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Exploring the impact of perceived control on thermal comfort and indoor air quality perception in schools

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ABSTRACT

Perceived control, as an integral part of the psychological impact, can be considered an important factor in the adaptive thermal comfort model. With the aim of exploring the relationship between perceived control and thermal comfort and indoor air quality (IAQ) in school buildings, a three-month field study was conducted during the heating season involving 26 school classrooms in the Italian Province of Pisa. The experimental campaign was conducted by carrying out measurements of thermal and IAQ parameters. In addition to instrumental measurements, subjective analysis was carried out by collecting 859 questionnaires filled in by students concurrently with objective measurements. The study demonstrate that the thermal neutral temperatures of the occupants with and without perceived control are, respectively, 21.7 °C and 22.2 °C and that the enhancing influence of the perceived control on the thermal sensation decreases with the increase of indoor operative temperature. The study shows that the perception of IAQ by the occupants is inversely proportional to the operative temperature and CO_2 concentration. Furthermore, it emerges that students with the perception of control express better subjective judgments regarding the IAQ. It is suggested to ensure environmental control in order to improve indoor comfort and decrease the energy demand for heating.

1. Introduction

In schools, it is essential to provide Indoor Environmental Quality (IEQ), as occupants can be particularly vulnerable in these environments [1–4]. In particular, it is fundamental to provide thermal comfort and indoor air quality without compromising energy consumption [5].

The perception of thermal comfort in educational buildings can depend on several aspects such as the educational stage, climatic zone, and operation mode [5]. The students' thermal sensations can largely depend on their age, as they have different adaptive capacities and carry out different activities [6]. Different neutral temperatures were recorded in diverse climatic zones [7] and even the operation mode can influence the thermal environment, which can be steady-state or transient [5]. Furthermore, since the combined effect of indoor air quality and thermal comfort has been widely recognized [8] but still debated, these two aspects were often analysed jointly in classrooms, and CO_2 concentration was the most frequently measured parameter as an indicator of air quality [9]. Indeed, air quality can be particularly critical in classrooms when ventilation is provided by opening windows only [10].

All these considerations show the complexity of providing a favourable environment for students thus several comfort models were

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List of abbreviations

Abbreviation	*Definition*
A	Area
ACH	Air Change per Hour
A_{Du}	Body Surface Area
CA	Central Air
CR	Central Radiator
EXP	Exposure
H	Height
HS	Heating System
IAQ	Indoor Air Quality
IAQV	Indoor Air Quality vote
I_{cl}	Clothing Thermal insulation
IEQ	Indoor Environmental Quality
MRT	Mean Radiant Temperature
MV	Mechanical Ventilation
NV	Natural Ventilation
PC	Perceived Control
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
RH	Relative humidity
RH_{rm}	Runnning mean outdoor relative humidity
RISK	Perceived risk vote
SA	Split Air
T_a	Air temperature
$T_{acceptability}$	Acceptability temperature
TAV	Thermal Acceptability Vote
T_g	Globe-thermometer temeperature
$T_{neutral}$	Neutral temperature
T_{op}	Operative temperature
TPV	Thermal Preference Vote
$T_{preference}$	Preference temperature
T_{rm}	Running mean outdoor temperature
TSV	Thermal Sensation Vote
V	Volume
V_a	Air velocity
VS	Ventilation System
W_b	Body weight

often applied. To inspect thermal comfort, the most commonly used models are Fanger's rational method and the adaptive one.

Fanger proposed the Predicted Mean Vote (PMV) - Predicted Percentage of Dissatisfied (PPD) model based on the heat balance equation of the human body [11]. However, many researchers have highlighted that the PMV value deviates from the actual thermal sensation vote (TSV), especially in school buildings [12–15].

Because human beings adapt to the thermal environment around them, over the years the theory of adaptive thermal comfort has been formulated. The adaptive comfort theory suggests that when people feel uncomfortable, they react to the discomfort with adaptive behaviour [16,17]. Hence, the acceptable temperature range could be extended wider than the comfort zones defined by the PMV-PPD model [12]. Several elements concerning adaptive thermal comfort have been investigated. According to Brager and de Dear there are three modes of adaptation: (1) behavioural adjustments (personal, environmental, technological, or cultural), (2) physiological (genetic adaptation or acclimatization), and (3) psychological (habituation or expectation) [18].

Therefore, perceived control, as an integral part of the psychological impact, can be considered an important factor in the adaptive thermal comfort model [19,20]. Perceived control refers to the fact that people realize that they have the ability to control their surrounding environment, for example by regulating the indoor temperature. In particular, these control methods may not necessarily be used; what matters is that the occupants know they have the means to modify the indoor parameters [21]. Therefore, perceived control is a form of psychological adaptation: occupants with more means of control think they have more chances to adapt to their surroundings and therefore are less likely to complain of discomfort than those with a lower level of perceived control [22,23].

Previous studies have highlighted the linkage between perceived control and indoor comfort and winter energy use. Brager et al.

[24] conducted a field study in naturally ventilated office buildings, which showed occupants with more opportunities to operate windows voted thermal sensation closer to neutral than those who had less capability to control windows. Largevin et al. [25] re-analysed the data of three case buildings from the RP-884 database in a more detailed way and reported significant correlations indeed appeared between comfort evaluation and perceived control variables even in air-conditioned buildings. Luo et al. [19] examined the influence of perceived control on thermal comfort through a chamber experiment. The study showed that the occupants with perceived control were more likely to report better thermal sensations and higher thermal satisfaction in both warm and cool conditions. The severer the thermal conditions were, the more subjects wanted to improve their current thermal environment, and the more effective the perceived control was. Xu and Li [26] analysed the impact of perceived control in a climate chamber and two residential buildings in China during the winter season, showing that the perceived control was able to decrease the neutral temperatures and that this effect is inversely proportional to the indoor operative temperature. In a study in a climate chamber, Yang et al. [27] defined perceived control as the ability of the people to freely move in an indoor space and showed that the fixed position affected thermal comfort, increasing the risk of discomfort. Considering that energy demand for buildings is increasing [26], providing perceived control over the environment can be a strategic way to reduce energy consumption, as it can enhance occupants' satisfaction and shift thermal neutrality.

Literature shows that perceived control in winter is capable of improving indoor comfort and can make occupants feel warmer in cold environments. Yet, too little is known about the impact of perceived control on indoor comfort in the context of school buildings, being these kinds of studies mainly conducted in residential buildings where occupants have a greater degree of control over the environment. It is therefore necessary to also investigate this correlation in school buildings, as different adaptive behaviours are expected depending on the type of building. In particular, seemingly diverse adaptive opportunities are available to students in a typical classroom scenario as classrooms are often equipped with various control measures such as operable windows, fans, or air conditioners.

Whether or not school children actually exercise such adaptive opportunities is another matter [17]. For example, school children may not actively interact with doors and windows because of their height and because it would require permission from their teacher [28]. We can reasonably say that the environmental conditions in classrooms often reflect the preferences of the teachers [29,30].

