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Article

Thermal Perception in Naturally Ventilated University Buildings in Spain during the Cold Season

Antonio J. Aguilar [1], María L. de la Hoz-Torres [2,*], María Dolores Martínez-Aires [2] and Diego P. Ruiz [1]

[1] Department of Applied Physics, University of Granada, Av. Severo Ochoa s/n, 18071 Granada, Spain; antojes@ugr.es (A.J.A.); druiz@ugr.es (D.P.R.)
[2] Department of Building Construction, University of Granada, Av. Severo Ochoa s/n, 18071 Granada, Spain; aires@ugr.es
* Correspondence: mlhoz@ugr.es

Abstract: The indoor thermal environment has become a critical factor, due to its impact on the energy efficiency of a building and the health and performance of its occupants. It is particularly important for educational buildings, where students and teachers are exposed to these thermal conditions. This study assessed the impact of natural ventilation efficiency and university students' thermal perception during the cold season. A field monitoring campaign and a questionnaire survey were conducted. A total of 989 students participated in this study. The results show that, although the CO_2 concentration in 90% of the evaluated classrooms was below the European recommended value (i.e., 800 ppm), only 18% of the classrooms were within the thermal comfort zone defined by national regulations. These thermal conditions caused 55% of the students surveyed to report that they were dissatisfied, and that this environment interfered with their academic performance. Significant differences were found between thermal sensation votes from female and male students ($p < 0.001$). The obtained neutral temperature was one degree higher for female students than for males. Our results suggest that ventilation protocols need to be modified by adjusting the window opening strategy, and these findings should be used as guidelines during their redesign.

Keywords: building; IEQ; monitoring; natural ventilation; thermal comfort

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1. Introduction

The indoor environmental quality (IEQ) is one of the many factors that influence occupants' satisfaction. A good value of IEQ is crucial, as it not only affects the building's energy efficiency and energy consumption [1–3], but also the health and emotions of the building' occupants [4]. This is of particular importance in educational buildings, where students, teachers and other staff spend long periods of the day. Previous studies have highlighted that students' concentration and learning abilities may be negatively affected by a poor IEQ [5–7], and health problems may even be created or worsened [8]. However, the management of indoor environmental conditions in educational buildings in Europe is different from that in other types of buildings (e.g., offices or residential buildings) due to their characteristics; for example, the high occupant density in classrooms (three to four times higher than in residential or commercial buildings [9]), and the fact that indoor air is renewed by natural ventilation [10].

An unsatisfactory indoor thermal environment can negatively influence the students' learning and performance [11]. Thermal comfort is defined as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" [12,13]. Thermal comfort is therefore a subjective variable, and has received attention from researchers in recent years. Previous research conducted in different climate regions has analysed indoor thermal conditions and students' subjective thermal perception in educational buildings. For instance, Jowkar et al. [14] conducted a study in university buildings in Scotland and England, and found evidence of the influence of students' acclimatisation (students from Edinburgh reported higher values of neutral mean thermal sensation votes (TSVs) than Coventry students). In addition, Stazi et al. [15] conducted a measurement campaign over several years in a school building in Italy, and concluded that students tended to suffer from poor air quality during the heating season, as the students placed a high priority on satisfying thermal perceptions. Stazi found that indoor and outdoor temperatures were the main factors driving window-opening behaviours, while CO_2 concentration was not a stimulus. Similar conclusions were reported in research by Duarte et al. [16] on Portuguese educational buildings, where it was reported that manual opening of windows provided adequate ventilation for average outdoor temperatures above 19 °C. However, it was also found that when average outdoor temperatures were below 16 °C, manual window opening was inadequate, and for average outdoor temperatures of 16–19 °C, manual window opening depended on the indoor air temperature. In the same vein, Heracleous and Michael [17] evaluated the thermal comfort and indoor air quality conditions in a typical classroom with natural ventilation, in a secondary school in Cyprus. They also concluded that window-opening behaviour was highly influenced by the outdoor temperature, and that windows were closed when outdoor temperatures were lower than 15 °C. Papadopoulos et al. [18] reported that, in transition season in classrooms (free-running), there is a correlation between operative temperature and mean outdoor temperature. Another research study performed by Korsavi et al. [19,20] found that 55% of all CO_2 measurements were above 1000 ppm, as ventilation was higher during the warm season than the cold season. They also concluded that indoor air quality was strongly affected by the adaptive behaviours of the occupants. Kim and de Dear [21] conducted a study in secondary school buildings located across temperate and subtropical climate regions in New South Wales and concluded that the students' 80% acceptability zone was wider than that suggested by the PMV model. Hamzah et al. [22] found that the students' neutral temperature obtained using the PMV model was lower than the value of neutral temperature obtained from the actual TSV. It is worth noting that, according to the adaptive thermal model, the neutral temperature in warm climates is higher than the neutral temperature in cold climates [23]. Previous studies concluded that students feel comfortable at cooler values of the thermal sensation scale [24,25].

In addition, previous studies have analysed thermal perception in other types of buildings, such as that of Ozarisoy and Altan [26], who explored the determinant factors of the development of adaptive thermal comfort of households through a field study conducted in flats in Cyprus. Their results reported that 80% of the participants were slightly comfortable in a temperature ranging from 28.5 to 31.50 °C. These findings suggest that, in hot and dry climates in which thermally uncomfortable indoor environments occurs, occupants of residential buildings appear to tolerate warmer conditions than in other climate regions, particularly in summer.

