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Analysis of the Interplay between Indoor Air Quality and Thermal Comfort in University Classrooms for Enhanced HVAC Control

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Abstract: While aspects of indoor environmental quality, such as thermal comfort, indoor air quality (IAQ), acoustic, and visual comfort, are usually studied separately, their interactions are crucial yet often overlooked. Understanding how these factors influence each other is essential for a comprehensive perception of the indoor environment. This paper investigates the relationship between indoor air quality (IAQ) and thermal comfort using an extensive field investigation conducted in university classrooms during the heating season, collecting 712 samples of subjective responses correlated with environmental measurements. Key findings reveal significant correlations between subjective responses related to the thermal environment and those related to air quality. Perceived control over the thermal environment shows stronger correlations with IAQ responses than with thermal responses, particularly with perceived ventilation (r = 0.41), COVID-19 risk (r = 0.28), and air quality (r = 0.28). Additionally, environmental parameters demonstrate stronger correlations with thermal responses than with IAQ responses. Higher CO_2 concentration is associated with increased thermal sensation and decreased thermal preference and perceived control. Conversely, IAQ responses remain relatively stable with changes in indoor operative temperature. The difference between the operative temperature to which the occupants are exposed and their expressed neutral temperature widens as CO_2 concentration rises, indicating a reduced adaptive capacity of occupants which is associated with increasing CO_2 levels. These insights are crucial for providing HVAC system management strategies that consider the interaction between different aspects of IEQ, aiming to improve occupants' well-being and reduce energy consumption.

Keywords: classrooms; indoor air quality; interaction effects; multi-domain IEQ; thermal comfort

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1. Introduction

Indoor environmental quality (IEQ) is recognized as a key factor in building design and construction, significantly impacting occupants' well-being, productivity, health, and safety [1]. IEQ is a broad concept encompassing various aspects, generally classified into four main environmental factors: thermal environment, air quality, acoustics, and lighting [2,3].

Ensuring adequate IEQ can mitigate symptoms associated with sick building syndrome (SBS) [4], and promote positive experiences indoors [5]. Moreover, IEQ also plays a significant role in a building's energy consumption, especially in relation to HVAC systems control [6,7]. In this context, indoor air quality (IAQ) and thermal comfort are essential for enhancing indoor experiences and minimizing energy consumption [8]. During the period of the COVID-19 pandemic, the need to optimize the use of resources in buildings was more relevant [9], and this conflicted with the demand for higher ventilation rates and the inability to recirculate air, given the need to reduce the risk of infection [10], which, on the contrary, lead to an increase in thermal discomfort and energy consumption. Moreover, many existing buildings are naturally ventilated; thus, the only way to provide proper

ventilation is by opening windows, with clear effects on thermal discomfort and energy consumption [11], especially during winter.

In the past, the various indoor environmental quality (IEQ) domains were often treated separately, attributing "weights" to the various aspects [12] to take into account the perceptions of occupants in relation to acoustic, thermal, air quality, and visual aspects. It became feasible to delineate the combined effects of various environmental factors, considering their significance in shaping overall comfort [13]. Currently, research has shifted towards integrating these aspects through multidisciplinary studies, examining how they are not distinct but rather interact with one another to achieve overall comfort [14].

Torresin et al. [2] examined multi-domain laboratory studies to evaluate methodologies for defining these interactions, suggesting that a deeper understanding of these effects would help in modelling and predicting occupants' comfort. Chinazzo et al. [15] reviewed multi-domain studies to offer research guidelines and recommendations, pointing out shortcomings in study design and research hypotheses. Zhao and Li [14] investigated the interactions between IEQ aspects as to occupants' satisfaction, finding inconsistencies. Bavaresco et al. [16] demonstrated that current building simulation processes hardly integrate different IEQ domains, despite the latter's recognized importance.

However, several studies [17,18] have reported on the combined effect of IEQ satisfaction. Therefore, overall satisfaction models have been developed which consider the interactions between thermal, acoustic, indoor air quality, and visual aspects [19,20].

While the interactions between thermal comfort and indoor air quality (IAQ) have been acknowledged, only few studies examine them [14]. Tang et al. [19] observed that IAQ satisfaction was influenced by the thermal environment, particularly by the predicted mean vote (PMV), whereas Bourikas et al. [21] found an association between thermal sensation and IAQ perception. Shin et al. [22] demonstrated that elevated CO_2 levels can increase warmth sensation, while Fang et al. [23] noted that higher temperatures and relative humidity reduced IAQ comfort, with this effect diminishing under higher levels of air pollution. Melikov and Kaczmarczyk [24] suggested that increased air velocity might reduce the adverse effects of high temperature, humidity, and pollution levels. Recognizing the significance of these interactions, models for thermal comfort [25] and control strategies for HVAC systems [22] have been proposed, integrating IAQ and thermal parameters.

Therefore, the significant interplay between air quality and thermal comfort can impact occupants' perceptions of their surroundings. Despite these connections, these aspects are often studied separately, and in the existing research, IEQ interaction and combined effects remain largely unexplored areas [14]. However, scientific evidence highlights the complex link between air quality and thermal conditions, emphasizing the need for comprehensive exploration. Bridging this research gap can lead to the development of more effective strategies for HVAC system management, improving indoor environmental quality and energy efficiency.

Therefore, this paper aims to explore the connections between indoor air quality and thermal comfort through objective and subjective measurements. This investigation will involve an extensive field study in university classrooms, featuring 712 subjective responses correlated with environmental measurements. The sample size was determined based on the recent literature on thermal comfort in similar settings.

2. Methods

This section will use two selected campuses as case studies to analyze the relationship between thermal comfort and indoor air quality. By correlating indoor environmental parameters measured at multiple points in the classrooms with the subjective responses provided by students, the study will examine the interplay between thermal comfort and IAQ parameters. Recognizing that teachers' needs may differ significantly from those of students, particularly younger pupils, we chose to focus solely on students in this analysis. The study was not interventive. The lessons proceeded as usual, with no interventions from the researchers. The students were invited (not obliged, they could also abstain) to

express, in a completely anonymous manner, their thermal sensations (e.g., hot or cold) and their perceptions of the air quality (e.g., presence of odors) at the end of the lessons. The researchers did not change any of these parameters during the experiment.

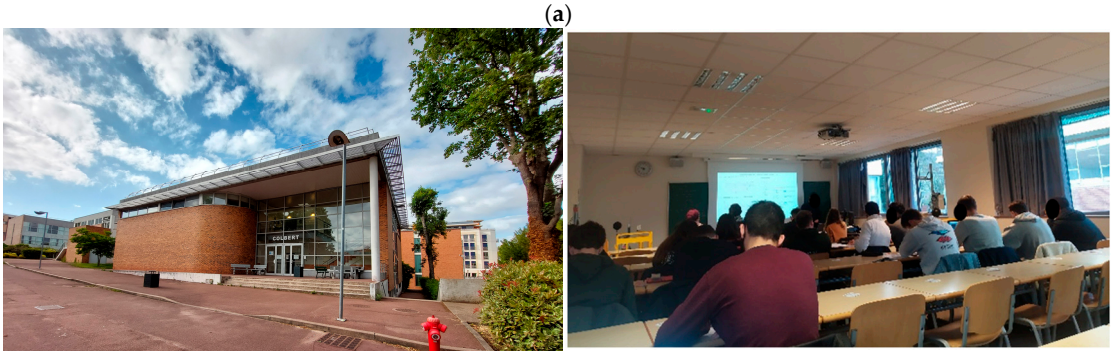
2.1. The Case Study

Two campuses in Europe were selected for the study: one in Pisa, with a hot Mediterranean climate (Csa), and the other in Paris, with a temperate climate (Cfb) [26]. The 17 classrooms, spread across 10 buildings in these campuses, showcased typical European building characteristics, particularly those associated with Italy and France [27]. All classrooms were naturally ventilated (via open windows) and had radiator-based heating systems in use during the study. This approach enabled the analysis of representative European case studies exploring interactions between thermal comfort and perceived IAQ in classrooms, with potential for extension to other contexts.

These classrooms varied in terms of shape, orientation, volume, and envelope type, ensuring a representative sample of typical European classroom settings (Figure 1). These characteristics can impact thermal and air quality conditions (e.g., larger volumes might reduce CO_2 levels, orientation can affect thermal parameters, etc.). Including a diverse set of classrooms facilitated the assessment of how varying conditions influenced students' perceptions during the measurement period. The average occupancy was 27 students for the Italian classrooms and 56 for the French ones. The low occupancy levels of the classrooms reflect typical conditions in the university settings of the case studies and are independent of COVID-19-related measures, as remote learning was no longer in effect in 2021. In this sample, low occupancy might lower CO_2 levels, but this was balanced by natural ventilation; continuous monitoring and a "right here, right now" questionnaire captured and accounted for variations in CO_2 and thermal conditions, ensuring the results accurately reflected students' immediate experiences. Heating systems typically consisted of radiators with manual controls, directly operated by occupants. Table 1 provides an overview of the characteristics of the classrooms included in the analysis.