Furthermore, students are immersed in the indoor environment and are subjected to all aspects of the IEQ, thus is important to analyse the interactions between them, focusing on a more complex model than the conventional 'dose-response' one [31]. In particular, the aspects of thermal comfort and air quality can be strongly related [8], but the effect of perceived control on indoor air quality and its interaction with thermal sensation is still unknown. The recent issue of COVID-19 and the consequent recognized need for increased ventilation has further highlighted the importance of investigating these two aspects of IEQ.

This study answers the following research questions: (1) In the school buildings, is there any correlation between the perceived control over the parameters of the surrounding indoor environment and (1.1) the thermal comfort of the occupants, (1.2) their perception of indoor air quality (IAQ), and (1.3) the perceived risk of COVID-19 infection? (2) If so, can these correlations be described

Table 1
Characteristics of the selected classrooms.

	School	Class	Type	Year	HS	VS	EXP	H (m)	A (m^2)	V (m^3)	Seats
Primary schools	P1	ID1	Teaching room	2016	CA	MV*	South	3.0	56.9	170.7	20
	P1	ID2	Teaching room	2016	CA	MV*	North West	3.0	56.9	170.7	25
	P1	ID3	Laboratory	2016	CA	MV*	North West	3.0	77.1	231.2	30
	P1	ID4	Teaching room	2016	CA	MV*	South West	3.0	56.9	170.7	25
	P2	ID5	Teaching room	1970	CR	NV	South	3.1	44.0	136.4	19
	P3	ID6	Teaching room	2018	SA	NV	North	3.1	45.0	144.0	21
	P3	ID7	Teaching room	2018	SA	NV	North	3.1	45.0	144.0	21
	P4	ID8	Teaching room	1970	CR	NV	South	3.1	50.0	155.0	25
	P4	ID9	Teaching room	1970	CR	NV	South	3.1	50.0	155.0	25
Middle schools	M1	ID10	Teaching room	1970	CR	NV	South	3.1	45.0	139.5	22
	M1	ID11	Teaching room	1970	CR	NV	North	3.1	45.0	139.5	26
	M1	ID12	Teaching room	1970	CR	NV	South	3.1	45.0	139.5	23
	M1	ID13	Teaching room	1970	CR	NV	South	3.1	45.0	139.5	23
	M2	ID14	Teaching room	2020	CR	NV	South East	3.1	44.0	136.4	24
	M2	ID15	Teaching room	2020	CR	NV	North West	3.1	44.0	136.4	23
	M2	ID16	Teaching room	2020	CR	NV	North West	3.1	44.0	136.4	23
	M2	ID17	Teaching room	2020	CR	NV	South East	3.1	44.0	136.4	27
High school	H1	ID18	Multipurpose room	2018	CR	MV**	North	3.0	100.0	300.0	28
	H1	ID19	Multipurpose room	2018	CR	MV**	South East	3.0	100.0	300.0	28
University	U1	ID20	Teaching room	1936	CR	NV	South East	6.0	80.0	476.0	70
	U1	ID21	Teaching room	1936	CR	NV	South East	6.0	80.0	476.0	100
	U1	ID22	Laboratory	1936	CR	NV	East	3.2	70.0	224.0	44
	U1	ID23	Laboratory	1936	CR	NV	East	3.2	70.0	224.0	44
	U2	ID24	Teaching room	1970	CR	NV	South	3.2	52.0	166.4	40
	U2	ID25	Teaching room	1970	CR	NV	North	3.2	93.0	297.6	98
	U3	ID26	Teaching room	1970	CR	NV	East	3.2	43.0	137.6	40

HS = Heating System (CA = Central Air System; CR = Central Radiator System; SA = Split Air System); VS = Ventilation System (NV = Natural Ventilation; MV = Mechanical Ventilation); EXP = Exposure; H = Height; A = Area; V = Volume; * ACH = 2.5; ** ACH = 5.

quantitatively? Therefore, in order to highlight the impact of perceived control on students' indoor comfort, this work investigated thermal comfort and IAQ in 26 school classrooms in Pisa Province and in the winter season by carrying out instrumental measurements and subjective analyses.

2. Methodology

The field study investigated 26 classrooms of 10 school buildings from different educational stages in Pisa Province in winter season. The field study was conducted during class hours between October and December 2021. Instrumental and subjective measurements were performed simultaneously.

2.1. Surveyed buildings

2.1.1. Selection criteria of the surveyed buildings

The following criteria were considered in order to have a homogeneous and representative selection of school buildings: (1) educational stage (primary, middle, high school, and university), (2) year of construction/renovation, (3) operation mode, (4) construction type, and (5) urban context. In particular, the sample is heterogeneous from the control of environmental parameters point of view.

2.1.2. Description of surveyed buildings

The case study comprised four primary schools (6–10 years), two middle schools (11–13 years), one high school (14–18 years), and three buildings of the Pisa University campus (18+ years).

The ten buildings are located within a 14 km distance from Pisa and fall all into the same climatic zone. The basic information about the classrooms is shown in Table 1.

M2, P1, P3, and H1 are new school buildings, which were built according to the principles of sustainability. P2, P4, M1, U2, and U3 were built in the 70s of the last century. U1 is the main building of the School of Engineering of the University of Pisa and was built in 1936.

The construction systems are different. P1 was built using a timber-based technology. P2, P4, M1, H1, U1, and U3 are brick-concrete buildings. U3 has a steel structure with facing brick walls. M2 is a brick-concrete building with a ventilated façade with thermal insulation. P3 is a temporary module with insulated walls.

The schools are all located in an urban context, except for H1 which is located in an industrial area.

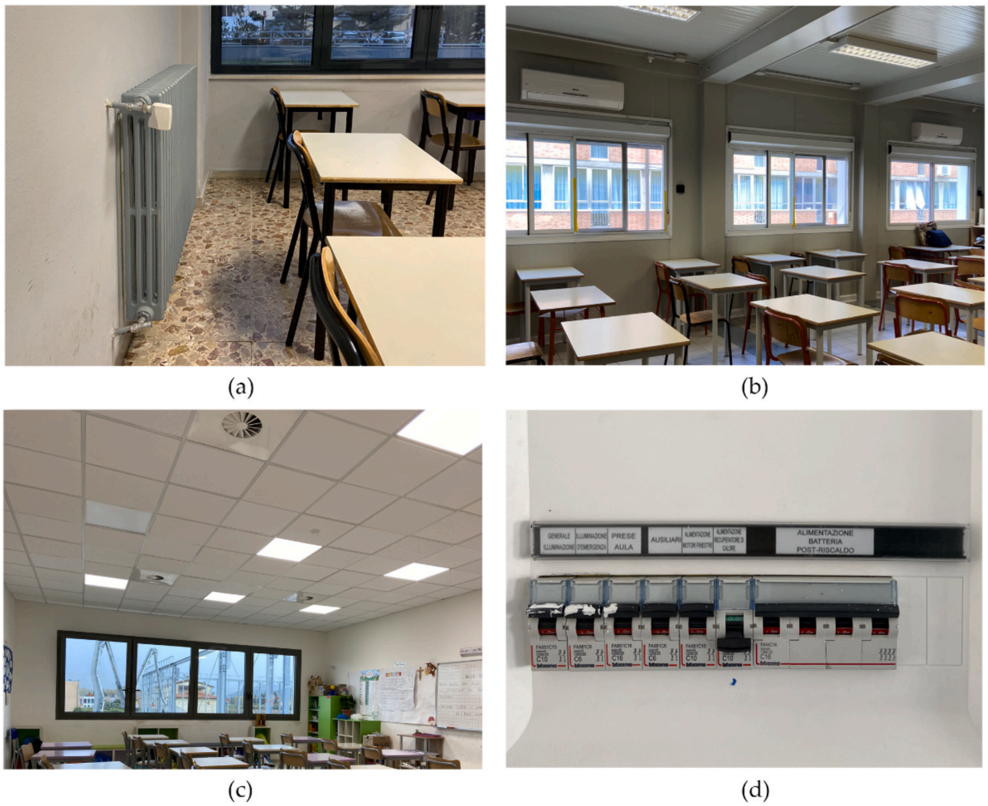

Fig. 1. Examples of different heating and ventilation systems in the surveyed buildings: (a) not controllable central heating system; (b) controllable split air conditioner system; (c) not controllable mechanical ventilation system; (d) controllable mechanical ventilation system: control panel.

