Energy & Buildings 294 (2023) 113227

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Investigating the effects of climate on thermal adaptation: A comparative field study in naturally ventilated university classrooms

Giulia Lamberti [a,b,*], Francesco Leccese [a], Giacomo Salvadori [a], Francesca Contrada [b,c], Andrea Kindinis [b]

[a] University of Pisa, School of Engineering, Pisa, Italy
[b] Institut de Recherche en Constructibilité, Université Paris-Est, Cachan, France
[c] Sitowie, 3 Rue Decrès, 75014 Paris, France

ARTICLE INFO

Keywords:
Thermal comfort
Adaptation
Classrooms
Climate differences
Field study

ABSTRACT

In educational buildings, adaptive strategies can be adopted for the achievement of thermal comfort and reduction of energy consumption. Since climate can largely affect thermal comfort, there is a need for understanding its role in the definition of different adaptive capacities, thermal neutrality, comfort, and preference.

To this end, 17 naturally ventilated university classrooms from 10 different buildings located in two sub-climates of Italy (Mediterranean climate) and France (Continental climate) were analysed. In total, 1377 questionnaires associated with environmental parameters were collected. The same educational stage (i.e. university classrooms) and operation mode (i.e. naturally ventilated during the heating period) were investigated to remove possible biases related to their influence on thermal comfort perception.

Field studies show that despite French students performing less adaptive actions, their neutral temperature (T_N) was 3.1 °C lower than the Italian ones ($T_{N,ITALY}$ = 23.6 °C and $T_{N,FRANCE}$ = 20.5 °C) and this difference was statistically significant.

Adaptation as a function of the sub-climate was evident from the comparison with the PMV-PPD model. Neutral temperatures calculated with PMV were higher than those obtained from TSV, and the difference increased for the French colder climate.

Practically, students' adaptation to colder environments can be deployed to ensure comfort while reducing the heating demand.

1. Introduction

Ensuring thermal comfort in classrooms is fundamental, as it can influence students' performance [1], health [2], and satisfaction [3]. To evaluate thermal comfort in classrooms, two main approaches have been used namely, Fanger's PMV-PPD, based on studies in climate chambers [4], and the adaptive model, developed on field studies [5].

Despite most studies being focused on the application of Fanger's model, research showed that the actual students' thermal perception is different from that predicted by the PMV-PPD [6,7]. This can be attributed to students' adaptive capacities, which can depend on features such as the educational stage (e.g. elementary, high schools, universities), the operation mode (e.g. naturally ventilated, air-conditioned, and mixed mode), or the climate [8]. Indeed, there is a relevant relationship between comfortable indoor conditions and the outdoor climate [9] and students largely adapt to their local climate [10] since thermal history can affect students' thermal sensation.

Singh et al. [11] showed that the comfort temperature range largely varied according to the climate, even at the same educational stage. Furthermore, by a large comparison of thermal comfort studies in classrooms, Zomorodian et al. [6] demonstrated that there are consistent differences in comfort temperatures even in the same climate zone. These differences are particularly relevant, especially for Köppen-Geiger zone C [12], which comprises several countries and, in particular, Continental and Mediterranean Europe. In this climate zone, differences in thermal perception can be mainly attributed to the wide range of sub-climates, and students presented a high capability to adapt to all of them.

Furthermore, most studies on adaptation were developed during summer [11] and little is known about the adaptive actions of students during the winter period. In fact, even the adaptive models included in

* Corresponding author.
E-mail address: giulia.lamberti@phd.unipi.it (G. Lamberti).

https://doi.org/10.1016/j.enbuild.2023.113227
Received 22 February 2023; Received in revised form 14 April 2023; Accepted 4 June 2023
Available online 8 June 2023

Nomenclature

%Sat	Percentage of satisfied (%)
I_{cl}	Clothing insulation (clo)
$I_{cl,i}$	Clothing insulation of the single garment (clo)
M	Metabolic rate (met)
PC	Perceived Control vote ((from −3 to +3))
P_c	Probability that the windows or doors are opened (–)
PD	Percentage of Dissatisfied (%)
PMV	Predicted Mean Vote (–)
PPD	Predicted Percentage of Dissatisfied (%)
RH	Relative humidity (%)
T_a	Indoor air temperature (°C)
T_C	Comfort temperature (°C)
TCV	Thermal Comfort Vote (from 1 to 4)
T_{diff}	Difference between T_{op} and T_C (°C)
T_g	Indoor globe temperature (°C)
T_N	Neutral temperature (°C)
T_{od-i}	Daily mean outdoor temperature for the days before the measurements (°C)
T_{op}	Indoor operative temperature (°C)
TPV	Thermal Preference Vote (from −3 to +3)
T_P	Preferred temperature (°C)
T_r	Indoor mean radiant temperature (°C)
T_{rm}	Running mean outdoor temperature (°C)
TSV	Thermal Sensation Vote (from −3 to +3)
V_a	Indoor air velocity (m/s)

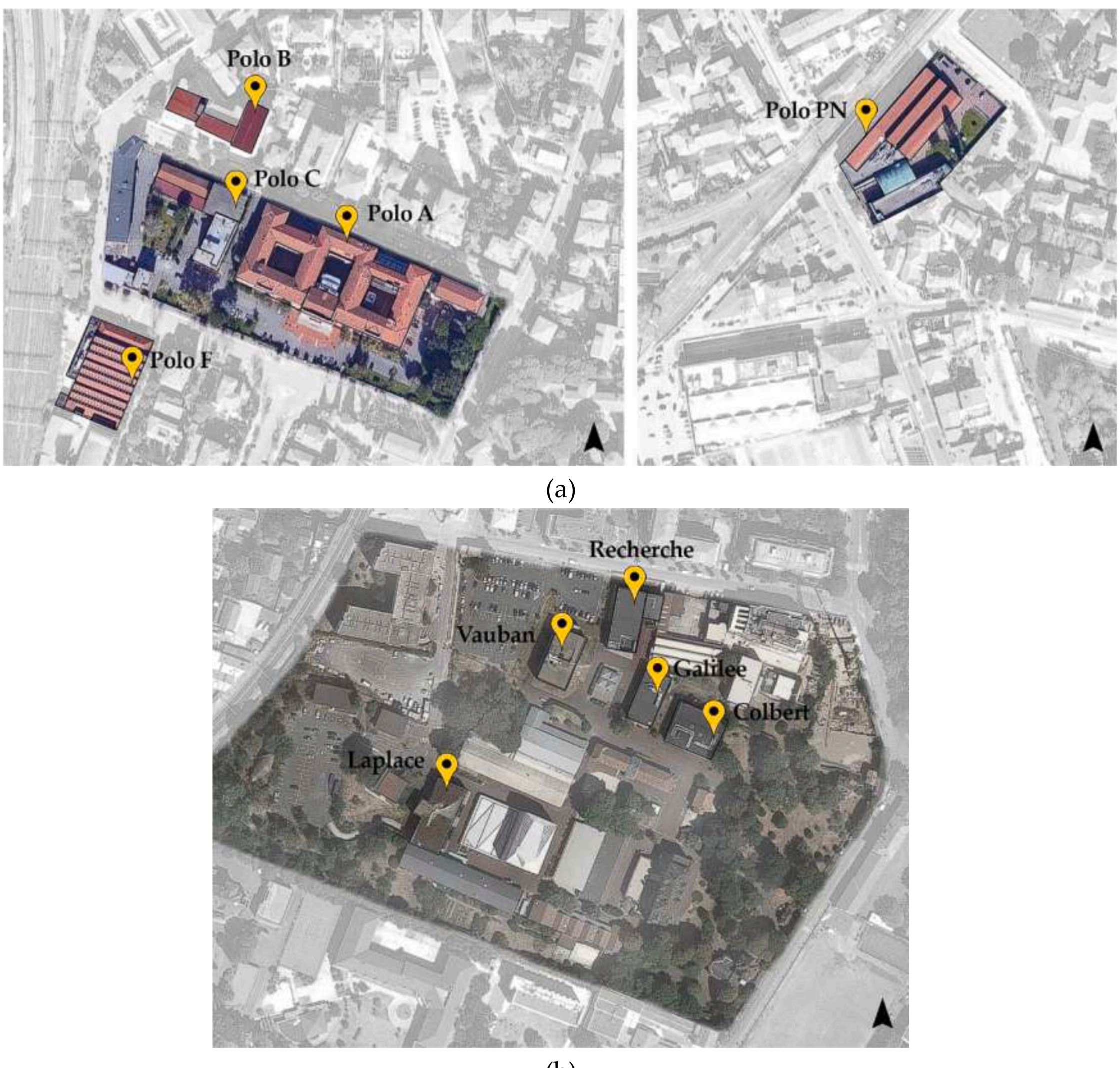


Fig. 1. Buildings surveyed in the university campus of Pisa (a) and Cachan (b).

the international standards ASHRAE 55 [13] and EN 16798-1 [14] refer to adaptation to external temperatures above 10 °C, although adaptive processes can also occur in colder climates [15,16]. However, adaptive actions such as clothing behaviour, window operation, or perceived control can largely affect student thermal sensation throughout the year, as shown by seasonal studies [10,17].

In climate zone C during the winter period, the neutral temperatures (that is, the temperature at which occupants are thermally neutral, T_N) reported by scientific studies in naturally ventilated university classrooms are widely different. Hu et al. [18] found a T_N equal to 17.2 °C, similar to the one found by Wang et al. [19] of 18.0 °C. In the case of Corgnati et al. [20] the neutral temperature was much higher (T_N = 24.6 °C), even increased than the one found by Buratti and Ricciardi [21] (T_N = 23.0 °C). Intermediate neutral temperatures were found by Cao et al. [22] (T_N = 20.7 °C), Serghides et al. [23] (T_N = 21.0–22.0 °C), and Wang et al. (T_N = 22.6 °C). These differences in neutral temperatures of up to 7.4 °C are present in the same climate zone (zone C) and in the same winter period, thus demonstrating the need to understand how sub-climates can influence thermal perception.