Indoor environmental conditions inside educational buildings have also been affected by the protocols implemented as a consequence of the COVID-19 outbreaks. Reopening college and university campuses after COVID-19 lockdowns posed a global challenge. Ensuring proper ventilation with outside air to reduce the concentration of airborne contaminants required the implementation of new ventilation protocols. International organisations have issued guidelines with the aim of minimising the transmission of the SARS-CoV-2 virus [27], and governments of countries around the world have taken measures to prevent and control its spread. In the case of Spain, these measures included increasing the ventilation rate in classrooms (to at least six air changes per hour) through continuous natural ventilation (i.e., windows and doors remaining continuously open during class lectures), increasing social distancing (to at least 1.5 m), and requiring hand washing and the use of facemasks indoors [28]. Regarding the EU guidelines for ventilation, the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) has recommended using CO_2 concentration as an indicator of good indoor air quality, and has suggested a traffic light indicator for effective ventilation, where concentration values of below 800 ppm indicate good ventilation (green light), values between 800 and 1000 ppm represent acceptable ventilation (orange light), and values above 1000 ppm indicate unacceptable ventilation (red light) [27]. Consequently, the normal use of classrooms was modified, and new protocols and ventilation strategies were implemented, resulting in alterations to the classroom's indoor environmental conditions [29–32].

Furthermore, it should be noted that students' freedom to apply adaptive behaviours has been limited as a result of these new pandemic protocols. Prior to the COVID-19 pandemic, students in higher education buildings had the freedom to choose appropriate adaptive behaviours, both personal (e.g., changing where they were sitting during the teaching-learning process) and environmental (e.g., closing or opening classroom windows, using blinds, etc.) [33,34]. However, in the current situation, students must not close windows and doors due to the ventilation protocols (i.e., continuous natural ventilation). Moreover, as social distancing must be maintained at all times (at least 1.5 m), students cannot freely choose their positions within the class.

As students' thermal perception can be influenced by the level of control possibilities within a space and the available adaptive behaviours, it is necessary to evaluate these new indoor environmental conditions, since the alterations in the thermal quality of the learning environment affects students' learning achievements and physical and psychological health. Given that the studies mentioned previously were conducted before the implementation of the COVID-19 protocols, this study aimed to evaluate students' thermal perception in higher educational buildings in southern Spain after the implementation of pandemic protocols. For this purpose, a questionnaire survey was conducted simultaneously with a sensor monitoring campaign during university lectures in the first semester of the academic year 2021–2022 (i.e., November 2021 to January 2022, corresponding to the cold season).

2. Materials and Methods

The methodology used in this field study included measurements of both objective parameters (through a sensor monitoring campaign) and subjective variables (through a questionnaire survey) to evaluate the indoor thermal perception of students. The following sections describe the characteristics of the buildings and lecture classrooms assessed, the sensors and survey applied, and the procedure followed during the measurement campaign. Figure 1 shows the methodological workflow developed for the study.

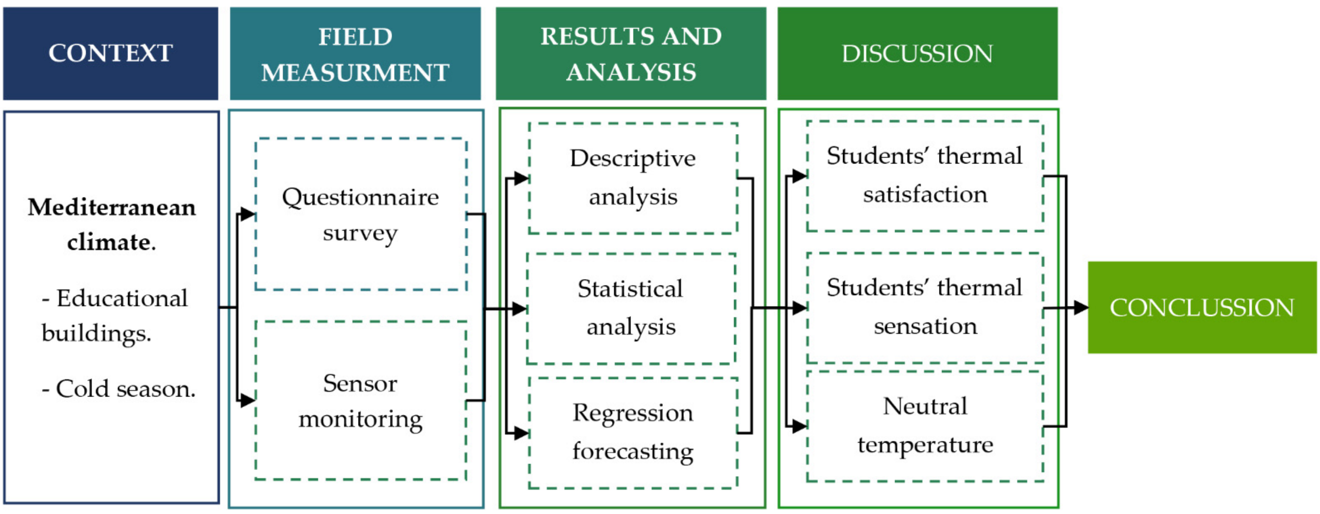

Figure 1. Methodological flow diagram.

2.1. Descriptions of the Buildings and Classrooms

Data collection took place in lecture rooms in the educational buildings of Fuentenueva Campus of the University of Granada (Figure 2). This campus is located in Granada, a city in Andalusia (in the southern region of Spain), which is characterised by a climate classified as Csa according to the Köppen–Geiger climate classification. The temperature is generally in the range 0–34 °C, and rarely rises above 38 °C or drops below −4 °C during the course of the year. All the buildings in which the field study was conducted were naturally ventilated. A summary of the characteristics of the investigated buildings is shown in Table 1. The selected classrooms were a representative sample of the typical classrooms in each building, and the study was conducted in classrooms where the lecturers gave consent and the teaching–learning activities were comparable (i.e., the lecture lasted at least one hour and students remained seated throughout).

Table 1. Summary of the characteristics of the investigated buildings.