The biggest difference between the schools is the heating mode in winter and the ventilation systems, which are important factors to be compared in this paper (Fig. 1).

The heating system of P2, P4, M1, M2, H1, U1, U2, and U3 is the widely used (in Italian school buildings) central heating system in which hot water flows inside radiators. Being a central heating system, students and teachers cannot adjust the temperature and they can only close single radiators. The heating system of P1 is a centralized air system that circulate warm air through a system of supply and return ducts. Therefore, also in this case, the occupants are not able to manage the system independently. P3 has no central heating system, but each classroom has a split air conditioner thanks to which the occupants can control the indoor temperature (thus, it is a full-air heating system).

Regarding ventilation, P1 and H1 have both a mechanical ventilation system. However, in the case of P1, the system has CO_2 probes which regulate the airflow based on the actual crowding of the classes and the occupants are not able to manage the system; on the contrary, in the case of H1, the mechanical ventilation system is directly controllable in each classroom. All other classrooms were naturally ventilated and students had access to the windows.

2.1.3. *Duration of monitoring*

For the analysis, the measurement campaign comprehensive of objective and subjective measurements was carried out during the heating period, from October 2021 to December 2021. Two hours and a half of monitoring in two different days were carried out in each of the classrooms.

2.2. *Onsite measurement*

2.2.1. *Objective measurements*

The objective measurements consisted of the acquisition of the environmental parameters in the classrooms. The air temperature (T_a), globe-thermometer temperature (T_g), relative humidity (RH), and air velocity (v_a) were measured through microclimate data-loggers DeltaOhm HD 32.3, equipped with the following instruments: a globe-thermometer TP3275, a hot-wire anemometer AP3203, and a temperature and humidity probe HP3217R. Then, outdoor air temperature and relative humidity were monitored with a PCE-HT110 probe. Furthermore, the CO_2 concentration was measured with PCE-AQD 10 probes and used as an indicator of IAQ. The technical information of the instruments is shown in Table 2.

When comparing the measurements of the various parameters obtained with the different probes, there was no appreciable difference in the measurements (the differences were less than the accuracy of the instruments).

The instruments were located in representative locations of the position of the students, chosen after a site inspection, and considering points that didn't disturb the normal operation of the classrooms. To provide a correct assessment of the parameters, the probes were shielded from direct solar radiation and placed away from walls, doors, windows, and heat sources (at least 1.5 m from them). The probes were placed at a height of 1.1 m to assess the sitting position of the students. The instruments were cleaned and periodically calibrated.

The monitoring started 30 min before the beginning of the lectures to ensure that the instruments were correctly operational and to allow students to acclimatize [26] and continued for 2.5 h for each class. Data were acquired with a measuring interval equal to 60 s, to include possible variations in the environmental parameters.

2.2.2. *Subjective measurements*

While the environmental parameters were monitored, questionnaires were submitted to students. Students were free to implement adaptive opportunities such as opening windows and doors, as well as changing their clothing. This choice was made in order not to compromise students' ability to restore their comfort conditions and not to inhibit perceived control over their environment. They were asked to fill in the questionnaire 1 h after entering the classroom so that they were acclimatised to the environment. In total, 859 questionnaires were collected. The sample was as balanced as possible from a gender point of view, with 362 male students (41.6%) and 507 female students (58.4%). This sample is comparable to others used in classroom studies in different countries [32].

The questionnaire was developed according to the ISO 28802 standard [33] and it was divided into fifth parts, as reported following.

The first part included personal information such as age, gender, height, weight, and location occupied in the classroom.

The second part asked for lists of the clothing ensembles worn by the students for the estimation of the clothing insulation according to ISO 9920 standard [34].

Table 2
Detailed information of instruments.

Physical quantity	Instrument	Range	Accuracy
Indoor air temperature	HP3217R temperature and humidity probe	−40 - 100 °C	±1/3 DIN
Outdoor air temperature	PCE-HT110 probe	0–50 °C	±0.8 °C
Globe-thermometer temperature	Globe-thermometer TP3275	−30 - 120 °C	±2 °C
Relative humidity	HP3217R temperature and humidity probe	0–100%	±1.5%
	PCE-HT110 probe	10–90%	±1%
Air velocity	AP3203 hot-wire anemometer	0.02–5 m/s	± (0.05 + 5% of the measure) m/s
CO_2	PCE-AQD 10 probe	0–4000 ppm	±70 ppm (<1000 ppm) ±5% of rdg. (<3000 ppm) ±250 ppm (>3000 ppm)

The third part studied the evaluation of the thermal environment (original questions in Italian – please see Supplementary data):

- Thermal Sensation Vote (TSV): "With reference to the temperature, how are you feeling now?" – From [−3] "Very cold" to [+3] "Very hot";
- Thermal Preference Vote (TPV): "Please state how you would prefer to be now:" – From [−3] "Much colder" to [+3] "Much warmer";
- Thermal Acceptability Vote (TAV): "On a personal level, this environment is for me:" From Ref. [1] "Perfectly acceptable" to Ref. [5] "Unacceptable".

The fourth part asked for the perceived control level:

- Perceived Control (PC): "How do you evaluate your control of comfort parameters at the moment? (e.g. opening and closing windows, thermostatic control, adjustment of blinds and other screens …)" – From [−3] "No control" to [+3] "Full control";

The fifth part evaluated the air quality:

- Indoor Air Quality Vote (IAQV): "How do you judge the air quality in the room at the moment?" – From [−3] "Terrible" to [+3] "Excellent";
- Perceived relation between COVID-19 and environmental factors (RISK): "How do you assess the risk associated with the spread of COVID-19 in this classroom?" – From [−3] "Very dangerous" to [+3] "Not dangerous";

2.3. Data processing

The indoor operative temperature T_{op} was calculated using the air dry-bulb temperature T_a and the mean radiant temperature MRT according to the ISO 7726 standard [35]:

$$T_{op} = \frac{T_a + MRT}{2} \tag{2.1}$$

The mean radiant temperature MRT was calculated using the indoor air dry-bulb temperature T_a, the black globe temperature T_g, the black globe diameter D, the black globe emissivity ε_g, and the indoor air velocity v_a, according to the ISO 7726 standard [35]:

$$MRT = \left[\left(T_g + 253\right)^4 + \frac{0.25 \bullet 10^8}{\varepsilon_g} \left(\frac{|T_g - T_a|}{D} \right)^{1/4} \bullet \left(T_g - T_a\right) \right]^{1/4} - 273 \tag{2.2}$$