As it was demonstrated that in educational buildings even in the same climate zone (and particularly in the climate zone C) the comfort temperatures can substantially vary, it is necessary to understand the role of sub-climates on students' thermal comfort and the reasons for these significant differences. It is necessary to understand what role these sub-climates play in the perception of comfort and whether it is attributable to indices such as running mean outdoor temperature. Moreover, aiming at reducing energy demands to cope with the energy crisis, it is necessary to explore the adaptive capacities of students during winter, also considering that this is the most challenging period in terms of energy demands (several schools are closed during the summer period, especially in Europe). In particular, it was shown that adaptive capacities in educational buildings are essentially related to three factors, namely the educational stage, climate zone, and operation mode [8]. To analyse the effect of climate on students' thermal perception, it is necessary to remove the other factors that could influence thermal sensation (i.e., educational stage, operation mode) by performing a comparative study.

Since significant differences in thermal perception within the same climate zone (and, in particular, in zone C) have been observed, this paper will identify the differences within this sub-climate, taking the European Mediterranean (Csa) and Continental (Cfb) climates as reference. The aim of this paper is then to analyse adaptive capacities, thermal neutrality, comfort, and preference as a function of these sub-climates, exploring the critical winter period.

To this end, reference was made to naturally ventilated university classrooms located in climate zone C (namely Italy and France). Indeed, this was shown to be the most critical climate zone in terms of defining comfort conditions. On a practical level, this will help to better understand the mechanisms of thermal perception as a function of students' thermal history, with a view to ensuring comfort and reducing the heating demand through the exploitation of winter thermal adaptation.

2. Methodology

The survey included the field study in 17 naturally ventilated university classrooms of 10 different buildings, investigated in the heating season during winter 2021. The present study was conducted during the COVID-19 pandemic when the measures taken to avoid its spread were in place (e.g. use of protective masks). Objective and subjective measurements were performed simultaneously.

2.1. Description of the case studies

2.1.1. Selection criteria of the buildings

The case studies were selected to include two university campuses at the same educational stage (university classrooms) and operation mode (naturally ventilated), in climate zone C. The first campus was located in Pisa, Italy (43°43′0.0012′'N, 10°24′0.0000′'E), which is part of "Zone Csa" in the Köppen-Geiger classification, and the second campus was in Cachan, France (48°47'30.678"N, 2°19'53.159"E), which is in "Zone Cfb" in Köppen-Geiger classification) (Fig. 1). The annual mean temperature is 15 °C and the mean temperature during the heating season is 7 °C in Pisa, while 12 °C and 6 °C in Cachan.

Classrooms were selected to provide a sample as diverse as possible in terms of building characteristics (year of construction, volumes, envelopes, etc.). Further information can be found in Appendix A.

2.1.2. Description of the classrooms

In total, 17 classrooms from 10 different buildings were selected and investigated, including:

- Nine classrooms in the university campus of Pisa (mean occupancy: 27 students);
- Eight classrooms in the university campus of Cachan (mean occupancy: 56 students).

The classrooms were all naturally ventilated. The sample selected included classrooms of different shapes, exposure, and volume. The classrooms had various exposures and in buildings built with various construction types (mainly massive constructions). Some classrooms were teaching rooms, auditoriums, and laboratories. The heating system usually consisted of radiators with manual control operated directly by the occupants. This choice was made to ensure a sample of classrooms as diverse as possible. Further information on the classrooms can be found in Appendix A.

2.2. Measurement campaign

2.2.1. Objective measurements

The objective measurements consisted of the assessment of the environmental parameters in the classrooms, which included air temperature (T_a), globe temperature (T_g), relative humidity (RH), and air velocity (V_a). Outdoor air temperature and relative humidity were also assessed to evaluate the outdoor thermal conditions. They were measured through microclimate data loggers in compliance with ISO 7726 [24], whose characteristics can be found in Supplementary Material.

The position of the instruments was chosen in representative locations of the students' positions and was selected after a site inspection to cover the different thermal zones, also considering that they should not disturb the normal operation of the classrooms. The probes were placed at least 1.5 m from walls, windows, and heat sources, and shielded from direct solar radiation, to provide a correct assessment of the environmental parameters. The position of the probes in the classrooms can be found in Supplementary Material.

The data loggers were put in operation at least 30 min before the beginning of the lectures and continued for the duration of the lectures (3 h). The acquisition interval of the probes was 60 s, to allow the inclusion of possible variations in the thermal environment.

Doors and windows operation was also monitored during the lecture.

2.2.2. Subjective measurements

During the environmental monitoring, questionnaires were submitted to the students, to evaluate their subjective sensations. Students filled out the questionnaire during the breaks, before leaving the classroom, and at least 60 min after entering it, to ensure their acclimatization to the environment.

The questionnaires were provided in the native language of the students (namely Italian and French) and were developed according to the ISO 28802 standard [25]. The complete questionnaire and its English translation can be found in Supplementary Material.

In particular, it was divided into four sections, as described below.

The first section asked for personal information including the gender, age, and location in the classrooms.

The second section includes the ensembles worn by the students for the evaluation of the clothing insulation according to the ISO 9920 standard [26].

The third section evaluates the perception of the thermal environment, including questions regarding:

- Thermal Sensation Vote (TSV), which assesses the thermal sensation of the students on a 7-point scale (From [−3] "Very cold" to [+3] "Very hot").

Table 1
Statistical summary of the objective measurements.

Location		T_{rm} (°C)	T_a (°C)	T_r (°C)	T_{op} (°C)	RH (%)	V_a (m/s)	I_{cl} (clo)	PMV (–)	PPD (%)
Italy	**Mean**	13.1	23.1	23.2	23.2	51.8	0.00	0.9	−0.2	11.8
	Max	18.7	27.1	26.8	27.0	75.6	0.80	1.8	1.0	94.7
	Min	5.0	16.9	16.9	16.9	25.4	0.00	0.5	−2.6	5.0
	SD	3.6	2.0	2.0	2.0	11.5	0.10	0.1	0.6	12.3
France	**Mean**	7.3	21.0	22.1	21.6	45.9	0.00	0.9	−0.8	23.0
	Max	10.3	23.4	29.0	26.2	63.7	0.20	1.3	0.7	98.8
	Min	5.1	16.4	17.1	16.8	30.4	0.00	0.4	−2.9	5.0
	SD	2.0	1.5	1.8	1.7	8.1	0.00	0.2	0.6	20.1

Table 2
Mean and standard deviation of the responses from the questionnaires for zone C, Italy, and France.

	Italy		France	
	Mean	**SD**	**Mean**	**SD**
Personal information				
Sex	464 males		257 males	
	351 females		248 females	
Age	26	4.5	22	2.8
Thermal environment				
TSV	−0.06	0.94	0.21	1.13
TCV	1.56	0.71	1.73	0.94
TPV	0.26	0.94	0.24	1.03
PC	0.19	1.38	−1	1.62

- Thermal Comfort Vote (TCV), which evaluates students' comfort on a 4-point scale (From [1] "Comfortable" to [4] "Very uncomfortable").
- Thermal Preference Vote (TPV), which considers the thermal preference of the students on a 7-point scale (From [−3] "Much colder" to [+3] "Much warmer").
- Perceived Control (PC), which assesses the control perceived by students over the environment, on a 7-point scale (From [−3] "No control" to [+3] "Full control").

In the questionnaire, the students were asked whether they were wearing a mask during the lesson or not.

2.3. Data processing

From the parameters evaluated, several indices were derived.

First, the mean radiant temperature (T_r) was calculated according to ISO 7726 standard [24].

Second, the operative temperature (T_{op}) was calculated from the air and mean radiant temperatures, as expressed in ISO 7726 standard [24].

Third, the running mean outdoor temperature (T_{rm}) was calculated as the weighted mean of the outdoor temperatures of the previous seven days, as described by EN 16798-1 standard [14]:

$$T_{rm} = (1-\alpha)\cdot(T_{od-1} + \alpha\cdot T_{od-2} + \alpha^2\cdot T_{od-3} + \alpha^3\cdot T_{od-4} + \alpha^4\cdot T_{od-5} + \alpha^5\cdot T_{od-5} + \alpha^6\cdot T_{od-7}) \quad (1)$$

where:

α was assumed 0.8 according to [14];
$T_{od\text{-}1}$, etc. are the daily mean outdoor temperature for the day before and the previous days before the measurement.

The clothing insulation was obtained from the lists of garments worn by students (obtained from questionnaires), associated with the thermal insulation defined by the ISO 9920 standard [26]. The total clothing insulation was calculated as the sum of the thermal insulation of each garment, as described in the ISO 7730 standard [27]:

$$I_{cl} = 0.83\cdot\sum_i I_{cl,i} + 0.161 \quad (2)$$

where

I_{cl} is the total clothing insulation (clo).
$I_{cl,i}$ is the clothing insulation of the single garment (clo).

The thermal insulation provided by chairs (0.1 clo) was also added to the total clothing insulation.

The metabolic rate (M) was evaluated considering the activities performed by the students during the lectures, considering the ISO 8996 standard [28].

Then, Fanger's PMV and PPD were calculated from the six basic parameters (T_a, T_r, V_a, RH, I_{cl}, and M) in line with the ISO 7730 standard [27].

The objective and subjective measurements were then processed to provide an association between the perception of the environment to which students were exposed.

Since students' location was available from questionnaires, their response was associated with the environmental parameters to which they were subjected at the time and in the position under consideration.

In total, 1377 samples of subjective responses associated with environmental parameters were collected.

3. Results

3.1. Monitored parameters

3.1.1. Objective measurements

Table 1 shows the statistical summary of the objective measurements associated with students' responses, considering the 1377 samples.

Regarding the running mean outdoor temperature, it was 5.8 °C higher for Italy than France.

Considering the indoor environment, the operative temperature in France was lower than in Italy, and the difference between the air and mean radiant temperature was low, showing that the environment was rather uniform. The mean relative humidity remained in the range of 45–50%. The air velocity was on average 0.0 m/s, with peaks of 0.8 m/s.

On average, the clothing insulation was the same in Italy and France, even if the highest values were recorded in Italy.

From the environmental and the individual parameters recorded the PMV and PPD indices were calculated. The mean PMV was attested to cold sensations, slightly lower for France (mean PMV = -0.8) and the mean percentage of dissatisfied expressed by PPD remained below 25%.