(**a**)



(**b**)

Figure 1. Internal and external views of Italian (**a**) and French (**b**) classrooms.

Table 1. Characteristics of the surveyed classrooms.

ID	Location	Orientation	Classroom Type	Number of Seats	Surface (m^2)	Volume (m^3)	Window Surface, (m^2)	Number of Windows
1	Pisa, Italy	East	Teaching room	109	85.7	476	11.4	3
2		North	Teaching room	50	70.5	228	10.8	3
3		North	Drawing lab	70	143.4	371	18.0	5
4		South	Teaching room	40	40.0	116	6.8	2
5		South	Computer lab	75	189.7	510	24.5	7
6		West	Teaching room	82	42.9	124	6.9	3
7		North	Teaching room	139	126.1	438	3.6	2
8		South	Drawing lab	100	210.4	955	5.4	5
9		North	Teaching room	198	142.1	1000	6.5	8
10	Paris, France	Northwest	Amphitheatre	212	183.4	623	2.4	2
11		East	Teaching room	33	85.3	230	3.9	3
12		North	Teaching room	50	79.7	203	4.8	2
13		East	Teaching room	90	128.7	348	5.2	4
14		Northeast	Teaching room	62	111.1	307	6.4	5
15		East	Teaching room	90	128.7	348	5.2	4
16		Northeast	Amphitheatre	240	227.1	614	9.0	10
17		Northwest	Amphitheatre	313	278.3	836	11.2	4

2.2. Measurement Campaign

The field campaign was conducted during the heating season, from 11th October to 17th December 2021, covering a total of 41 days when lecture classes were in session. This period was characterized by a heightened attention to indoor environmental quality due to the ongoing COVID-19 pandemic. During the period under analysis, strict measures were not in place, but there was a greater focus on air quality. Occupants did not wear masks during the experiment.

To measure indoor environmental parameters, such as the thermal indicators of air temperature (T_a), relative humidity (RH), globe temperature (T_g), and air velocity (V_a) and the IAQ indicator of CO_2 concentration levels, a microclimate datalogger compliant with the ISO 7726 standard [28] was employed. The characteristics of the probes are reported in Appendix A. The probes were strategically positioned within the classrooms, near the occupants' seating areas, at a height of 1.1 m to assess the students' sitting positions. Each classroom had 3 to 5 measurement points to cover various occupied zones, ensuring simultaneous recording of environmental data that could be correlated with students' locations.

Due to the variability in natural ventilation, precise ventilation rates are challenging to assess. Therefore, CO_2 levels were used as indicators of IAQ. Outdoor environmental parameters such as temperature (T_{out}) and humidity (RH_{out}) were also measured with a microclimate datalogger compliant with the ISO 7726 standard [28] located within each campus, both in Italy and in France; these provided continuous monitoring for the whole duration of the campaign. The indoor dataloggers were positioned in the classrooms 30 min before the start of each lecture. They then recorded data for 3 h, corresponding to the typical duration of a lecture, with measurements taken every minute to capture potential fluctuations in the thermal environment. The measurement points are reported in the Supplementary Material.

During the measurement of environmental parameters, students were given questionnaires regarding their perceptions of the environment. During the environmental monitoring, students completed these questionnaires to assess their subjective sensations. The questionnaires were provided during breaks, before students left the classroom, and at least 60 min after their arrival to ensure they had acclimated to the environment. The study gathered 712 individual subjective responses, each from a "right here, right now" questionnaire in a transversal survey, in response to which participants provided immediate feedback on their current comfort level.

The questionnaire comprised five sections:

- Section 1: General information (date, hour, sex, age, and location in the classroom);
- Section 2: Clothing insulation;
- Section 3: General evaluation (overall comfort);
- Section 4: Thermal environment (thermal sensation, comfort, preference, acceptability, and perceived control over the thermal environment);
- Section 5: Indoor air quality (air quality perception, humidity, ventilation, odors, and COVID-19 risk).

Questionnaires were provided in the mother language of the students (Italian and French) and were in line with the requirements of the ISO 28802 standard [29]. Table 2 presents the specific questions and the scale used for the subjective parameters analyzed, while the complete questionnaire can be found in Appendix B.

Table 2. Information contained in the questionnaires.

Category	Vote	Abbreviation	Measured Parameter	Scale
General evaluation	Overall Comfort Vote	OCV	Global comfort (considering all IEQ aspects)	7-point, from −3 (Terrible) to +3 (Excellent)
	Rating of IEQ Aspects	-	Relative importance of IEQ aspects	From 1 (Most important) to 4 (Less important)
Thermal environment	Thermal Sensation Vote	TSV	Occupants' thermal sensations	7-point, from −3 (Cold) to +3 (Hot)
	Thermal Comfort Vote	TCV	Occupants' thermal comfort	4-point, from 1 (Comfort) to 4 (Much discomfort)
	Thermal Preference Vote	TPV	Occupants' thermal preferences	7-point, from −3 (Much colder) to +3 (Much warmer)
	Thermal Acceptability Vote	TAV	Occupants' acceptability of the thermal environment	5-point, from 1 (Acceptable) to 5 (Unacceptable)
	Perceived Control	PC	Occupants' perceived control over the thermal environment	7-point, from −3 (No control) to +3 (Full control)
Indoor air quality	Air Quality Vote	IAQV	Occupants' perceptions of the indoor air quality	7-point, from −3 (Terrible) to +3 (Excellent)
	Humidity Vote	HUM	Occupants' perceptions of the indoor humidity	7-point, from −3 (Very dry) to +3 (Very humid)
	Ventilation Vote	VEN	Occupants' perceptions of the ventilation	7-point, from −3 (Terrible) to +3 (Excellent)
	Odor Vote	ODO	Occupants' perceptions of odors	7-point, from −3 (Terrible) to +3 (No odor)
	COVID-19 Risk Vote	RISK	Occupants' risk perception regarding COVID-19	7-point, from −3 (Very dangerous) to +3 (No risk)

2.3. Calculation of Comfort Parameters

The mean radiant temperature (T_r) and operative temperature (T_{op}) were computed following the ISO 7726 standard [28].

$$T_r = \left[\left(T_g + 273\right)^4 + \frac{0.25 \cdot 10^8}{\varepsilon_g} \cdot \left(\frac{\left|T_g - T_a\right|}{D} \right)^{\frac{1}{4}} \cdot \left(T_g - T_a\right) \right]^{1/4} - 273 \quad (1)$$

where T_g is the globe temperature, ε_g is the globe emissivity, T_a is the indoor air temperature, and D is the diameter of the globe.

The T_{op} for indoor environments with low air velocity can be calculated using the following formula [28]:

$$T_{op} = \frac{T_a + T_r}{2} \quad (2)$$

Additionally, the running mean outdoor temperature was determined in accordance with EN 16798-1 as follows [30]:

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

where α is a coefficient, assumed to be 0.8 according to [30], and T_{od-n} are the daily mean outdoor temperatures for the days previous to the measurement.

Once environmental parameters were defined, they were linked to occupants' subjective responses. Specifically, student responses were matched with the environmental conditions at the relevant times and locations. This allowed the calculation of neutral temperatures (T_N) for each subject, using Griffiths' method [31]:

$$T_N = T_{op} - \frac{TSV}{b_{adj}} \quad (4)$$

where T_{op} is the operative temperature; TSV is the thermal sensation vote given by each occupant; and b_{adj} is the adjusted Griffiths coefficient, which was assumed to be equal to 0.320 $^{\circ}C^{-1}$, as this is the value calculated for university students [32]. Griffiths' method was employed in the calculation because it enables the determination of the neutral temperature corresponding to each occupant's thermal sensation response [33].

2.4. Assessment of the Interaction between Thermal Comfort and Indoor Air Quality

To evaluate the interplay between thermal comfort and IAQ, correlations among subjective responses and between environmental parameters and thermal/IAQ responses were analyzed using Pearson's correlation index. To quantify the differences between subjects' operative temperatures and their calculated neutral temperatures via Griffiths' method, the mean difference (dT) was computed as follows:

$$dT = \frac{\sum_{i=1}^{n}\left(T_{op,i} - T_{N,i}\right)}{n} \quad (5)$$

where $T_{op,i}$ is the operative temperature to which each individual was subjected, $T_{N,i}$ is its neutral temperature, and n is the number of subjective responses considered. To assess the impact of CO_2 on occupants' adaptation to the operative temperatures to which they were subjected, dT values were calculated across varying CO_2 concentration ranges. Specifically, dT was computed for CO_2 concentration increments of 800 ppm, ranging from 500 to 6100 ppm.