The clothing insulation was evaluated from questionnaires, listing participants a selection of garments whose thermal insulation is defined in the ISO 9920 standard [34]. In particular, the clothing insulation was estimated as the sum of the thermal insulation supplied by each garment in accordance with ISO 7730 standard [36]:

$$I_{cl} = 0.83 \bullet \sum_i I_{cl,i} + 0.161 \tag{2.3}$$

The metabolic rate (M) was assessed from the activity performed by the students in the classrooms, according to the international standard ISO 8996 [37]. The metabolic rate was corrected by taking into account the different body surfaces of the children and adolescents, in accordance with previous studies [38–40]. In particular, the correction was based on each student's body surface area and hiring 1.8 m^2 as the average body surface area of an adult. The students' body surface area A_{du} was calculated using Eq. (4) [41]:

$$A_{Du} = 0.202 \bullet W_b^{0.425} \bullet H_b^{0.725} \tag{2.4}$$

where W_b is the body weight (kg) and H is the height (cm).

The ratio of each student's body surface area to the average body surface area of an adult has been used to correct the metabolic rate value.

From these parameters, Fanger's index PMV was calculated according to the ISO 7730 standard [36].

Since the outdoor air temperature and relative humidity were recorded during the measurement campaigns, the running mean outdoor temperature (T_{rm}) was calculated from the seven days before the measurements according to EN 16798-1 [30] and related to all the 859 samples. The running mean outdoor relative humidity (RH_{rm}) was calculated with the same methodology of the T_{rm}.

Objective and subjective measurements were processed to acquire information regarding the environmental and individual parameters to which students were subjected. The subjective answers were filtered so that there were no inconsistencies. No outliers values were found. For each student the measurement location was available (since it was derived from questionnaires), then each student's response was associated with the environmental parameters relating to the time at which they responded and at the position corresponding to the measuring instrument belonging to that area of the class.

The questionnaires sample was divided into two groups based on the perceived control vote. The students were divided into the ones who perceived control of the environmental conditions (votes >0) and others that did not (votes<0). The ones who voted 0 on the perceived control scale were excluded from the analysis, as they were considered neutral [42] and therefore not aware of the possibility to control the conditions. Out of the total sample of 859 subjective responses, 274 votes were then excluded. It resulted in 377 occupants with perceived control and 208 occupants without perceived control.

A common binning method was used for data analysis [26,43,44]. The indoor operative temperatures were binned into 0.5 °C

Table 3
Running mean outdoor temperature, and relative humidity in Pisa Province for the measurement period.

	Mean	Max	Min	SD
T_{rm} (°C)	11.5	18.7	5.0	3.4
RH_{rm} (%)	82.3	88.1	61.7	5.8

increments to calculate the average value of thermal sensation vote (TSV), thermal preference vote (TPV), thermal acceptability vote

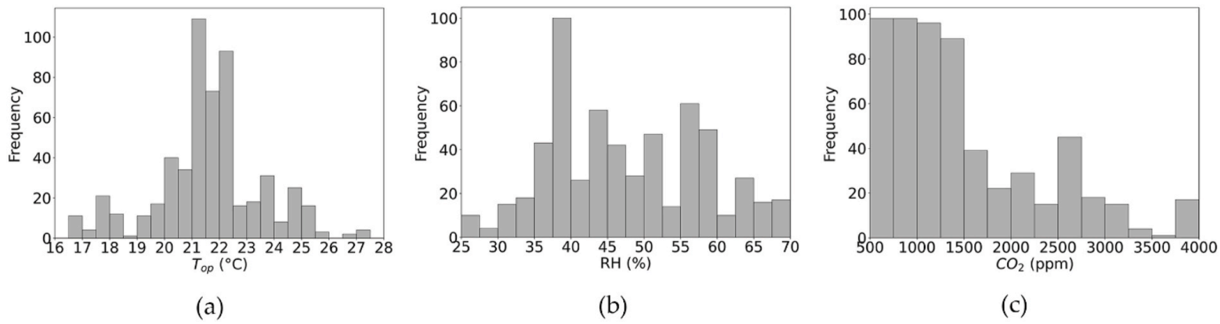

Fig. 2. Histograms for observed operative temperature, relative humidity, and CO_2.

(TAV), and indoor air quality vote (IAQV). The CO_2 concentration was binned into 200 ppm increments to calculate the average value of the risk associated with the spread of COVID-19 vote (RISK).

3. Results

3.1. The outdoor climate

The statistical summary of the running mean outdoor temperature (T_{rm}) and the running mean outdoor relative humidity (RH_{rm}) associated with each subjective response is reported in Table 3. The T_{rm} and RH_{rm} values are typical of a winter season in a Mediterranean zone such as Pisa Province.

3.2. Measured indoor environmental parameters

The statistical summary of the indoor environmental variables recorded during the measurement period and associated with each subjective response is reported in Fig. 2 and Table 4. Fig. 2 shows that in most cases CO_2 concentrations remained below the limits indicated by standards [45]. The mean indoor air temperature was 21.5 °C with a standard deviation of 1.8. The difference between the air and mean radiant temperature was negligible, showing that the thermal environment was rather uniform, and thus easing the use of operative temperature as an indicator. The mean RH remained in the range of 45–50% for the large majority of the time despite having reached a minimum of RH = 25.5% and a maximum of RH = 68.8%. The air velocity was on average lower than 0.1 m/s, with peaks of 0.5 m/s. The clothing insulation was on average 0.8 clo, with a maximum of 1.8 and a minimum of 0.45.

The metabolic rate, assessed from the activity performed by students [37], ranged between 1.2 and 2.1 met. These high values can be attributed to the correction applied to children and adolescents by considering their different body surfaces. The application of this correction resulted in an enhancement of the predictive performance of PMV (Mean MAE between PMV and TSV equal to 0.7 and 1.0 with and without correction, respectively). The PMV index was attested to cool sensations (mean PMV = −0.7), which means that students tended to be slightly cold, while the mean percentage of dissatisfaction expressed by PPD remained below 25% (Table 4).

3.3. Subjective responses

The mean and standard deviation of the responses from the questionnaire are reported in Table 5.

Concerning the thermal environment, on average students were feeling slightly cool (mean $-0.50<TSV<0.00$) and they tended to

Table 4
Statistical summary of the indoor environmental variables recorded during the measurement period.

	Mean	Max	Min	SD
T_a (°C)	21.5	27.4	16.9	1.8
T_r (°C)	21.6	27.2	16.9	1.9
RH (%)	47.6	68.8	25.5	10.2
V_a (m/s)	0.00	0.51	0.00	0.11
I_{cl} (clo)	0.8	1.8	0.45	0.15
Met (met)	1.6	2.1	1.2	0.3
PMV	−0.7	0.8	−2.0	0.6
PPD	22.9	94	5	19.4
CO_2 (ppm)	1490	3899	568	815

Table 5
Mean and standard deviation of the subjective responses.