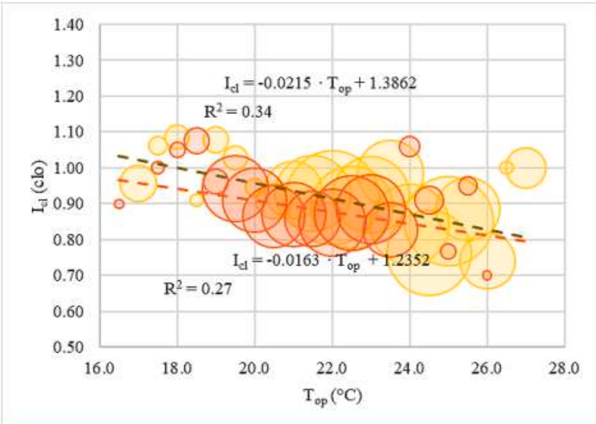


Fig. 2. Relationship between T_{op} and I_{cl} for Italy (in yellow) and France (in red). Legend: the centre of the circles corresponds to the T_{op}-I_{cl} couple value, while the diameter represents the sample size. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.1.2. Subjective measurements

Table 2 reports the mean and standard deviation of the subjective response of the students for the 1377 samples.

In France, the sample was equally distributed between males and females, while in Italy the number of males was slightly higher. The mean age was higher for Italian students (26 years old) in comparison to the French ones (22 years old).

Regarding thermal sensation (TSV), French students felt warmer than the Italian ones (TSV = -0.06 for Italy, and TSV = 0.21 for France), despite the French students being subjected to a colder indoor environment. To evaluate the possible influence of the masks on students' thermal perception, a Mann-Whitney *U* test was performed to assess whether the difference between the TSV of occupants with and without a mask was statistically significant. However, it resulted that the difference between the two is not statistically significant (p-value > 0.05), therefore the samples were treated jointly. For this reason, the clothing insulation of the protective mask was not added, as it may also be affected by the use of different types of masks (e.g. surgical masks, highly protective masks, etc.).

On average, students were feeling slightly uncomfortable regarding the thermal environment (TCV = 1.56 for Italy and TCV = 1.73 for France). All the students preferred a slightly warmer environment (TPV = 0.26 and TPV = 0.24 for Italy and France, respectively). The perceived control was generally low, especially for French students (PC = −1.00).

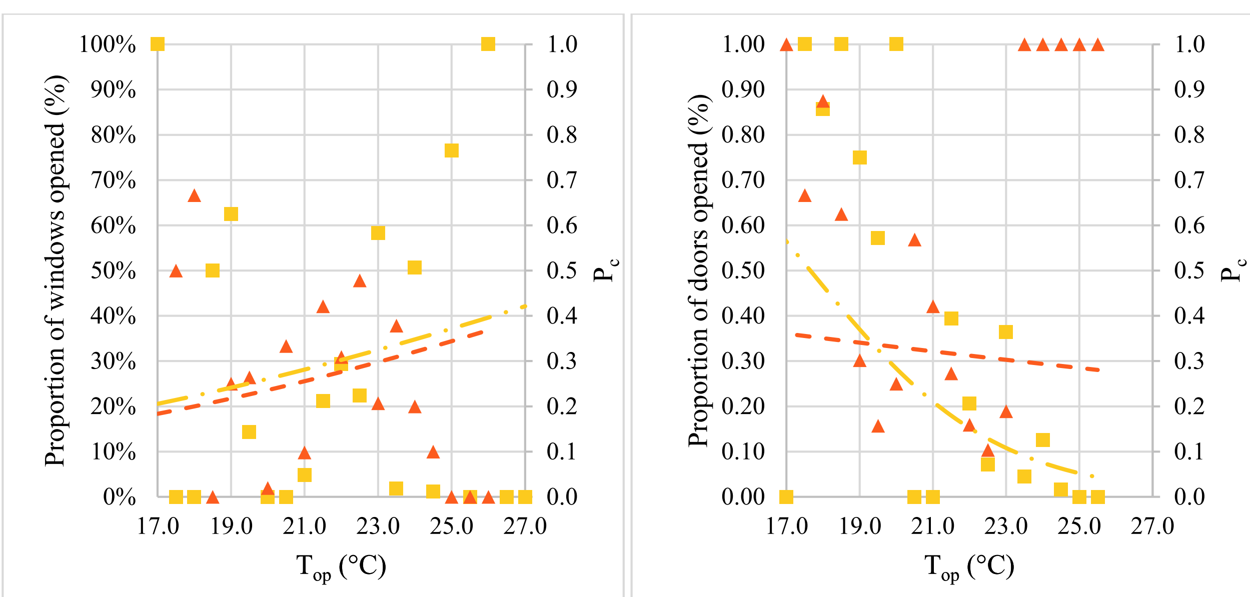
3.2. Adaptive opportunities in relation to climate

In this paragraph, the adaptive capacities that are possibly adoptable by students within the classroom are analysed. These include clothing behaviours, windows, and doors' operation, and perceived control, which are investigated as a function of the climate.

3.2.1. Clothing adaptive behaviours

To analyse the clothing adaptive behaviours, the relationship between the indoor clothing insulation (I_{cl}) obtained from questionnaires and the operative temperature (T_{op}) and running mean outdoor temperature (T_{rm}) was inspected (Fig. 2).

For the analysis, a typical binning method was used [10,29]. In particular, 0.5 °C increments in T_{op} were considered according to ISO 7726 [24], so that differences in subjective responses are attributable to a different thermal perception and not to any inaccuracies in the measurement. Then, to include the size of each bin in the regression model, a weighted linear regression between the T_{op} and the subjective responses was performed. This allows evaluating the thermal perception of a group of individuals subjected to certain environmental conditions,



$$P_{c,ITALY} = \frac{\exp(-3.11+0.10\cdot T_{op})}{1+\exp(-3.11+0.10\cdot T_{op})}, \text{Accuracy}=0.74$$

$$P_{c,FRANCE} = \frac{\exp(-3.29+0.11\cdot T_{op})}{1+\exp(-3.29+0.11\cdot T_{op})}, \text{Accuracy}=0.70$$

(a)

$$P_{c,ITALY} = \frac{\exp(6.97+0.40\cdot T_{op})}{1+\exp(6.97+0.40\cdot T_{op})}, \text{Accuracy}=0.82$$

$$P_{c,FRANCE} = \frac{\exp(0.17-0.40\cdot T_{op})}{1+\exp(0.17+0.40\cdot T_{op})}, \text{Accuracy}=0.70$$

(b)

Fig. 3. Proportion of windows (a) and doors (b) opened and P_c as a function of T_{op} for Italy (in yellow) and France (in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 3
Proposed regression equations (with R^2 and p-value), comfort temperatures and percentage of satisfied with and without perceived control.

Location		Regression equation	R^2	p-value	T_C (°C)	% Sat
Zone C	With perceived control (360*)	$\%Sat = -0.005 \bullet T_{op}^2 + 0.261 \cdot T_{op} - 2.117$	0.39	<0.05	24.2	96%
	Without perceived control (664)	$\%Sat = -0.013 \bullet T_{op}^2 + 0.638 \cdot T_{op} - 6.798$	0.78	<0.05	24.3	83%
Italy	With perceived control (254)	$\%Sat = -0.011 \bullet T_{op}^2 + 0.526 \cdot T_{op} - 5.160$	0.39	<0.05	23.7	94%
	Without perceived control (352)	$\%Sat = -0.015 \bullet T_{op}^2 + 0.789 \cdot T_{op} - 7.560$	0.69	<0.05	24.1	87%
France	With perceived control (106)	–	–	–	–	92%
	Without perceived control (312)	$\%Sat = -0.016 \bullet T_{op}^2 + 0.739 \cdot T_{op} - 7.741$	0.51	<0.05	23.5	79%

*The numbers between parenthesis represent the number of samples with and without perceived control.

accordingly to thermal comfort analysis. For the T_{rm}, 1.0 °C increments were considered. The dimension of the circles represents the relative weight of each bin.

As the campaigns were carried out during the normal operation of the classrooms, students were free to adapt.

Considering the relationship between T_{op} and I_{cl} (Fig. 2a), students experienced a wide range of operative temperatures in both climates (between 17 °C and 26 °C).

From the regression, the expected inverse relationship between I_{cl} and T_{op} was derived. All the regressions were significant (p-value < 0.05), and the R^2 was slightly higher for the Italian case. When analysing clothing insulation, high R^2 values cannot be expected [15], as there is always inter-individual variability in people's clothing preferences. However, the values obtained are promising and show a clear relationship between I_{cl} and T_{op}.

Given the slope of the regression, it can be noted that this is slightly higher for the Italian case, which means that the students in Italy tended to adapt more through changes in clothing than the French did.

Moreover, from the intercept of the regression, it is shown that Italian students wore higher insulating clothing than in France when subjected to the same indoor operative temperature.

Regarding the relationship between T_{rm} and I_{cl}, the regression is weaker than the one with the indoor operative temperature ($R^2 < 0.20$). This can be attributed to the fact that students directly experience indoor and not outdoor temperatures.

3.2.2. Windows and doors operation

Another behavioural adaptive opportunity is the possibility that occupants have to interact with their indoor environments through the modification of the openings' configuration, such as windows and doors. In the classrooms investigated, students were free to interact with windows and doors.

For the analysis of students' windows and doors operation, logistic regression was used. The Logit can be defined from the following relationship [15]:

$$LogitP_c = Log\left(\frac{P_c}{1 - P_c}\right) = c + d \cdot T \quad (3)$$

where

P_c is the probability that the windows or doors are opened, as a function of the temperature index (T), which is T_{op} for the indoor and T_{rm} for the outdoor environment,
c is the intercept of the Logit line.
d is the slope of the Logit line.

The values c and d are calculated from the data obtained from field studies, through logistic regression.

P_c can be expressed as [15]:

$$P_c = \frac{\exp(c + d \cdot T)}{1 + \exp(c + d \cdot T)} \quad (4)$$

For the regression, data were binned with steps of 0.5 °C of T_{op}, and 1 °C of T_{rm}.

Fig. 3 shows the probability that the windows (Fig. 3a) or doors (Fig. 3b) are opened as a function of the operative temperature. Furthermore, it shows the proportions of windows and doors opened at a certain T_{op}. They were considered open if at least one of them was opened, regardless of the degree of openness. This choice was made because the aim was not to assess the ventilation of the classrooms, but the interaction of students with doors and windows.

