomfort for the others. Limited access to environmental opportunities like windows or HVAC systems for some of the occupants and low levels of freedom to adjust the thermal environment are other reasons why personal behaviour is more preferred in such spaces. Nevertheless, the influence of climatic condition and indoor air temperature on the selection of adaptive behaviours should not be overlooked. As mentioned above, in educational buildings with indoor air temperatures between 22°C and 30°C, personal behaviours are preferred over environmental ones [19,20,67,70,71], while in extreme conditions with indoor air temperatures from 27°C to 35°C, environmental actions are more common [4,61,72]. In other words, in extreme thermal conditions, environmental behaviours are more preferred because the personal adjustments may not properly provide comfort for the occupants [73]. Such information on the prediction of occupants' adaptive behaviours helps to provide the proper adaptive opportunities in teaching and learning spaces, which not only provides the subjects with thermal comfort, but also helps to save energy and minimise the buildings' running costs.

## 4. Conclusions

This study evaluates thermal comfort in higher learning environments in two climates within the UK (Coventry and Edinburgh) through environmental measurements, questionnaire surveys and observations. In total, 3,511 undergraduate and postgraduate students in art and science- based subjects participated in this study whilst in lecture rooms, studios and PC labs. The output of this work shows that the same thermal environment is not required in all operation modes or in all classroom types as the occupants' activities and exposure duration to each classroom differs one from the other. Comfort temperature is shown to be approximately 2ºC lower under HT mode compared to the FR and CL modes, which suggests 2ºC decrease of the indoor air temperature set point under HT mode.

In terms of classroom type, comfort temperature is shown to be around 23ºC in studios and 22ºC in lecture rooms under HT mode, therefore, 1ºC lower indoor air temperature can be set in the lecture rooms than studios.

According to Humphreys et al. [30], in the UK, reduction of the indoor air temperature for only 1ºC can save 10% of energy used for heating purposes. Considering the number of campuses and learning environments in higher educational buildings, 10% reduction of energy consumption in each building can lead to a considerable energy saving in this sector.

Thus, it should be considered that providing the same thermal environment in all classroom types, not only causes overheating/overcooling and students' discomfort, but also leads to waste of energy and related emissions in higher educational buildings.

We have also summarized the key findings as follows:

- In terms of thermal sensation votes (TSV) and thermal preferences (TP), respondents do not prefer extreme changes in uncomfortably warm or cold thermal environments. Occupants with a TSV of 3, 2 or −3, −2, preferred to be 2, 1 or −2, −1, respectively, showing a one unit move toward '0 no change' from the corresponding TSV value. However, students with a TSV of '1 slightly warm' or '−1 slightly cool' prefer to be '−1 slightly cooler' and '1 slightly warmer', respectively.
- Considering the standard of a minimum 80% acceptability as recommended in regulatory documents, the thermal comfort zone evaluated by Probit regression analysis is wider in lecture rooms than in studios and PC labs. The apparent reason for this is due to students' wider exposure to temperature ranges in lecture rooms than in studios and PC labs and students' preferences for personal behaviours in lecture rooms.

- Comfort temperature calculated by Griffiths' method tends to be 1°C higher in studios than lecture rooms and PC labs in Coventry. Comfort temperature in lecture rooms is similar (23°C) in Coventry and Edinburgh under free-running (FR) mode, but there is a 1°C higher comfort temperature in Edinburgh than Coventry under heating (HT) mode.
- There is a very close and linear relationship between comfort and operative temperatures in studios and PC labs. This shows the occupants' thermal adaptation to their thermal environments as a result of long occupancy periods and high levels of freedom/control over the space.

In terms of adaptive behaviour, students' priorities differ in lecture rooms, studios and PC labs as a result of different freedom levels in such spaces. The majority of occupants in lecture rooms prefer personal adaptive behaviours before environmental ones. However, in studios and PC labs, they prefer environmental behaviours before the personal ones.It should also be noted that the findings in this study are limited to the mean outdoor air temperatures 5°C to 16°C in the UK under which access to the heating systems (along with the air conditioning) were available for the occupants. It was targeted to collect data in both academic semesters (September-December and January-March) in higher learning environments to cover the thermal comfort of the occupants in such spaces in both semesters.

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## References


[1] T.P. Agreement, ed., United Nations climate change, (2015).

[2] S. Barbhuiya, S. Barbhuiya, Thermal comfort and energy consumption in a UK educational building, Build. Environ. 68 (2013) 1–11. doi:10.1016/j.buildenv.2013.06.002.