		Mean	SD
TSV	With perceived control	−0.13	0.95
	Without perceived control	−0.32	1.50
TPV	With perceived control	0.04	1.12
	Without perceived control	0.16	1.51
TAV	With perceived control	1.35	0.69
	Without perceived control	1.99	1.06
PC	With perceived control	1.58	0.70
	Without perceived control	−1.55	0.72
IAQV	With perceived control	1.24	1.17
	Without perceived control	−0.35	1.48
RISK	With perceived control	1.42	1.79
	Without perceived control	1.14	2.11

accept the thermal environment, especially when they perceived to have control over it. The students preferred a slightly warmer environment ($0.00<TPV<0.50$). The perception of the air quality was good for subjects with perceived control (IAQV = 1.24) and close to neutral (neither excellent nor terrible) for subjects without perceived control (IAQV = −0.35). Regarding the perceived risk of COVID-19 infection, both subjects with and without perceived control didn't perceive the environment as very dangerous (RISK = 1.42 for subjects with perceived control and RISK = 1.14 for subjects without perceived control).

3.4. Effect of perceived control on thermal sensation

The relationship between thermal sensation and the operative temperature was calculated for PMV and TSV with and without perceived control. Weighted linear regressions between the two variables were obtained and the neutral temperatures were calculated by imposing the conditions TSV = 0 and PMV = 0. The regression equation, R^2, p-value, and $T_{neutral}$ calculated from the predicted and observed thermal sensation with and without perceived control are reported in Table 6.

Fig. 3 shows PMV and TSV of subjects with and without perceived control. It can be noticed that the TSV of subjects with perceived control is on average in the interval between [−1] and [+1]. On the contrary, the TSV of subjects without perceived control range on

Table 6
Regression equation, R^2, p-value, and $T_{neutral}$ calculated from the predicted and observed thermal sensation with and without perceived control.

	Regression equation	R^2	p-value	$T_{neutral}$ (°C)
PMV	$PMV = 0.26 \bullet T_{op} - 6.50$	0.95	<0.001	24.6
TSV with perceived control	$TSV = 0.25 \bullet T_{op} - 5.58$	0.82	<0.001	21.7
TSV without perceived control	$TSV = 0.32 \bullet T_{op} - 7.13$	0.88	<0.001	22.3

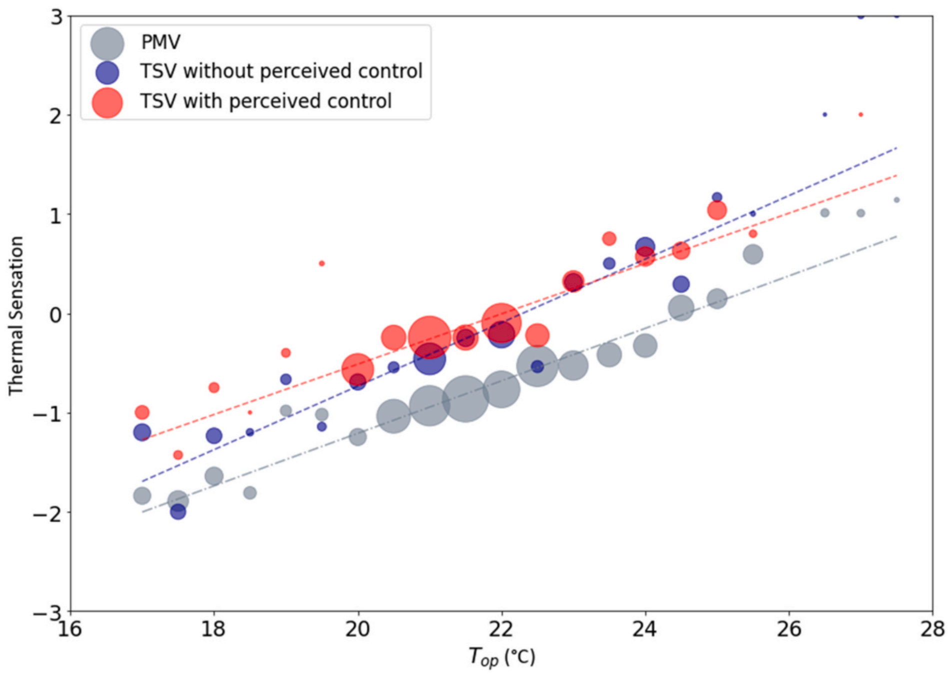

Fig. 3. Relationship between students TSV/PMV and T_{op}.

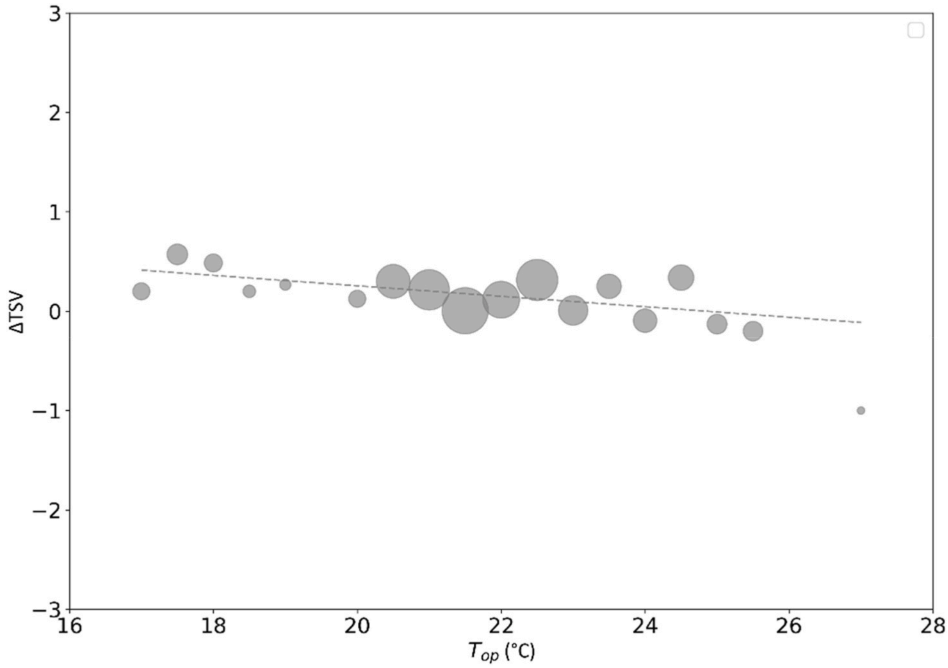

Fig. 4. Difference of thermal sensation vote of subject with and without perceived control depending on indoor operative temperature.

average in the interval between about [−2] and [+2].

It can be seen from Fig. 3 that there is an obvious "scissor difference" phenomenon between the two TSV lines. This "scissor difference" is the result of a different slope of the regression line between the operative temperature and the TSV with and without perceived control.

Observing the linear regression line of the PMV in Fig. 3, we can see that it generally underestimates the thermal sensation.

Table 6 shows that the regression line of the TSV of subjects with perceived control has lower slopes.

Furthermore, regarding neutral temperature, it can be noticed that it is 0.3 °C lower in case the students perceived to have personal control.

The impact of perceived control on the thermal sensation vote is inversely proportional to the indoor temperature (Fig. 4). As the indoor operative temperature increases in winter, the positive effect of the perceived control decreases.