Building	Finishing Materials	Type of Windows	Average Area (m^2)	No. of Surveyed Rooms	Ave. Occupancy Ratio (m^2/person)
1	Wall: Gypsum plaster Floor: Terrazzo Ceiling: Registrable suspended ceiling	Aluminium glazed windows (tilt and turn)	144 ± 44	6	2.0 ± 0.6
2	Wall: Gypsum plaster Floor: Terrazzo Ceiling: Registrable suspended ceiling	Aluminium glazed windows (sliding)	173 ± 53	8	1.7 ± 0.9
3	Wall: Gypsum plaster Floor: Terrazzo Ceiling: Registrable suspended ceiling	Aluminium glazed windows (tilt and turn)	92 ± 12	10	1.2 ± 0.2

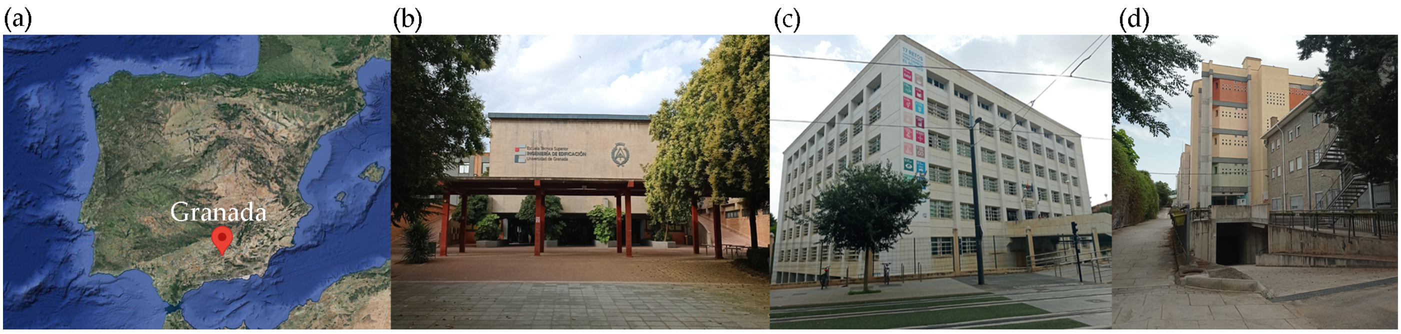

Figure 2. (**a**) Investigated buildings' location. (**b**) Building 1. (**c**) Building 2. (**d**) Building 3.

2.2. Enviromental Evaluation

Ambient parameters can affect the heat balance of the human body and thus the thermal comfort of the occupants of buildings [35]. In this study, the indoor environmental variables recorded during field measurements were the air temperature (°C), mean radiant temperature (°C), air velocity (m/s), relative humidity (RH) (%) and CO_2 concentration (ppm). The variables were recorded at a sampling interval of 1 min. The characteristics of the sensors are summarised in Table 2. The sensors were positioned 10 min before the lecture started, and were evenly distributed in the classroom at 0.6 m above floor level, following the recommendations in ISO 7726:1998. An example of the layout of the sensors' locations is shown in Figure 3. The layout was similar in all classrooms.

Table 2. Characteristics of the sensors used in the field measurement campaign.

Sensor	Model	Parameter	Range	Accuracy
CO_2 analyser HOBO®	MX1102	CO_2 concentration	0 to 5.000 ppm	±50 ppm ±5% reading accuracy
AHLBORN air temperature sensor	FHAD 46-C41A	Air temperature meter	−20 to +80 °C	Typical ±0.2 K at 5 to 60 °C maximum ±0.4 K at 5 to 60 °C maximum ±0.7 K at −20 to +80 °C
AHLBORN RH sensor	FHAD 46-C41A	RH	0 to 98% RH	±2.0% RH in the range 10–90% RH ±4.0% RH in the range 5–98% RH
Delta OHM hotwire air speed transmitter	HD403TS2	Air speed	0.1–5 m/s	±0.2 m/s + 3% f.s.
AHLBORN black ball thermometer	FPA805GTS	Mean radiant temperature	−50 to 200 °C	0.1 °C

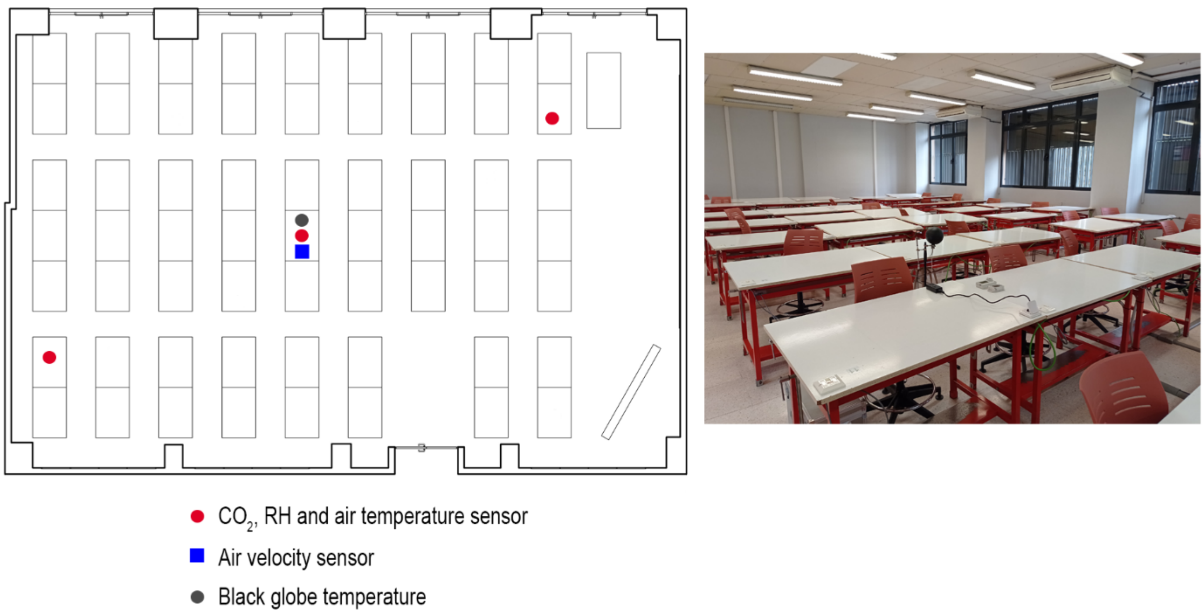

Figure 3. Example of the layout of the sensor locations during field measurements.

