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Investigating students' subjective comfort with window-airing during the cold season: Thermal sensation, humidity, air movement, and perceived air quality

Sen Miao [*], Marta Gangolells, Blanca Tejedor

Department of Project and Construction Engineering, Group of Construction Research and Innovation (GRIC), Universitat Politècnica de Catalunya, C/ Colom, 11, Ed. TR5, Terrassa (Barcelona) 08222, Spain

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ABSTRACT

Balancing the need for indoor air quality and thermal comfort during cold seasons is challenging for naturally ventilated schools. For students' health concerns, opening windows to ventilate during class time could be inevitable in winter, especially during flu season. However, there is a lack of field studies investigating its potential impacts on students' comfort. In this context, this study investigated students' subjective comfort with window airing in winter through a field study in the Mediterranean climate, with a total of 34 field experiments with different window opening scenarios conducted in two university classrooms. The study analyzed the effect of thermal sensation, humidity, air movement, and perceived air quality on students' comfort and identified correlated environmental parameters. The results showed that students' comfort was mainly determined by thermal sensation and air movement, while they were not very sensitive to indoor humidity and air quality. Their thermal sensation was found to be directly determined by the indoor temperature and not correlated with the outdoor temperature. Achieving the required ventilation rate would not cause obvious discomfort in terms of air movement. Moreover, the study validated 4 main adaptive PMV models (nPMV, adPMV, arPMV, and e_{pm}PMV) and found them to be ineffective with forced window openings. The proposed comfort prediction model suggests that to meet the ventilation rate requirement, the indoor temperature should be maintained above 21 °C to avoid causing thermal discomfort problems. The specific practical recommendations are given in the conclusions.

1. Introduction

The main goal of educational buildings is to provide students with a favorable learning environment [1]. Indoor air quality and thermal comfort are the key aspects of indoor environmental quality that affect students' well-being, productivity, and learning performance [1,2]. The experience of the COVID-19 pandemic has made the public, government, and education community aware of the importance of maintaining good air quality in classrooms [3,4]. Nevertheless, most schools are not equipped with mechanical ventilation systems and rely entirely on natural ventilation to maintain indoor air quality [5]. Previous studies have highlighted the challenge of balancing indoor air quality and thermal comfort needs in these naturally ventilated schools, especially during cold seasons [3,6].

In naturally ventilated classrooms, poor air quality has been frequently reported during cold seasons due to inadequate ventilation [6–9]. It is usually believed that occupants are unwilling to open windows for their comfort reasons, as the exchange of indoor and outdoor air could affect indoor thermal conditions [6,10,11]. However, recent studies have emphasized the importance of opening windows during the occupied period (class time) in the classroom, because window-airing does not always provide the required ventilation rate due to the uncertainty of natural ventilation, and short-term ventilation during class breaks cannot effectively renew the stale air in the space [12,13].

Abbreviations: TSV, thermal sensation vote; HSV, humidity sensation vote; AMV, air movement vote; AQV, air quality vote; CV, comfort vote; T_{op}, operative temperature; T_{out}, outdoor air temperature; T_{rm}, running mean temperature; RH, indoor relative humidity; RH_{out}, outdoor relative humidity; V_a, indoor air velocity; V_w, wind speed; V_d, wind direction; CO_2, indoor CO_2 concentration; $CO_{2\text{-}out}$, outdoor CO_2 concentration; VOC, volatile organic compound; WOA, window opening area; ACH, air change rate; OCR, occupancy ratio; MAE, mean absolute error; MLR, multiple linear regression.

* Corresponding author.
E-mail address: sen.miao@upc.edu (S. Miao).

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Therefore, opening windows to ventilate during class time could be unavoidable in winter, especially during the flu season when indoor air quality is given priority to avoid the risk of infection from respiratory diseases [9,13]. In this context, it is necessary to consider the potential impact of window-airing on students' comfort.

The study of thermal comfort in naturally ventilated schools during the cold season is not a new topic [14–18]. However, most studies have mainly focused on assessing the indoor thermal conditions and students' thermal sensations [19–23]. There is a limited number of studies that shed light on the relationship between ventilation and thermal comfort. Based on two years of field monitoring in a Portuguese secondary school, Duarte et al. [24] concluded that window-airing would not significantly affect thermal comfort when the outdoor running mean temperature is above 16 °C. Lovec et al. [25] studied a Slovenian kindergarten during winter and found that the higher the ventilation rate, the worse the indoor thermal conditions. Monge-Barrio et al. [26] conducted a field study in Spanish secondary schools in winter and discovered that the indoor temperature was acceptable (18 °C on average) even with forced ventilation protocols. Miranda et al. [4] conducted a field investigation in a Spanish university in winter. They found that natural ventilation had no decisive influence on comfort when the outdoor temperature was above 12 °C. Ding et al. [12] investigated secondary schools in The Netherlands in winter and concluded that natural ventilation cannot maintain a comfortable thermal environment. Miao et al. [27] assessed the fluctuation of indoor thermal conditions under natural ventilation in Spanish primary and secondary schools. They found that the thermal environment remained stable in most cases, with an indoor temperature variation of less than 1 °C within an hour. However, these studies were completely based on the assessment of environmental parameters (e.g., temperature, humidity) and did not investigate the subjective sensations of students. The reported results cannot truly reflect the comfort of students, and it is unknown whether the people have different thermal sensations and comfort than usual in window-airing scenarios.

In recent years, some field studies have shed light on not only thermal comfort but also perceived air quality, considering the effects of natural ventilation on both aspects. Liu et al. [28] investigated students' thermal sensation and perceived air quality with windows opened in winter in a Chinese university. They found that students' perception of indoor air quality reached the highest level when they felt neutral about the thermal environment. Korsavi et al. [29] studied children's thermal sensation, perceived air quality, and comfort in naturally ventilated primary schools in the UK. It was discovered that low CO_2 levels could not guarantee acceptable indoor air quality perceptions when children are thermally uncomfortable in classrooms. Wang et al. [30] conducted a subjective survey of thermal sensation, air movement, and perceived air quality in a Chinese university. They found that nearly 60 % of students were satisfied with the thermal environment in winter, but poor ventilation caused more than 50 % of students to be dissatisfied with air movement. The students complained more about the air quality than about the thermal environment. Torriani et al. [31] investigated thermal comfort, perceived air quality, and perceived control in Italian schools during winter. They revealed that students with perceived control over the indoor environment were more likely to experience a neutral thermal sensation and a better perception of indoor air quality. Llanos-Jiménez et al. [32] explored objective and subjective indoor air quality and thermal comfort in Spanish secondary schools. It was reported that students near the windows perceived better air quality, and the heating system was important for maintaining thermal comfort in winter. Alonso et al. [33] surveyed thermal comfort and perceived air quality in Spanish secondary schools. They discovered that CO_2 concentration was insignificant for both thermal sensation and perceived air quality, and the discomfort rate was close to 40 % at a temperature below 19 °C during the heating season. Certainly, these studies provide valuable findings on the subjective comfort of students regarding both thermal environment and indoor air quality in naturally ventilated educational buildings. However, the review of existing studies revealed a major research gap that still needs to be addressed: To the best of the author's knowledge, existing studies have not specifically investigated and analyzed the relationship between student comfort and natural ventilation rate. In most studies, the ventilation rate was not reported and analyzed. Wang et al. [30] reported an air change rate of 0.37 times/hour in winter, but such a low ventilation rate indicates that the windows were rarely opened.

In this context, the following issues remain to be further investigated to understand students' comfort with window-airing during cold seasons:

(1) What are the decisive factors of students' comfort in terms of thermal sensation, humidity, air movement, and perceived air quality?
(2) What is the relationship between ventilation rate, students' thermal comfort, and perceived air quality?
(3) Are the adaptive thermal comfort models still effective in predicting occupant thermal sensations with forced window openings?
(4) How to predict students' comfort in such window-airing scenarios?

With the main objective of addressing these questions, this study conducted a field experiment in a Spanish university to investigate students' subjective comfort with window-airing during the cold season.

Following this introduction, Section 2 describes the methodology, Section 3 analyzes and discusses the results, and Section 4 summarizes the conclusions and recommendations.

2. Methodology

This section describes the methodology of this study in detail, including the description of the field experiment (Section 2.1), environmental measurement and subjective survey (Section 2.2), data processing (Section 2.3), and data analysis (Section 2.4). Fig. 1 briefly summarizes the main contents of the methodology.

2.1. Description of the field experiment

The study was conducted during the winter between November and December 2024 at the Terrassa campus of the Universitat Politècnica de Catalunya (UPC). Terrassa is the third largest city in the Barcelona metropolitan area of Catalonia, Spain. It has a typical Mediterranean climate, with warm, dry summers and mild, wet winters. The Köppen climate classification defines Terrassa as a humid subtropical climate (Cfa). Fig. 2 shows the outdoor temperature and humidity in Terrassa during the study period, measured by the official weather service Meteocat [34].

The field experiment was conducted in two courses in the School of Industrial, Aerospace and Audiovisual Engineering (ESEIAAT), in the TR1 building of the UPC Terrassa campus. The TR1 building has three floors, with administrative offices on the ground floor and classrooms on the first and second floors. The courses were held in classrooms R111 and R203. These two classrooms are completely naturally ventilated and are equipped with radiators, while no thermostats are installed. Fig. 3 shows photos of the two classrooms and their architectural characteristics. The facade of the classrooms is made of 30 cm bricks with 2 cm plaster, with a reference U-value of 1.5 W/m^{2}K. The classrooms have single-glazed windows with wooden frames, with a U-value of 5.7 W/m^{2}K for the glass and 2.2 W/m^{2}K for the frames. The doors are also wooden. The floors are covered with ceramic tiles. The partitions separate the classrooms from the unconditioned space under the sloping roof, with a reference U-value of 1.36 W/m^{2}K. The course in the classroom R111 was enrolled with 18 students, with 15 male students and 3 female students. The course in the classroom R203 had 12 students enrolled, including 10 male students and 2 female students. There were