Considering Fig. 3a, it can be observed that windows remained closed regardless of the operative temperature, both in Italy and France. A slight tendency to open the windows as the temperature rises was detected, but P_c always remained below 0.5, which means that the windows were generally kept closed.

Fig. 3b shows the inverse trend for door operation because doors are closed as the temperature increases. However, in most cases, doors were kept closed regardless of the indoor operative temperature. It can be also noticed a difference between the Italian and the French situations. In Italy, doors tended to be opened at lower temperatures, while in France this trend is less evident. This shows a tendency of the French students to adapt less than the Italian ones, in line with the previous analysis on clothing insulation.

On the other hand, the relationship between window and door operation and T_{rm} did not lead to any significant relationships. In particular, there was just a greater tendency of Italian students than French ones to modify the windows and doors operation according to external conditions.

3.2.3. Effect of perceived control

Perceived control can be defined as the ability of occupants to recognise that they have the opportunity to control the environment and is part of psychological adaptation [3].

Perceived control refers to how students perceive their ability to modify environmental conditions to achieve comfort. This includes their perceptions regarding various adaptive capacities, including the possibility of changing the opening configuration of doors or windows, acting on HVAC systems, or changing their clothing. Whereas in previous cases the actual actions of the students to restore comfort (behavioural adaptation) were assessed, in this case, these control methods are not necessarily used.

To evaluate perceived control the 7-point PC scale was used, from −3 (no control) to + 3 (full control). From this, it was possible to divide the sample into people who perceived control of the environmental conditions (votes > 0) and others that did not (votes < 0). Students who voted 0 on the perceived control scale were excluded from the analysis, as they were considered not aware of the possibility to control the environment.

In total, 664 samples were without perceived control and 360 with perceived control, while 352 votes were excluded.

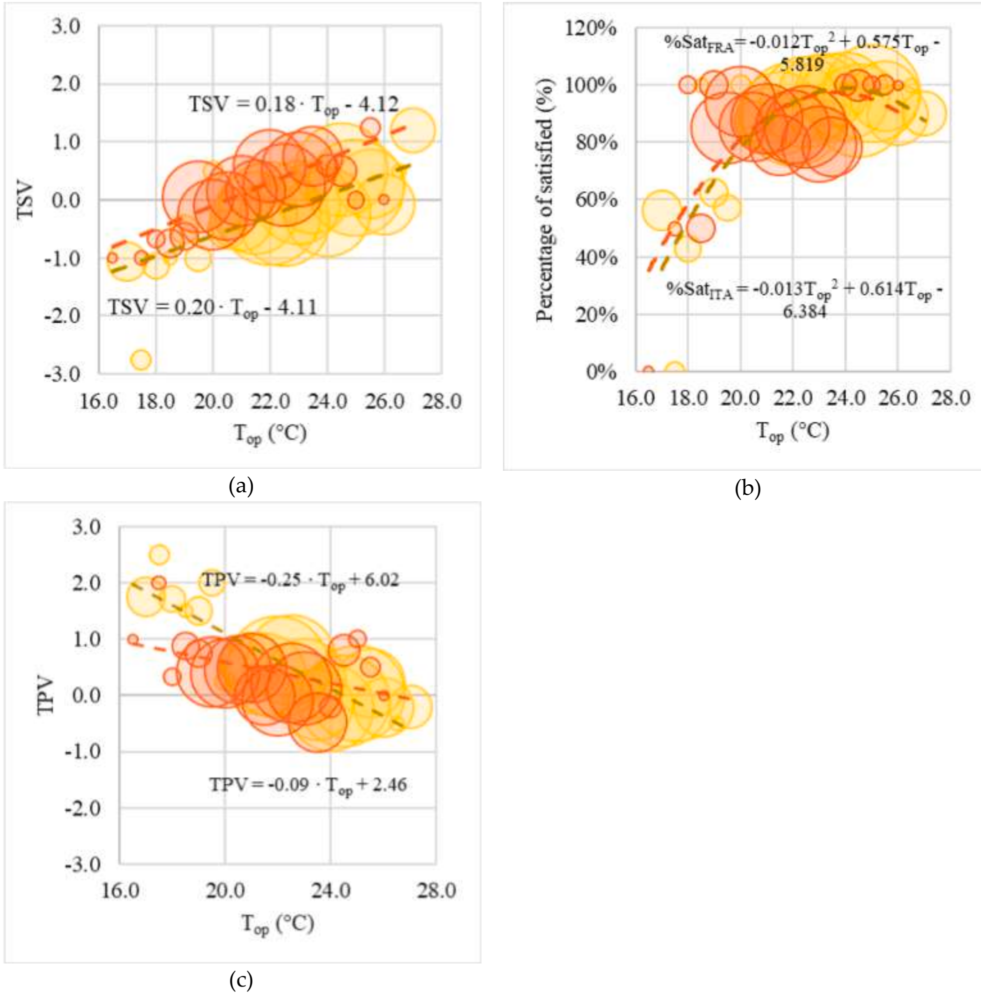


Fig. 4. Relationship between students' TSV (a), Percentage of satisfied (b), and TPV (c), and operative temperature for Italy (in yellow) and France (in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Proposed regression equations (with R^2 and p-value) and neutral, comfort, and preferred temperatures in Italian and French classrooms. In brackets the analysis considering non-binned data.

Location	Regression	R^2	p-value	T_N (°C)	T_C (°C)	T_P (°C)
Italy	$TSV = 0.1751 \cdot T_{op} - 4.1234$	0.64 (0.14)	< 0.05	23.6 (23.5)	24.0	24.1 (24.5)
	$\%Sat = -0.013 \cdot T_{op}^2 + 0.614 \bullet T_{op} - 6.384$	0.60	< 0.05			
	$TPV = -0.2454 \cdot T_{op} + 6.0165$	0.79 (0.18)	< 0.05			
France	$TSV = 0.2009 \cdot T_{op} - 4.1149$	0.68 (0.10)	< 0.05	20.5 (20.5)	23.7	27.3 (24.9)
	$\%Sat = -0.012 \cdot T_{op}^2 + 0.575 \bullet T_{op} - 5.819$	0.52	< 0.05			
	$TPV = -0.0934 \cdot T_{op} + 2.4615$	0.23 (0.04)	< 0.05			

The effect of perceived control was assessed considering students' thermal satisfaction, taking into account data of either zone C and Italy and France separately (Table 3).

The Percentage of satisfied (% Sat) was calculated from TCV, considering satisfied those who voted "Comfortable" or "Slightly uncomfortable".

The comfort temperature (T_C) was calculated by plotting a weighted quadratic regression between the T_{op} and the percentage of satisfied, assuming comfort temperature as the maximum of the curve (the operative temperature at which the satisfaction was the highest).

The regressions were all significant (p-value < 0.05), although the R^2 was lower for the subjects with perceived control. For the French case with perceived control, no regression was derived, as the students were generally satisfied.

The T_C was higher for the students without perceived control, although the difference was modest for zone C (0.1 °C) and higher for the Italian classes (0.4 °C).

Furthermore, a statistical Mann-Whitney-*U* test was carried out to compare TCV with and without perceived control for zone C, Italy, and France. It resulted that the difference between TCV with and without perceived control is statistically significant for the three cases (p-value < 0.01).

In general, there do not appear to be significant differences between different sub-climates. It can be noted, however, that although there are no substantial differences between the different sub-climates, the percentage of satisfied students with perceived control increased by about 10%, showing its importance in the perception of comfort.

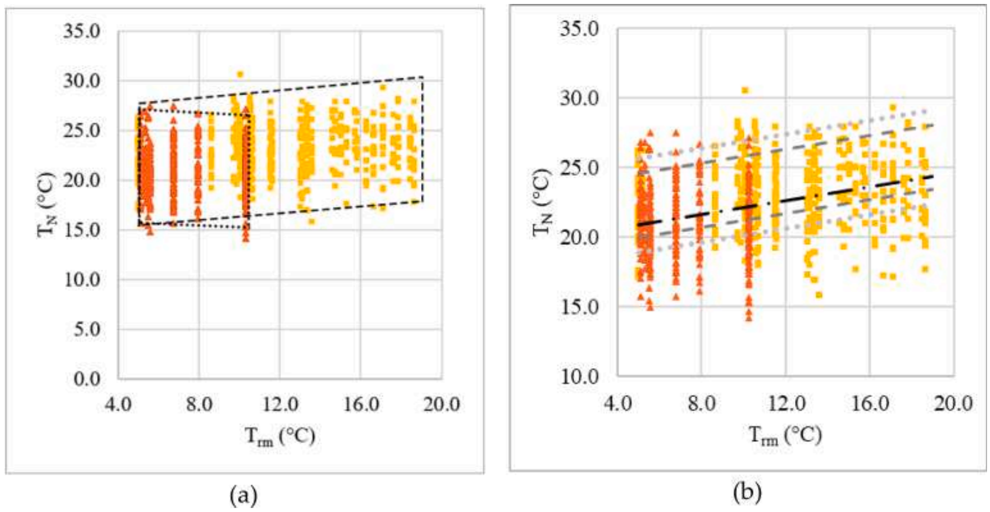


Fig. 5. Comfort clouds for Italy (yellow squares) and France (red triangles) (a). Relationship between T_{rm} and T_N (dashed and dotted line), 90% comfort range (dashed line), and 80% comfort range (dotted line) for the surveyed classrooms (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Defining thermal comfort in different climates

3.3.1. Calculation of neutral, comfort, and preferred temperatures

The neutral (T_N), comfort (T_C), and preferred (T_P) temperatures were evaluated (Fig. 4).

T_N and T_P were calculated from the linear weighted regression between T_{op} and TSV and TPV, respectively, by setting them to zero.

T_C was calculated by plotting a weighted quadratic regression between the T_{op} and the percentage of satisfied, assuming comfort temperature as the maximum of the curve (the operative temperature at which the satisfaction was the highest). The percentage of satisfied was calculated by considering satisfied the students voting "Comfortable" ([1]) or "Slightly uncomfortable" ([2]) on the TCV.

Data were binned considering 0.5 °C steps in operative temperature. All the regressions were statistically significant, and values of T_N, T_C, and T_P for Italy and France are resumed in Table 4.