[3] M.J. Mendell, G.A. Heath, Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature, Indoor Air. 15 (2005) 27–52. doi:10.1111/j.1600-0668.2004.00320.x.

[4] P. Ricciardi, C. Buratti, Environmental quality of university classrooms: Subjective and objective evaluation of the thermal, acoustic, and lighting comfort conditions, Build. Environ. 127 (2018) 23–36. doi:10.1016/j.buildenv.2017.10.030.

[5] U. Haverinen-Shaughnessy, R.J. Shaughnessy, E.C. Cole, O. Toyinbo, D.J. Moschandreas, An assessment of indoor environmental quality in schools and its association with health and performance, Build. Environ. 93 (2015) 35–40. doi:10.1016/j.buildenv.2015.03.006.

[6] W. Zeiler, G. Boxem, Effects of thermal activated building systems in schools on thermal comfort in winter, Build. Environ. 44 (2009) 2308–2317. doi:10.1016/j.buildenv.2009.05.005.

[7] H. Levin, Physical factors in the indoor environment, Occup. Med. 10 (1995) 59–94.

[8] S. Ter Mors, J.L.M. Hensen, M.G.L.C. Loomans, A.C. Boerstra, Adaptive thermal comfort in primary school classrooms: Creating and validating PMV-based comfort charts, Build. Environ. 46 (2011) 2454–2461. doi:10.1016/j.buildenv.2011.05.025.

[9] A. Montazami, F. M. Gaterell, M. Nicol, M. Lumley, C. Thoua, Developing an algorithm to illustrate the likelihood of the dissatisfaction rate with relation to the indoor temperature in naturally ventilated classrooms, Build. Environ. 111 (2017) 61–71. doi:doi.org/10.1016/j.buildenv.2016.10.009.

[10] D. Teli, M.F. Jentsch, P.A.B. James, Naturally ventilated classrooms: An assessment of existing comfort models for predicting the thermal sensation and preference of primary school children, Energy Build. 53 (2012) 166–182. doi:10.1016/j.enbuild.2012.06.022.

[11] V. De Giuli, O. Da Pos, M. De Carli, Indoor environmental quality and pupil perception in Italian primary schools, Build. Environ. 56 (2012) 335–345. doi:10.1016/j.buildenv.2012.03.024.

[12] H. Liang, T. Lin, R. Hwang, Linking occupants' thermal perception and building thermal performance in naturally ventilated school buildings, Appl. Energy. 94 (2012) 355–363. doi:10.1016/j.apenergy.2012.02.004.

[13] S.P. Corgnati, R. Ansaldi, M. Filippi, Thermal comfort in Italian classrooms under free running conditions during mid seasons: Assessment through objective and subjective approaches, Build. Environ. 44 (2009) 785–792. doi:10.1016/j.buildenv.2008.05.023.

[14] F. Ambrosio Alfano, E. Ianniello, B. Palella, PMV–PPD and acceptability in naturally ventilated schools, Build. Environ. 67 (2013) 129–137. doi:10.1016/j.buildenv.2013.05.013.

[15] L. Dias Pereira, D. Raimondo, S.P. Corgnati, M. Gameiro Da Silva, Assessment of indoor air quality and thermal comfort in Portuguese secondary classrooms: Methodology and results, Build. Environ. 81 (2014) 69–80. doi:10.1016/j.buildenv.2014.06.008.

[16] M.C. Katafygiotou, D.K. Serghides, Thermal comfort of a typical secondary school building in Cyprus, Sustain. Cities Soc. 13 (2014) 303–312.