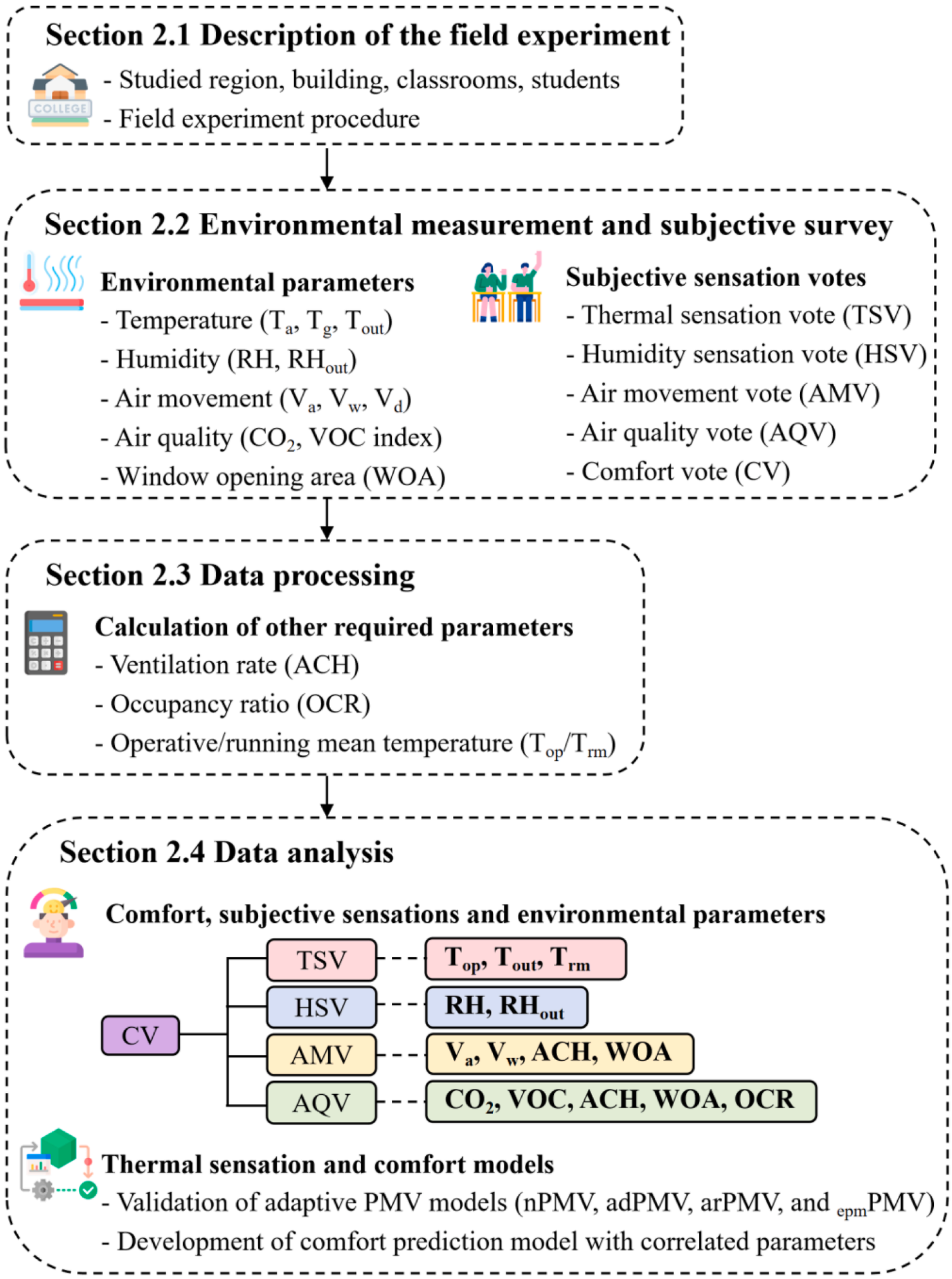


Fig. 1. Brief summary of the research methodology.

more male students than female students in both courses, reflecting the general gender ratio of students in the engineering schools. These students ranged from 19 to 24 years old, with an average age of 22.

The field experiment lasted for 6 weeks, from November 11 to December 19, 2024. The first 3 weeks were the non-heating mode (November), while the last 3 weeks were the heating mode (December). A total of 34 field surveys were conducted in the experiment, with 17 surveys in the non-heating mode and 17 surveys in the heating mode. The number of surveys in the two classrooms was also equal. The field experiment tested different window opening scenarios, including opening partial windows and opening all windows. The door remained closed during the experiments. The window opening scenarios tested in the non-heating and heating modes were generally balanced. Each field experiment lasted for 1 h (Fig. 4), and the students remained sedentary during the experiment (1.2 met). The windows were opened at the beginning of the experiment and the opening area remained unchanged throughout the experiment. The first 30 min were used to stabilize the measurement sensors and offer students enough time to adapt to the thermal environment [35], while the last 30 min were used to record valid measurement readings for calculating the average values of the environmental parameters. At the end of the experiment, students were asked to complete a questionnaire regarding their subjective feelings.

The next section introduces environmental measurement and subjective survey in detail.

2.2. Environmental measurement and subjective survey

Indoor environmental parameters were measured by a "Delta Ohm-HD32.2″ microclimate station at 1 min intervals, including temperature, humidity, air velocity, CO_2 concentration, volatile organic compound (VOC) index, etc. The sensor was placed in the center of the classroom at a height of 1.1 m and at least 1 m away from disturbances (i.e., windows,

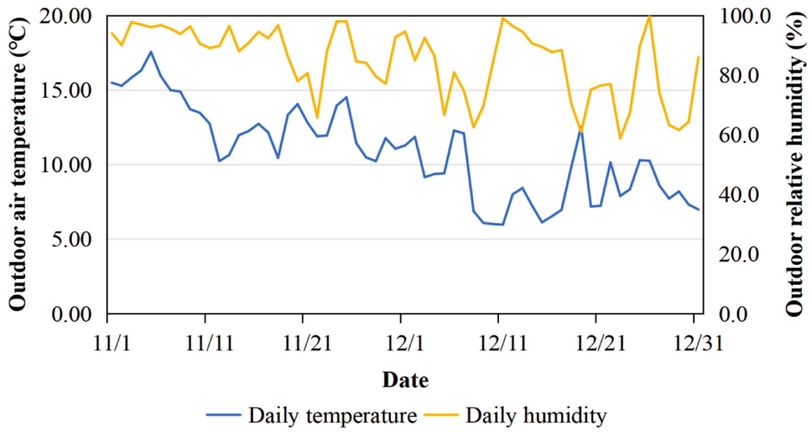
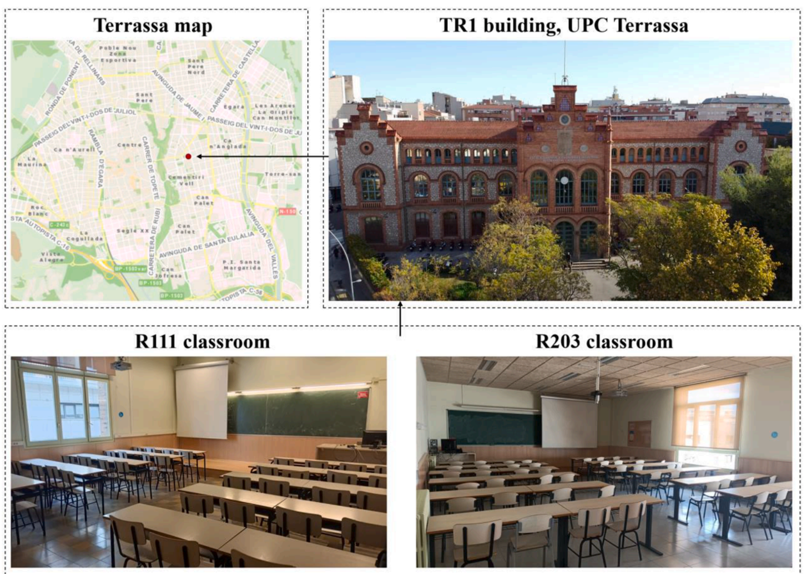


Fig. 2. Daily temperature and humidity in Terrassa during the study period.



Classroom characteristics

Room	Floor	Floor area (m²)	Height (m)	Facade orientation	Number of window	Window area (m²)	Number of door	Door area (m²)
R111	1	55.6	3.8	N	2	1.09	1	2.12
R203	2	78.0	3.2	N	4	0.85	1	1.89

Fig. 3. Studied region, building, and classrooms.

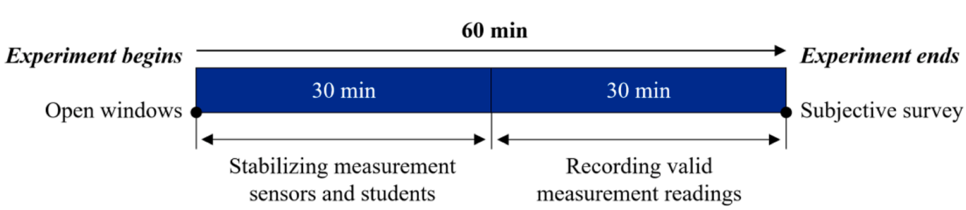


Fig. 4. Field experiment procedure.

radiators, occupants), following the specifications of ISO 7726 [36], ASTM D6245–18 [37], and ASHRAE 55 [38] standards. A "Comet U3430" was placed on the exterior windowsill to measure the temperature, humidity, and CO_2 concentration of the outdoor airflow at 1 min intervals. Appendix A shows the placement of these sensors in the classroom. In addition, a "Bresser 5 in 1" weather station located inside the UPC Terrassa campus, 300 m southwest of the TR1 building, was used to record outdoor wind conditions at 5 min intervals. Fig. 5 summarizes the technical specifications of the measurement instruments.

The subjective feelings of the students were surveyed using the questionnaire presented in Appendix B. Due to privacy concerns, the questionnaire was completely anonymous and collected only the most fundamental personal information including gender, age, and clothing (clothing insulation value referred to the ASHRAE 55 [38] standard.

Measurement instrument	Parameter	Range	Resolution	Accuracy
Indoor environmental parameters				
Classroom center				
Delta Ohm HD32.3 	Air temperature (T_a)	-20–80 °C	0.1 °C	±0.1 °C
	Globe temperature (T_g)	-30–120 °C	0.1 °C	±0.1 °C
	Relative humidity (RH)	0–100%	0.1%	±2%
	Air velocity (V_a)	0.02–5 m/s	0.01 m/s	±0.05 m/s
	CO_2 concentration (CO_2)	0–5000 ppm	1 ppm	±50 ppm
	VOC index (VOC)	0–500	1	±1
Outdoor environmental parameters				
Exterior windowsill				
Comet U3430 	Air temperature (T_{out})	-20–60 °C	0.1 °C	±0.4 °C
	Relative humidity (RH_{out})	0–100%	0.1%	±1.8%
	CO_2 concentration ($CO_{2\text{-}out}$)	0–5000 ppm	1 ppm	±50 ppm
University campus				
Bresser 5 in 1 	Wind speed (V_w)	0–50 m/s	0.1 m/s	±0.5 m/s
	Wind direction (V_d)	0–360°	1°	±5°

Fig. 5. Technical specifications of the measurement instruments.

Many field studies only investigate the thermal sensation without separating temperature, humidity, and air movement. In this study, these aspects were distinguished and the perceived air quality was also surveyed. In this case, temperature, humidity, air movement, and perceived air quality were considered independent of each other, in order to identify the most critical factors affecting students' comfort and to quantify the environmental parameters. The thermal sensation vote (TSV), humidity sensation vote (HSV), air movement vote (AMV), and air quality vote (AQV) were collected using the 7-point scale, while the comfort vote (CV) was gathered with the 3-point scale (Appendix B). It should be noted that the comfort vote (CV) in this study mainly characterizes the students' subjective comfort with the thermal environment and indoor air quality.

At the beginning of the field experiment, the researcher gave a

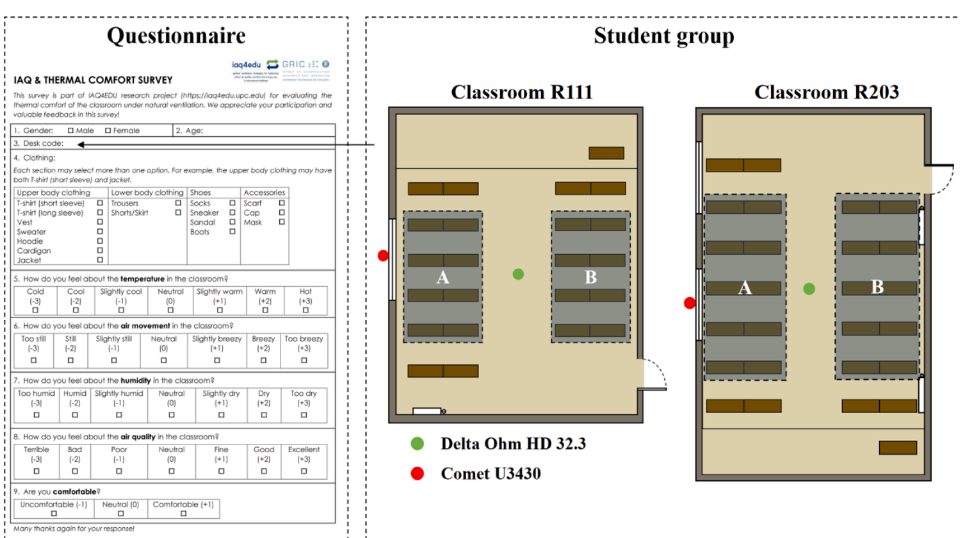


Fig. 6. Subjective survey questionnaire and student group.

presentation to explain the concepts of thermal comfort and indoor air quality, the corresponding environmental parameters, and the contents of the questionnaire to ensure that the students understood everything correctly. In addition, in order to further analyze the potential impact of window-airing on thermal comfort, the students were divided into different groups depending on where they were seated in the classroom. Group A represents the students whose seats were close to the windows, while Group B represents those who were seated far from the windows (Fig. 6). The first and last rows of the desks in the classrooms remained unoccupied during the field experiment. The group of students was marked in the "Desk Code" column in the questionnaire. The students were free to choose where to sit in each field experiment, which ensured the randomness of the student samples in groups A and B. The researcher only recommended where to sit when the number of students in the two groups was very disproportionate, in order to obtain relatively balanced data for analysis.

