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Students' thermal and indoor air quality perception in secondary schools in a Mediterranean climate

Alicia Alonso [a,*], Rafael Suárez [a], Jesús Llanos-Jiménez [a], Carmen M. Muñoz-González [b]

[a] *Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Av. Reina Mercedes, 2, 41012 Seville, Spain*

[b] *Arte y Arquitectura, Universidad de Málaga, Campus Universitario El Ejido, 29071 Malaga, Spain*

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ABSTRACT

In the wake of the COVID-19 pandemic, the importance of achieving adequate indoor air quality (IAQ) and addressing its impact on hygrothermal conditions has become paramount. Environmental quality in classrooms significantly influences students' health, well-being, and academic performance. Natural ventilation faces challenges related to efficiency and thermal comfort, even the development of recent standards focuses on the continuous measurement of CO_2 to enhance health and well-being. This study addresses a research gap by simultaneously addressing both thermal comfort (TC) and IAQ analyses, focusing on students' perceptions across seasons in secondary schools within the Mediterranean climate of southern Spain. A field study conducted between 2022 and 2023 involved long-term monitoring and 1,056 surveys from students aged 12–18 in 54 classrooms across seven schools. Data were collected during heating and non-heating periods in naturally ventilated spaces, analysing subjective perceptions and their relationship with objective parameters. Results show that high temperatures strongly influence thermal and air quality perceptions, while CO_2 levels have minimal impact on Air Sensation Voting (ASV), even at concentrations exceeding 1,400 ppm. During non-heating seasons, 60 % of students reported thermal comfort at temperatures between 23-27 °C, while discomfort increased to 38 % at temperatures below 19 °C during heating seasons. Neutral temperatures derived from subjective impressions reveal significant seasonal variations. Predicted Mean Vote (PMV) underestimated actual sensations, particularly during cold seasons in warm climates. These findings highlight the impact of outdoor temperatures on students' perceptions and offer insights for refining comfort models and adapting ventilation strategies to improve learning environments in schools.

1. Introduction

Students spend a significant number of hours in classrooms, environments characterised by high occupant density and, often, adverse hygrothermal and air quality conditions. In some cases in the Mediterranean region, deficient environmental conditioning systems result in poor thermal comfort (TC) and indoor air quality (IAQ) conditions [1,2]. Prolonged exposure to adverse indoor environmental conditions (IEQ) negatively impacts academic development and long-term health outcomes [3–5]. In addition, research underscores the need for improved building envelopes to address poor insulation and ventilation, which exacerbate overheating risks in Mediterranean climates. Enhancing the thermal performance of buildings is essential for mitigating climate change impacts, including the increasing frequency of extreme heat events [6]. These challenges are particularly relevant in schools, where high occupant density and prolonged exposure worsen comfort and health outcomes.

Thermal comfort is closely linked to health problems [7] and cognitive performance, with suboptimal conditions reducing concentration and academic productivity [8,9]. This connection underscores the relevance of United Nations Goals, known as Sustainable Development Goals, specifically it refers to Goal 4, which emphasizes the need to

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Abbreviations: APD, Actual Percentage Dissatisfied; ASV, Air Sensation Vote; IAQ, Indoor Air Quality; IEQ, Indoor Environmental Quality; PMV, Predicted Mean Vote; PPD, Predicted Percentage Dissatisfied; Ta, Air temperature; TC, Thermal Comfort; TCV, Thermal Comfort Vote; TSV, Thermal Sensation Vote; Top, Operative temperature; Tout, Outdoor temperature; TPV, Thermal Preference Vote; Tr, Radiant temperature; Trm, Mean radiant temperature.

* Corresponding author.
E-mail address: aliciaalonso@us.es (A. Alonso).