From the analysis of the neutral and comfort temperatures, it is possible to highlight that they are dependent on the sub-climate to which students were subjected.

T_N for Italian students was 3.1 °C higher than for French students, while T_C was almost the same (only a 0.3 °C difference).

Regarding T_P, it was the highest and increased for French students. However, such a high temperature seems to be implausible in winter conditions (as is also evident from the lower R^2 of 0.23). This shows that students in winter conditions tend to express warmer temperature preferences.

As the number of male students in Italy was slightly higher than that of females, possible biases related to this issue were evaluated. By randomly reducing the number of male students to obtain the same ratio between males and females, the results remained unchanged.

3.3.2. Relationship between neutral temperature and climate

In this section, the aim was to understand whether the variation of neutral temperature as a function of sub-climate can be related to running mean outdoor temperature alone or whether there are additional factors on which it depends.

The neutral temperature was therefore calculated for each of the 1377 samples using Griffiths' method [30]. In this case, a Griffiths constant of 0.5 $°C^{-1}$ was chosen, according to SCAT's and ASHRAE databases [31]. This value was chosen because it is representative of a large number of studies, although Griffiths' constant for students should be investigated, as it is currently missing.

The difference between the T_{rm} in Italy and France was then compared by means of a Mann-Whitney *U* test, to assess if the differences between them were statistically significant. Since the temperature range in France was in a narrower range of T_N (5 °C to 10 °C), only samples from this range of external temperatures were compared.

The result was that the difference between the T_N in Italy and France was statistically significant (p-value < 0.01). By comparing the median values, it resulted that they are 22.1 °C for Italy and 21.0 °C for France. Applying the test to the whole sample, the same result was obtained.

The results show therefore that, considering thermal neutrality as a punctual condition, there are differences that cannot be explained by the T_{rm} alone.

However, it was demonstrated that comfort should not be considered a punctual condition but is instead referred to as "comfort clouds" [32] and a wide range of temperatures are comfortable for occupants [33].

The comfort clouds for the Italian and French cases were then analysed to understand whether, considering a comfort area, the climatic differences in neutral temperature can be explained by the T_{rm} (Fig. 5a). Fig. 5a shows a comfort cloud, so the dependent variable is the T_N calculated with Griffiths for each sample.

Removing the outliers (using Tukey's Fences method), the comfort clouds are very wide, about 11 K, which is consistent with the results found in the literature [32].

The lower adaptation of French students is also confirmed by the minor dependence of T_N on T_{rm}. However, it is notable that the two comfort clouds can be approximated into a single cloud comprising all the data. Studies on a wider range of T_{rm} for the French case should confirm this result.

Given the comfort clouds, it can be deduced that the different perceptions due to climate differences can be mainly expressed by the relationship between T_N and T_{rm}. For this reason, a relationship between T_N and T_{rm} was derived ($R^2 = 0.55$, p-value < 0.05):

$$T_N = 0.25 \cdot T_{rm} + 19.63 \quad (5)$$

This relationship is comparable to the original one developed for free-running buildings and included in the standard [14], even if it presents a lower slope.

It should be noted that this is not intended to be a new adaptive relationship, as more data would be needed to obtain it, but it allows us to show that there is the possibility of exploiting occupant adaptation also during winter.

Then, with the purpose to show the extent of the comfort clouds, the bands of comfort temperature corresponding to 90% and 80% of acceptability were calculated (Fig. 5b).

Table 5
Adaptive behaviours (regression, R^2 and p-value) for studies available in the literature.

Clothing adaptive behaviour					
Reference	**Location**	**Time of survey**	**Regression**	**Model performance**	**p-value**
Current study	Italy	Winter	$I_{cl} = -0.02 \cdot T_{op} + 1.39$	0.34	< 0.05
	France	Winter	$I_{cl} = -0.03 \cdot T_{op} + 1.47$	0.27	< 0.05
Mishra et al. [9]	India	Spring, Winter	$I_{cl} = -0.03 \cdot T_{op} + 1.47$	0.82	< 0.05
Jowkar et al. [34]	UK	Autumn, Winter	$I_{cl} = -0.03 \cdot T_{op} + 1.10$	0.69	–
			$I_{cl} = -0.03 \cdot T_{op} + 1.00$	0.61	
Kumar et al. [35]	India	Spring, Summer	$I_{cl} = -0.03 \cdot T_{op} + 1.35$	0.77	–
Wang et al. [10]	China	Spring, Autumn	$I_{cl} = -0.06 \cdot T_{op} + 2.37$	0.91	< 0.05
Windows operation					
Current study	Italy	Winter	$P_c = \frac{\exp(-3.11 + 0.10 \cdot T_{op})}{1 + \exp(-3.11 + 0.10 \cdot T_{op})}$	0.74	<0.05
	France	Winter	$P_c = \frac{\exp(-3.29 + 0.11 \cdot T_{op})}{1 + \exp(-3.29 + 0.11 \cdot T_{op})}$	0.70	<0.05
Kumar et al. [36]	India	Summer, Winter	$P_c = \frac{\exp(-3.43 + 0.12 \cdot T_g)}{1 + \exp(-3.43 + 0.12 \cdot T_g)}$	0.12	<0.05
Kumar and Singh [17]	India	Summer, Autumn, Winter	$P_c = \frac{\exp(-7.22 + 0.30 \cdot T_g)}{1 + \exp(-7.22 + 0.30 \cdot T_g)}$	0.14	<0.05
Wang et al. [10]	China	Spring, Autumn	$P_c = \frac{\exp(-13.64 + 0.61 \cdot T_{op})}{1 + \exp(-13.64 + 0.61 \cdot T_{op})}$	0.92	<0.05

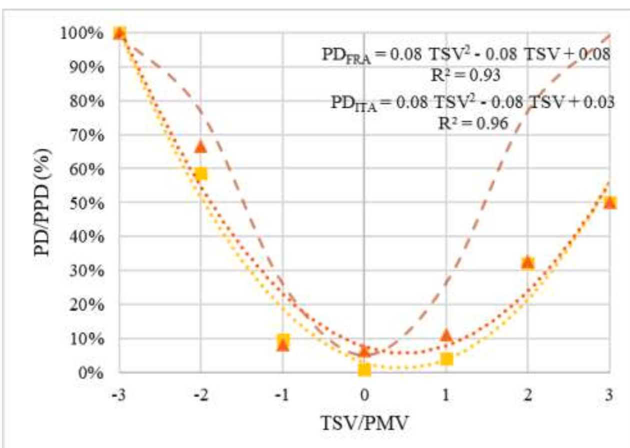


Fig. 6. Relationship between occupants' TSV and PD compared to the classic PMV-PPD for Italy (yellow squares) and France (red triangles). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For this investigation, the temperature difference between the operative temperature (T_{op}) and the neutral temperature (T_N) calculated with the previous equation was considered:

$$T_{diff} = T_{op} - T_N \tag{6}$$

Then, T_{diff} was related to the percentage of satisfied, obtained from the thermal comfort vote (TCV). Again, individuals voting [1] or [2] on TCV were considered satisfied.

From the resulting equation, it was possible to determine the temperature differences corresponding to 90% (minimum T_{diff} = -0.9, maximum T_{diff} = +3.7) and to 80% of satisfied (minimum T_{diff} = -2.0, maximum T_{diff} = +4.8). Fig. 5b shows that students are more tolerant to higher temperatures during winter, as the upper range of acceptability is larger than the lower range.

It can therefore be concluded that, if comfort were to be treated as a punctual condition, there are differences between the different sub-climates that cannot be explained by the trend in the T_{rm}.

If, on the other hand, comfort conditions are considered through comfort clouds, the sub-climatic differences can be explained by the T_{rm} and as it increases, the T_N also increases.

4. Discussion

4.1. Students' adaptive capacity in different climates

Students' adaptive capacity was analysed in terms of clothing behaviours, window and door operation, and perceived control.

Overall, French students adapted less than Italian ones during winter. This could be due to French students being more accustomed to colder conditions. Concerning windows and doors operation, as well as perceived control, the differences could be due to a higher occupancy of French classrooms.

Clothing behaviour was present for university students, despite some restrictions due to dress codes in this building type. Adaptation was mostly related to the indoor environment and its extent varied in relation to the sub-climate considered.

French students adapted less than Italians (lower slope) e wore lower insulating clothing (lower intercept). This shows that clothing adaptive behaviours are dependent on the climatic conditions to which the students are generally subjected.

This result is confirmed by the comparison with other studies carried out in universities (Table 5).

The intercept of the regression among studies was variable and was the lowest for the study by Jowkar et al. during the autumn–winter in the UK [34]. This confirms what was found in the present study, i.e. that occupants are used to lighter clothing in colder climates (as for French students).

The slope, showing the ability to modify clothing according to T_{op}, was the same for the studies of Mishra et al. [9], Kumar et al. [35], and Jowkar et al. [34] and was the highest for Wang et al. [10]. In the present study, clothing modification occurred to a lower extent.

This means that clothing modifications depend not only on indoor/outdoor temperatures but also on physiological and psychological aspects that alter the extent of adaptation, which depends on the environmental conditions that occupants usually experience.

Regarding **windows and doors operation**, for low T_{op} doors were opened and windows closed, which can be attributed to the student's preference for opening doors instead of windows to ensure classroom ventilation. This is confirmed by the inverse trend of keeping doors closed for high T_{rm} when windows were opened.