The next section describes the further processing of the raw data collected from the field experiment.

2.3. Data processing

Several environmental parameters need to be further calculated based on the measured parameters for analysis. Firstly, the ventilation rate during each field experiment was calculated based on the transient mass balance method using CO_2 as the tracer gas (Eq. (1)). This method has been widely used in field studies to estimate the natural ventilation rate in educational buildings and has been found to have the highest accuracy [39,40]. Relevant studies usually assume a constant value of CO_2 generation for all occupants when estimating the ventilation rate [8,41,42]. To further improve the accuracy of the estimated ventilation rate, the CO_2 generation rate used in this study was taken from Persily and Jonge [43], depending on the gender, age, and activity level of the occupants. In addition, considering that the two classrooms have different volumes, the air change rate per hour (ACH) was calculated (Eq. (2)) based on the ventilation rate to characterize the ventilation effect of the classroom, which is a more unified parameter for analysis.

$$C_{t+1} = C_{out} + \frac{N_t \cdot G_p \cdot 10^6}{Q_{vent}} - \left(C_{out} - C_t + \frac{N_t \cdot G_p \cdot 10^6}{Q_{vent}}\right) \cdot e^{\left(\frac{-Q_{vent} \cdot \Delta t}{V}\right)} \tag{1}$$

$$ACH = \frac{60 \cdot Q_{vent}}{V} \tag{2}$$

Where C_t is the indoor CO_2 concentration (ppm) at time t, C_{t+1} is the indoor CO_2 concentration at time t+1, Δt is the measurement interval (1-min), C_{out} is the outdoor CO_2 concentration, N_t is the number of occupants at time t, G_p is the CO_2 generation rate of occupant (m^3/min), V is the room volume (m^3), Qvent is the estimated ventilation rate (m^3/min), and ACH is the air change rate per hour (times/h).

Then, the operative temperature was calculated from the air temperature and the mean radiant temperature using Eqs. (3) and (4) [22]. The mean radiant temperature was directly calculated by the Delta Ohm HD32.2 with the measured air and globe temperatures.

$$T_{op} = \frac{(T_a + T_{mrt})}{2} (0 < V_a < 0.2m/s) \tag{3}$$

$$T_{op} = \frac{\left(\left(T_a \times \sqrt{10V_a}\right) + T_{mrt}\right)}{\left(1 + \sqrt{10V_a}\right)} (V_a > 0.2m/s) \tag{4}$$

Where T_a denotes the indoor air temperature (°C), T_{mrt} is the mean radiant temperature (°C), V_a is the air velocity (m/s), and T_{op} is the operative temperature (°C).

Next, the running mean temperature was calculated using Eq. (5), based on the daily mean outdoor air temperatures for the 7 days prior to the day of measurement [44,45].

$$T_{rm} = (T_{out-1} + 0.8 \cdot T_{out-2} + 0.6 \cdot T_{out-3} + 0.5 \cdot T_{out-4} + 0.4 \cdot T_{out-5} + 0.3 \cdot T_{out-6} + 0.2 \cdot T_{out-7})/3.8 \tag{5}$$

Where $T_{out\text{-}n}$ is the daily mean outdoor air temperature for the prior day n, and T_{rm} is the running mean temperature.

Lastly, the occupancy ratio was calculated based on the actual number of students in the classroom for each field experiment (Eq. (6)).

$$OCR = \frac{N_s}{A_{room}} \tag{6}$$

Where N_s denotes the number of students in the classroom, A_{room} is the floor area of the classroom (m^2), and OCR is the occupancy ratio (m^2/p).

Table 1 summarizes all the variables used in the analysis, along with their units and abbreviations. For the analysis, the average values of the environmental parameters measured in the experiments were calculated. The average values of the subjective sensation votes were also calculated for group A, group B, and all students in each experiment.

The next section describes the analysis of the processed data.

2.4. Data analysis

The data analysis involves two main aspects. One aspect identifies the main factors that affect students' comfort and the corresponding environmental parameters, as shown in Fig. 7.

This step first examined the relationship between the students' subjective sensation votes (TSV, WSV, HSV, AQV) and the comfort vote (CV), and then analyzed the relationship between each subjective sensation vote and the related environmental parameters. The statistical differences in the environmental parameters between the heating and non-heating modes were examined using the Kruskal–Wallis H test. The correlation between variables was examined using the Spearman's correlation test, which includes 5 levels depending on the Spearman's correlation coefficient ρ: very weak (0-0.2), weak (0.2-0.4), moderate (0.4-0.6), strong (0.6-0.8), and very strong (0.8-1.0). The statistical significance of the results included three levels: $p < 0.05$*, $p < 0.01$**, and $p < 0.001$***. The dependency between the variables was further analyzed through regression, which can be reflected by the regression equation and its coefficient of determination (R^2). In addition, the machine learning technique of feature importance was used to quantify the effect of each subjective sensation vote on the comfort vote. Conventional statistical analysis methods mainly demonstrate the relative

Table 1
Variables used in the analysis.

Variable	Abbreviation	Unit
Environmental parameters		
Operative temperature	T_{op}	°C
Outdoor air temperature	T_{out}	°C
Running mean temperature	T_{rm}	°C
Indoor relative humidity	RH	%
Outdoor relative humidity	RH_{out}	%
Indoor air velocity	V_a	m/s
Wind speed	V_w	m/s
Wind direction	V_d	°
Indoor CO_2 concentration	CO_2	ppm
Outdoor CO_2 concentration	$CO_{2\text{-}out}$	ppm
Volatile organic compound index	VOC	–
Window opening area	WOA	m^2
Air change rate	ACH	times/h
Occupancy ratio	OCR	m^2/p
Subjective sensation votes		
Thermal sensation vote	TSV	–
Humidity sensation vote	HSV	–
Air movement vote	AMV	–
Air quality vote	AQV	–
Comfort vote	CV	–

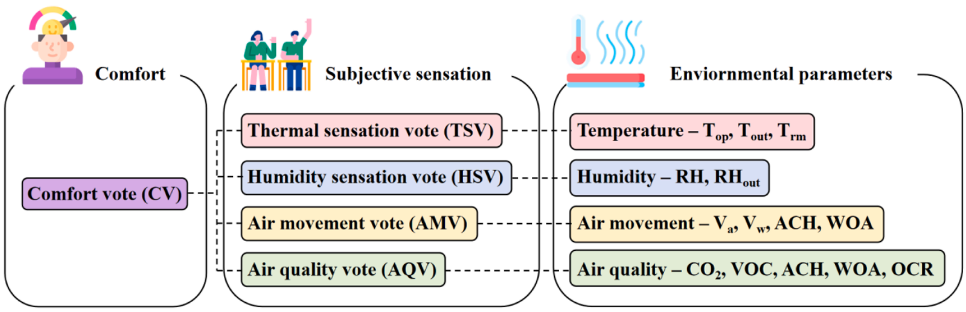


Fig. 7. Influential factor analysis of students' comfort.

dependence between the two variables. In contrast, the feature importance is a widely applied technique based on the random forest algorithm [46], which quantifies the weight of each variable considering the effects of all independent variables on the dependent variable [47,48], as shown in Eq. (7). In this case, the effect of each subjective sensation on the students' comfort can be observed in a more intuitive way.

$$FI_x = \frac{I_x}{\sum_{i=1}^{n} I_i} \tag{7}$$

Where FI_x is the weighted importance of subjective sensation x, I_x is the importance score of subjective sensation x calculated by the random forest algorithm, n is the total number of subjective sensations ($n = 4$), and the sum of the importance of all subjective sensations equals to 1.

The other aspect is to explore the modeling of students' thermal sensation and comfort with window-airing. The adaptive predicted mean vote (PMV) model has been proposed to predict the thermal sensation of occupants in naturally ventilated buildings [49]. Therefore, this study validated the effectiveness of the 4 existing main adaptive PMV models, including nPMV, arPMV, e_{pm}PMV, and adPMV models. To calculate adaptive PMV models, the PMV index can be calculated according to the ASHRAE 55 [38] standard based on indoor air temperature (T_a), mean radiant temperature (T_{mrt}), relative humidity (RH), air velocity (V_a), clothing insulation value (I_{clo}), and metabolic rate (met).

The nPMV model was proposed by Humphreys and Nicol [50], which modified the original PMV model with an empirical function of $f_{PMV\text{-}ASHRAE}$. The nPMV model is expressed as:

$$nPMV = 0.8 \cdot \left(PMV - f_{PMV-ASHRAE}\right) \tag{8}$$

The function $f_{PMV\text{-}ASHRAE}$ is calculated by:

$$f_{PMV-ASHRAE} = -4.03 + 0.0949 \cdot T_{op} + 0.00584 \cdot RH + 1.201 \cdot M \cdot I_{clo} + 0.000838 \cdot T_{out}^2 \tag{9}$$

Where T_{op} is the operative temperature, RH is the relative humidity, M is the metabolic rate, I_{clo} is the clothing insulation value, and T_{out} is the outdoor mean air temperature.

The arPMV model was proposed by Zhang and Lin [51] based on the adaptive PMV model introduced by Yao et al. [52]. This model considers the adaptive coefficient λ_v as a variable that is linearly related to the reciprocal of the ambient temperature, which reflect the dynamic characteristics of thermal adaptation. The arPMV model is expressed as:

$$arPMV = \frac{PMV}{1 + \lambda_v \cdot PMV} \tag{10}$$

$$\lambda_v = q \cdot \frac{1}{T_{op}} + p \tag{11}$$

Where T_{op} is the operative temperature, while parameters q and p can be calculated by the least squares minimization.

The e_{pm}PMV model was proposed by Zhang and Lin [53] based on the ePMV model introduced by Fanger and Tofum [54]. This model involves an expectancy factor e_{pm} characterized by a linear function of ambient temperature to reflect the dynamic characteristics of thermal adaptation, and a thermal neutrality factor c_m to enhance thermal adaptation around neutrality. The e_{pm}PMV model is expressed as:

$$ePMV_m = e_m \cdot PMV + c_m \tag{12}$$

$$e_m = a_m \cdot T_{op} + b_m \tag{13}$$

Where T_{op} is the operative temperature, while parameters a_m, b_m, and c_m can be calculated by the least squares minimization.

The adPMV model was proposed by Lamberti et al. [55]. This model involves a adaptive factor α characterized by a linear function of running mean temperature rather than ambient temperature. The adPMV model is expressed as:

$$adPMV = \alpha \cdot PMV \tag{14}$$

$$\alpha = a \cdot T_{rm} + b \tag{15}$$

Where T_{rm} is the running mean temperature, while parameters a and b can be calculated by the least squares minimization.