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ensure quality education in safe learning environments [10]. In parallel, poor IAQ has been identified as a key factor in the onset of illnesses in developed countries [11]. The COVID-19 pandemic further highlighted the significance of managing IAQ to mitigate airborne disease transmission [12], emphasizing the importance of managing IAQ in educational settings. This situation has promoted the development of standards such as UNE 171380 [13], focused on the continuous measurement of CO_2 indoors to improve the health and well-being of users, which responds to the need to complement and improve the requirements established by quality standards and current legislation. In this regard, proper ventilation is critical for health, as it helps to reduce airborne pollutants and prevent respiratory issues. However, natural ventilation comes with challenges, including the uncontrolled influx of outdoor pollutants, difficulty in ensuring its effectiveness, and potential impacts on energy efficiency and thermal comfort.

Over recent decades, research on indoor environmental quality in educational buildings has worked on the analysis of students' perceptions of thermal comfort or indoor air quality [14,15]. Integrating these subjective insights with objective environmental parameters enables the refinement of comfort models. This adjustment supports the development of improved natural ventilation protocols and optimised mechanical HVAC systems in schools, enhancing overall environmental conditions and student well-being.

1.1. Literature review

Despite the international acceptance of models such as Fanger's Predicted Mean Vote (PMV) ISO 7730 [16] and ASHRAE 55 [17], these models have limitations. Originally developed for adult office workers in controlled environments, they often fail to accurately represent the diversity of thermal comfort in different settings, particularly schools [18]. Furthermore, climatic adaptation factors, socio-cultural and even socio-economic factors are only loosely considered in many studies on indoor environmental quality, despite their potential influence on occupants' comfort and health. Recent research emphasizes the need to integrate these aspects to develop more comprehensive and effective strategies for improving indoor environments [19,20].

According to research, perceptions differ depending on parameters such as climatic zones or age ranges of respondents. Romero et al. [21] evaluated PMV and Thermal Sensation Vote (TSV) in university classrooms in Spain and Portugal, with a Csa climate in the Köppen-Geiger classification [22,23]. The findings revealed that PMV underestimated heat sensation, with a neutral temperature (Tn) of 24 °C in summer. Similarly, Torriani et al. [24] found that PMV-based regressions yielded higher Tn values (0.8–2.7 °C) compared to TSV regressions in Pisa schools during winter. Conversely, in cold climates, TSV-based Tn values exceed those based on PMV. Studies also show a range of acceptable temperatures that is both higher than in the static model [25] and closer to the adaptive model [26,27,28,29]. Students' thermal awareness also develops with age. Torriani et al. [30] concluded that primary school children lack full awareness of their thermal environment, complicating subjective assessments in younger age groups.

Unlike thermal comfort, whose subjective assessment in extreme cases is clearly identified by the user, indoor air quality (IAQ) is harder to assess through perception alone. Substances like carbon dioxide (CO_2), a substance emitted by occupants in indoor environments commonly used as an IAQ indicator, can cause health issues even at low concentrations without being immediately noticeable [31,32]. The studies by Cabovská et al. [33] and Vásquez et al. [34] explore IAQ in Swedish school classrooms, with an emphasis on ventilation and its impact on children's perception and well-being. While Cabovská et al. work [33] shows higher pollutant concentrations in classrooms with natural ventilation, Vásquez et al. [34] extend this analysis by including students' subjective perception. Both studies highligh the importance of adequate ventilation strategies to optimise comfort and health in educational settings. Elevated CO_2 levels correlate with symptoms like fatigue and discomfort, as demonstrated in the study of Dorizas et al. [35], which examined nine primary schools in Greece (Csa climate). Similarly, Smedje et al. [36], found that high levels of respirable dust, mould, and bacteria were linked to poorer IAQ perceptions in 38 Swedish schools (hemiboreal Dfb climate) of different educational levels. The aforementioned studies are carried out in different climatic zones (Csa climate and Dfb climate, respectively). In this regard, Wang et al. [37] determined personal and demographic factors has influence on change of subjective indoor air quality reported by school children.