3. Results

3.1. Environmental Parameters

During the field campaign, various environmental parameters were measured; these are summarized in Table 3, which includes the mean, standard deviation, minimum, and maximum values. Further analysis regarding the objective measurements in the different classrooms are reported in the Supplementary Material.

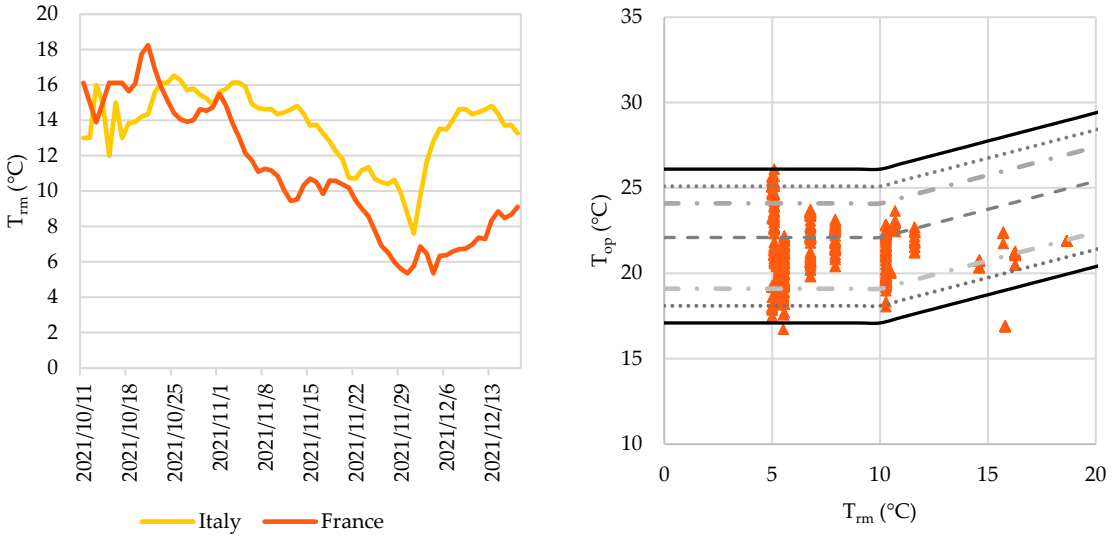
Table 3. Statistics associated with the monitored parameters.

	Indoor Parameters					**Outdoor Parameters**			
Statistics	T_a (°C)	T_{op} (°C)	T_g (°C)	T_r (°C)	**RH (%)**	V_a (m/s)	CO_2 (ppm)	T_{rm} (°C)	RH_{out} (%)
Mean	21.1	21.5	21.9	21.8	45	<0.05	1829	8.6	77
SD	1.8	1.8	1.9	1.9	8	0.05	1137	3.6	5
Min	16.4	16.7	16.9	16.9	25	<0.05	558	5.0	62
Max	26.0	26.1	29.0	27.3	64	0.76	5714	18.7	88

Indoor air temperature and mean radiant temperature showed slight differences, measuring 21.1 °C and 21.8 °C, respectively. The average operative temperature was 21.5 °C, and ranged from 16.7 °C to 26.1 °C. Relative humidity remained within the healthy range, with an average of 45%. Air velocity remained low, with a mean of 0.01 m/s and a maximum of 0.05 m/s. Indoor CO_2 concentration showed significant variation, ranging from 558 ppm, indicative of excellent air quality, to 5714 ppm, exceeding healthy thresholds.

Outdoor mean radiant temperature ranged from 5 °C to 18.7 °C, with an average of 8.6 °C. Outdoor relative humidity exhibited relatively stable levels, fluctuating between 62% and 88%.

Figure 2a shows the running mean outdoor temperature for the sites in Italy and France during the monitored period, calculated according to Equation (3). It is evident that the running mean outdoor temperature (T_{rm}) was generally lower in France. Figure 2b, on the other hand, presents the adaptive graph from EN 16798-1 [30] that relates the running mean outdoor temperature to the operative temperature.



(**a**) (**b**)

Figure 2. Running mean outdoor temperature (**a**) and adaptive graph (**b**) for the monitored periods. Legend: Comfort temperature (dashed line); Category I (dashed and dotted line); Category II (dotted line); and Category III (solid line).

In particular, the standard defines varying comfort temperatures as a function of the running mean outdoor temperature, expressed as follows [30]:

$$T_C = 0.33 \cdot T_{rm} + 18.8 \quad (6)$$

Additionally, the standard specifies three categories of adaptation. Category I is defined as [30]

$$T_{op} = 0.33 \cdot T_{rm} + 18.8 + 2 \quad Upper\ limit \quad (7)$$

$$T_{op} = 0.33 \cdot T_{rm} + 18.8 - 3 \quad Lower\ limit \quad (8)$$

Category II [30],

$$T_{op} = 0.33 \cdot T_{rm} + 18.8 + 3 \quad Upper\ limit \quad (9)$$

$$T_{op} = 0.33 \cdot T_{rm} + 18.8 - 4 \quad Lower\ limit \quad (10)$$

and Category III [30],

$$T_{op} = 0.33 \cdot T_{rm} + 18.8 + 4 \quad Upper\ limit \tag{11}$$

$$T_{op} = 0.33 \cdot T_{rm} + 18.8 - 5 \quad Lower\ limit \tag{12}$$

For T_{rm} values below 10 °C, as adaptive mechanisms become less effective, the comfort categories are extended using horizontal lines [33,34].

In general, the monitored operative temperatures were within the comfort bands, although they frequently exceeded the Category I comfort threshold (dashed and dotted line).

3.2. Subjective Responses

During the campaign, 712 questionnaires were collected, with subjects being evenly distributed between genders (356 males and 356 females), and having an average age of 22 years. The mean level of clothing insulation, representative of winter conditions, was 0.90 clo. Table 4 provides an overview of occupants' responses during the campaign, while further details of the responses in the different classrooms can be found in the Supplementary Material. Evaluation of the global environment (OCV) indicated neutral to positive environments, with a mean OCV of 0.4. Considering the relative importance of the different IEQ aspects, the responses indicate that thermal comfort is perceived as the most important IEQ aspect (45% of respondents rated it as the most important and only 12% as the least important). The second- and third-most-important aspects were IAQ and visual comfort (23% and 21% of responses, respectively). Interestingly, only 13% of respondents considered acoustic comfort to be the most important IEQ aspect in school classrooms.

Table 4. Statistics associated with the subjective responses.

						Thermal Environment			**Indoor Air Quality**		
Statistics	**OCV**	**TSV**	**TCV**	**TPV**	**TAV**	**PC**	**IAQV**	**HUM**	**VEN**	**ODO**	**RISK**
Mean	0.4	0.1	1.7	0.4	0.5	−0.7	0.3	0.0	−0.4	1.1	0.5
SD	1.3	1.1	0.9	1.1	0.8	1.6	1.3	1.1	1.5	1.5	2.0

Regarding the thermal environment, occupants' thermal sensations tended towards neutrality (TSV = 0.1), with the overall thermal comfort evaluated as being comfortable to slightly uncomfortable (TCV = 1.7). Thermal preference showed a tendency towards no change to slightly warm sensations (TPV = 0.4), while the perceived control over the thermal environment was negative (PC = −0.7).

In terms of indoor air quality (IAQ), it was generally considered neutral to slightly positive (IAQV = 0.3), as was the relative humidity (HUM = 0.0). Indoor ventilation, however, was perceived as being neutral to negative (VEN = −0.4), with the perceived risk of COVID-19 being neutral (RISK = 0.5). No odor issues were reported during the field campaign (ODO = 1.1).

Pearson's correlation coefficient (r) was used to analyze the data. This statistical measure indicates the strength and direction of the linear relationship between two variables, ranging from −1 to +1. A positive correlation (r = 1) means both variables increase together, while a negative correlation (r = −1) means one variable increases as the other decreases. The closer r is to 1 or −1, the stronger the linear relationship.

Figure 3 shows the correlation coefficients (r) between the different subjective responses. Higher thermal sensations were linked with lower thermal preferences (TPV, r = −0.60), greater acceptability (TAV, r = −0.30), and lower perceived ventilation rates (VEN), possibly due to closed windows (r = −0.20). Higher comfort levels (TCV) were found at higher TSV values (r = −0.17), which was consistent with perceptions of thermal acceptability.