To date, there is still no widely recognized existing model specifically for predicting occupants' comfort votes. Therefore, this study explored the modeling of the comfort vote (CV) with multiple linear regression (MLR) based on the correlated subjective sensation votes and environmental parameters identified in the first step, which can be expressed as:

$$CV = \alpha_0 + \alpha_1 \cdot V_1 + \alpha_2 \cdot V_2 + \ldots + \alpha_m \cdot V_m \tag{16}$$

$$CV = \beta_0 + \beta_1 \cdot P_1 + \beta_2 \cdot P_2 + \ldots + \beta_n \cdot P_n \tag{17}$$

Where V denotes the correlated subjective sensation vote, m is the total number of the correlated subjective sensation votes, P denotes the correlated environmental parameter, n is the total number of the correlated environmental parameters, α and β are model parameters.

For all of the above models, their performance can be evaluated using the following metrics:

(1) Mean absolute error (MAE):

$$MAE = \frac{1}{n} \sum_{i=1}^{n} |y_i - \hat{y}_i| \tag{18}$$

Where n is the number of observations, y_i is the actual value of the observation i, and $\hat{y}_i$ is the predicted value of the observation i.

A lower MAE indicates a better prediction accuracy of the model.

(2) Coefficient of determination (R^2):

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \tag{19}$$

Where n is the number of observations, y_i is the actual value of the observation i, and $\hat{y}_i$ is the predicted value of the observation i, and $\bar{y}$ is the average value of all observations.

R^2 characterizes the proportion of variance in the observation that can be explained by the correlated factors involved in the model. A higher R^2 suggests better fit of the model to the data.

In this study, the calculation and analysis were performed on the Google Colab platform using Python 3.7.3. The Pythermalcomfort package developed by the Center for the Built Environment (CBE Berkeley) was used to calculate the PMV index. The Numpy and Pandas packages were used for data processing. The Statsmodels package was used for statistical tests and multiple linear regression.

3. Results and discussion

This section analyzes and discusses the results of the field experiment. Section 3.1 summarizes the measured environmental parameters and the students' subjective sensation votes. Section 3.2 analyzes the relationship between the students' comfort and their subjective sensations and the corresponding environmental parameters. Section 3.3 validates the effectiveness of the adaptive PMV models for thermal sensation prediction and develops the empirical models for comfort prediction. Section 3.4 discusses the practical implications of the results and the limitations of the study.

3.1. Environmental parameters and subjective sensation votes

This section summarizes the environmental parameters measured in the field experiments (Section 3.1.1) and the students' subjective sensation votes (Section 3.1.2).

3.1.1. Environmental parameters

As mentioned in Section 2.1, the study coducted a total of 34 field experiments, with 17 during the non-heated period (November) and 17 during the heated period (December). The number of field experiments in the two classrooms was equal (50 % each). Table 2 summarizes the environmental parameters measured in the field experiments.

In terms of temperatures, the outdoor air temperature (T_{out}) ranged from 9.56 to 19.33 °C, with an average of 15.35 °C. Notably, relevant studies usually use the outdoor air temperature measured by urban weather stations. In this study, in order to accurately analyze the effect of ventilated outdoor air, the outdoor air temperature (T_{out}) was measured by the sensor on the exterior windowsill. Due to the urban heat island effect, this temperature could be around 2 °C higher than that measured by the urban weather station, due to the effect of urban heat island. The running mean temperature (T_{rm}) was calculated using the outdoor temperature measured by the Meteocat urban weather station, which ranged from 6.88 to 14.67 °C, with an average of 10.82 °C. On average, the outdoor air temperature during the heating mode (13.62 °C) was significantly lower than that during the non-heating mode (17.08 °C), while the Kruskal-Wallis H-test showed a statistically significant difference between them ($p < 0.001$***). However, due to the heating of the classrooms, the indoor operative temperature (T_{op}) was generally maintained above an acceptable level. The operative temperature ranged from 18.73 to 23.35 °C, with an average of 21.16 °C. These values are generally in line with the requirements of a minimum temperature of 19 °C and a comfortable temperature of 21 °C defined by the Spanish regulations Royal Decree 486/2004 [56] and RITE 178/2021 [57]. The average operative temperature during the heating mode (21.40 °C) was slightly higher than that during the non-heating mode (20.92 °C), but their other statistical values were very similar. The Kruskal-Wallis H-test did not find a statistically significant difference between the two periods ($p = 2.78 > 0.08$).

With regard to humidity, the outdoor relative humidity (RH_{out}) ranged from 35.2 to 80.6 %, with an average of 54.3 %. The Kruskal-Wallis H-test did not find a statistically significant difference between the heated and non-heated periods ($p = 0.08 > 0.05$). The indoor relative humidity (RH) ranged from 36.0 to 67.2 %, with an average of 49.9 %. The values are in line with the range of 30 %–70 % defined by the Spanish regulation Royal Decree 486/2004 [56] and, on average, satisfied the comfort requirement of 40–50 % defined by ISO 7730 [58]. However, as the heating and ventilation effectively remove the moisture from the indoor air [9], the average relative humidity during the heating mode was significantly lower (44.7 %) than that during the non-heating mode (55.1 %), and the Kruskal-Wallis H-test confirmed the statistical significance of such a difference ($p < 0.001$***).

As for air movement, the indoor air velocity (V_a) ranged from 0.001 to 0.129 m/s, with an average of only 0.021 m/s. These values are far below the 0.200 m/s threshold for the cooling effect defined by ASHRAE 55 [38]. The average indoor air velocity in the heating mode (0.025

Table 2
Descriptive statistics of environmental parameters.

Parameter	T_{op} (°C)	RH (%)	V_a (m/s)	CO_2 (ppm)	VOC (-)	ACH (times/h)	WOA (m^2)	OCR (m^2/p)	T_{out} (°C)	T_{rm} (°C)	RH_{out} (%)	V_w (m/s)	V_d (°)	$CO_{2\text{-}out}$ (ppm)
Non-heating mode														
mean	20.92	55.1	0.017	780	75	3.4	2.1	5.7	17.08	12.75	56.0	0.86	229	425
std	1.20	6.8	0.021	241	49	1.6	1.0	2.0	1.65	0.98	6.0	0.65	57	9
min	18.73	44.8	0.001	443	24	1.0	0.9	3.1	12.70	11.56	46.5	0.04	90	405
25 %	20.13	50.5	0.003	576	43	2.3	1.1	3.7	16.32	12.14	50.6	0.51	206	423
50 %	21.03	54.8	0.007	742	53	3.7	2.2	6.0	16.87	12.68	55.7	0.71	259	426
75 %	21.38	58.5	0.035	935	97	4.6	3.4	7.8	18.58	13.36	59.4	0.96	270	432
max	23.09	67.2	0.063	1143	194	6.6	3.4	9.3	19.31	14.67	67.2	2.91	274	437
Heating mode														
mean	21.40	44.7	0.025	739	40	4.1	1.9	6.0	13.62	8.89	52.5	1.34	235	426
std	1.07	4.9	0.031	203	22	2.4	0.9	2.0	2.97	1.78	10.8	1.20	66	4
min	18.98	36.0	0.003	418	10	1.2	0.9	3.3	9.56	6.88	35.2	0.01	64	415
25 %	20.63	42.2	0.008	578	27	2.9	1.1	4.0	11.19	7.43	47.1	0.34	236	423
50 %	21.35	45.3	0.013	753	37	3.4	1.7	6.2	13.15	8.78	49.3	1.26	269	426
75 %	22.11	47.7	0.026	848	50	4.7	2.2	7.8	15.58	10.37	56.3	1.74	270	428
max	23.35	52.0	0.129	1253	92	11.6	3.4	9.7	19.33	11.29	80.6	4.34	277	433
All scenarios														
mean	21.16	49.9	0.021	759	58	3.8	2.0	5.8	15.35	10.82	54.3	1.10	232	425
std	1.14	7.9	0.026	220	42	2.0	0.9	2.0	2.95	2.42	8.8	0.98	61	7
min	18.73	36.0	0.001	418	10	1.0	0.9	3.1	9.56	6.88	35.2	0.01	64	405
25 %	20.53	44.8	0.005	577	29	2.5	1.1	3.8	12.81	8.78	48.3	0.47	213	423
50 %	21.19	50.1	0.010	748	44	3.6	1.9	6.1	16.16	11.43	53.8	0.85	263	426
75 %	21.96	54.4	0.033	891	72	4.7	3.1	7.8	17.46	12.55	58.9	1.58	270	429
max	23.35	67.2	0.129	1253	194	11.6	3.4	9.7	19.33	14.67	80.6	4.34	277	437

m/s) was slightly higher than that in the non-heating season (0.017 m/s), while the Kruskal-Wallis H-test confirmed the statistical significance ($p < 0.001$***). The reason for a higher indoor air velocity in the heating season can be attributed to the nature of the natural ventilation. As mentioned in Section 2.1, the window opening scenarios tested in the heating and non-heating modes were generally balanced. As a result, the average window opening area (WOA) in the heating mode (1.9 m^2) was very close to the value of the non-heating mode (2.1 m^2). However, the mean air change rate (ACH) during the heating mode (4.1 times/h) was considerably higher than the non-heating mode (3.4 times/h). This is because natural ventilation depends on both buoyancy (indoor-outdoor temperature difference) and wind effects [27,59,60]. On one hand, the indoor-outdoor temperature difference was larger in the heating season, resulting in a higher buoyancy effect. On the other hand, the outdoor wind speed (V_w) was higher during the heating mode (1.34 m/s) than in the non-heating mode (0.86 m/s). These two factors collectively lead to a higher ventilation rate with the same window opening area, which provides the potential to achieve a higher indoor air velocity.

Lastly, concerning parameters related to air quality, the occupancy ratio (OCR) of the classrooms ranged from 3.1 to 9.7 m^2/student, with an average of 5.8 m^2/student. Accordingly, the indoor CO_2 concentration (CO_2) ranged from 418 to 1253 ppm, with an average of 759 ppm. Their statistical values were close for the heating and non-heating modes, and the Kruskal-Wallis H-test did not find statistically significant differences ($p = 0.579$ and 0.667, >0.05). In contrast, the volatile organic compound index (VOC) of the classrooms ranged from 10 to 194, with an average of 58. The mean VOC index during the non-heating mode (75) was slightly higher than that during the heating mode (40), and the Kruskal-Wallis H-test confirmed the statistical significance of the difference ($p = 0.01$**). Notably, the VOC index is affected by many factors and has many uncertainties, such as occupants, outdoor air quality, and ventilation effects [61,62].

3.1.2. Subjective sensation votes

Since students did not always attend all classes, the number of students in each experiment ranged from 6 to 18, with an average of 13.1 (non-heating mode: 12.4, heating mode: 13.7). As a result, a total of 421 valid questionnaires were obtained in the field experiments, with 48 % from the non-heating mode and 52 % from the heating mode. The proportions of the students in groups A and B were generally balanced. In the non-heating mode, 52 % of the students were in group A and 48 % in group B on average. In the heating mode, 49 % were in group A and 51 % were in group B. The clothing insulation of the students ranged from 0.54 to 1.28, with an average of 0.82 (non-heating mode: 0.83, heating mode: 0.81). The Kruskal-Wallis H-test did not find a statistical difference between the two periods ($p = 0.534>0.05$).

Fig. 8 shows the frequency of subjective sensation votes collected in the field experiment, including thermal sensation vote (TSV), humidity sensation vote (HSV), air movement vote (AMV), air quality vote (AQV), and comfort vote (CV). Firstly, the thermal sensation vote (TSV) was concentrated between neutral (0) and slightly cool (−1). The average TSV in the non-heating mode was −0.49, while that in the heating mode was −0.74. It can be seen that compared to the non-heating mode, the heating mode had a much lower proportion of neutral (0) votes at 29.5 % and a higher proportion of cold (−3) votes at 7.3 %. These votes in the non-heating mode were 43.8 % and 1.5 % respectively. In the non-heating mode, students in group A felt slightly "colder" than those in group B, with 16 % more students voting slightly cool (−1) and 12 % fewer students voting neutral (0). The mean TSV was −0.66 for student group A and −0.30 for student group B. This could mean that students near windows are more sensitive to cold air in the absence of heating. In contrast, thanks to the heating of the classroom, the TSV distributions of students in Group A and Group B were generally equal during the heating mode.