The parameters of the outdoor thermal environment (air temperature, RH and air velocity) were obtained from the state meteorological agency AEMET [36], whose meteorological station is located in Cartuja Campus, close to the study area.

2.3. Thermal Perception Survey

The thermal perceptions of the higher education students were evaluated using a questionnaire survey during regular lectures. The questionnaire was based on the UNE–CEN/TR 16798-2:2019 Standard's recommendations for evaluation of the indoor environmental quality, and included items related to personal information (gender, age and clothing, and type of masks worn by students during the survey) and thermal perception (thermal satisfaction vote (TSaV), TSV and thermal interference with the students' performance (TIP)). TSaV, TSV and TIP were examined based on a seven-point Likert scale. Table 3 shows the scale used in the questionnaire survey. The questionnaires were filled out by the students during the final minutes of the lecture. The clothing insulation values were calculated based on the clothing selected by the students and using the guidelines stated in ISO 7730.

Table 3. Scales used in the questionnaire survey.

Index	Level	Scale
TSaV	Very dissatisfied, dissatisfied, slightly dissatisfied, neutral, slightly satisfied, satisfied, very satisfied	(−3), (−2), (−1), (0), (1), (2), (3)
TSV	Cold, cool, slightly cool, neutral, slightly warm, warm, hot	(−3), (−2), (−1), (0), (1), (2), (3)
TIP	Interfere a lot, interfere, slightly interfere, neutral, slightly enhance, enhance, enhance a lot	(−3), (−2), (−1), (0), (1), (2), (3)

Note: TSaV: thermal satisfaction vote; TSV: thermal sensation vote, TIP: thermal interference in the students' performance.

The collected subjective data were analysed and the significant differences between the responses were evaluated. For this purpose, the normality of the data was checked using a Kolmogorov–Smirnov test. A *t*-test was then used to examine the significant differences from normally distributed data, and a non-parametric Mann–Whitney U test was used to examine non-normally distributed data. Spearman's correlation test was used to determine the relationship between the variables. Linear fits were used to assess the relationship between TSVs and T_{op}. The neutral temperature (T_n) was calculated based on these linear fits. An exponential fit was used to explore the relationship between CO_2 concentration inside the classroom and the total open area (m^2) and the occupation density (m^2/student). The statistical analysis was conducted using SPSS (v. 23.0) software (IBM Corp, Armonk, NY, USA).

3. Results

3.1. Indoor and Outdoor Environments

The average, standard deviation, minimum and maximum values obtained from measurements of the indoor and outdoor environmental parameters are shown in Table 4. It can be seen that there were significant differences between the indoor and outdoor parameters. The indoor air was renewed by continuous natural ventilation through opening of the doors and windows, and the indoor environmental variables were therefore influenced by this ventilation protocol. The results obtained for the indoor operating temperature and RH show a wide variation (14.6–28.2 °C and 19.6–50.1%, respectively).

Table 4. Summary of values obtained from the sensor monitoring campaign.

Type	Outdoor			Indoor			
	Air Temperature (°C)	RH (%)	Air Velocity (m/s)	Operative Temperature (T_{op}) (°C)	RH (%)	Air Velocity (m/s)	CO_2 Concentration (ppm)
Average	13.1	58.4	5.07	20.6	37.9	0.03	566.4
STD *	7.5	21.2	5.48	3.9	7.3	0.04	118.2
Max	30.4	94.0	23.00	28.2	50.1	0.19	897.3
Min	2.1	16.0	<0.01	14.6	19.6	<0.01	410.0

* STD: standard deviation value.

3.2. Students' Thermal Perceptions

A total of 1100 questionnaires were collected in this field study, of which 989 were valid (111 were discarded as incomplete). Table 5 shows the distributions of the general information on the respondents. An approximately equal number of male and female subjects participated in this study (with only 8% more males than females). In addition, 84% of the participants were aged between 18 and 24, a figure that rose to 91% when participants aged 25–30 were included. These values were as expected, since the statistical data published in the annual report for the academic year 2020/2021 by the University of Granada indicated that 95% of the students enrolled in university degrees were aged between 18 and 30 [37]. In terms of the masks worn by students, the type most frequently used was a surgical mask (75%), followed by an FFP2 mask (16%). Only 8% of the students who participated in this study wore different types of mask.

Table 5. Characteristics of the sensors used in the field measurement campaign.

Variable	Number of Respondents, N (%)	
Gender	Male	539 (54%)
	Female	450 (46%)
Age	n/a	31 (3%)
	18–24	829 (84%)
	25–30	107 (11%)
	+30	22 (2%)
Type of mask	FFP2	163 (16%)
	Surgical	742 (75%)
	Cloth	60 (6%)
	n/a	24 (2%)

The clothing insulation value was calculated on the basis of the clothing worn by each student, following the conventional clo table defined in ISO 7730 [38]. The distribution of the clothing insulation values is shown in Figure 4. The median clothing insulation value was 0.60 clo for males and 0.77 clo for females. Although previous research on the effect of clothing on people's perception of the thermal environment has found that differences in clothing insulation between males and females were negligible for the cold seasons [39], the results obtained in this study show significant differences ($p < 0.001$).