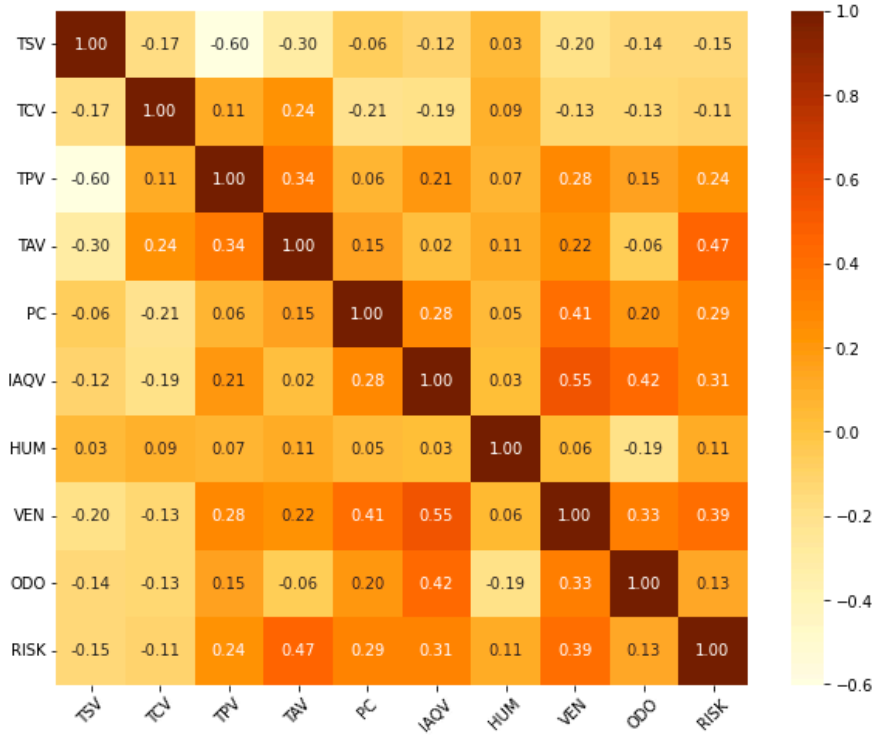


Figure 3. Heatmap showing the correlations between subjective responses. The numbers show the correlation coefficients (r).

Thermal comfort vote (TCV) values suggested that greater comfort aligned with higher acceptance of the thermal environment (TAV, r = 0.24) and perceived IAQ (IAQV, r = −0.19). Interestingly, TCV showed a negative correlation (r = −0.21) with perceived control (PC), indicating that increased discomfort was associated with reduced perceived control.

A preference for warmer conditions was associated with lower acceptability (r = 0.34), but better ventilation (r = 0.28) and perceived air quality (r = 0.21). Additionally, TPV showed a correlation (r = 0.24) with perceived COVID-19 risk, likely due to occupants opening windows in response to perceived risk.

The thermal acceptability vote (TAV) suggested that environments perceived as unacceptable were associated with higher risk perceptions (r = 0.47) and lower perceived levels of ventilation (r = 0.22).

Higher levels of perceived control (PC) were associated with better ventilation (r = 0.41) and lower risk perception (r = 0.29), but also with better IAQ (r = 0.28) and less odor (r = 0.20).

Indoor air quality vote (IAQV) values suggested that better IAQ was associated with better ventilation (r = 0.55), less odor (r = 0.42), and lower perceived COVID-19 risk (r = 0.31).

The humidity vote (HUM) values showed low correlations, notably with odor (r = −0.19), indicating that environments perceived to be drier were associated with less odor. Perceived ventilation (VEN) was linked to less odor (r = 0.33) and lower levels of perceived risk (r = 0.39).

For the analysis of the subjective responses, regressions were performed between the various subjective responses related to both thermal environment and air quality. For clarity, only the regressions with a good R^2 and a *p*-value lower than 0.05 are reported in Table 5. The full analysis is available in the Supplementary Material. It is important to note that, given the subjective nature of these responses and the inherent variability in personal perception, high R^2; values should not be expected.

Table 5. Regression analysis of the subjective responses.

Equation	R^2	*p*-Value
TSV = −0.56·TPV + 0.42	0.36	<0.01
TAV = 1.16·RISK − 0.07	0.22	<0.01
IAQV = 0.62·VEN − 0.61	0.30	<0.01
IAQV = 0.46·ODO + 1.00	0.18	<0.01
VEN = 0.52·RISK + 0.75	0.15	<0.01
PC = 0.38·VEN − 0.19	0.16	<0.01

Overall, the regressions align with the trends observed in Figure 3. As expected, thermal sensation (TSV) is closely correlated with thermal preference, with a stronger sensation of warmth leading to a preference for cooler conditions (negative TPV). In terms of indoor air quality (IAQ), a positive perception (IAQV) was strongly associated with better ventilation (VEN) and the absence of odors (ODO).

Interestingly, as shown in Table 5, the perception of the thermal environment was also linked to air quality. For example, perceived thermal control (PC) was associated with the perception of ventilation (VEN), with greater perceived control corresponding to perceptions of better ventilation. This confirms that thermal adaptation influences not only thermo–hygrometric conditions, but also factors related to indoor air quality (IAQ). Similarly, thermal acceptability (TAV) was correlated with the perceived risk associated with poor air quality (RISK), indicating that individuals' acceptance of the thermal environment was also influenced by their perception of risk due to inadequate air quality.

3.3. Mutual Effects of Thermal Comfort and Indoor Air Quality

Figure 4 shows the correlation coefficients (r) between the monitored environmental parameters and the subjective responses.

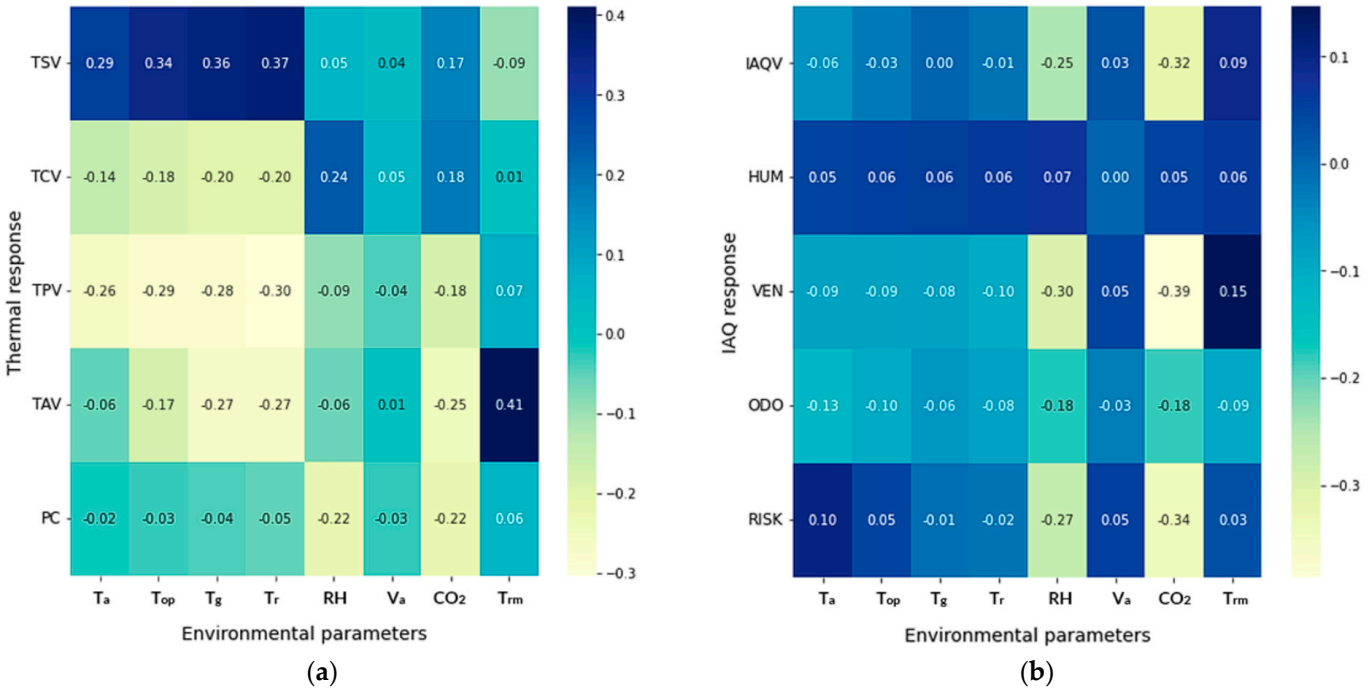


Figure 4. Heatmap showing the correlations between environmental parameters and the thermal comfort (**a**) or air quality (**b**) answers. The numbers show the correlation coefficients (r).