The relationship between the difference in the TSV of the subject with and without perceived control and the indoor operative temperature was calculated through linear regression analysis:

$$\Delta TSV = - 0.0527\ T_{op} + 1.3088 \tag{3.1}$$

3.5. *Impact of perceived control on satisfaction*

To analyse the impact of perceived control on satisfaction, weighted polynomial regressions between operative temperature and the rate of satisfaction were calculated. In particular, they were considered satisfied the students who voted "Perfectly acceptable" or "Slightly unacceptable" on the 5-point Thermal Acceptability Vote (TAV). Fig. 5 shows the relationship between occupants' percentage of satisfaction and T_{op}, whose specifications are reported in Table 7. Subjects with perceived control showed greater acceptance of the thermal environment, especially for more severe thermal conditions. Even at neutral temperatures, there is greater acceptability of the environment by subjects with perceived control. This can be seen from the greater opening of the regression curve of students who thought they could control the environment.

Taking into account the maximum value of the regression equations it was possible to find the temperature at which there was the highest satisfaction rate. This acceptability temperature was lower in the case of subjects with perceived control ($T_{acceptability}$ = 21.4 °**C** for subjects with perceived control and $T_{acceptability}$ = 22.0 °**C** for subjects without perceived control).

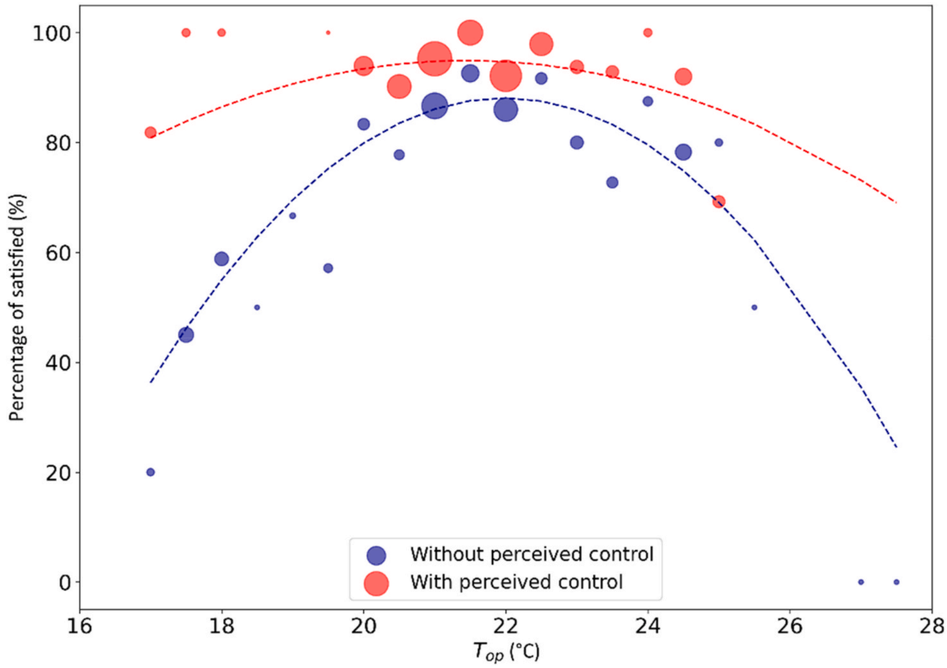

Fig. 5. Relationship between the percentage of satisfied and T_{op}.

Table 7
Regression equation, R^2, p-value, and $T_{acceptability}$ calculated from the thermal comfort vote with and without perceived control.

	Regression equation	R^2	p-value	$T_{acceptability}$ (°C)
With perceived control	$\%Satisfied = -0.0285 \bullet T_{op}^2 + 1.24 \bullet T_{op} - 12.721$	0.44	0.014	21.4
Without perceived control	$\%Satisfied = -0.0075 \bullet T_{op}^2 + 0.30 \bullet T_{op} - 2.119$	0.90	<0.001	22.0

3.6. Effect of perceived control on thermal preference

The relationship between thermal preference and the operative temperature was calculated for the Thermal Preference Vote (TPV) with and without perceived control (Fig. 6). Weighted linear regressions between the two variables were calculated and the preference temperatures were calculated by imposing the condition TPV = 0. The regression equation, R^2, p-value, and $T_{preference}$ calculated from the predicted and observed thermal preference with and without perceived control is reported in Table 8.

Regarding thermal preference, the "scissor difference" between the regression obtained for data with and without perceived control is evident as the slope of the regression line with perceived control is lower than the one without perceived control.

The preferred temperatures were also calculated with and without perceived control and showed that the $T_{preference}$ was 0.7 °C lower with the perceived control.

3.7. Effect of perceived control on indoor air quality perception

The relationship between the perception of IAQ and the operative temperature was calculated for the Indoor Air Quality Vote (IAQV) with and without perceived control (Fig. 7). The weighted regression equation, R^2, and p-value calculated from the IAQV with and without perceived control is reported in Table 9.

The perception of IAQ is inversely proportional to the indoor operative temperature (Fig. 7). With the increase of indoor operative temperature, the perception of IAQ gradually gets worst. Furthermore, Fig. 7 shows that subjects with perceived control expressed better subjective judgments about the IAQ as positive values indicate better indoor air quality votes IAQV.

The relationship between the perception of air quality and CO_2 concentration was also investigated. The results showed that there is not a strong correlation between the two parameters ($R^2 < 0.1$ and p-value>0.9 for both subjects with and without perceived control).

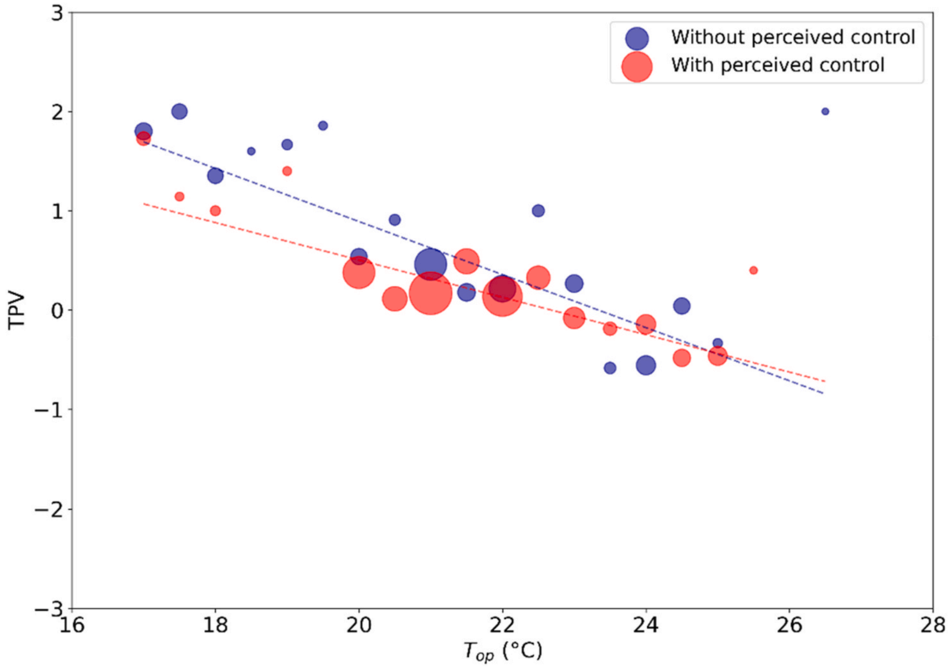

Fig. 6. Relationship between occupants' TPV with and without perceived control and T_{op}.