In literature, studies focused on the relationship between T_{op} and windows opening (Table 5). While in this work there was no evident relationship between the T_{op} and window operation, in other studies this was clear, and windows were opened at higher indoor temperatures [10

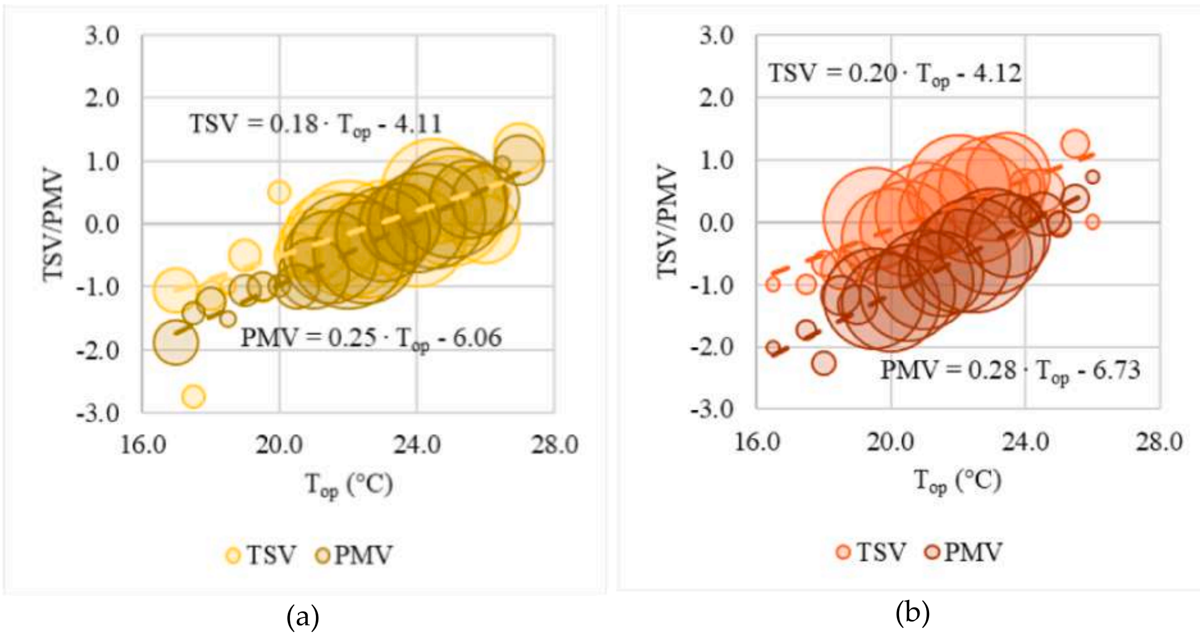


Fig. 7. Relationship between occupants' TSV/PMV and T_{op} for Italy (a) and France (b).

17,35].

This is an interesting result because it means that students tended not to adapt to the indoor environment, at least regarding window and door operation. This can be attributed to several causes, including the limited possibility of effectively acting on the window opening during the lesson, other constraints such as external noise, classroom occupancy, or a larger passivity to indoor conditions, as a higher relationship with T_{rm} was detected.

Considering **perceived control**, no relationship with sub-climates was detected, but generally, subjects with it were more satisfied and decreased comfort temperatures in winter.

These results are consistent with the studies available in the literature. Luo et al. [37] showed that perceived control reduces discomfort complaints, Xu and Li [38] demonstrated that during winter the neutral temperatures in buildings with perceived control were lower than the ones without it, and Torriani et al. [3] highlighted that the neutral temperatures in the heating period were 0.5 °C lower for students with perceived control.

These results highlight the importance to provide control in buildings, improving satisfaction, and reducing energy consumption.

4.2. Relationship between thermal neutrality, comfort, and preference in different climates

Thermal comfort often refers to the temperature at which occupants achieve thermal neutrality, which is highly dependent on the sub-climate. This study confirms that there is a 3.1 °C reduction in neutral temperature for France compared to Italy, despite they being in the same Köppen-Geiger zone C. These differences must be taken into account in both design and standards for a matter of comfort and consumption.

The neutral temperatures found are consistent with other European studies, which show ranges between 18.5 °C and 24.5 °C [11], confirming the differences present in the same Köppen Geiger climate zone [8].

The neutral temperatures for Pisa are consistent with those found in other studies in Italian university classrooms during the heating season, which was 24.6 °C [20] and 23.0 °C [21], demonstrating that T_N is climate-dependent. It was not possible to compare the French results as they were not available in the literature.

The difference between T_N, T_C, and T_P obtained from the TSV, TCV, and TPV scales respectively was then analysed, and it emerged that their differences are significant. In the French case, T_P is 6.8 °C higher than T_N, and its high value (27.3 °C) seems implausible for winter conditions.

A comparison with existing studies has shown that in cold climates (or during the heating period) occupants prefer higher temperatures than T_N [39], whereas in hot climates they prefer lower temperatures [40,41].

This shows the implausibility of using T_P for setting HVAC systems, as it would lead to an unjustified increase in consumption and possible discomfort.

T_C was also higher than T_N, showing the suitability of using the neutral temperature for setting HVAC systems. Despite this, the use of the TCV scale is indicated for the evaluation of the percentage of satisfied, since there is no perfect symmetry between the percentage of satisfied/dissatisfied and TSV, as will be shown in the next section.

Considering the relation between neutral temperatures and the running mean outdoor temperature, in literature, a relationship for European classrooms is currently missing [11].

Furthermore, only one study [42] derived a relationship between T_N and T_{rm} during the heating period in South Korea. In this study, the slope of the regression was higher than in the present work (0.42 instead of 0.25), probably due to differences such as socio-cultural background, etc.

Comparing the relationship derived by Singh for all university classes available in the literature [11], the differences in the slope are smaller (0.30 instead of 0.25).

It means that the adaptation found for our classes is not very dissimilar to that of universities in general, even over a longer survey period and in different climates. It is therefore reasonable to extend the adaptive relationships for lower T_{rm}.

Clearly, the relationship developed in Fig. 5 cannot be considered an adaptive model, since it is based on a limited period (winter period in Europe), but it is essential to show how adaptation can also be exploited during the heating season.

4.3. Comparison with Fanger's rational model

For the comparison, the relationship between TSV and the Percentage of Dissatisfied (PD) was analysed and compared to the typical PMV-PPD model (Fig. 6). PD was calculated from TCV as shown in paragraph 3.3.1.

The minimum percentage of dissatisfied was lower than the 5% given by Fanger and reached almost zero for a slightly warm thermal sensation. It means that students during winter were more accepting the warm sensations than cold ones. This could be a similar effect to that found for TPV, where students preferred higher temperatures to T_N.

Furthermore, the relationship is not symmetrical, showing again how students accepted more the thermal sensation of warmth than cold.

It is interesting to remark, however, that the relationships found between TSV and PD for the Italian and French cases have a minimum at the same point, i.e. for TSV between 0 and 1. Based on the results of the present study, for the sub-climates considered during the heating season, the relationship between the thermal sensation and the Percentage of Dissatisfied does is not symmetrical and reaches the minimum for slightly warm sensations.

Then, the relationship between the predicted and observed comfort temperatures was analysed. The neutral temperatures were evaluated through the weighted regression analysis between the operative temperature and the predicted (PMV) and observed (TSV) thermal sensation, binning data for 0.5 °C steps of operative temperature (Fig. 7).

The regressions were all significant (p-value < 0.05, $R^2 = 0.97$ for PMV, $R^2 = 0.64$, and $R^2 = 0.68$ for TSV in Italy and France, respectively).

The slope of the regression was lower for TSV, showing that people tend to adapt to their usually experienced thermal environments, and therefore they are more thermally neutral than the PMV predicts.

Regarding the neutral temperatures, the PMV tended to predict higher neutral temperatures than the TSV, and the calculated neutral temperatures were:

- 24.2 °C for PMV and 23.6 °C for TSV in Italy
- 24.0 °C for PMV and 20.5 °C for TSV in France

The difference in neutral temperatures is particularly evident for France ($\Delta T_N = 3.5$ °C), where the outdoor conditions were colder, and less for Italy ($\Delta T_N = 0.6$ °C). This is further evidence of the influence of the outdoor environment on thermal comfort.

This means that using PMV as an index for assessing thermal comfort and setpoint temperatures can lead to an overestimation of the neutral thermal sensation in the winter case, with consequent discomfort and an increase in energy consumption.

4.4. Limitations and future studies

This study investigated the influence of climate on students' thermal comfort and provided results that can be useful to deploy their thermal adaptation. However, some limitations are present and further studies are needed.

First, in the present study, it was possible to analyse the comfort clouds, but more samples (also extended for wider T_{rm}) are needed to derive an adaptive model for school buildings. Students in fact present different needs and preferences compared to other building types that should be analysed.

Second, the adaptive actions may have been inhibited by the COVID-19 pandemic situation. Indeed, the survey was carried out during the pandemic, when people were more aware of the need for ventilating classrooms. Even if the expectation is that attention to air quality will not decrease in the future, this may have affected the window and door operation.

Third, Griffiths' method was used to derive comfort clouds. Although this is a widely used method in the literature, recent investigations have shown that Griffiths' constant may in fact be variable [43,44]. However, as no studies defining a constant for university classrooms are currently available, it was deemed reasonable to use the value of 0.5 $°C^{-1}$ (a value widely used in the literature) to derive comfort clouds. Future studies could analyse thermal sensitivity by deriving Griffiths' constant in school buildings.

Finally, this study showed how climatic conditions can influence students' thermal perception, especially by reducing thermal neutrality in colder climates. This can have consequences on the management of HVAC systems and therefore on the reduction of energy consumption by linking the indoor setpoint temperatures to the running mean outdoor temperatures. Future studies should quantify these energy savings.

5. Conclusive remarks

This study investigated the effect of sub-climates on thermal comfort, analysing Italian and French university classrooms and collecting 1377 samples of subjective responses associated with measured environmental parameters.

The main results can be summarised in the following points:

1. Adaptive capacities (clothing behaviours, windows and doors' operation, and perceived control) change according to the sub-climate. Despite colder indoor conditions, French students adapted less than Italian students. This suggests that there is a different perception of thermal sensation depending on the environmental conditions students are generally subjected to.
2. The neutral temperatures were affected by the outdoor climate, and they significantly reduced in the French colder climate compared to the Italian one, as much as 3.1 °C, despite French students presenting less adaptive capacities.
3. Students preferred warmer conditions and were satisfied at temperatures above neutrality ($T_N = 23.6$ °C, $T_C = 24.0$ °C, $T_P = 24.1$ °C in Italy and $T_N = 20.5$ °C, $T_C = 23.7$ °C, $T_P = 27.3$ °C in France).
4. The adaptive capacities of the students can be also deployed in the winter period (even for outdoor temperatures below the 10 °C suggested by the standards).
5. The presence of sub-climate-dependent adaptation is evident in the comparison with the PMV-PPD model. T_N in winter conditions calculated with PMV are higher than those obtained from TSV and the difference increases for colder climates ($\Delta T_{N,ITALY} = 0.6$ °C; $\Delta T_{N,FRANCE} = 3.5$ °C).
6. There are differences between neutral temperatures that cannot be explained by the TSV alone but depend on a different perception of the environment linked to the environmental conditions to which students are usually subjected. The differences between Italian and French T_N are statistically significant (p-value < 0.01) and the median values of the T_N were 22.1 °C for Italy and 21.0 °C for France.
7. However, there is a strong relationship between thermal comfort and the T_{rm} and to account for inter-individual differences, it is necessary to consider comfort clouds.