There are relatively few studies which develop a combined analysis of TC and IAQ approaches. Research by Korsavi et al. [38] assessed IAQ perceived in primary schools in the Cfb (oceanic) climate of UK, and found that high temperatures negatively impacted perceived IAQ even when CO_2 levels were within acceptable limits in UK primary schools. Other Mediterranean studies include the work of Dias Pereira et al. [25] also evaluated the TC and IAQ preferences of secondary school students during mid-season in Portugal, and Almeida et al. [28], which assessed perceptions in free-running schools. Both studies show that students tolerate higher indoor temperatures than recommended and that traditional models, like PMV, fail to accurately reflect their thermal sensations, particularly in non-air-conditioned buildings, due to physiological differences between children and adults. Torriani et al. [24,30], which explored the impact of perceived control in Italian schools during the heating season, highlight that perceived control over the environment, such as opening windows, enhances both thermal comfort and IAQ while also reducing heating energy demand in classrooms. These findings call for tailored approaches to balance comfort, ventilation, and energy efficiency in schools.

Al-Dmour's [39] research carried out in the educational context stated subjective assessments may not always correspond with objective measures. His findings emphasize the need for a holistic approach that considers both type of data to enhance indoor environments, ultimately leading to improved occupant satisfaction and productivity in educational settings. Table 1 presents a review of the literature on the perceptual assessment of thermal comfort and air quality in classrooms situated in different climate zones. The table also illustrates the primary attributes of the case studies, including the sample size, level of education, and type of HVAC system. Information on the type of analysis carried out (objective and/or subjective) in order to determine the influence of other factors on perception, is also included.

The review of 23 studies compiled in Table 1 shows that short-term measures, that covers one or two seasons, or interrupted intervals over consecutive years, were implemented in 60 % of cases while only 26 % of research covered warm and cold seasons simultaneously. Despite the fact that 29 % of these studies conducted evaluations from TC and IAQ approaches, only one of them (4 %) carried out an in-depth analysis from both perspectives, although it does not calculate the neutral temperature. The rest of the studies (78 %) carried out an in-depth evaluation of one of the two aspects (TC or IAQ), or carried out a non in-depth analysis (15 %) without making comparisons and correlations with other objective parameters or subjective indices. Limitations and gaps in the state of the art can be identified thanks to the review of existing studies. In this respect, more attention must be paid to understanding students' perceptions of thermal and indoor quality through the relationship of parameters and subjective variables during the different seasons of the year.

1.2. Research objective

This study aims to improve our understanding of students' perceptions of thermal comfort and indoor air quality in representative secondary schools located in the most representative Mediterranean climate zones of southern Spain. The research makes a significant contribution by using a novel approach: year-long measurements covering heating (3-month period in winter), non-heating (3-month period in summer) and mid-season (3-month period in spring/autumn)

Table 1
Summary review of studies according to climate zone, HVAC systems and description of the subjective analysis conducted.