In terms of thermal comfort responses (Figure 4a), as expected, there is a notable positive correlation between thermal sensation (TSV) and indoor temperatures (r ranging from 0.37 to 0.29), highlighting the significance of temperature relative to thermal sensation.

Of particular interest is the relationship between thermal comfort responses and the IAQ indicator of CO_2. Higher CO_2 concentrations are associated with decreased thermal acceptability (r = −0.25) and lower levels of perceived control over the thermal environment (r = −0.22). Additionally, increased CO_2 levels correlate with preferences for colder environments (r = −0.18) and warmer thermal sensations (r = 0.17), but also with reduced thermal comfort (r = 0.18). This suggests that CO_2 concentration, an air quality parameter, impacts not only IAQ responses such as perceived IAQ (r = −0.32), ventilation (r = −0.39), and COVID-19 risk (r = −0.34), but also thermal comfort.

Similarly, thermal parameters can impact IAQ responses, albeit to a lesser degree (Figure 4b). Lower relative humidity (RH) was associated with improved perceived IAQ (r = −0.25), ventilation (r = −0.30), and COVID-19 risk perception (r = −0.27). Notably, RH, which typically has a lower impact on thermal comfort, showed no correlation with perceived RH itself (r = 0.07).

Indoor temperatures and air velocity exhibited weak correlations with the IAQ responses. However, a moderate correlation was observed between the running mean outdoor temperature and ventilation perception (r = 0.15), likely due to increased ventilation when outdoor temperatures were higher. Overall, Figure 4 suggests an influence of CO_2 on thermal comfort which is greater than the influence of thermal conditions on perceived air quality.

Two key indicators, CO_2 concentration and operative temperature, were analyzed as to their impacts on thermal and IAQ responses on a 7-point scale (Figure 5). The data were binned into CO_2 increments of 800 ppm and T_{op} increments of 2 °C, and the mean response was calculated for each bin. The 800 ppm CO_2 variation was selected to account for user perception thresholds, with 6100 ppm chosen for clustering purposes, even though the highest measured level was 5714 ppm, highlighting the unhealthy IAQ, which may occur in naturally ventilated and crowded classrooms during winter.

In terms of CO_2's effect on thermal responses (Figure 5a), thermal sensation (TSV) remained relatively constant around thermal neutrality, up to 4000 ppm, then increased towards warmer sensations beyond this threshold. Conversely, thermal preference (TPV) exhibited an opposite trend, favoring slightly warmer conditions up to 4000 ppm and decreasing towards colder sensations beyond that point. Notably, perceived control over the thermal environment showed a strong correlation with CO_2 levels, with the highest perception of control observed when CO_2 was below 1000 ppm, likely due to increased window accessibility. This perception gradually decreased with successive CO_2 increments and sharply declined below 5000 ppm.

CO_2 concentration significantly influenced IAQ responses (Figure 5b), with decreasing perceived air quality (IAQV) and ventilation (VEN) and increasing negative odor perception (ODO) and perceived COVID-19 risk (RISK) observed as CO_2 levels increased. Perceived humidity (HUM) appeared to be unaffected by CO_2 concentration.

Examining the impact of operative temperature on thermal responses (Figure 5c), an increase in thermal sensation (TSV) and a decrease in thermal preference (TPV) were observed with rising temperatures, as expected. Notably, TPV never reached negative values, indicating a preference for warmer thermal sensations regardless of temperature. Perceived control over the thermal environment (PC) seemed less influenced by temperature and generally remained negative (indicating reduced control).

Consistently with previous results, the effect of T_{op} on IAQ responses (Figure 5d) appeared to be less pronounced, with values remaining relatively stable as temperatures increased. However, the T_{op} above 24 °C showed slight increases in perceived air quality (IAQV), ventilation (VEN), odor reduction (ODO), and perceived COVID-19 risk (RISK).

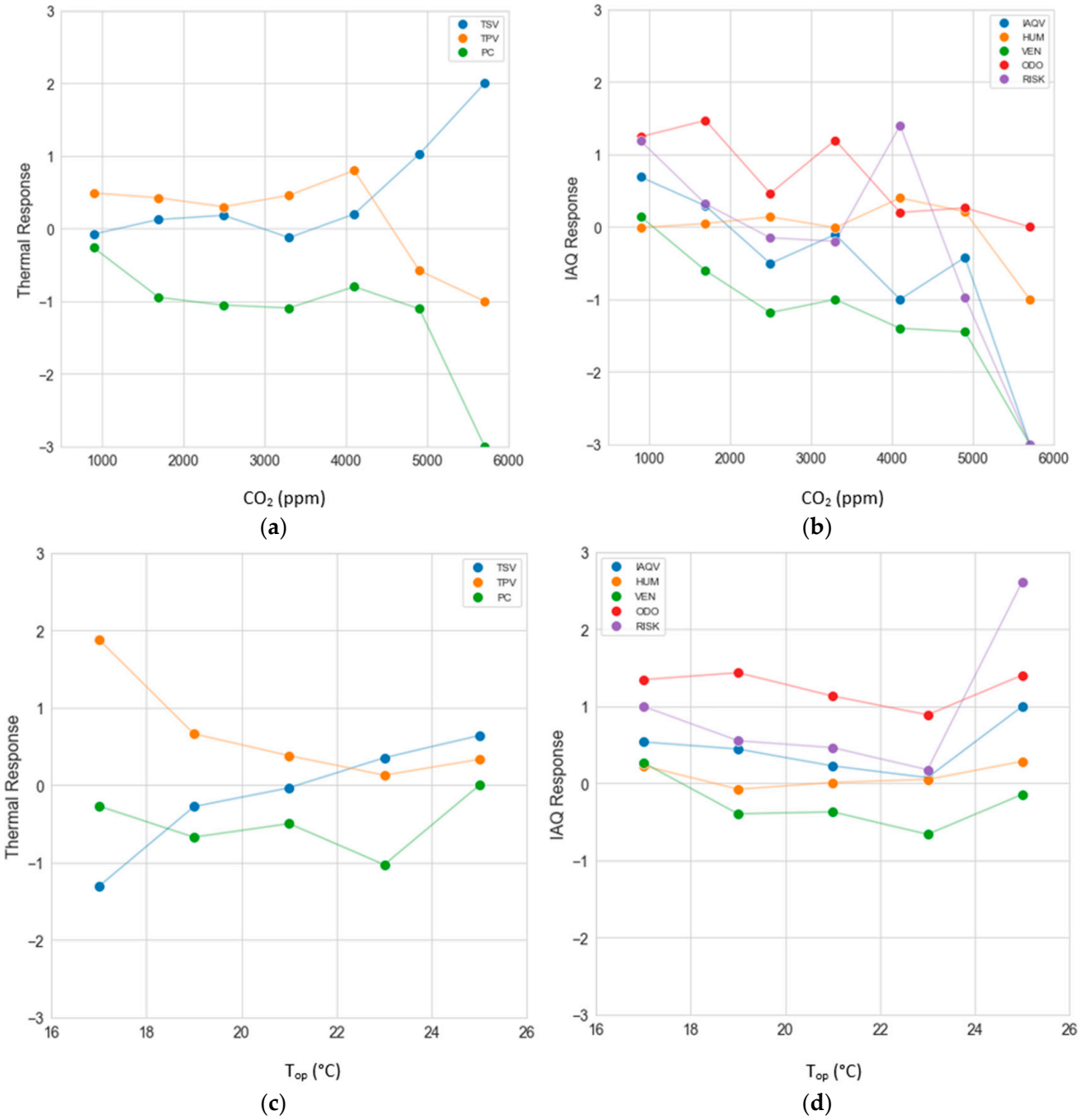


Figure 5. Relationships between CO_2 and thermal responses (**a**); CO_2 and IAQ responses (**b**); (**c**) T_{op} and thermal responses; and T_{op} and IAQ responses (**d**).

Finally, to explore the mutual effects of thermal and indoor air quality parameters on subjective responses, regression analysis was conducted. Initially, the data were clustered in 0.5 °C increments for the T_{op} parameter, and regression analyses were performed to examine the relationships between the monitored environmental parameters (objective domain) and the subjective responses from questionnaires (subjective domain). Table 6 summarizes the results of these regression analyses, including only those with significant performance and *p*-values less than 0.05.

Table 6. Regression analyses between objective and subjective parameters, with data clustered per 0.5 °C T_{op} increments.