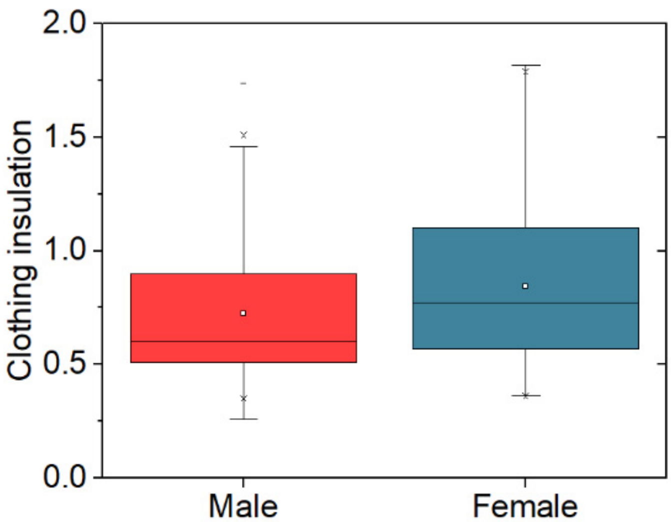

Figure 4. Distribution of clothing insulation values by gender. Red indicates males' clothing insulation. Blue colour indicates females' clothing insulation. Circle indicates the mean value.

Figure 5 shows the subjective thermal perception data collected through the questionnaires, including the percentage distributions of TSaV (Figure 5a), TSV (Figure 5b) and TIP (Figure 5c). The collected data were divided into two groups based on gender, and significant differences were found for these three subjective variables between the votes reported by female and male students ($p < 0.001$). With respect to the TSaV, the predominant responses of students of both genders were 'very dissatisfied', 'dissatisfied' or 'slightly dissatisfied' with the indoor thermal conditions (accounting for a total response of 47% for males and 64% for females). Only 11% of females and 18% of males reported a 'neutral' response. It should be noted that the percentage of females reporting satisfaction with the temperature was lower than the percentage of males. For the TSV, 55% of the female students' votes and 63% of the males' were in the comfort range (i.e., between 'slightly cool' (−1) and 'slightly warm' according to [12]). Of the TSVs that were outside the comfort range, the percentage of students who considered the environment 'cold' or 'cool' (40% of females and 28% of males) was higher than those that considered it to be 'warm' or 'hot' (5% and 9% of females and males, respectively).

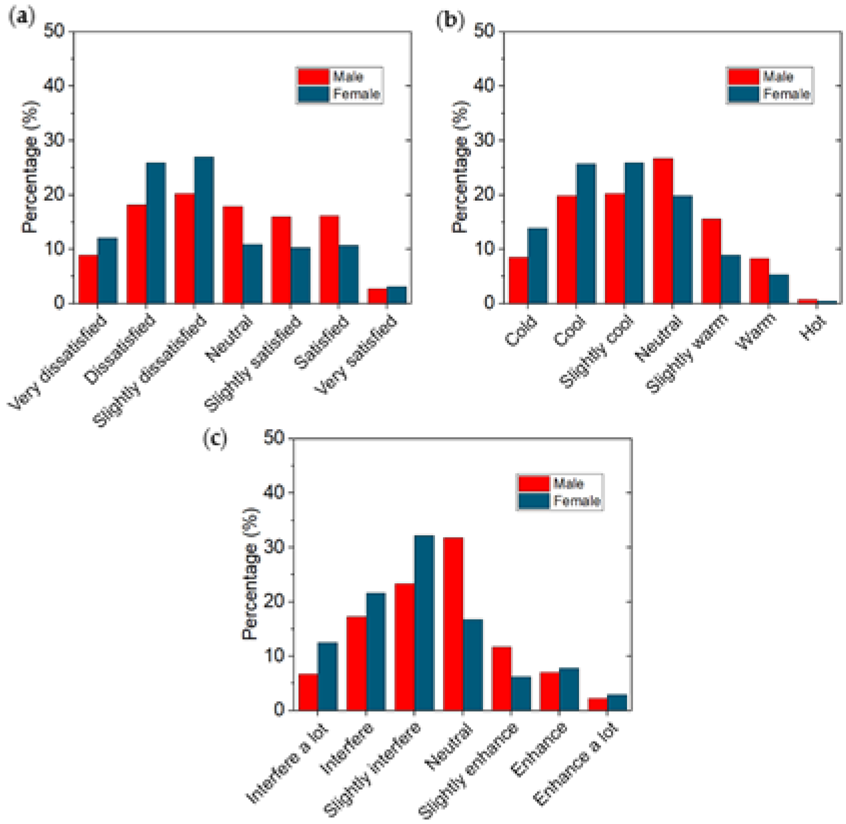

Figure 5. Distribution of responses obtained for (**a**) TSaV; (**b**) TSV; (**c**) TIP.

About 47% of the male and 66% of the female occupants reported that the indoor thermal conditions interfered with their academic performance (based on the total responses of 'interfere a lot', 'interfere' and 'slightly interfere'). However, only 21% of males and 17% of females indicated that the indoor thermal conditions enhanced learning (based on the total responses of 'slightly enhance', 'enhance' and 'enhance a lot'). It was notable that only 17% of the female students gave a neutral response to this question, a much lower value than for the males (32%). In view of these results, it is possible to conclude that the percentage of female students who reported that the indoor thermal conditions interfered with their academic performance was much higher than for the male students.

The relationships between the subjective variables were also examined, and the distributions of the values of TSaV and TIP reported by the students in relation to the TSV values are shown in Figure 6. Between 95% and 100% of the students who voted that the indoor thermal conditions were cold or cool were also dissatisfied, and reported that these conditions interfered with their academic performance.

Of the students who reported that the temperature was within a comfortable range (between 'slightly cool' and slightly 'warm'), both male and female students indicated that a slightly warm indoor environment was more satisfactory and enhanced their academic work. In the case of female students who reported a 'slightly cool' TSV, a higher percentage of dissatisfaction was observed (80%) than for male students (64%). Similar results were found with regard to interference in academic performance.

In contrast, of those students who reported a 'warm' TSV, lower percentages were dissatisfied (13% of male students and 21% of female students) or indicated that the thermal conditions interfered with their academic performance (16% and 21% of male and female students, respectively). These results evidence a preference for a warmer indoor environment during cold season.