doi:10.1016/j.scs.2014.03.004.
[17] M.A. Nico, S. Liuzzi, P. Stefanizzi, Evaluation of thermal comfort in university classrooms through objective approach and subjective preference analysis, Appl. Ergon. 48 (2015) 111–120. doi:10.1016/j.apergo.2014.11.013.
[18] A.K. Mishra, M.T.H. Derks, L. Kooi, M.G.L.C. Loomans, H.S.M. Kort, Analysing thermal comfort perception of students through the class hour, during heating season, in a university classroom, Build. Environ. 125 (2017) 464–474. doi:10.1016/j.buildenv.2017.09.016.
[19] S.A. Zaki, S.A. Damiati, H.B. Rijal, A. Hagishima, A. Abd Razak, Adaptive thermal comfort in university classrooms in Malaysia and Japan, Build. Environ. 122 (2017) 294–306. doi:10.1016/j.buildenv.2017.06.016.
[20] M.S. Mustapa, S.A. Zaki, H.B. Rijal, A. Hagishima, M.S.M. Ali, Thermal comfort and occupant adaptive behaviour in Japanese university buildings with free running and cooling mode offices during summer, Build. Environ. 105 (2016) 332–342. doi:10.1016/j.buildenv.2016.06.014.
[21] C. Cândido, R. de Dear, R. Lamberts, Combined thermal acceptability and air movement assessments in a hot humid climate, Build. Environ. 46 (2011) 379–385. doi:10.1016/j.buildenv.2010.07.032.
[22] A.K. Mishra, M. Ramgopal, A thermal comfort field study of naturally ventilated classrooms in Kharagpur, India, Build. Environ. 92 (2015) 396–406. doi:10.1016/j.buildenv.2015.05.024.
[23] M.K. Singh, S. Kumar, R. Ooka, H.B. Rijal, G. Gupta, A. Kumar, Status of thermal comfort in naturally ventilated classrooms during the summer season in the composite climate of India, Build. Environ. 128 (2018) 287–304. doi:10.1016/j.buildenv.2017.11.031.
[24] R. Lawrence, C. Keime, Bridging the gap between energy and comfort: Post-occupancy evaluation of two higher-education buildings in Sheffield, Energy Build. 130 (2016) 651–666. doi:10.1016/j.enbuild.2016.09.001.
[25] G.A. Vargas, F. Stevenson, Thermal Memory and Transition in Lobby Spaces, Energy Procedia. 62 (2014) 502–511. doi:10.1016/j.egypro.2014.12.412.
[26] G. Vargas, R. Lawrence, F. Stevenson, The role of lobbies: short-term thermal transitions, Build. Res. Inf. 45 (2017) 759–782. doi:10.1080/09613218.2017.1304095.
[27] CIBSE Guide A: Environmental Design, 7th ed., CIBSE, London, 2010. doi:10.1016/b978-0-240-81224-3.00016-9.
[28] ANSI/ASHRAE standard 55: thermal environmental conditions for human occupancy, American Society of Heating, Refrigerating and Air- Conditioning Engineers, Atlanta, 2010. http://library.hartford.edu/eres/reserves/Haggan/ANSI_ASHRAE/ASHRAE-D-86150.
[29] EN ISO 7730: Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, European committee for standardization, Brussels, 2005. doi:10.1016/j.soildyn.2004.11.005.
[30] F. Nicol, M. Humphreys, S. Roaf, Adaptive thermal comfort: principles and practice, 1st ed., Earthscan, Abingdon, Oxon, 2012.
[31] I.A. Raja, J.F. Nicol, K.J. McCartney, M.A. Humphreys, Thermal comfort: Use of controls in naturally ventilated buildings, Energy Build. 33 (2001) 235–244. doi:10.1016/S0378-7788(00)00087-6.
[32] H. Feriadi, N.H. Wong, Thermal comfort for naturally ventilated houses in Indonesia, Energy Build. 36 (2004) 614–626. doi:10.1016/j.enbuild.2004.01.011.
[33] N.H. Wong, H. Feriadi, P.Y. Lim, K.W. Tham, C. Sekhar, K.W. Cheong, Thermal