Subjective Domain	Objective Domain	Equation	R^2	*p*-Value
Thermal comfort	Thermal comfort	$TSV = 0.222 \cdot T_a - 4.608$	0.73	<0.01
		$TSV = 0.217 \cdot T_{op} - 4.603$	0.77	<0.01
		$TSV = 0.205 \cdot T_g - 4.430$	0.77	<0.01
		$TSV = 0.213 \cdot T_r - 4.593$	0.78	<0.01
		$TCV = -0.089 \cdot T_a + 3.602$	0.33	0.01
		$TCV = -0.089 \cdot T_a + 3.628$	0.35	0.01
		$TCV = -0.085 \cdot T_g + 3.583$	0.36	0.01
		$TCV = -0.087 \cdot T_r + 3.632$	0.36	0.01
		$TCV = 0.038 \cdot RH + 0.006$	0.32	0.01
		$TPV = -0.177 \cdot T_a + 4.118$	0.52	<0.01
		$TPV = -0.172 \cdot T_{op} + 4.077$	0.54	<0.01
		$TPV = -0.161 \cdot T_g + 3.908$	0.53	<0.01
		$TPV = -0.171 \cdot T_r + 4.113$	0.56	<0.01
		$PC = -0.057 \cdot RH + 1.879$	0.32	0.01
Thermal comfort	IAQ	$TSV = 0.001 \cdot CO_2 - 0.778$	0.24	0.03
		$TPV = -0.001 \cdot CO_2 + 1.423$	0.42	<0.01
		$PC = 0.001 \cdot CO_2 + 0.177$	0.31	0.01
IAQ	Thermal comfort	$IAQV = -0.049 \cdot RH + 2.474$	0.32	0.01
		$RISK = -0.129 \cdot RH + 6.344$	0.45	0.00
IAQ	IAQ	$IAQV = -0.001 \cdot CO_2 + 1.246$	0.56	<0.01
		$VEN = -0.001 \cdot CO_2 + 0.733$	0.55	<0.01
		$ODO = -0.001 \cdot CO_2 + 2.178$	0.51	0.00
		$RISK = -0.001 \cdot CO_2 + 1.872$	0.21	0.04

As expected, the strongest correlations were observed within the thermal comfort domain, where subjective responses were notably influenced by the monitored thermal parameters. Perceived indoor air quality was consistently associated with CO_2 concentration, particularly affecting perceptions of IAQ (IAQV), ventilation (VEN), odors (ODO), and COVID-19 risk (RISK).

Interestingly, interactions between the thermal and IAQ domains were also evident. Increases in CO_2 levels led to slight increases in thermal sensation (TSV) and decreases in thermal preference (TPV). Additionally, higher CO_2 levels were associated with a decrease in perceived control, which became negative at high CO_2 concentrations (above 1500 ppm).

Subjective perceptions of air quality were also influenced by thermal parameters. Specifically, higher relative humidity was linked to a decreased perception of IAQ (IAQV) and perceived risk of COVID-19 (RISK)

3.4. Varying Neutral Temperatures at Different CO_2 Concentrations

First, the relationship between operative temperature and thermal sensation vote (TSV) was analyzed through regression, with the aim of comparing it to results obtained using Griffiths' method (Figure 6). The data were grouped in 0.5 °C increments of operative temperature to capture the mean thermal sensation of individuals exposed to similar thermal conditions. A weighted regression analysis was then performed. The slope of the regression (0.220 $°C^{-1}$) was slightly lower than the value obtained for university students (0.320 $°C^{-1}$) [32], indicating that the occupants were slightly less sensitive to temperature changes.

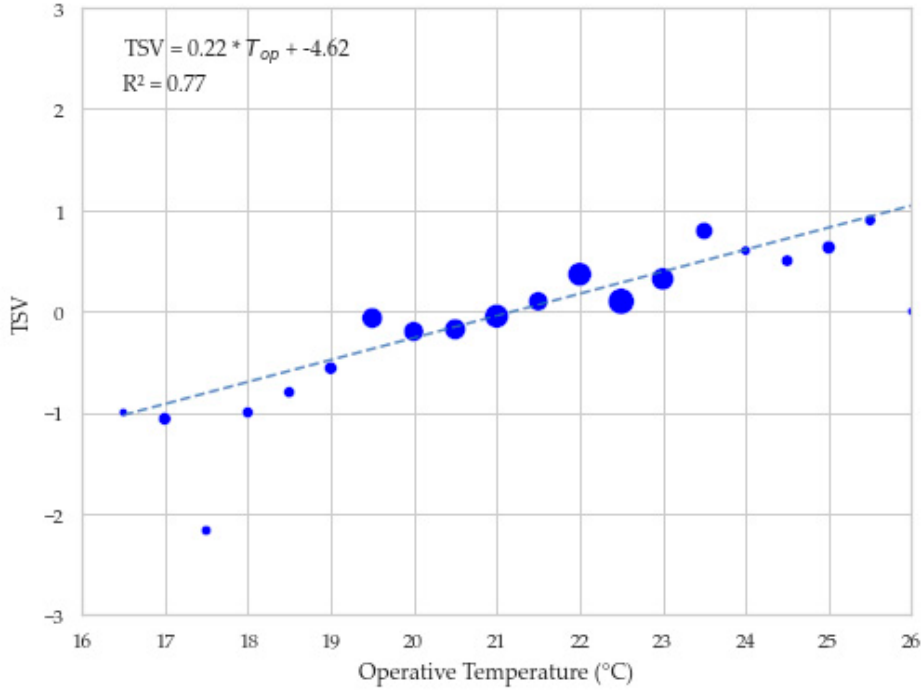


Figure 6. Weighted regression analysis considering the operative temperature and TSV. The dotted line represents the weighted regression, while the circles indicate the clustered TSV in 0.5 °C intervals of T_{op}.

To assess whether significant differences occurred, the neutral temperature was calculated with the two methods. For the regression method, this was done by setting the equation in Figure 6 as being equal to zero, and thus determining the operative temperature corresponding to a neutral thermal sensation (TSV = 0). For Griffiths' method, the neutral temperature was calculated individually for each occupant, using Equation (4), and then averaged across all subjects.

The results showed a neutral temperature of 21.0 °C using the regression method, and 21.3 °C with Griffiths' method. These differences are minor and fall within the measurement accuracy defined by ISO 7726 [28]. Consequently, subsequent calculations will use Griffiths' method, as it provides neutral temperatures for each occupant's thermal sensation response.

Therefore, the influence of CO_2 concentration on thermal comfort was examined by calculating neutral temperatures (T_N) at various CO_2 concentrations using Griffiths' method, with data grouped into 800 ppm increments (Figure 7). The mean T_{op} in the different clusters was 21.8 °C with a standard deviation of 0.8, so the various clusters can be considered as being comparable to each other in terms of the operative temperatures to which the subjects were exposed. Notably, the mean winter T_N generally hovers around 22 °C, but drops significantly above 4500 ppm (Figure 7a).

An analysis of the mean difference between neutral and operative temperatures reveals a trend of increasing disparity with rising CO_2 concentration levels (Figure 7b). Particularly, T_N surpasses T_{op} for CO_2 concentrations below 1300 ppm, while it remains lower for higher CO_2 levels, except within the 2900–3700 ppm range. This phenomenon may stem from increased levels of T_N among the sample considered. Nonetheless, it is evident that the disparity between neutral temperature and internal operative temperature widens with increasing CO_2 levels, suggesting an influence of the latter on occupants' ability to adjust to their thermal environment.