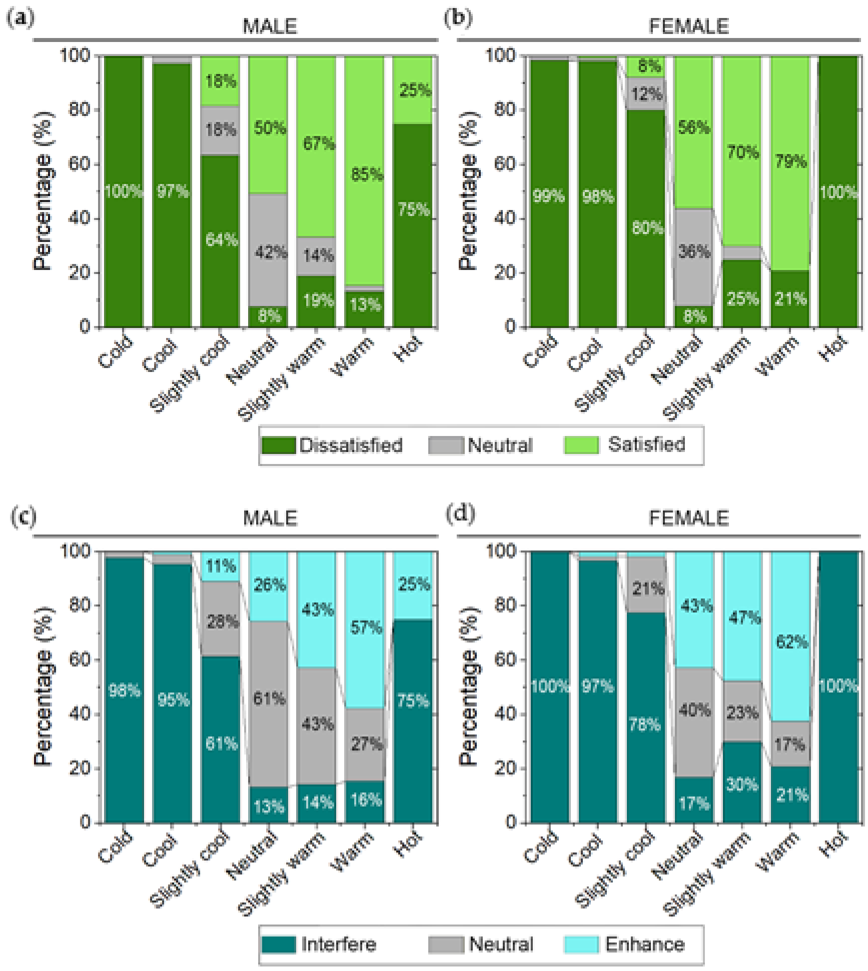

Figure 6. (**a**) Distributions of TSaV versus TSV results for male students; (**b**) Distributions of TSaV versus TSV results for female students; (**c**) Distributions of TIP versus TSV results for male students; (**d**) Distributions of TIP versus TSV results for female students.

To illustrate the relationship between the objective and subjective variables, Figure 7 shows the values of TSV against T_{op}. A linear regression was used to analyse the thermal neutrality (T_n), and the fitting equations obtained in this way are shown in Table 6. Since significant differences were found between the TSVs reported by male and female students, the data were evaluated separately. The overall total T_n was 23.8 °C, with values of 23.2 °C for males and 24.2 °C for females.

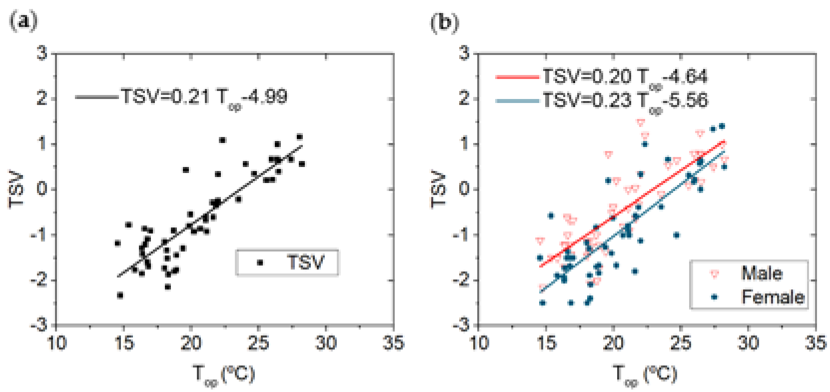

Figure 7. (**a**) TSV values reported by students versus T_{op}; (**b**) values of TSV reported by female and male students versus T_{op}.

Table 6. Fitting equations of TSV against t_{op}.

	Fitting	*p*-Value	R^2
Total	$TSV = 0.21\ t_{op} - 4.99$	$p < 0.001$	0.74
Male	$TSV = 0.20\ t_{op} - 4.64$	$p < 0.001$	0.65
Female	$TSV = 0.23\ t_{op} - 5.56$	$p < 0.001$	0.68

The difference between the values of T_n obtained for the male and female students shows that the female students had a preference for warmer temperatures. This finding is also reflected in Figure 8, which shows the relationships between the difference between T_{op} and T_n (i.e., DT) and the percentages of dissatisfied students (Figure 8a) and those reporting learning interference (Figure 8b). These results indicate a lower percentage of dissatisfied students (≤20%) when DT ranges from −2 to 4 °C.