Table 8
Regression equation, R^2, p-value, and $T_{preference}$ calculated from the thermal comfort vote with and without perceived control.

	Regression equation	R^2	p-value	$T_{preference}$ (°C)
With perceived control	$TPV = -0.188 \bullet T_{op} + 4.267$	0.68	<0.001	22.7
Without perceived control	$TPV = -0.267 \bullet T_{op} + 6.237$	0.67	0.015	23.4

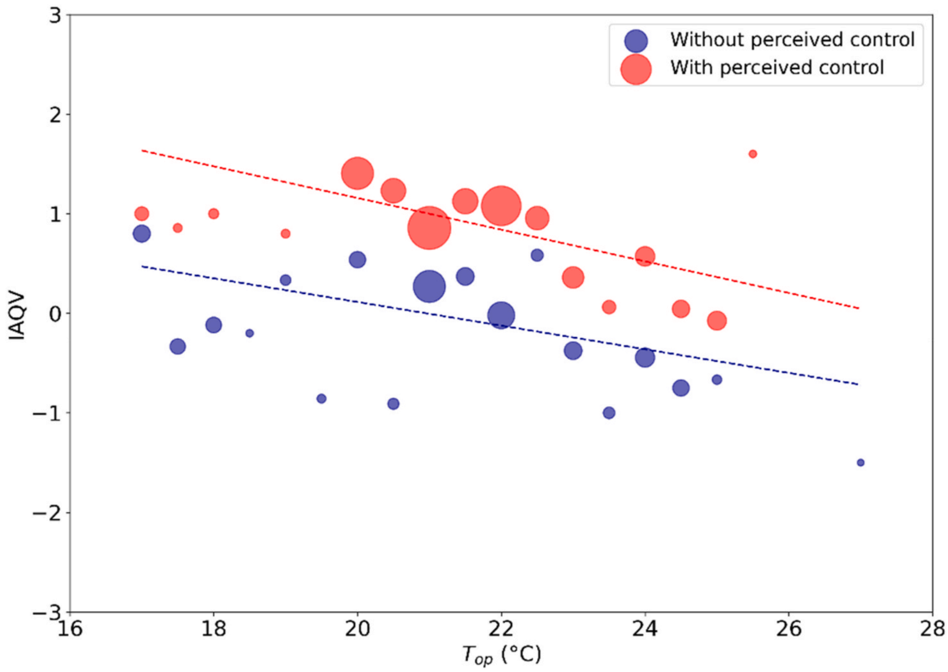

Fig. 7. Relationship between occupants' IAQV with and without perceived control and T_{op}.

Table 9
Regression equation, R^2, and p-value calculated from the IAQV with and without perceived control.

	Regression equation	R^2	p-value
With perceived control	$IAQV = -0.159 \bullet T_{op} + 4.336$	0.45	<0.001
Without perceived control	$IAQV = -0.119 \bullet T_{op} + 2.488$	0.29	<0.001

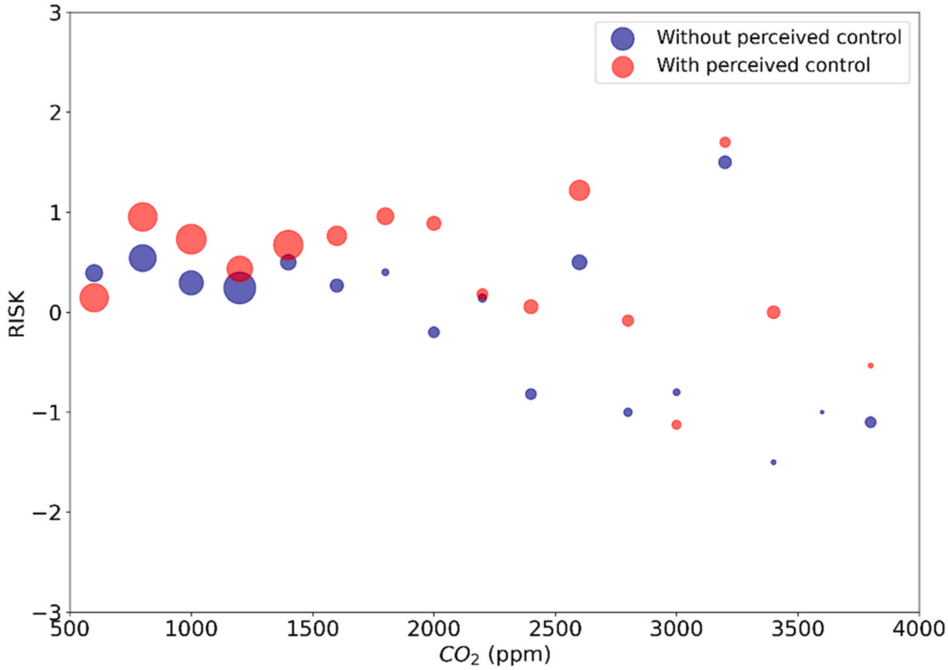

Fig. 8. Relationship between occupants' perceived risk of COVID-19 infection with and without perceived control and T_{op}.

3.8. *Effect of perceived control on the perceived risk of COVID-19 infection*

The relationship between the perceived risk of COVID-19 infection and the CO_2 concentration was calculated for the RISK vote with and without perceived control, clustering data for 200 ppm CO_2 steps (Fig. 8).

There is no strong correlation between the two parameters that cannot be explained by linear regression ($R^2 = 0.001$ and p-value = 0.9 in the case of subjects with perceived control; $R^2 = 0.13$ and p-value = 0.15 in the case of subjects without perceived control).

However, it is possible to observe a precise trend. In the case of subjects without perceived control, with the increase in CO_2 concentration, the perceived risk gets worst showing more negative values. On the other hand, in the case of subjects with perceived control, this link is much less marked.

4. Discussion

This study had the purpose to demonstrate the hypothesis that students with higher degrees of perceived control tend to accept wider ranges of indoor thermal environment and air quality, which will be discussed in this section.

4.1. *Effect of perceived control on thermal comfort*

First, the thermal sensation of the students assessed through questionnaires was analysed. The Thermal Sensation Votes of subjects with and without perceived control suggest that subjects with perceived control were on average in a situation of thermal neutrality, considering neutral occupants voting TSV = 0 as agreeing with Fanger's theory [11]. On the other hand, at the same indoor operative temperatures, subjects without perceived control were more sensitive to temperature changes. Overall, there are some differences between the relationship found for the real occupants in the case study (both with and without perceived control) and the one found for PMV. In general, PMV tended to underestimate students' thermal sensation, as emerged in previous studies conducted in schools [46].