comfort evaluation of naturally ventilated public housing in Singapore, Build. Environ. 37 (2002) 1267–1277. doi:10.1016/S0360-1323(01)00103-2.
[34] J. Liu, R. Yao, R. McCloy, An investigation of thermal comfort adaptation behaviour in office buildings in the UK, Indoor Built Environ. 23 (2014) 675–691. doi:10.1177/1420326X13481048.
[35] P. O’Paul, Patterns and trends in UK higher education, Focus Univ. UK. (2018).
[36] Weather Observation Website, WOW Met Office, 2016-2018. (n.d.). http://wow.metoffice.gov.uk/ (accessed April 8, 2019).
[37] G. Brager, S. Borgeson, Y. Lee, Control strategies for mixed-mode buildings, University of California, Berkeley, California, 2007.
[38] Universal instrument, SWEMA 3000. (n.d.). https://www.swema.com/instrument.php?p=Swema 3000&k=Universal (accessed August 28, 2019).
[39] EN ISO 7726: Ergonomics of the thermal environment — Instruments for measuring physical quantities, 2001. doi:10.3403/02509505.
[40] ANSI/ASHRAE standard 55: Thermal environmental conditions for human occupancy, ASHRAE, Atlanta, 2017.
[41] EN ISO 7730: Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, European committee for standardization, Brussels, 2005.
[42] Y.F. Zhang, D.P. Wyon, L. Fang, A.K. Melikov, The influence of heated or cooled seats on the acceptable ambient temperature range, Ergonomics. 50 (2007) 586–600. doi:10.1080/00140130601154921.
[43] T. Goto, J. Toftum, R. de Dear, P.O. Fanger, Thermal sensation and comfort with transient metabolic rates, Proc, Indoor Air. (2000) 1038–1043.
[44] M. Humphreys, F. Nicol, S. Roaf, Adaptive Thermal Comfort: Foundations and Analysis Principles and practice, Routledge, Taylor & Francis group, London and New York, 2015. doi:10.4324/9781315765815.
[45] P.O. Fanger, Analysis and Applications in Environmental Engineering, Danish Technical Press, 1970.
[46] H.B. Rijal, M. Humphreys, J.F. Nicol, Towards an adaptive model for thermal comfort in Japanese offices, Build. Res. Inf. 45 (2017) 717–729. doi:10.1080/09613218.2017.1288450.
[47] I.D. Griffiths, Thermal Comfort in Buildings with Passive Solar Features: Field Studies, Commission of the European Communities, Guildford, 1991.
[48] F. Nicol, G.N. Jamy, O. Sykes, M. Humphreys, S. Roaf, M. Hancock, A survey of thermal comfort in Pakistan toward new indoor temperature standards, School of Architecture, Oxford Brookes University, Oxford, United kingdom, 1994.
[49] H.B. Rijal, P.G. Tuohy, M. Humphreys, F. Nicol, A. Samuel, J. Clarke, I. Raja, Development of adaptive algorithms for the operation of windows, fans and doors to predict thermal comfort and energy use in Pakistani buildings, ASHRAE Trans. 114 (2008) 555–573. doi:10.1016/j.buildenv.2006.10.027.
[50] H.B. Rijal, H. Yoshida, N. Umemiya, Seasonal and regional differences in neutral temperatures in Nepalese traditional vernacular houses, Build. Environ. 45 (2010) 2743–2753. doi:10.1016/j.buildenv.2010.06.002.
[51] M. Humphreys, J.F. Nicol, An investigation into the thermal comfort of office workers, Inst. Heat. Vent. Eng. J. 38 (1970) 181–189.
[52] J.F. Nicol, I.A. Raja, A. Allaudin, G.N. Jamy, Climatic variations in comfortable temperatures: The Pakistan projects, Energy Build. 30 (1999) 261–279.

doi:10.1016/S0378-7788(99)00011-0.
[53] ANSI/ASHRAE Standards No.55-2013. Thermal Environmental Conditions for Human Occupancy, 2013. doi:10.1007/s11926-011-0203-9.
[54] S. Shahzad, H.B. Rijal, Preferred vs neutral temperatures and their implications on thermal comfort and energy use: Workplaces in Japan, Norway and the UK, in: Energy Procedia, 2019. doi:10.1016/j.egypro.2019.01.1007.
[55] M.A. Humphreys, M. Hancock, Do people like to feel “neutral”?. Exploring the variation of the desired thermal sensation on the ASHRAE scale, Energy Build. 39 (2007) 867–874. doi:10.1016/j.enbuild.2007.02.014.
[56] M. Jowkar, R. de Dear, J. Brusey, Influence of long-term thermal history on thermal comfort and preference, Energy Build. online (2019) 109685. doi:10.1016/j.enbuild.2019.109685.
[57] M. Jowkar, A. Montazami, Thermal comfort in the UK higher educational buildings: the influence of thermal history on students’ thermal comfort, in: Wind. Conf., Windsor, UK, 2018.
[58] M.O. Fadeyi, Initial study on the impact of thermal history on building occupants’ thermal assessments in actual air-conditioned office buildings, Build. Environ. 80 (2014) 36–47. doi:10.1016/j.buildenv.2014.05.018.
[59] G. Brager, G. Paliaga, R. de Dear, Operable windows, personal control, and occupant comfort, ASHRAE Trans. 110 (2004) 17–35.
[60] W. Ji, B. Cao, M. Luo, Y. Zhu, Influence of short-term thermal experience on thermal comfort evaluations: A climate chamber experiment, Build. Environ. 114 (2017) 246–256. doi:10.1016/j.buildenv.2016.12.021.
[61] L. Zagreus, C. Huizenga, E. Arens, D. Lehrer, Listening to the occupants: a Web-based indoor environmental quality survey, Indoor Air. 14 Suppl 8 (2004) 65–74.
[62] B. Cao, Y. Zhu, Q. Ouyang, X. Zhou, L. Huang, Field study of human thermal comfort and thermal adaptability during the summer and winter in Beijing, Energy Build. 43 (2011) 1051–1056. doi:10.1016/j.enbuild.2010.09.025.
[63] Z. Wang, A. Li, J. Ren, Y. He, Thermal adaptation and thermal environment in university classrooms and offices in Harbin, Energy Build. 77 (2014) 192–196. doi:10.1016/j.enbuild.2014.03.054.
[64] S.S.Y. Lau, J. Zhang, Y. Tao, A comparative study of thermal comfort in learning spaces using three different ventilation strategies on a tropical university campus, Build. Environ. 148 (2019) 579–599. doi:10.1016/j.buildenv.2018.11.032.
[65] M.K. Singh, R. Ooka, A. Kumar, H.B. Rijal, S. Kumar, S. Mahapatra, Progress in thermal comfort studies in classrooms over last 50 years and way forward, Energy Build. 188–189 (2019) 149–174. doi:10.1016/j.enbuild.2019.01.051.
[66] C. Huizenga, S. Abbaszadeh, L. Zagreus, E. A., Air quality and thermal comfort in office buildings: results of a large indoor environmental quality survey, in: Heal. Build., Lisbon, 2006: pp. 393–397. doi:10.12659/PJR.894050.
[67] S.A. Damiati, S.A. Zaki, H.B. Rijal, S. Wonorahardjo, Field study on adaptive thermal comfort in office buildings in Malaysia, Indonesia, Singapore, and Japan during hot and humid season, Build. Environ. 109 (2016) 208–223. doi:10.1016/j.buildenv.2016.09.024.
[68] C.P. Chen, R.L. Hwang, W.M. Shih, Effect of fee-for-service air-conditioning management in balancing thermal comfort and energy usage, Int. J. Biometeorol. 58 (2014) 1941–1950. doi:10.1007/s00484-014-0796-6.
[69] Q. Tao, Z. Li, Field study and adaptive equation of thermal comfort in university classrooms in the Subtropics in Winter, in: Proc. 8th Int. Symp. Heating, Vent. Air Cond. , Springer, Berlin, Heidelberg, 2014: pp. 121–129. doi:10.1007/978-3-642-