Then, regarding the humidity sensation vote (HSV), more than 70 % of the students felt neutral (0) in both the heating and non-heating modes, and there was no discernible difference between the students in the two groups. On average, the HSV was −0.12 in the non-heating mode and −0.09 in the heating mode, which were very close. Interestingly, as mentioned earlier, the indoor air was actually much drier during the heating mode. The HSV results imply that students are not sensitive to indoor humidity when it falls within the acceptable range.

Next, the air movement vote (AMV) was concentrated between neutral (0) and slightly breezy (+1), and there was not much difference between the heating and non-heating modes. On average, the AMV was 0.43 in the heating mode and 0.34 in the non-heating mode. The proportion of students voting for neutral (0) was about 7 % higher in the non-heating mode. It is also worth mentioning that since the students in group A were close to the windows, they felt the movement of fresh air more intuitively. In comparison, students in group B had a relatively higher proportion of votes for feeling a "still" (−1 to −2) air in both the heating and non-heating modes.

Subsequently, the air quality vote (AQV) was concentrated between neutral (0) and good (+2), with only less than 11 % of students perceiving the air quality as not ideal (−3 to −1). In comparison, there is no discernible difference in the distribution of AQV between the non-heating and heating modes. These results indicate that most students were satisfied with the indoor air quality under ventilation by window-airing.

Lastly, the comfort vote (CV) results show that almost 60 % of the students felt neutral (0), while the proportions of students who felt comfortable (+1) and uncomfortable (−1) were about 20 %, respectively. It is noteworthy that the CV distributions of students in groups A and B were very close in the heating mode. However, in the non-heating mode, about 4 % fewer students in group A felt comfortable (+1), and nearly 15 % more students in group B were comfortable (+1). This suggests that the heating of the classroom has a positive effect on the comfort of the students sitting near the windows.

The next section further analyzes the relationship between TSV, HSV, AMV, AQV and CV, as well as the relationship between these subjective sensation votes and related environmental parameters.

3.2. Influential factors of student's comfort

This section analyzes the influence of each subjective sensation on the student's comfort (Section 3.2.1), and the relationship between these subjective sensations and environmental parameters (Section 3.2.2).,

3.2.1. Relationship between comfort vote and subjective sensation votes

The correlation between comfort vote (CV) and thermal sensation vote (TSV), humidity sensation vote (HSV), air movement vote (AMV), and air quality vote (AQV) was examined using Spearman's test. Appendix C presents the correlation matrix. The results show that CV has a strong and positive correlation with TSV (Spearman's coefficient $\rho=0.74$, $p < 0.001$***), and a moderate and negative correlation with AMV ($\rho=-0.56$, $p < 0.001$***). In contrast, CV is weakly correlated with HSV ($\rho=0.38$, $p < 0.05$*), and has almost no correlation with AQV ($\rho=-0.25$, $p > 0.05$).

Fig. 9 shows the regression of CV and each subjective sensation vote (Fig. 9a) and the impact of each subjective sensation vote on CV quantified by the feature importance technique (Fig. 9b). It can be seen that, in general, students were more likely to feel uncomfortable when they felt cold (−2 to −3), while they tended to be comfortable when they felt neutral (0). TSV was found to have the largest impact on CV. The regression shows a strong linear dependence, with a R^2 of 0.645. The feature importance results show that the impact weight of TSV reaches 0.70, indicating that TSV has a 70 % determining effect on CV. The regression lines of group A and group B students are very close, meaning that the importance of temperature to comfort is generally the same for both groups of students.

Then, AMV also has a considerable impact on CV. The regression

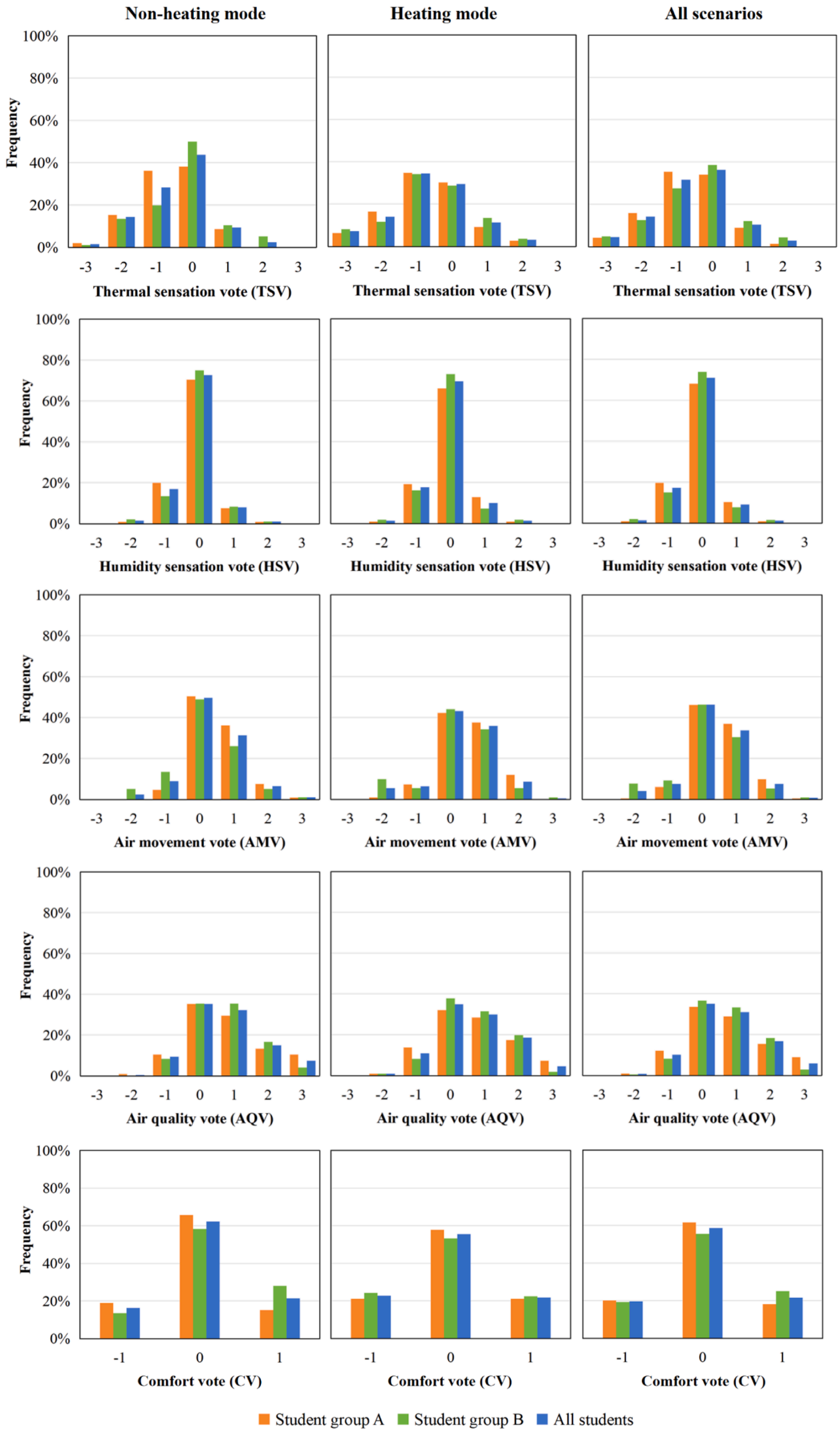


Fig. 8. Frequency of subjective sensation votes collected in the field experiments.

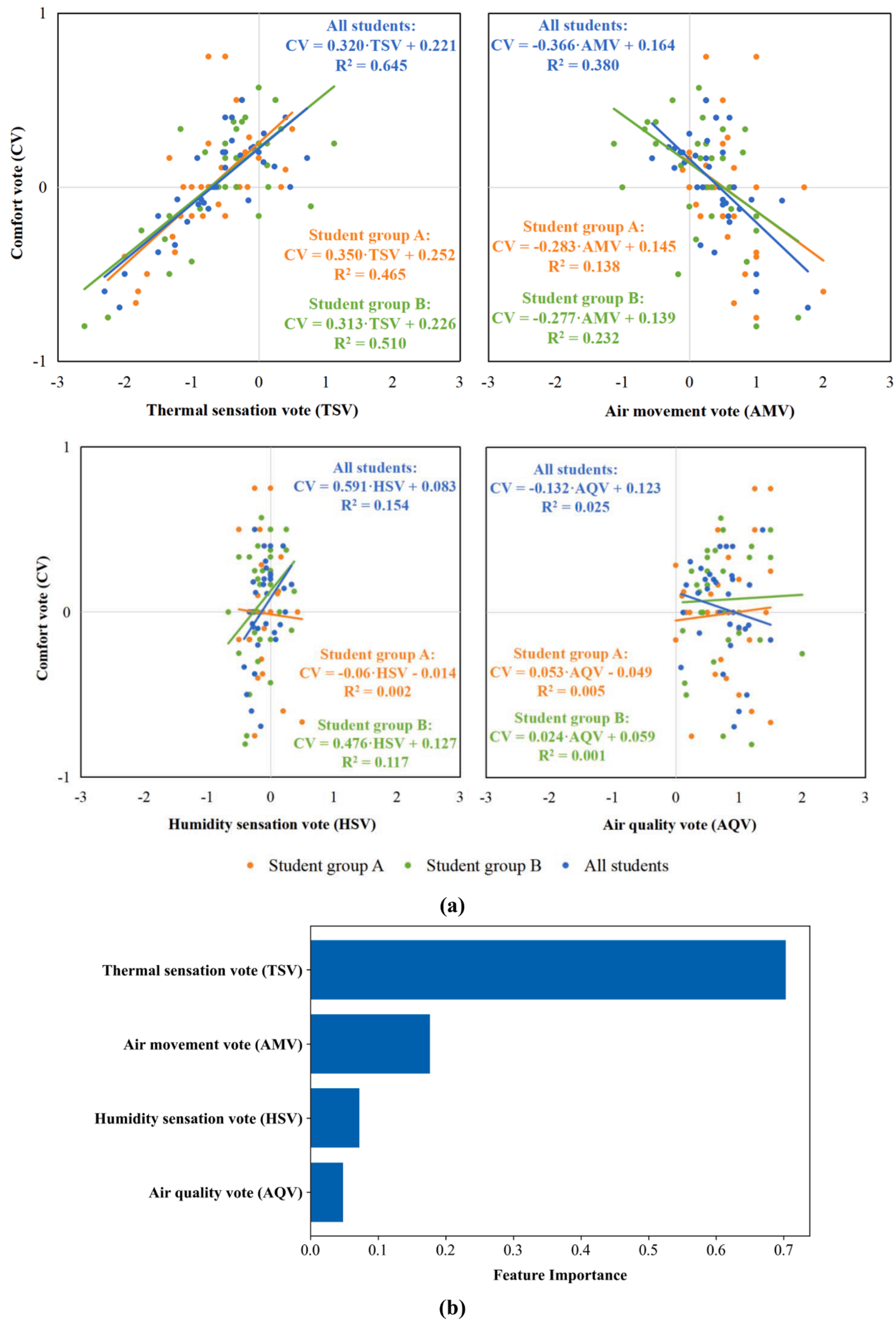


Fig. 9. Relationship between comfort and subjective sensation votes.

shows a negative linear relationship between CV and AMV, with a R^2 of 0.380. The feature importance results show that AMV has an impact weight of 18 % on CV. It can be seen that the likelihood of feeling uncomfortable increased greatly with the growth of breezy feelings (from +1 to +3). Students tended to be comfortable when they felt closer to neutral (0). Similar to the case of TSV, the regression lines of students in group A and group B are almost the same.