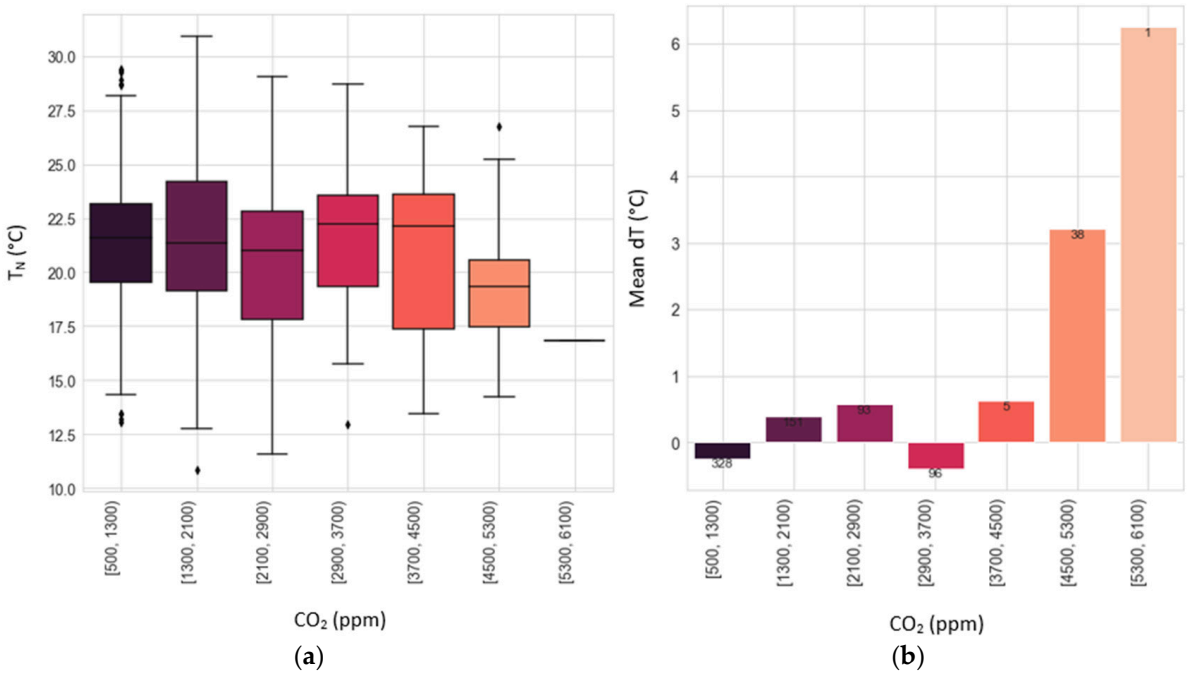


Figure 7. Boxplot of neutral temperatures (**a**) and mean difference between T_{op} and T_N (**b**) at different CO_2 concentration ranges.

4. Discussion

4.1. The Interplay between Thermal Comfort and IAQ

When considering neutral temperatures irrespective of CO_2 concentration, the values obtained were 21.0 °C using the regression method and 21.3 °C using Griffiths' method. These results align well with values reported in the literature for university classrooms during the winter season and in the heating mode. In China, neutral temperatures of 20.7 °C and 22.6 °C were observed in Beijing and Harbin, respectively [35,36]. In Europe, field studies conducted from October to March using regression methods identified comfort temperatures of 22.6 °C in Coventry and 22.3 °C in Edinburgh [37]. Using Griffiths' method, neutral temperatures in heated classrooms were found to be 22.0 °C in Coventry and 21.6 °C in Edinburgh [38]. In Italy, comfort temperatures ranged between 21.6 °C and 25.6 °C during both summer and winter, with winter conditions being comparable to those found in this study [39]. The broad variability in neutral temperature ranges is further confirmed by Singh et al. [40], who reviewed recent studies on thermal comfort in school buildings. They highlighted that university students in Asia experience the widest range of comfort temperatures, while in Europe, comfort temperatures are more constrained, typically ranging from 19 °C to 25 °C across all seasons [40].

Furthermore, the influence of CO_2 on neutral temperatures (Figure 7a) shows that the neutral temperature ranges for various CO_2 clusters are consistent with values reported in the literature.

Indeed, the present analysis reveals a significant impact of CO_2 concentration on thermal comfort. Higher CO_2 levels correlate with decreased thermal acceptability and decreased levels of perceived control (Figure 4). The observed rise in thermal sensation with increasing CO_2 (Figure 5), despite consistent indoor microclimatic conditions across CO_2 clusters (mean T_{op} 21.8 $\pm$ 0.8 °C), underscores the substantial influence of this parameter on thermal perception and preference. This finding is further supported by neutral temperature analysis across various CO_2 concentrations (Figure 7). At increased CO_2 levels, T_N significantly decreases, and the differences between occupants' experienced operative temperatures and their neutral temperatures widen.

This indicates that as CO_2 concentration rises (especially at very high levels), occupants, who typically adapt to their ambient temperatures [33], exhibit notable differences between their operative and neutral temperatures, despite comparable T_{op} within each CO_2 cluster. This divergence can thus be attributed to the impact of CO_2 on occupants' thermal comfort. These findings align with prior research on multi-domain IEQ. Previous studies have demonstrated a strong correlation between indoor air quality (IAQ) and thermal comfort [19], while thermal sensation vote has been linked to perceptions of air quality [21]. Specifically, elevated CO_2 levels have been associated with increased sensations of warmth and heat sensitivity [22,41]. Furthermore, higher CO_2 concentrations tend to heighten occupants' susceptibility to thermal discomfort [22], and air pollution can raise the level of thermal sensations [24]. In contrast, the impact of thermal parameters on IAQ perception appears to be more restrained. Indeed, the correlations between IAQ responses and thermal parameters are moderate (Figure 4), and IAQ responses tend to remain stable as operative temperatures rise (Figure 5). Several factors could contribute to this, including occupants' lower sensitivity to air quality given the thermal conditions, a phenomenon often associated with unpleasant odors [42,43]. Additionally, indoor air temperature and relative humidity may only significantly affect perceived IAQ beyond certain thresholds (e.g., 28 °C and 70%, according to [43]) not surpassed in the present study. Moreover, if CO_2 concentration is used as an air quality indicator, scientific evidence suggests that values below 5000 ppm may have limited influence on perceived air quality [44], despite the fact that values higher than 2000 ppm may cause discomfort in occupants [45]. Thus, since most cases in this study remained below this threshold, responses regarding perceived air quality might remain unaffected by thermal parameters, as occupants may not distinctly perceive air quality under these conditions. However, it is essential to assess these parameters through real-time, multi-environmental monitoring in order to enhance indoor conditions and reduce energy consumption [46,47].

Previous research on thermal comfort's impact on perceived IAQ has primarily focused on temperature, humidity, and air velocity parameters [14]. Generally, occupants reported poorer air quality under uncomfortable thermal conditions [48,49]. Given the case study's relatively neutral thermal conditions (i.e., TSV around thermal neutrality and TCV around comfortable-to-slightly-uncomfortable), the conditions may have had minimal impact on perceived air quality. Furthermore, studies indicate that increased air temperatures may affect perceived IAQ [19,23], implying that in winter conditions with lower indoor temperatures, the thermal environment may exert less influence on perceived air quality.

Concerning the effect of the pandemic period on environmental sensation, perceptions of COVID-19 risk related to IEQ may have differed based on past pandemic experiences (e.g., Italy's longer lockdowns and higher death rates), but as measured by the quesiton asked in the questionnaire (RISK), there was no significant differences between the two countries. Increased awareness of IAQ and lower CO_2 levels during the pandemic have been well documented [50,51], though balancing thermal comfort with IAQ and safety remains challenging, particularly in naturally ventilated classrooms during colder periods [52]. Nevertheless, the COVID-19 pandemic improved adaptation, especially in environments with significant fluctuations in thermal parameters [53].

4.2. Effect of Multi-Domain Studies on Environmental Quality and Energy Consumption

Determining the interactions among different aspects of indoor environmental quality is crucial for ensuring occupants' overall comfort [14]. Indeed, the consideration of the simultaneous exposure to various stimuli from different physical domains is crucial [16]. With the advancing capabilities of smart HVAC systems, it becomes feasible to manage these parameters more effectively [54], and thereby ensure occupants' comfort by considering the interplay of IEQ aspects.

This study underscores the fact that maintaining good IAQ enhances occupants' thermal satisfaction. Additionally, neutral temperatures show variations based on CO_2 concentration, despite consistent measured thermal parameters.

Previous research has demonstrated the energy efficiency benefits of introducing demand-controlled ventilation methods and leveraging thermal indices like predicted mean vote (PMV) and CO_2 concentration. These methods have shown potential for substantial energy savings, particularly in transitional seasons, with reductions in energy consumption reaching up to 74% [22]. Consequently, the increased sensitivity to heat among occupants exposed to elevated CO_2 concentrations can be leveraged to develop control methods based on both thermal and air quality parameters.

These findings offer support for dual-application possibilities. In heating scenarios, dual control over the thermal environment and IAQ can enhance occupants' perceptions of the thermal environment while maintaining consistent setpoint temperatures. In cooling scenarios, maintaining lower CO_2 levels can aid in preserving higher indoor temperature setpoints, aligning with principles of building resilience, particularly in the face of climate change. These strategies are promising for fostering healthier indoor environments, especially concerning air quality, given their significant impact on occupants' productivity [55].

5. Conclusions

This study investigated the interplay between thermal comfort and indoor air quality using naturally ventilated university classrooms as a case study, gathering a total of 712 samples of subjective responses linked to environmental parameters. The key findings are summarized as follows:

- Strong correlations exist between subjective responses concerning the thermal environment and those regarding air quality. Notably, perceived control over the thermal environment shows a stronger correlation with IAQ responses compared to thermal responses, with correlations observed for perceived ventilation (r = 0.41), perceived COVID-19 risk (r = 0.28), and perceived air quality (r = 0.28).
- Environmental parameters such as temperature, relative humidity, air velocity, CO_2 concentration, and running mean outdoor temperature demonstrate stronger correlations with thermal responses than with IAQ responses.
- Increasing CO_2 concentration leads to higher thermal sensation, reduced thermal preference, and reduced perceived control. In contrast, IAQ responses show no significant variations with changes in indoor operative temperature.
- The difference between the operative temperature the occupants are exposed to and their expressed neutral temperature, calculated using Griffiths' method, increases with rising CO_2 concentration. This suggests a diminished adaptive capacity of occupants as CO_2 levels increase.