5.1. Future implications

The differences in thermal perception within the two sub-climates considered show that it is indeed complex to define "comfort for all" because even in close sub-climates there are substantial differences, especially in terms of thermal neutrality.

In fact, within the same climatic zone (Zone C), the variations in thermal adaptation and perception are particularly high. Contrary to what is usually reported in the literature, the assessment of indoor comfort requires the evaluation of differences related to sub-climates and not only the macro-categories defined according to the Koppen-Geiger classification. This has repercussions on the setting of HVAC systems, which should be modified according to the differences found, in order to improve comfort and reduce energy consumption.

Furthermore, it is crucial not to consider comfort as a punctual condition, as it is highly dependent on the variability of inter-individual perception. The ranges defined by PMV are too narrow to accurately predict occupants' thermal sensations, even considering the mean thermal sensation rating of a group of people.

To ensure comfort and reduce energy consumption, it is necessary to consider comfort clouds, which do not depend on the sub-climate, defined through the running mean outdoor temperature.

By moving within these comfort clouds, possibly with the addition of Personal Comfort Systems, winter setpoint temperatures can be reduced to the lower limit to decrease energy consumption while preserving comfort.

Finally, it is necessary to consider winter adaptation, as this study showed that it also occurs during the heating season below the 10 °C T_{rm} that is generally indicated. Future studies should focus on this issue to obtain an adaptive relationship that considers winter adaptation.

Funding

This research was partially funded by University of Pisa, within the program PRA 2022, competitive call for the financial support to multi-disciplinary research projects developed at the university Pisa (ID research project PRA_2022_70.

CRediT authorship contribution statement

Giulia Lamberti: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Francesco Leccese:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Giacomo Salvadori:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Francesca Contrada:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Andrea Kindinis:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Characteristics of the classrooms

In this appendix, the characteristics of the classrooms are reported. Tables A1 and A2 show data on the building, classroom, doors, windows, ventilation type, and heating system for the Italian and French cases, respectively. Figs. A1 and A2 display the external view of the different buildings and the indoor configuration of the probes during the monitoring campaign.

Table A1
Characteristics of the selected university classrooms located in Pisa.

		U1	U2	U3	U4	U5	U6	U7	U8	U9
Building		Polo A	Polo A	Polo A	Polo B	Polo B	Polo C	Polo F	Polo PN	Polo PN
Classroom	Classroom type	Teaching room	Teaching room	Drawing Lab	Teaching room	Computer Lab	Teaching room	Teaching room	Drawing Lab	Teaching room
	Classroom orientation	East	North	North	South	South	West	North	South	North
	Floor	1	2	2	2	0	4	0	0	0
	Seats	109	50	70	40	75	82	139	100	198
	Width (m)	7.2	8.2	6.7	8.5	10.6	5.8	9.7	14.7	9.8
	Length (m)	11.9	8.6	21.4	4.7	17.9	7.4	13.0	15.8	14.5
	Height max (m)	5.6	3.2	2.6	2.9	2.9	2.9	3.6	4.5	7.5
	Floor area (m^2)	85.7	70.5	143.4	40.0	189.7	42.9	126.1	210.4	142.1
	Volume (m^3)	476	228	371	116	550.1	124.4	438.0	955.0	1000
Doors	N° of doors	2	1	4	1	1	1	4[1]	2	2[2]
	Total door surface (m^2)	6.2	3.0	12.0	2.2	2.5	4.5	11.8	6.3	7.2
Windows	N° of openable windows	3	3	5	2	7	3	2	5	8
	Total window surface (m^2)	11.4	10.8	18	6.8	24.5	6.9	3.6	5.4	6.5
	Window frame	Wood	Wood	Wood	Metal	Metal	Metal	Metal	Metal	Metal
	Type of glass	Single	Single	Single	Single	Single	Single	Double	Double	Double
	Shading system	Curtains	–	–	External	External	External	–	Curtains	–
Ventilation	Ventilation system	NV	NV	NV	NV	NV	NV	NV	NV	NV
Heating	Heating system	Radiators	Radiators	Radiators	Radiators	Radiators	Radiators	Air system	Air system	Air system
	Heating control	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Manual

[1]Two doors are towards the outside, two towards the corridor.
[2]One door is towards the outside, one towards the corridor.

Table A2
Characteristics of the selected university classrooms located in Cachan.

		U10	U11	U12	U13	U14	U15	U16	U17
Building		Colbert	Vauban	Laplace	Vauban	Colbert	Vauban	Galilee	Recherche
Classroom	Classroom's type	Amphi	Teaching room	Teaching room	Teaching room	Teaching room	Teaching room	Amphi	Amphi
	Classroom's orientation	North-West	East	North	East	North-East	East	West-North-East	North-West
	Floor	1	1	2	1	0	1	1	−1
	Seats	212	33	50	90	62	90	240	313
	Width (m)	11.5	10.8	8.2	9.9	9.0	9.9	14.9	16.2
	Length (m)	15.9	7.9	9.8	13.0	12.9	13	17.7	17.5
	Height max (m)	3.7	2.7	2.6	2.7	2.8	2.7	2.9	3.3
	Floor area (m^2)	183.4	85.3	79.7	128.7	111.1	128.7	227.1	278.3
	Volume (m^3)	623.3	230.4	203.3	347.5	306.6	347.5	613.5	835.9
Doors	N° of doors	3[1]	2	2	2	2	2	5[2]	4[3]
	Total door surface (m^2)	8.4	3.6	4.6	4.6	10.73	4.6	10.25	11.2
Windows	N° of openable windows	2	3	2	4	5	4	10	0
	Total window surface (m^2)	2.4	3.9	4.8	5.2	6.4	5.2	9.02	–
	Window frame	Metal	Metal	Metal	Metal	Metal	Metal	Metal	–
	Type of glass	Double glass	Double glass	Double glass	Double glass	Double glass	Double glass	Double glass	–
	Shading system	Completely shaded	Curtains	Curtains	Curtains	–	Curtains	Curtains	–
Ventilation	Ventilation system	NV	NV	NV	NV	NV	NV	NV	NV
Heating	Heating system	Air system	Radiators	Radiators	Radiators	Radiators	Radiators	Radiators	Radiators
	Heating control	Central	Manual	Manual	Manual	Manual	Manual	Manual	Manual

[1]One door is towards the outside (very permeable), one to the corridor and the last one to a technical room.
[2]One door is towards the outside, one towards the corridor and three towards other rooms.
[3]Two doors are towards the corridor and two towards the outside.

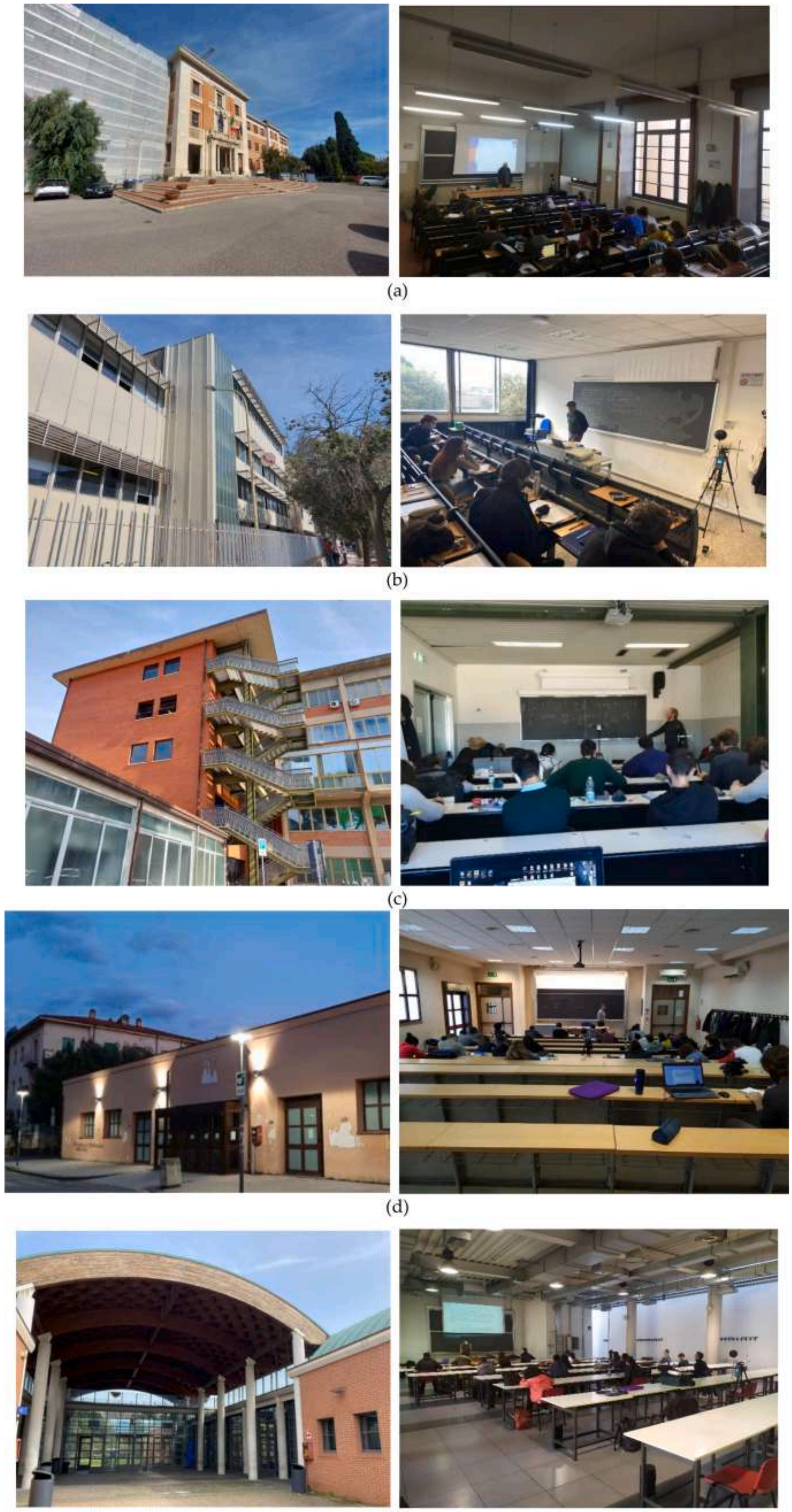


Fig. A1. Pictures of the university buildings located in Pisa and of standard classrooms of the “Polo A” (a), “Polo B” (b), “Polo C” (c), “Polo F” (d), and “Polo PN” (e).