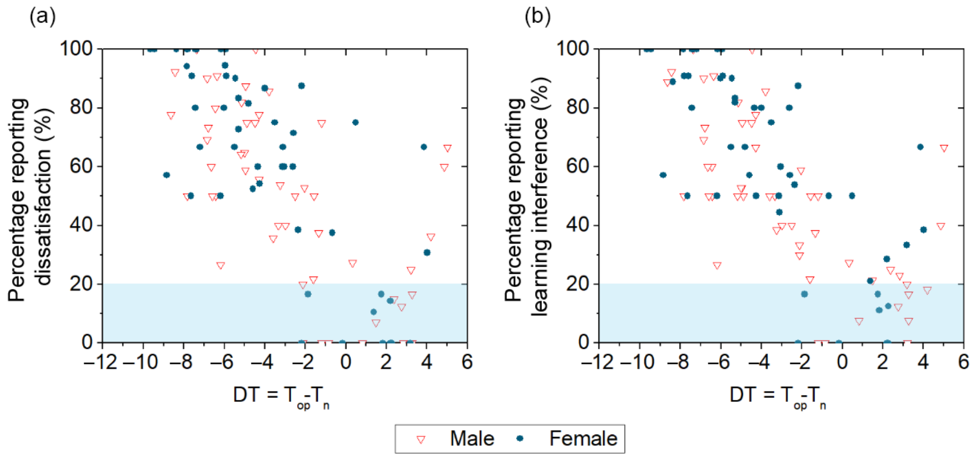

Figure 8. (**a**) Percentage of dissatisfied students versus DT; (**b**) percentage reporting learning interference versus TSV.

3.3. Continuous Natural Ventilation and the Indoor Thermal and Air Quality Environment

Figure 9a shows the relationship between the total open area (m^2) of windows and doors used to provide continuous natural ventilation, and the CO_2 concentration inside the classrooms. If the recommendations for ventilation efficiency given in the REHVA guidelines are considered, we see that 90% of the lectures in which measurements were conducted had values lower than 800 ppm, meaning that the ventilation strategy provided enough air circulation according to these guidelines. Figure 9b shows the occupation density (m^2/student) against CO_2 concentration. As expected, the lower the area per occupant, the higher the CO_2 concentration in the classroom. The fitting equations are shown in Table 7. In addition, the relationship was examined using the Spearman correlation test. The results showed a moderate relationship between CO_2 concentration and the total open area ($\rho = -0.515$, $p < 0.01$). Regarding the CO_2 concentration and occupation, a moderate-low relationship was obtained ($\rho = -0.451$, $p < 0.01$).

Table 7. Fitting equations.

Variables	Fitting	*p*-Value	R^2
CO_2 concentration/total open area (m^2)	$CO_2 = 599.3\ e^{-0.57x} + 499.5$	$p < 0.001$	0.42
CO_2 concentration (ppm)/occupation (m^2/student)	$CO_2 = 1894.6\ e^{-0.90x} + 526.9$	$p < 0.001$	0.40

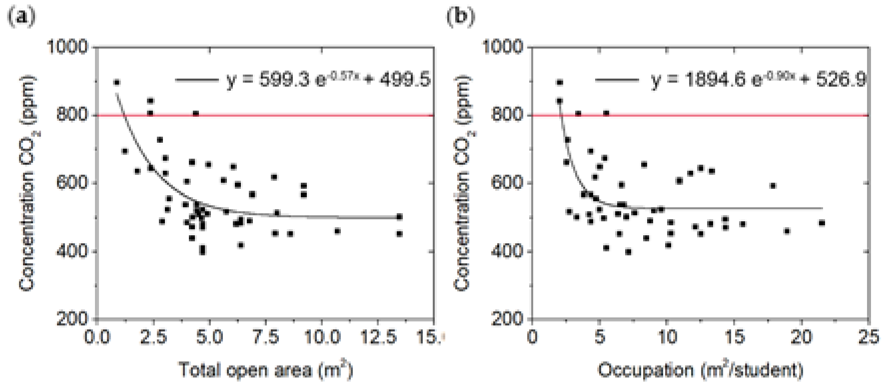

Figure 9. (**a**) CO_2 concentration versus total open area (m^2); (**b**) CO_2 concentration versus occupation density (m^2/student). Red line indicates the REHVA CO_2 concentration limit recommendation.

Although the CO_2 concentrations remained below 800 ppm in most of the analysed scenarios, these ventilation strategies also affected the indoor environmental conditions. In fact, the results presented in the previous section indicate that a high percentage of students were dissatisfied with the indoor thermal conditions, and considered that the indoor environment was 'cold', 'cool' or 'slightly cool' (49.2%). This was due to the influence of the outside temperature on the indoor thermal conditions, from the open windows. This is evident in Figure 10, which shows the total percentage of students who were dissatisfied with the indoor thermal conditions as a function of the outdoor temperature and the total area of open windows.

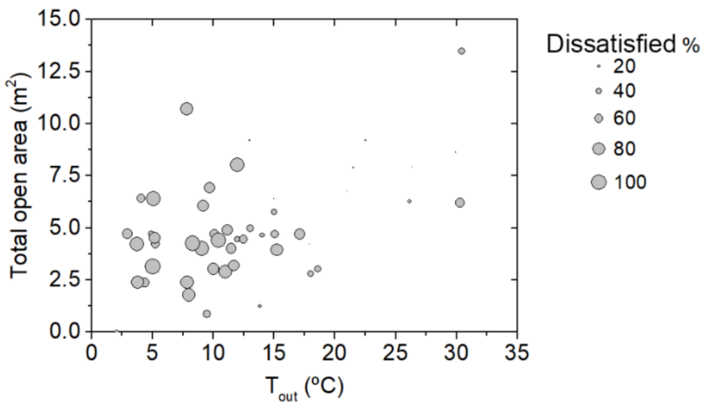

Figure 10. Relationship between the percentage of dissatisfied students, outdoor temperature and total area of open windows.

4. Discussion

The results obtained in this study represent the students' perceptions of the indoor thermal environment during the cold season in a naturally ventilated higher education building. The reopening of educational buildings for the academic year 2021/2022 posed a challenge to building managers, and the need to ensure that indoor spaces were healthy and safe for students and teachers led to the implementation of ventilation protocols to ensure effective air renewal.