39584-0_14.
[70] R. Yao, J. Liu, B. Li, Occupants' adaptive responses and perception of thermal environment in naturally conditioned university classrooms, Appl. Energy. 87 (2010) 1015–1022. doi:10.1016/j.apenergy.2009.09.028.
[71] Y. Zhang, J. Wang, H. Chen, J. Zhang, Q. Meng, Thermal comfort in naturally ventilated buildings in hot-humid area of China, Build. Environ. 45 (2010) 2562–2570. doi:10.1016/j.buildenv.2010.05.024.
[72] F.S. Bauman, T.G. Carter, A. V. Baughman, E.A. Arens, Field study of the impact of a desktop task/ambient conditioning system in office buildings, in: ASHRAE Trans., 1998: pp. 1–19. doi:10.1016/j.enbuild.2013.06.009.Keywords.
[73] M. Frontczak, P. Wargocki, Literature survey on how different factors influence human comfort in indoor environments, Build. Environ. 46 (2011) 922–937. doi:10.1016/j.buildenv.2010.10.021.

## *Survey questionnaire*

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

**1) Are you…**

◯ Female ◯ Male ◯ Other ◯ Do not wish to specify

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

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

**3) Please write down the country and the city in which you are mainly living at the moment.**

Country ………………….. City …………………….

**4) How long have you been living in the UK?**

◯ < 1 year ◯ 1 – 3 years ◯ > 3 years

**5) Please write down the country and city in which you were mainly living before moving to Portsmouth.**

Country ………………….. City …………………….

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

Country ………………….. City …………………….

**7) How do you describe the climate condition of your hometown compared to Portsmouth's weather?**

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

**8) At your home before moving to Portsmouth** (if you are from Portsmouth, please answer this question based on your family home ther condition)**,**

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

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

My accommodation is:

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

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

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

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

In **warm** condition

First
Second
Third

In **cold** condition

First
Second
Third

**12) How do you feel right now?**

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

**13) Do you find this…?**

○ Comfortable ○ Slightly uncomfortable ○ Uncomfortable ○ Very uncomfortable

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

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

**15) At this moment, do you find this climatic environment …?**

○ Clearly acceptable ○ Just acceptable ○ Just unacceptable ○ Clearly unacceptable

**16) Please tick the circle for each item of clothing that you are wearing <u>right now</u>.**

Example


**Any additional comments?**

……………………………………………………....

*Thank you for taking part in this study*