Next, HSV has almost no impact on CV. There is no clear linear dependence between them, while the R^2 is only 0.154. HSV was concentrated near neutral (0), but CV is evenly distributed between uncomfortable (−1) and comfortable (+1). The feature importance results show that HSV has only 7 % of the impact on CV. Notably, the R^2 of the regression line for group A students is almost 0. This implies that for students near the window, the impact of HSV on CV is almost negligible, and their comfort is mainly determined by thermal sensation and air movement.

Lastly, AQV was also found to have no direct effect on CV. By observing the regression line, it can be found that regardless of the student group, AQV was concentrated around fine (+1), but CV is evenly distributed between uncomfortable (−1) and comfortable (+1). The R^2 of the regression is only 0.025. The feature importance results show that AQV has only a 5 % impact on CV, which is even lower than in the HSV case. The results suggest that the students were generally satisfied with the air quality with opening windows, thus their attention was mainly on the indoor temperature and the movement of the airflow.

The results in this section suggest that when performing window-airing in cold seasons, thermal sensation has the most critical effect on student's comfort, followed by the sensation of air movement. Students tend to be uncomfortable when it is cold (−2 to −3) and breezy (+2 to +3), while they feel comfortable with a neutral (0) environment. Besides, whether they feel comfortable or not is basically independent of the humidity sensation and their perceived air quality.

The next section further discusses the relationship between each subjective sensation vote and the corresponding environmental parameters.

3.2.2. Relationship between subjective sensation votes and related environmental parameters

The correlation matrix in Appendix C shows the correlation between students' subjective sensation votes and environmental parameters. Firstly, the TSV was found to have a strong and positive correlation with the operative temperature – T_{op} (Spearman correlation coefficient ρ=0.72, $p < 0.001$***). However, it has no correlation with outdoor air temperature – T_{out} and running mean temperature – T_{rm} (ρ<0.2, $p >$ 0.05). The regression results (Fig. 10) are consistent with the results of the correlation test. For outdoor air temperature and running mean temperature (Fig. 10b and 10c), the slope and R^2 of the regression lines are almost close to 0. In contrast, the slope of the operative temperature regression (Fig. 10a) reached 0.488 and the R^2 reached 0.604. Based on this TSV regression equation, the student's neutral temperature was found to be 22.4 °C. This number is generally 1 °C lower than the neutral temperature of 23.0 to 23.8 °C reported in relevant studies conducted in the naturally ventilated universities of the Mediterranean climate during the cold seasons [20,23,63], which can be attributed to the adaptation of the students. In addition, the comparison showed that there was a small difference in the slope of the regression line between students in groups A and B. This suggests that the indoor and ventilated outdoor air may not be uniformly mixed with window-airing, resulting in a small temperature difference between the two areas of the classroom.

Interestingly, HSV was found to have no correlation with both indoor relative humidity – RH (ρ=0.02, $p >$ 0.05) and outdoor relative humidity – RH_{out} (ρ=0.09, $p >$ 0.05). The regression results are consistent with the correlation test results. The slope and R^2 of the regression lines are close to 0 (Fig. 11). This result suggests that the students are insensitive to humidity when it is within the acceptable range.

Next, the AMV was found to have a strong and positive correlation with the window opening area – WOA (ρ=0.72, $p < 0.001$***), and moderately correlated with indoor air velocity – V_a (ρ=0.44, $p < 0.01$**) and air change rate – ACH (ρ= 0.43, $p < 0.05$*). In contrast, there was no direct correlation between AMV and outdoor wind speed - V_w (ρ= 0.23, $p >$ 0.05). In fact, the window opening area determines the ACH and the indoor air velocity. The larger the window opening area, the higher the ventilation rate and the indoor air velocity. Fig. 12 shows the regression of AMV with these environmental parameters. As seen, the AMV is neutral (0) when the indoor air velocity is 0 m/s. As the indoor air velocity increases to 0.1 m/s, the students begin to feel slightly breezy (+1). It is worth noting that when AMV is 1, the corresponding ACH is 8 times/h. This value is much higher than the 4 times/h required by EN 16,798–7 [44] and the 6 times/h required by the Harvard T.H. Chan School of Public Health in the context of the COVID-19 pandemic [64]. This means that the air change rate specified in the building standards would not cause an obvious sense of discomfort to the students in terms of air movement. Theoretically, the outdoor wind speed can affect the indoor air velocity. However, during the field experiment, there was mainly southwest wind (Table 2), while the windows of both classrooms faced north, which is the leeward side. As a result, the students did not feel the strong wind blowing into the classrooms.

Finally, the AQV had a positive and moderate correlation with occupancy ratio – OCR (ρ=0.52, $p < 0.01$**), and a negative correlation with indoor CO_2 concentration – CO_2 (ρ=−0.45, $p < 0.01$**). Interestingly, AQV was found to be moderately correlated with window opening area – WOA (ρ=0.46, $p < 0.01$**), but had no direct correlation with ACH and volatile organic compound index – VOC (ρ=0.22 and −0.21, p > 0.05). The regression results were consistent with the correlation test results, with both the slope and R^2 of the regression lines approaching 0 (Fig. 13). It can be seen that higher occupancy ratios and larger window opening areas made the students subconsciously perceive that the air quality was better (Figs. 13c and 13d). However, these factors are not indicators of air quality in a real sense. The students were satisfied with the air quality (AQV>0) even when CO_2 exceeded the commonly recommended threshold of 1000 ppm (Fig. 13a). The indoor air was not fresh when the VOC index exceeded 100, but the AQV was not obviously dropped. In addition, the regression of ACH shows that the slope and R^2 of group A students were much higher than those of group B students (Fig. 13e), meaning that which means that ACH has a greater impact on the perceived air quality for students near the windows. This could be

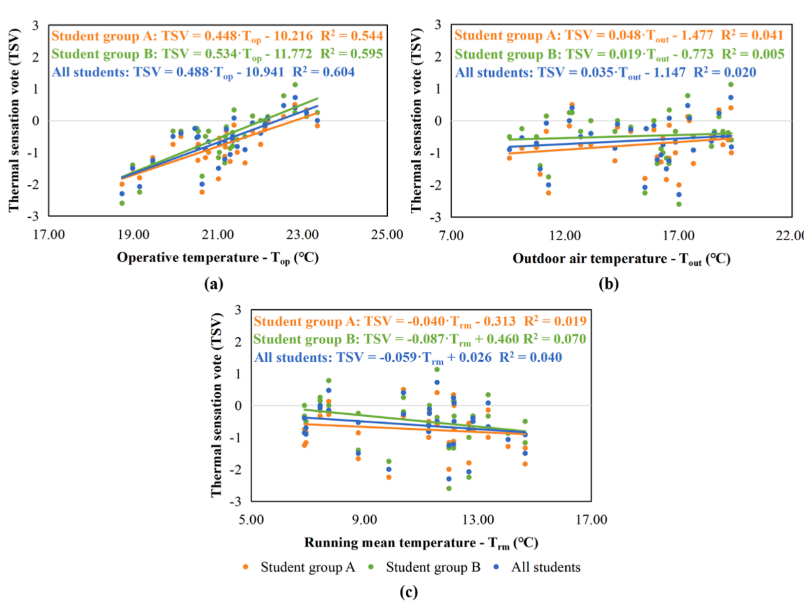


Fig. 10. Relationship between thermal sensation vote and operative temperature (a), outdoor air temperature (b), and running mean temperature (c).

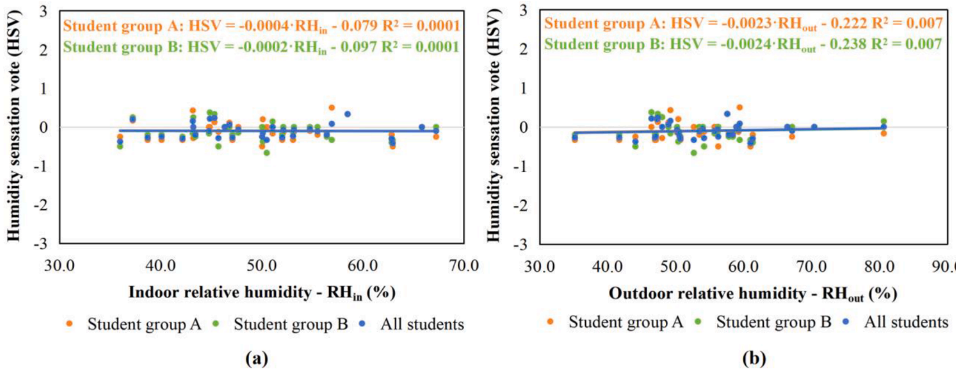


Fig. 11. Relationship between humidity sensation vote and indoor relative humidity (a) and outdoor relative humidity (b).

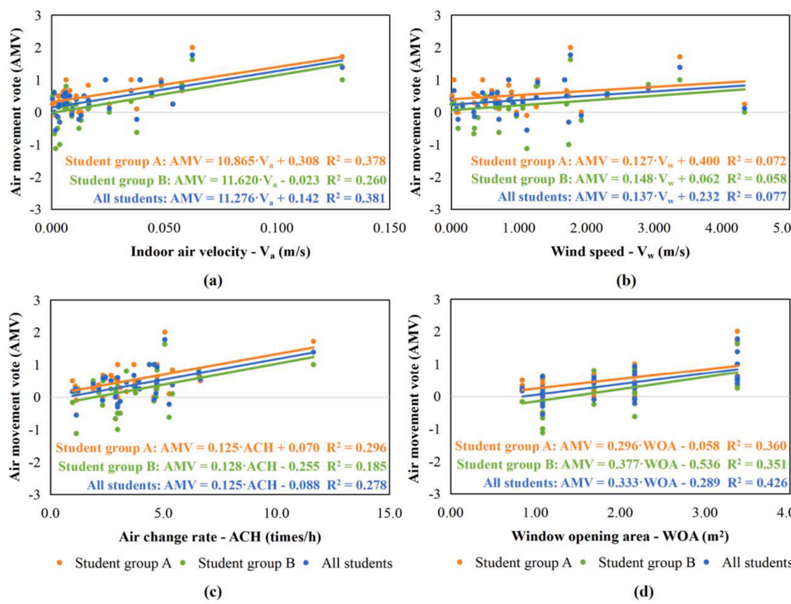


Fig. 12. Relationship between air movement vote and indoor air velocity (a), wind speed (b), air change rate (c), and window opening area (d).

because students near the window can feel the airflow more intuitively and thus perceive better air quality. Therefore, the above evidence suggests that under natural ventilation, students' perception of air quality could be more of a very subjective judgment influenced by factors that can be intuitively visualized or sensed.

The results in this section suggest that with window-airing in cold seasons, students' thermal sensation is directly determined by the indoor temperature rather than the outdoor temperature. Students are not sensitive to indoor humidity as long as it is within an acceptable range. Their sensation of air movement is mainly affected by the indoor air velocity and ventilation rate, while whether the outdoor wind speed also has an effect depends on the incident wind direction. Moreover, students' perception of air quality is likely to be a highly subjective feeling. Larger window openings and higher occupancy ratios make them tend to "believe" that the air quality is better. However, they are unlikely to directly feel the deterioration of some air parameters, such as CO_2 and VOC, as long as these parameters are too bad to tolerate (e.g., CO_2 exceeds 4000 ppm instead of 1000 ppm).

The next section discusses the modeling of thermal sensation and comfort.

3.3. Modeling of thermal sensation and comfort

This section analyzes the modeling of thermal sensation (Section 3.3.1) and develops the comfort vote prediction model (Section 3.3.2).