Furthermore, the results show that there is a "scissor difference" among the TSV lines with and without perceived control (Fig. 3). This "scissor difference" is the result of a different slope of the regression line between the operative temperature and the TSV with and without perceived control. The result is that subjects with perceived control tend to feel more thermally neutral than those without control, showing a lower regression slope. This is consistent with the outcomes of previous studies in residential buildings during the winter season [19,26]. The more the operative temperature differs from the thermal neutral temperature toward lower temperature, the more the perceived control influences students' thermal sensation. At higher temperatures than the neutral temperature, the difference in the perception of the two groups is lower; on the other hand, at temperatures lower than those of thermal neutrality, the subjects with perceived control were able to feel more thermally neutral than the group of subjects without perceived control. Furthermore, subjects with perceived control presented a neutral temperature 0.3 °C lower than the ones without perceived control. These difference in neutral temperature is lower than other found in studies in different building type which showed differences of 1.9 °C [26] or even 2.6 °C [47] This can be related to a higher possibility to control the environmental conditions in residential buildings rather than in schools. However, this difference is still relevant in terms of providing comfort and reducing energy consumption. Moreover, the beneficial effect of perceived control on thermal environment perception decreases with increasing indoor operative temperature (Fig. 4). This trend is in line with previous studies conducted in residential buildings and during the winter season [26, 48].

The influence of perceived control did not affect thermal sensation only, but it also influenced the thermal acceptability of the students. Students tended to be more satisfied when they thought to have control of their indoor environment, regardless of the operative temperature that they were experiencing (Fig. 5). In fact, the percentage of satisfied occupants with perceived control has never decreased below 70%. This is in line with previous studies conducted in climate chambers which showed that perceived control can alleviate subjects' thermal discomfort [48,49].

Finally, regarding thermal preference, the results showed that in general students tended to prefer different environments (colder or warmer) when they had no control over them (Fig. 6). On the contrary, they did not wish to modify the environmental conditions when they perceived to have control. This is evident from a lower slope of the regression between operative temperature and TPV for subjects with perceived control.

All these aspects that can affect the perception of the thermal environment, including thermal sensation, acceptability, and preference, can be regarded as a form of adaptation and these findings offer good support to the hypothesis of the adaptive model [23, 50]. Indeed, in this study it was demonstrated that students who just believe to have the possibility to interact with their environments experience a modified perception of it in terms of sensation, acceptability, and thermal preference. This can mainly be considered a form of psychological adaptation, since the perceived control does not necessarily imply that the occupant effectively changes the indoor environmental conditions but that he believes in having the possibility to do it. Since it can largely influence the perception of the thermal environment and promote comfort, it would be necessary to give students the opportunity to control their environment, within certain limits.

4.2. Effect of perceived control on indoor air quality perception

The results put in evidence that there is a correlation between the indoor operative temperature and IAQ perception (Fig. 7). This is in line with previous studies which demonstrated that indoor operative temperature can affect air quality perception [8].

The study also investigated the effect of perceived control on the perceived risk of COVID-19 infection. The perceived risk of infection can influence the actions of occupants, the classroom operation, and students' adaptive capacities.

During COVID-19 pandemic, it was recommended to use the CO_2 concentration as an indicator of the risk of transmission by air, indicating specific limits but not taking into account other aspects such as classroom overcrowding, etc. [51]. Apart from this link between CO_2 concentration and actual risks, it was interesting to investigate whether there was also a link between CO_2 concentration and the perceived risk.

It was possible to notice that, with the increase in CO_2 concentration, the perceived risk got worst in particular for students who did not think they had control over their surroundings. Such a trend can be explained considering that the occupants who could operate adaptive behaviours for their own health (for example, opening windows) thought they were experiencing a smaller risk than those without perceived control.

5. Conclusions

This work investigated the impact of perceived control on indoor comfort in school buildings. A field survey on thermal comfort and IAQ in 26 Italian classrooms was carried out during the heating season. The results show that:

(1) With the same indoor operative temperatures, occupants with perceived control were more likely to experience neutral thermal sensations than subjects without perceived control. This supports the idea that having the perception of being able to control the environment increase the likelihood of perceiving that environment as more comfortable.
(2) In winter, the neutral operative temperatures of students with and without perceived control are 21.7 °C and 22.3 °C, respectively. The thermal preference temperatures are 22.7 °C and 23.4 °C, respectively. Finally, the thermal acceptability temperatures are 21.4 °C and 22.0 °C, respectively. Students should be aware of having the possibility to control the environment, which is conducive to reducing the comfort temperatures, setting lower setpoint temperatures, and lowering the energy demand for heating.
(3) The beneficial impact of perceived control depends on the indoor operative temperature. In winter, when the indoor operative temperature rises, the improvement in thermal sensation gradually decreases.
(4) Subjects with perceived control expressed better IAQ Votes with the same indoor operative temperatures and CO_2 concentrations than subjects without perceived control. As the CO_2 concentration increases, subjects without perceived control

believed there was a greater risk of contracting the virus COVID-19. On the other hand, subjects capable of performing adaptive actions such as opening windows thought they experienced a lower risk even for higher CO_2 levels.

In practice, it is recommended that school occupants should be provided sufficient opportunities to control their indoor environments through operable windows, fans, terminal controllable conditioning systems, etc. By allowing students to act on their environment, classrooms could be operated with lower setpoint temperatures, leading to significant energy savings. In addition, perceived control also affects the perception of air quality, which is also closely related to thermal parameters. Analysing the relationship between the two could improve students' perception of the indoor environment making them more satisfied, although control of objective parameters (especially air quality) is always necessary.

5.1. Limitations and future work

This study is one of the first that investigates the influence of perceived control over indoor comfort in school buildings. It was possible to understand the importance of using personal control approaches in the design of schools. However, further investigations are desirable.

The sample of respondents in this study included students of all educational stages without distinction. This was because the purpose of the work was to first understand whether or not the perceived control had any influence on the thermal comfort of the students, regardless of the educational stage. Furthermore, this was done in order not to fragment the sample, which in this way remained quite large. Since differences in thermal comfort perception due to different ages are widely recognized, future studies should focus on the effect of perceived control at diverse educational stages.

This study focused on the psychological adaptation of perceived control on students' thermal and perceived air quality responses. However, the behavioural adaptive actions at different educational stages should be further investigated, to understand how effectively students interact with their indoor environment and how this might affect thermal comfort and indoor air quality in the classrooms.

Furthermore, this study showed a relationship between thermal environment parameters and the perception of indoor air quality. This indicates that a precise evaluation of a comfortable IEQ should be determined considering the correlations between the different factors (IAQ, thermal environment, lighting environment, acoustic environment) rather than evaluating each factor independently. It is important to study in depth these links in the future.

When comparing people with and without perceived control, some previous studies grouped the sample based on the effective control system [26]. Using another approach, the authors decided to divide the students according to their perceived control vote as it seemed to best way to evaluate if people know to have the means to control the environment or not. In fact, perceived control refers to the fact that people realize that they can have control more than effectively having it. However, it would be interesting to evaluate the relationship between perceived and effective control in a future study.

CRediT authorship contribution statement

Giulia Torriani: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Giulia Lamberti**: Conceptualization, Methodology, Investigation, Writing – review & editing. **Fabio Fantozzi**: Conceptualization, Writing - review & editing, Supervision. **Francesco Babich**: Conceptualization, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2022.105419.

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