Limitations and Future Outlook

The current study has some limitations that need to be addressed. Given that the monitoring campaign took place during the COVID-19 pandemic, when indoor air quality issues were particularly relevant, the CO_2 concentration samples indicating lower CO_2 levels were more numerous, due to increased ventilation during this period. Although the results appear promising and align with the current scientific literature, more samples are needed at higher CO_2 levels, while ensuring healthy conditions for the occupants. Moreover, despite lectures continuing as usual, health concerns during this period significantly raised the importance of IAQ. The heightened attention to thermal comfort and IAQ may persist post-pandemic, as IAQ is generally relevant to overall health, not just COVID-19. Therefore, the present results are likely applicable both during and after the pandemic, offering a new perspective on the perceptions of different IEQ aspects. However, future post-pandemic investigations are needed to confirm this hypothesis.

Furthermore, although the sample size is consistent, the study was conducted during the heating period. To propose future techniques for HVAC control systems, a follow-up study during the cooling period is needed to confirm the results, by which researchers could thereby understand what occurs at higher indoor operative temperatures.

Future research should explore summer scenarios to assess whether reducing CO_2 levels can raise perceived neutral operative temperatures. Additionally, investigations into winter conditions should examine whether decreasing indoor operative temperatures maintains low differences between experienced and neutral temperatures for healthy CO_2 concentration ranges (e.g., below 1000 ppm), indicating occupants' consistent adaptive capacities relative to low CO_2 levels. Moreover, since the interplay of all IEQ aspects is crucial for overall perception, future studies should focus on how these factors collectively determine the entire environmental experience of the students.

Furthermore, given that students' needs may differ from those of teachers, further research is needed to evaluate teachers' perceptions of thermal environment and air quality, along with the interactions of these parameters.

To apply these findings in real-world building environments, it is essential to implement HVAC control systems that dynamically adjust based on CO_2 levels, thermal comfort, and other IEQ factors. Strategies could include integrating real-time monitoring systems and adaptive controls that respond to changes in indoor environmental conditions, thus enhancing occupant well-being and reducing energy consumption. Implementing such strategies will not only improve the indoor environment but also ensure more efficient energy use in line with current IEQ research.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en17205053/s1, S1—Measurement location; S2—Objective measurements; S3—Subjective measurements; S4—Regression analysis. Reference [56] is cited in the supplementary materials.

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Institutional Review Board Statement: According to The Italian Privacy Code (Legislative Decree 196/2003, updated with the amendments made by the Law of the Italian Parliament of 29 April 2024, number 56) and Legislative Decree 10 August 2018, n. 101, in implementation of Art. 13 of Law 25-10-2017, 163, this study was non-interventive and the acquired data was anonymous. The ethics approval could therefore be waived.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data are available on request.

Conflicts of Interest: The authors declare no conflicts of interest.

List of Symbols

Symbol	Description	Measurement Unit
α	Coefficient for T_{rm} calculation	-
b_{adj}	Adjusted Griffiths coefficient	$^{\circ}C^{-1}$
CO_2	CO_2 concentration	ppm
D	Globe thermometer diameter	m
dT	Mean difference between operative and neutral temperatures	$^{\circ}C$
ε_g	Globe emissivity	-
HUM	Humidity vote	7-point, from −3 (Very dry) to +3 (Very humid)
HVAC	Heating ventilation and air conditioning systems	-
IAQ	Indoor air quality	-

IAQV	Air quality vote	7-point, from −3 (Terrible) to +3 (Excellent)
I_{cl}	Clothing insulation	clo
IEQ	Indoor environmental quality	-
M	Metabolic rate	Met
OCV	Overall comfort vote	7-point, from −3 (Terrible) to +3 (Excellent)
ODO	Odor vote	7-point, from −3 (Terrible) to +3 (No odor)
PC	Perceived control vote	7-point, from −3 (No control) to +3 (Full control)
PMV	Predicted mean vote	7-point, from −3 (Cold) to +3 (Hot)
PPD	Predicted percentage of dissatisfied	%
RH	Relative humidity	%
RH_{out}	Outdoor relative humidity	%
RISK	COVID-19 risk vote	7-point, from −3 (Very dangerous) to +3 (No risk)
T_a	Air temperature	°C
TAV	Thermal acceptability vote	5-point, from 1 (Acceptable) to 5 (Unacceptable)
TCV	Thermal comfort vote	4-point, from 1 (Comfort) to 4 (Much discomfort)
T_g	Globe temperature	°C
T_N	Neutral temperature	°C
$T_{N,i}$	Neutral temperature of each individual	°C
$T_{od\text{-}n}$	Daily mean of the outdoor temperatures for the days previous to the measurement	°C
$T_{op,i}$	Operative temperature to which each individual was subjected	°C
T_{out}	Outdoor temperature	°C
TPV	Thermal preference vote	7-point, from −3 (Much colder) to +3 (Much warmer)
T_r	Mean radiant temperature	°C
T_{rm}	Running mean outdoor temperature	°C
TSV	Thermal sensation vote	7-point, from −3 (Cold) to +3 (Hot)
V_a	Air velocity	m/s
VEN	Ventilation vote	7-point, from −3 (Terrible) to +3 (Excellent)

Appendix A. Characteristics of the Probes

Table A1 reports the characteristics of the probes used for the measurement campaign (LSI M-Log datalogger).

Table A1. Technical specifications of the microclimate dataloggers used for the analysis of indoor and outdoor parameters.

	T_a	T_g	RH	V_a	CO_2
Measuring range	−30.0 ÷ 70.0 °C	−30.0 ÷ 70.0 °C	0 ÷ 100%	0.01 ÷ 20.00 m/s	0 ÷ 5000 ppm
Resolution	0.06 °C	0.01 °C	0.5% RH	0.01 m/s	±50 ppm
Accuracy	±0.1 °C	0.15°C	±1.5% (5% if RH > 95%)	±0.05 m/s	3% of the measurement

Appendix B. Questionnaires

Table A2 shows the English version of the questionnaire.

Table A2. English version of the questionnaire.

Question	Label
General information	
Sex	Male; Female; Non-binary, Prefer not to indicate
Age	-
Students' location	-
Clothing insulation	
Indicate the clothing you are wearing at the moment.	Shirt/blouse: short-sleeved shirt; light shirt, long sleeves; normal shirt, long sleeves; none of the above; other.
Overall comfort (IEQ)	
How do you rate the overall comfort level inside the classroom at the moment?	−3 Intolerable; −2; −1; 0; 1; 2; 3 Perfectly tolerable
In your opinion, what is the most important aspect of a comfortable school environment?	- Air quality - Thermal comfort - Visual quality - Acoustic quality
Thermal comfort	
With reference to the temperature, how are you feeling now?	Cold (−3); cool (−2); slightly cool (−1); neutral (0); slightly warm (1); warm (2); hot (3)
Do you find this:	- Comfortable (1) - Slightly uncomfortable (2) - Uncomfortable (3) - Very uncomfortable (4)
In this moment, you would like to be:	Much warmer (3); warmer (2); slightly warmer (1); no change (0); slightly cooler (−1); cooler (−2); much cooler (−3)
How do you consider this environment at the moment?	Perfectly tolerable (1); slightly difficult to tolerate (2); difficult to tolerate (3); very difficult to tolerate (4); intolerable (5)
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. . .)	−3 No control; −2; −1; 0; 1; 2; 3 Full control
Indoor Air Quality	
How do you judge the air quality in the room at the moment?	−3 Intolerable; −2; −1; 0; 1; 2; 3 Perfectly tolerable
How do you assess the humidity level inside the classroom?	−3 Very dry; −2; −1; 0; 1; 2; 3 Very humid
How do you judge the ventilation inside the classroom?	−3 Intolerable; −2; −1; 0; 1; 2; 3 Perfectly tolerable
Do you find the air to be. . .?	−3 Very smelly; −2; −1; 0; 1; 2; 3 Not smelly
How do you assess the risk associated with the spread of COVID-19 in this classroom?	−3 Very dangerous; −2; −1; 0; 1; 2; 3 Not dangerous
Do you think that good environmental quality can reduce the risk of infection?	- Yes - No
Do you wear a mask during the lesson?	- Yes - No

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