3.3.1. Thermal sensation vote prediction models

Considering that thermal sensation has a decisive influence on the comfort of the students, the thermal sensation vote (TSV) prediction models are analyzed. As mentioned in Section 2.4, the adaptive PMV models have been used to predict the thermal sensation of the occupants in naturally ventilated buildings. Therefore, 4 existing main adaptive PMV models are validated using the evaluation metrics of mean absolute error (MAE) and coefficient of determination (R^2), which reflect the prediction accuracy and the model's fit to the data. Their performances are summarized and presented in Fig. 14. It can be seen that among all the adaptive PMV models, the nPMV model performs the worst with the highest MAE (0.697) and the lowest R^2 (0.456). The adPMV model based on running mean temperature has a significantly lower MAE (0.406) and a slightly higher R^2. In contrast, the other two operative temperature-based models, the arPMV and e_{pm}PMV models, perform better. The epmPMV model performed the best among all adaptive PMV models, with a MAE of 0.382 and a R^2 of 0.527.

In fact, further comparison shows that the TSV regression model outperforms all other models, with the lowest MAE (0.354) and the highest R^2 (0.604). This is mainly because the adaptive PMV models are developed based on the adaptive theory, which assumes that occupants have the ability to proactively adjust and adapt to the thermal

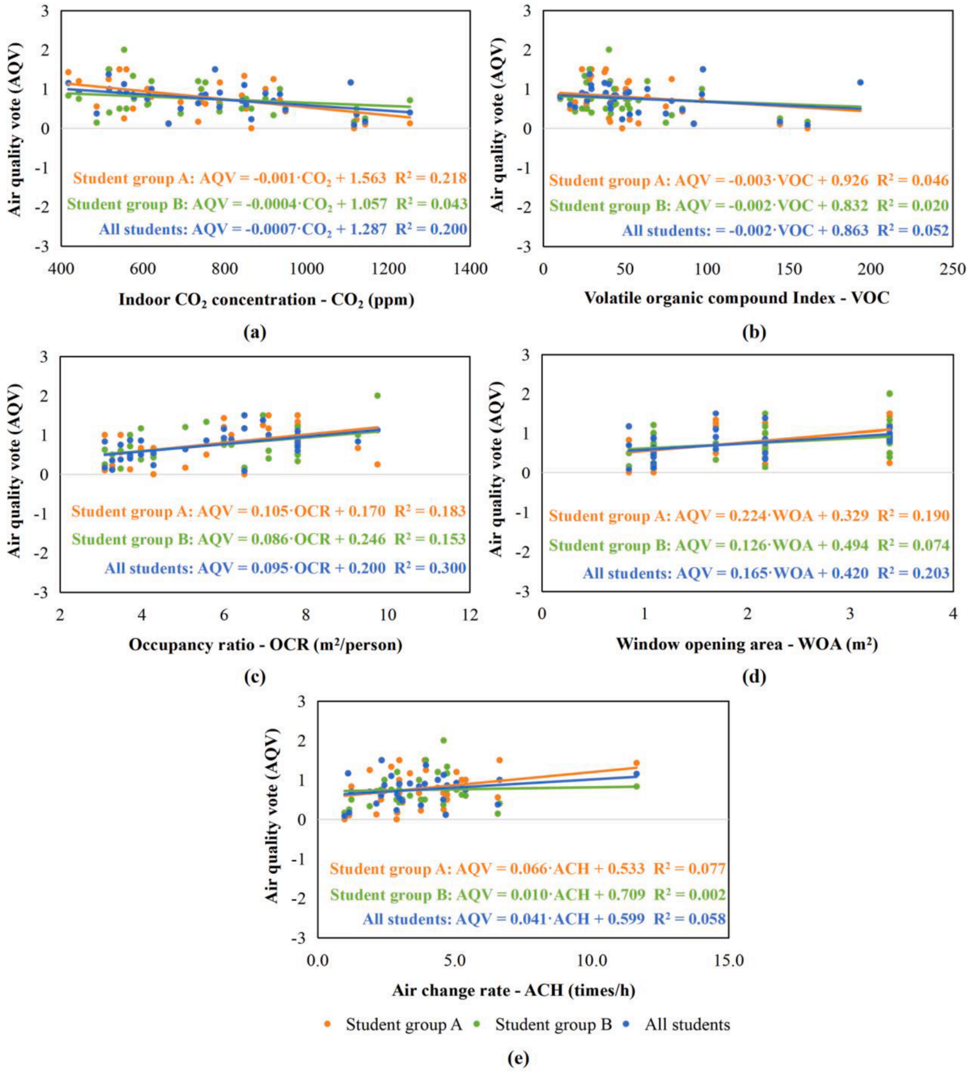


Fig. 13. Relationship between air quality vote and indoor CO_2 concentration (a), volatile organic compound index (b), occupancy ratio (c), window opening area (d), and air change rate (e).

environment. Accordingly, they would feel warmer in the cold season than predicted by the original PMV model due to adaptive behaviors such as operating windows, adjusting clothing, etc. However, in the field experiment of this study, the windows were kept open to investigate the situation where forced ventilation protocol has to be performed in cold seasons to ensure indoor air quality. This scenario limits the adaptive behavior of the students, making them passively adapt to the thermal environment. Their thermal sensation is actually colder than predicted by PMV (Fig. 14b). As a result, the adaptive theory is not applicable to this scenario and the adaptive PMV models are ineffective. This is also consistent with the findings of Liu et al. [28].

Furthermore, as mentioned in Section 3.2, the students' TSV was found to be only correlated with the indoor operative temperature. This explains why the models based on the operative temperature perform better than the adPMV model that is based on the running mean temperature. As one of the most commonly used thermal sensation models, TSV regression can be considered an effective prediction model in the window-airing scenario. The operative temperature is the most critical determinant of TSV (R^2=0.645), while the residuals of the model can be explained by other unobservable factors such as individual differences and uncertainties. Notably, the TSV regression had a higher slope than the PMV regression (Fig. 14b), suggesting that students are more sensitive to temperature changes with window openings than in an adaptive thermal environment.

3.3.2. Comfort vote prediction models

As discovered in Section 3.2, students' comfort is mainly determined by thermal sensation and air movement. Therefore, following Section 2.4, an MLR-based comfort vote (CV) prediction model was established based on thermal sensation vote (TSV) and air movement vote (AMV), as well as the corresponding environmental parameters of operative temperature (T_{op}) and indoor air velocity (V_a). Besides, a CV model was also developed based on the operative temperature and the air change rate (ACH), which can determine the indoor temperature set point under forced ventilation protocol in the cold season. Table 3 summarizes the developed CV prediction model. It was calculated that when meeting an ACH of 4 times/h required by EN 16,798–7 [44], maintaining the indoor temperature at 21.06 °C would not cause an obvious sense of discomfort to students in general (CV=0). During the flu season, the ACH should be increased to 6 times/h [64], while the indoor temperature should be increased to 21.63 °C to offset the negative effect of the higher air movement.

In general, the developed CV model demonstrates a satisfactory performance, with a MAE of only 0.122 and an R^2 of 0.663. Due to the uncertainty between the subjective sensation votes and the corresponding environmental parameters, the CV model developed with the

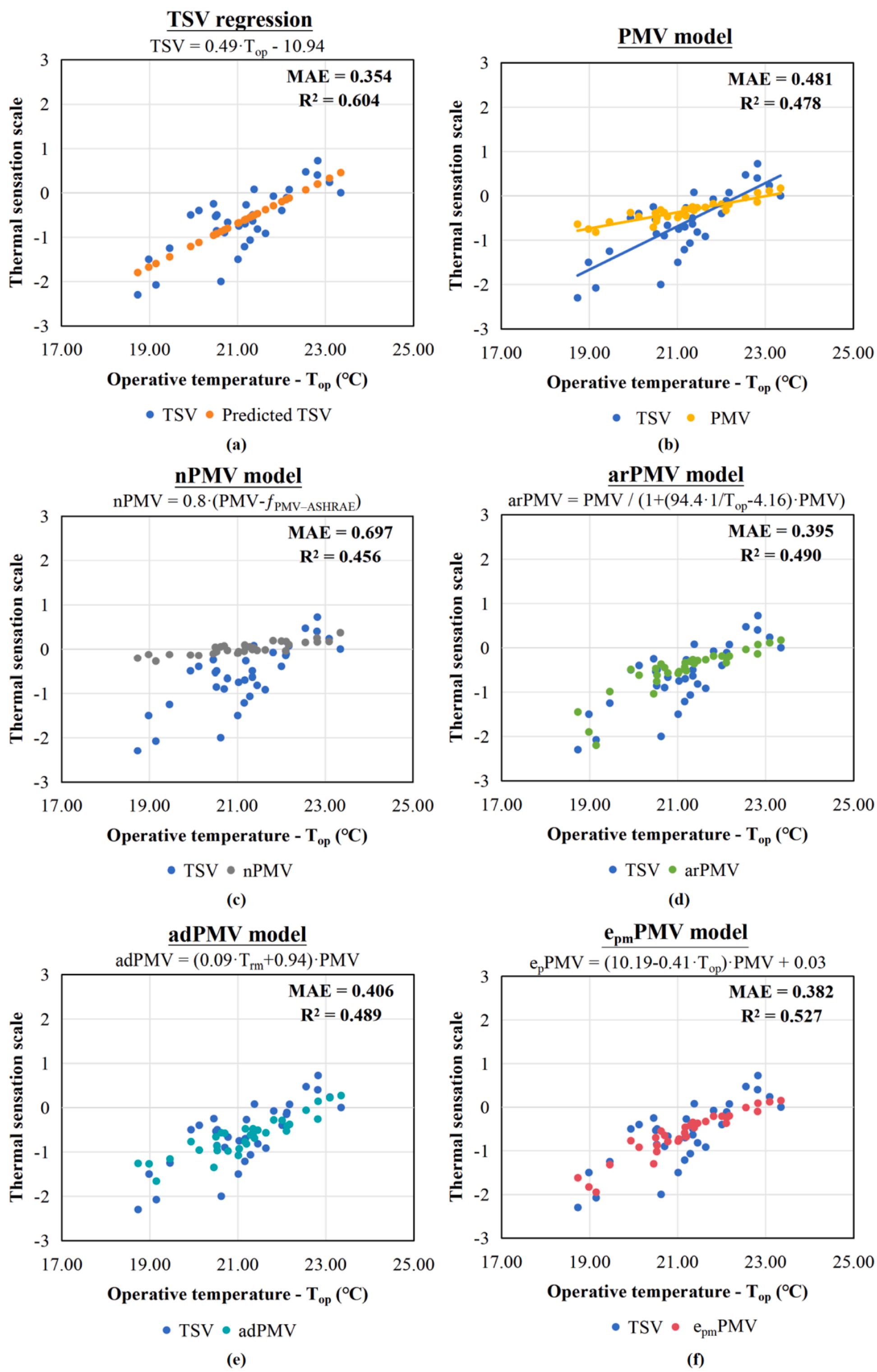


Fig. 14. PMV, TSV, and adaptive PMV models.

Table 3
Developed comfort vote prediction model.

Model	Mean absolute error (MAE)	Coefficient of determination (R^2)
CV = 0.276·TSV - 1.04·AMV + 0.233	0.122	0.663
CV = 0.121·T_{op} - 2.676·V_a −2.483	0.180	0.323
CV = 0.128·T_{op} - 0.036·ACH - 2.552	0.178	0.328

operative temperature, indoor air velocity, and air change rate has a slightly higher MAE and a comparatively lower R^2. The developed CV model generally has a good prediction accuracy with acceptable errors (Fig. 15), which has certain practical values. Relevant studies can develop an effective prediction model with these identified simple environmental parameters to predict the occupants' comfort in practice.