Fig. A2. Pictures of the university buildings located in Cachan and of standard classrooms of “Colbert” (a), “Galilee” (b), “Laplace” (c), “Recherche” (d), and “Vauban” (e).

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2023.113227.

References

[1] P. Wargocki, D.P. Wyon, Providing better thermal and air quality conditions in school classrooms would be cost-effective, Build. Environ. 59 (Jan. 2013) 581–589, https://doi.org/10.1016/j.buildenv.2012.10.007.

[2] S. Sadrizadeh, et al., Indoor air quality and health in schools: A critical review for developing the roadmap for the future school environment, J. Build. Eng. 57, p. 104908, Oct. 2022, doi: 10.1016/j.jobe.2022.104908.

[3] G. Torriani, G. Lamberti, F. Fantozzi, F. Babich, Exploring the impact of perceived control on thermal comfort and indoor air quality perception in schools, J. Build. Eng. (2022) 105419, https://doi.org/10.1016/j.jobe.2022.105419.

[4] P.O. Fanger, Thermal comfort. Analysis and applications in environmental engineering, Danish Technical Press, McGraw-Hill, Copenhagen, 1970.

[5] G.S. Brager, R.J. de Dear, Thermal adaptation in the built environment: a literature review, Energ. Build. 27 (1) (Feb. 1998) 83–96, https://doi.org/10.1016/S0378-7788(97)00053-4.

[6] Z.S. Zomorodian, M. Tahsildoost, M. Hafezi, Thermal comfort in educational buildings: A review article, Renew. Sustain. Energy Rev. 59 (Jun. 2016) 895–906, https://doi.org/10.1016/j.rser.2016.01.033.

[7] N.H. Wong, S.S. Khoo, Thermal comfort in classrooms in the tropics, Energ. Build. 35 (4) (May 2003) 337–351, https://doi.org/10.1016/S0378-7788(02)00109-3.

[8] G. Lamberti, G. Salvadori, F. Leccese, F. Fantozzi, P.M. Bluyssen, Advancement on Thermal Comfort in Educational Buildings: Current Issues and Way Forward, Sustainability 13(18) (2021), doi: singh.

[9] A.K. Mishra, M. Ramgopal, Thermal comfort in undergraduate laboratories — A field study in Kharagpur, India, Build. Environ. 71 (Jan. 2014) 223–232, https://doi.org/10.1016/j.buildenv.2013.10.006.

[10] X. Wang, L. Yang, S. Gao, S. Zhao, Y. Zhai, Thermal comfort in naturally ventilated university classrooms: A seasonal field study in Xi'an, China, Energ. Build. 247 (Sep. 2021), 111126, https://doi.org/10.1016/j.enbuild.2021.111126.

[11] M.K. Singh, R. Ooka, H.B. Rijal, S. Kumar, A. Kumar, S. Mahapatra, Progress in thermal comfort studies in classrooms over last 50 years and way forward, Energ. Build. 188–189 (2019) 149–174, https://doi.org/10.1016/j.enbuild.2019.01.051.

[12] H.E. Beck, N.E. Zimmermann, T.R. McVicar, N. Vergopolan, A. Berg, E.F. Wood, Present and future Köppen-Geiger climate classification maps at 1-km resolution, Sci. Data 5 (2018), pp. 180214–180214, doi: 10.1038/sdata.2018.214.

[13] ASHRAE, ANSI/ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy, 2004.

[14] EN 16798-1, Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, 2019.

[15] M. Humphreys, F. Nicol, R. S., Adaptive Thermal Comfort: Foundations and Analysis, Routledge, London, 2016. [Online]. Available: https://doi.org/10.4324/9781315765815.

[16] F. Nicol, M. Humphreys, R. S., Adaptive Thermal Comfort: Principles and Practice, Routledge, London, 2012, p. 175. doi: 10.4324/9780203123010.

[17] S. Kumar, M.K. Singh, Seasonal comfort temperature and occupant's adaptive behaviour in a naturally ventilated university workshop building under the composite climate of India, J. Build. Eng. 40 (Aug. 2021), 102701, https://doi.org/10.1016/j.jobe.2021.102701.

[18] P.F. Hu, W. Liu, Z. Jiang, Study on indoor thermal sensation of young college students in the area which is hot in summer and cold in winter, 2008.

[19] Z. Wang, H. Ning, X. Zhang, Y. Ji, Human thermal adaptation based on university students in China's severe cold area, Sci. Technol. Built Environ. 23 (3) (2017) 413–420.

[20] 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 (4) (Apr. 2009) 785–792, https://doi.org/10.1016/j.buildenv.2008.05.023.

[21] C. Buratti, P. Ricciardi, Adaptive analysis of thermal comfort in university classrooms: Correlation between experimental data and mathematical models, Build. Environ. 44 (4) (Apr. 2009) 674–687, https://doi.org/10.1016/j.buildenv.2008.06.001.

[22] 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, Energ. Build. 43 (5) (May 2011) 1051–1056, https://doi.org/10.1016/j.enbuild.2010.09.025.

[23] D.K. Serghides, C.K. Chatzinikola, M.C. Katafygiotou, Comparative studies of the occupants' behaviour in a university building during winter and summer time, Int. J. Sustain. Energ. 34 (8) (2015) 528–551.

[24] ISO 7726, Ergonomics of the thermal environment – Instruments for measuring physical quantities, 2001.

[25] ISO 28802, Ergonomics of the physical environment - Assessment of environments by means of an environmental survey involving physical measurements of the environment and subjective responses of people, 2012.

[26] ISO 9920, Ergonomics of the thermal environment. Estimation of thermal insulation and water vapour resistance of a clothing ensemble, 2009.

[27] 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, 2006.

[28] ISO 8996, Ergonomics of the thermal environment - Determination of metabolic rate, 2005.

[29] R.J. de Dear, G.S. Brager, Developing an adaptive model of thermal comfort and preference, ASHRAE Trans. 104 (1998) 1–18.

[30] I. Griffiths, Thermal Comfort Studies in Buildings with Passive Solar Features. Field Studies, 1990.

[31] M.A. Humphreys, H.B. Rijal, J.F. Nicol, Updating the adaptive relation between climate and comfort indoors; new insights and an extended database, Build. Environ. 63 (May 2013) 40–55, https://doi.org/10.1016/j.buildenv.2013.01.024.

[32] F. Nicol, Temperature and adaptive comfort in heated, cooled and free-running dwellings, Build. Res. Inf. 45 (7) (Oct. 2017) 730–744, https://doi.org/10.1080/09613218.2017.1283922.

[33] F. Nicol, H. Bahadur Rijal, H. Imagawa, R. Thapa, The range and shape of thermal comfort and resilience, Energ. Build. 224 (2020) 110277.

[34] M. Jowkar, H.B. Rijal, J. Brusey, A. Montazami, S. Carlucci, T.C. Lansdown, Comfort temperature and preferred adaptive behaviour in various classroom types in the UK higher learning environments, Energ. Build. 211 (Mar. 2020), 109814, https://doi.org/10.1016/j.enbuild.2020.109814.

[35] S. Kumar, M.K. Singh, A. Mathur, J. Mathur, S. Mathur, Evaluation of comfort preferences and insights into behavioural adaptation of students in naturally ventilated classrooms in a tropical country, India, Build. Environ. 143 (Oct. 2018) 532–547, https://doi.org/10.1016/j.buildenv.2018.07.035.

[36] S. Kumar, J. Mathur, S. Mathur, Adaptive use of environmental controls in composite climate of India, 2016.

[37] M. Luo, B. Cao, W. Ji, Q. Ouyang, B. Lin, Y. Zhu, The underlying linkage between personal control and thermal comfort: Psychological or physical effects? Energ. Build. 111 (Jan. 2016) 56–63, https://doi.org/10.1016/j.enbuild.2015.11.004.

[38] C. Xu, S. Li, Influence of perceived control on thermal comfort in winter, A case study in hot summer and cold winter zone in China, J. Build. Eng. 40 (Aug. 2021), 102389, https://doi.org/10.1016/j.jobe.2021.102389.

[39] 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, Energ. Build. 53 (Oct. 2012) 166–182, https://doi.org/10.1016/j.enbuild.2012.06.022.

[40] R.-L. Hwang, T.-P. Lin, N.-J. Kuo, Field experiments on thermal comfort in campus classrooms in Taiwan, Energ. Build. 38 (1) (Jan. 2006) 53–62, https://doi.org/10.1016/j.enbuild.2005.05.001.

[41] N.S.M. Taib, et al., Associating thermal comfort and preference in Malaysian universities' air-conditioned office rooms under various set-point temperatures, J. Build. Eng. 54 (2022), p. 104575, doi: 10.1016/j.jobe.2022.104575.

[42] G.J. Jung, S.K. Song, Y.C. Ahn, G.S. Oh, Y.B. Im, Experimental research on thermal comfort in the university classroom of regular semesters in Korea, J. Mech. Sci. Technol. 25 (2) (Feb. 2011) 503–512, https://doi.org/10.1007/s12206-010-1219-1.

[43] R.F. Rupp, J. Kim, E. Ghisi, R. de Dear, Thermal sensitivity of occupants in different building typologies: The Griffiths Constant is a Variable, Energ. Build. 200 (Oct. 2019) 11–20, https://doi.org/10.1016/j.enbuild.2019.07.048.

[44] J. Ryu, J. Kim, W. Hong, R. de Dear, Defining the thermal sensitivity (Griffiths constant) of building occupants in the Korean residential context, Energ. Build. 208 (Feb. 2020), 109648, https://doi.org/10.1016/j.enbuild.2019.109648.