The results presented here show that a strategy of continuous natural ventilation was able to provide effective air renewal and kept the CO_2 concentration below 800 ppm in more than 90% of the classrooms (Figure 9). However, this protocol also influenced the indoor thermal conditions of these spaces. The average indoor temperature was 20.5 °C, below the lower limit given in the Regulation on Building Heating Installations (RITE) (which states that the indoor operative temperature should be in the range 21.0–23.0 °C during the winter season) [40]. Only 18% of the evaluated classrooms were in this range, which was reflected in the high percentage of dissatisfied students. Our findings are similar to those reported by Monge-Barrio et al. [41], who conducted a study to evaluate the use of natural ventilation to improve IAQ in educational buildings in northern Spain. They found that, although natural ventilation helped to improve IAQ (with lower CO_2 concentrations), this resulted in lower temperatures inside the classroom, especially on the coldest days of the winter season.

The values obtained for T_n (23.2 °C for males and 24.2 °C for females) were slightly above the range given in the RITE standard. It was observed that students preferred a warmer environment during the cold season. The percentage of dissatisfied students was lower when the difference between T_n and T_{op} was between −2 and 4 °C (see Figure 8). Lower values of TSV were detected for female students than for male students, and significant differences between the overall votes of males and females were detected. This effect has been also found in previous research conducted in cold regions [42]. Similar results were reported by Jowkar et al. [14], who conducted a study of higher educational buildings in Coventry and Edinburgh, and concluded that women tended to have statistically higher thermal preferences and lower thermal TSVs than men. Although the clothing insulation value for females was higher than for males, female students assessed the indoor environment as cooler and preferred warmer thermal conditions.

If these results are compared with those reported by other studies carried out in educational buildings in different climatic regions, it is found that the T_n in cold climates is lower than the T_n in warmer climates [23]. Regarding the analysis of students' thermal comfort in regions located in the Tropics, Hamzah et al. [22] carried out a study in the tropical city of Makassar and found that the T_n values were 29.0 and 28.5 °C for TSV and TCV, respectively, with an average clothing insulation of 0.69 clo. Kim and Dear [21] conducted a study in secondary school buildings located across temperate and subtropical climate regions in New South Wales and investigated the students' perception of classroom thermal environment in relation to adaptive comfort guidelines. They found a neutral temperature of 24.4 °C with an average clothing insulation of 0.48 clo. In contrast a the study conducted by Liu et al. [23] in rural school classrooms in Northwest China reported a neutral temperature of 15 °C. Nevertheless, this study reported that the students' average clothing insulation was found to be 1.6 clo, which is much higher than that found in studies in warmer regions.

Considering studies conducted in other types of buildings, the T_n also differs from the T_n obtained in the present study. As an example, Ozarisoy [26] conducted a study during summer in multi-family social-housing units in Cyprus and found a T_n of 28.5 °C. However, it should be noted that households' freedom to apply adaptive behaviours has not been limited due to the COVID-19 pandemic, as in the case of students in educational buildings.

It should be also noted that significant differences were found between the clothing insulation values for female and male students, with the median value for female students being 0.17 clo above the value for the male students. It should be also be borne in mind that the adaptive behaviour of students during lectures was limited due to the pandemic protocols; it is possible that students came to class expecting different indoor environmental conditions, and did not dress appropriately for this new scenario. As a result, their indoor thermal comfort may have been compromised. This is evidenced in Figure 8, which shows the percentage of dissatisfied students as a function of outdoor temperature and the total area of open windows. In a study of thermal comfort in university classrooms of southwest Spain during mid-season (spring), Miranda et al. [32] also reported that different natural ventilation strategies are recommended when the outdoor temperature is below 12 °C (i.e., limiting the number of open windows) in order to minimise the number of dissatisfied students.

In view of the fact that the implemented protocols affected the students' perception of the thermal environment, not only resulting in a high percentage of students who were dissatisfied with the indoor thermal conditions, but also in 56% stating that these thermal conditions negatively affected their academic performance, we conclude that these new protocols need to be adapted.

5. Limitations

Unlike other types of buildings (i.e., commercial, industrial or residential buildings), educational buildings should provide a conducive environment to enhance the teaching and learning process [24]. The specific characteristics of educational buildings are especially important in the analysis of the thermal environment and the thermal perception of students. The reopening of university campuses after lockdowns due to the COVID-19 pandemic and the implementation of new ventilation protocols has resulted in limiting students' freedom to apply adaptive behaviour. In this context, this study aimed to assess the thermal perception of students in educational buildings and, therefore, the obtained results should not be extrapolated to other populations without prior considerations.

6. Conclusions

The indoor thermal environmental conditions were significantly affected by the new ventilation protocols resulting from the COVID pandemic during the cold season. Adaptive behaviours by students were limited, as they were prevented from opening or closing windows, and the results reflect the high number of dissatisfied students. Although our results show that continuous natural ventilation allowed these spaces to be safe and healthy, its effect on thermal conditions must be taken into account, as it had a strong impact on student satisfaction and performance.

Amongst our other findings, we observed statistically significant differences between the TSav, TSV and TIP values reported by male and female students. Female students reported a value for T_n that was 1 °C higher than that for men, showing a preference for warmer temperatures for comfort. It is worth noting that, even though the clothing insulation values were higher for females than for males, there were significant differences in the results, and females indicated a preference for warmer thermal conditions.

Finally, we recommend that the findings obtained in this study are taken into account and the protocols modified to ensure that indoor thermal conditions do not negatively affect student satisfaction and academic performance. From the results obtained in this study, we conclude that the maximum range of deviation in the temperature from T_n, to ensure the percentage of dissatisfied students does not exceed 20%, is −2 to 4 °C. Consequently, additional measures should be considered to adapt these protocols during the cold-mid season, in order to contribute to keeping spaces safe while minimising the negative impact on students' academic performance.

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