3.4. Further discussions on practical implications and limitations

Certainly, it is necessary to further discuss the practical implications of the results of this study. The COVID-19 pandemic has reminded the educational community of the importance of maintaining good indoor air quality in schools. However, many schools are completely dependent on natural ventilation and HVAC systems are not available due to financial constraints. For these schools, it could be inevitable to open windows to ventilate during class time in the winter for the sake of students' health, especially during flu season. This study found that achieving the required ventilation rates with window-airing would not lead to a serious discomfort problem in terms of air movement. Students' comfort is primarily determined by the indoor operative temperature. Therefore, whenever the windows have to be opened to maintain good indoor air quality, the effect of outdoor cold air can be offset by increasing the temperature setting of the heating system. Llanos-Jiménez et al. [65] suggested that in the context of climate change, temperature increases in the Mediterranean climate may reduce heating demand in future scenarios. This could be a positive sign for natural ventilation in winter in the long term. In the short term, however, window-airing in winter should be considered an "emergency" countermeasure to deal with the flu season, given the energy loss in heating. Schools also may have to make a trade-off between additional energy costs and investment in mechanical ventilation systems. In addition, it is very important to limit the number of students in the classroom. For example, the occupancy ratio of the classroom is often recommended to be above 2.0 m^2/student [66]. A crowded classroom not only affects students' perceived air quality but also leads to higher CO_2 concentration and infection risks, requiring higher ventilation rates to maintain air quality. Lastly, this study proposed a way to model students' comfort with simple parameters of indoor temperature and ventilation rate, which can provide a reference for appropriate temperature settings in the corresponding scenarios.

It is also necessary to discuss the limitations of this study to further help future research. On one hand, due to the availability of research participants, the sample size in this study is relatively small (30 students) and they are mainly composed of male students. This may limit the generalization ability of the proposed model. Therefore, it is recommended that future studies validate and enhance the proposed model with more student samples and further investigate the differences between female and male students as they may have slight differences [22, 67]. On the other hand, this study focused on the most important natural ventilation strategy of window-airing, as cross ventilation is not always applicable in schools due to the influence of noise from the corridor [9, 68]. The experiments were conducted with a typical adaptation period of 30 min. Future studies are recommended to further investigate the cross ventilation scenario and different adaptation time lengths for a comparative study.

4. Conclusions and recommendations

Based on a field experiment conducted in a Spanish university in winter, this study investigated students' comfort with window-airing during the cold season. The study identified the main subjective sensations and environmental parameters that affect the students' comfort, and developed the comfort prediction model with the correlated parameters. The main conclusions are summarized below:

(1) When performing window-airing in cold seasons, students' comfort is mainly determined by thermal sensation (70 %) and air movement (18 %) and is generally not affected by humidity sensation (7 %) and perceived air quality (5 %).

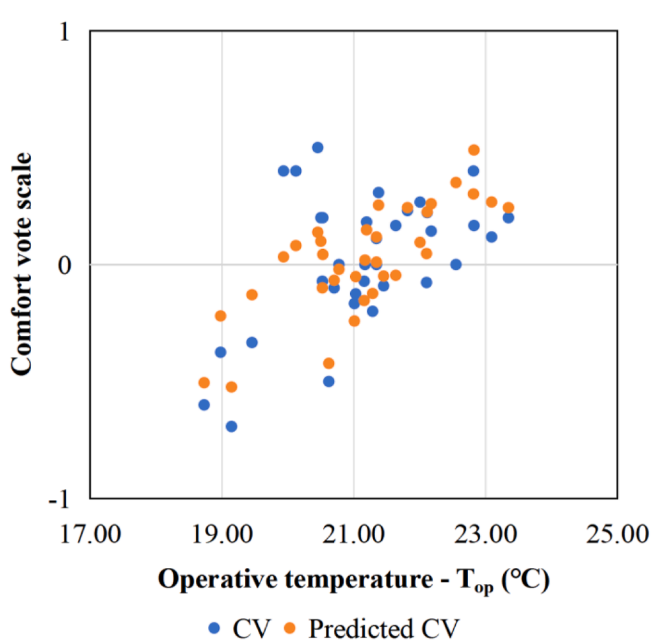


Fig. 15. Comfort vote and predicted comfort vote.

(2) Students' thermal sensation is directly determined by the indoor operative temperature rather than the outdoor temperature. Under window airing, students can be more sensitive to temperature changes, and their neutral temperature was found to be 22.4 °C, which is on average 1 °C lower than the adaptive environment. The adaptive PMV models were found to be ineffective under such a scenario where students' adaptive behavior is limited.

(3) Students' sensation of air movement is directly related to the indoor air velocity, which is determined by the window opening area and ventilation rate. Those who sit closer to the windows are more likely to feel the fresh breeze. Achieving the ventilation rate required by the building codes would not cause obvious discomfort to the students as the corresponding indoor air velocity is far below the threshold of the cooling effect specified in the standard.

(4) Students are not very sensitive to indoor humidity and air quality under natural ventilation. Their perception of air quality is more of a very subjective judgment based on intuitive factors such as window opening area, occupancy rate, and fresh breeze from outside. They do not directly feel the changes in the air quality parameters (such as CO_2, VOC index) in a real sense.

(5) Since comfort is mainly determined by thermal sensation and air movement, the comfort prediction model based on related environmental parameters (T_{op} and V_a/ACH) was proposed. According to the developed model, to meet the ACH of 4 times/h required by the standard, the indoor temperature should be maintained at around 21.0 °C to avoid causing discomfort to the students. The indoor temperature needs to be increased to 21.6 °C when the ventilation rate is increased to 6 times/h to cope with the flu season.

These findings address the existing gaps in the research topic (mentioned in the introduction) and have clear practical implications for naturally ventilated schools where HVAC systems are not available. Several topics are recommended for future research, including the comparative analysis in other climates, the gender differences in subjective comfort, the case of cross ventilation, as well as the effects of different adaptation periods on students' subjective comfort.

CRediT authorship contribution statement

Sen Miao: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marta Gangolells:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Blanca Tejedor:** Writing – review & editing, Supervision, Conceptualization.

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.

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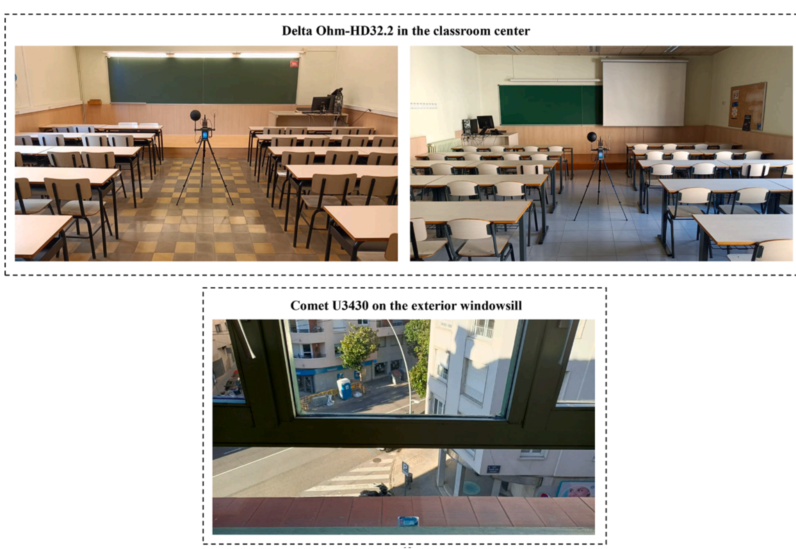
Appendix A. Placement of measurement sensors in the classrooms



Appendix B. Subjective survey questionnaire used in the field experiment

iaq4edu optimal ventilation strategies for balancing indoor air quality, comfort and energy use in educational buildings
GRIC GROUP OF CONSTRUCTION RESEARCH AND INNOVATION UNIVERSITAT POLITÈCNICA DE CATALUNYA

IAQ & THERMAL COMFORT SURVEY

This survey is part of IAQ4EDU research project (https://iaq4edu.upc.edu) for evaluating the thermal comfort of the classroom under natural ventilation. We appreciate your participation and valuable feedback in this survey!

1. Gender: ☐ Male ☐ Female
2. Age:
3. Desk code:
4. Clothing:

Each section may select more than one option. For example, the upper body clothing may have both T-shirt (short sleeve) and jacket.

Upper body clothing	Lower body clothing	Shoes	Accessories
T-shirt (short sleeve) ☐	Trousers ☐	Socks ☐	Scarf ☐
T-shirt (long sleeve) ☐	Shorts/Skirt ☐	Sneaker ☐	Cap ☐
Vest ☐		Sandal ☐	Mask ☐
Sweater ☐		Boots ☐	
Hoodie ☐			
Cardigan ☐			
Jacket ☐			

5. How do you feel about the **temperature** in the classroom?

Cold (-3)	Cool (-2)	Slightly cool (-1)	Neutral (0)	Slightly warm (+1)	Warm (+2)	Hot (+3)
☐	☐	☐	☐	☐	☐	☐

6. How do you feel about the **air movement** in the classroom?

Too still (-3)	Still (-2)	Slightly still (-1)	Neutral (0)	Slightly breezy (+1)	Breezy (+2)	Too breezy (+3)
☐	☐	☐	☐	☐	☐	☐

7. How do you feel about the **humidity** in the classroom?

Too humid (-3)	Humid (-2)	Slightly humid (-1)	Neutral (0)	Slightly dry (+1)	Dry (+2)	Too dry (+3)
☐	☐	☐	☐	☐	☐	☐

8. How do you feel about the **air quality** in the classroom?

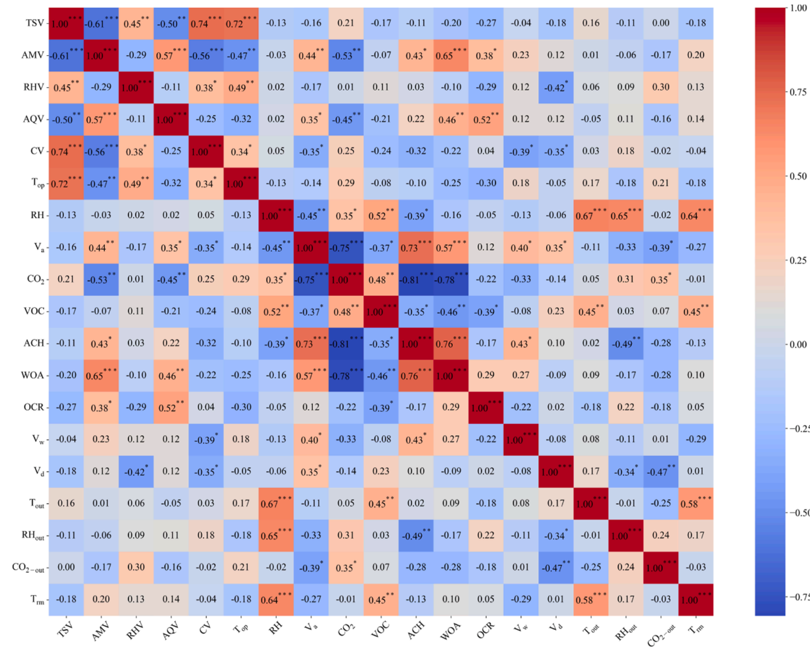
Terrible (-3)	Bad (-2)	Poor (-1)	Neutral (0)	Fine (+1)	Good (+2)	Excellent (+3)
☐	☐	☐	☐	☐	☐	☐

9. Are you **comfortable**?

Uncomfortable (-1)	Neutral (0)	Comfortable (+1)
☐	☐	☐

Many thanks again for your response!

Appendix C. Correlation matrix for all analyzed variables (in Table 1)



Data availability

Data will be made available on request.

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