Ref.	Case Studies	Köppen Climate Zone	HVAC	TC Subjective				IAQ Subjective			
	Monitoring Period			TSV	vs other indices	vs other param	T_n	ASV	vs other indices	vs other param	Predominant parameter
Abreu-Harbich et al. [55]	1 class UN Short-term measurements, warm season	AwBrasilia (Brasil)	MV AC	✓	–	✓	25.9 °C	–	–	–	–
Mishra and Ramgopal [56]	1 class UN Short-term measurements, mid-season	Aw,Kharagpur (India)	NV	✓	✓	✓	29 °C TSV = 0.22 Top – 6.37	–	–	–	–
Kim and de Dear, [57]	11P/S.SCH Short-term measurements, warm season	BSh,Australia (New South Wales)	NVR/AC	✓	✓	✓	24.4 °C TSV = 0.15 Tdiff + 0.12	–	–	–	–
Haddad et al. [58]	2 S.SCH Annual	Cfa,Australia (Sydney)	NV AC	✓	–	✓	23.7 °C	–	–	–	–
Miao et al. [59]	16P/S.SCH Long-term measurements, warm and mid-season	Cfa, CsaSpain (Catalonia)	NVR	✓	✓	✓	21–25.3 °C	✓	✓	–	CO_2
Wu and Wagner [29]	1 S.SCH Annual	Cfa,China (Hengyang)	NV	✓	–	✓	25.7 °C summer, 19.2 °C mid-season,14.9 °C winter TSV = 0.0883 • Top – 7.13	✓	–	✓	T
Korsavi et al. [38]	29 classes, 8P.SCH Annual	Cfb,UK (Coventry)	NVR	✓	✓	✓	–	✓	✓	✓	CO_2
Teli et al. [60]	2P.SCH Short-term measurements, cold season	Cfb, UK (Southampton)	NVR	✓	✓	✓	20.6 °C	–	–	–	–
Almeida et al [28]	8 classes, 6 entire educational range Short-term measurements, mid-season	CsaPortugal (Viseu)	NVR	✓	✓	✓	–	–	–	–	–
Aparicio-Ruiz et al. [27]	3 classes P.SCH Short-term measurements, warm seasons	CsaSpain (Sevilla)	NVR, AC	✓	✓	✓	–	–	–	–	–
Calama et al. [61]	1 S.SCH Annual	CsaSpain (Sevilla)	NV AC	–	–	–	–	✓	–	–	CO_2
Dhalluin et al. [62]	2 class UN Annual	Csa,La Rochelle (France)	MV + HRR	✓	✓	✓	–	✓	–	✓	CO_2
Di Perna et al. [63]	1 S.SCH Short-term measurements, cold season	CsaItaly (Pisa)	MV + HRR	✓	–	–	–	✓	–	–	CO_2
Dias Pereira et al. [25]	4 classes S.SCH Short-term measurements, mid-season	CsaPortugal (Beja)	NVR	✓	✓	✓	–	✓	–	✓	Olf
Dorizas et al. [35]	9P.SCH Short-term measurements, mid-season	CsaGreece (Athens)	NVR	✓	✓	✓	18 °C	✓	–	✓	T
Heracleous and Michael [26]	1 class S.SCH Annual	Csa Cyprus (Nicosia)	NVR	✓	✓	✓	–	–	–	–	–
Romero et al. [21]	29 classes, 3 UN Short-term measurements, warm season	Csa,Spain (Badajoz) Portugal (Beja)	NVR, AC	✓	✓	✓	24 °C TSV = 0.2908 · Top – 6.9489	✓	–	✓	T
Torriani et al. [24]	24 classes, 11 schools across the entire educational range Short-term measurements, cold season	CsaItaly (Pisa)	NVR	✓	✓	✓	21.7 °C TSV = 0.29 • Top – 6.17	–	–	–	–

(*continued on next page*)

Table 1 (*continued*)

Ref.	Case Studies Monitoring Period	Köppen Climate Zone	HVAC	TC Subjective				IAQ Subjective			
				TSV	vs other indices	vs other param	T_n	ASV	vs other indices	vs other param	Predominant parameter
Torriani et al. [30]	24 classes, 11 schools across the entire educational range Short-term measurements, cold season	CsaItaly (Pisa)	NVR	✓	✓	✓	22.3 °C TSV = 0.32 • Top – 7.13	✓	–	✓	T IAQV = −0.119 • Top + 2.488
Cablé et al. [64]	1 S.SCH Short-term measurements, cold and mid-season	Dfb,Drammen (Norway)	MV	✓	–	–	–	✓	–	–	CO_2
Smedje et al. [36]	96 classes, 38 entire educational range Long-term measurements, cold season	Dfb,Sweden (Uppsala)	MV + HRR	–	–	–	–	✓	–	✓	Olf
Vornanen-Winqvist et al. [65]	2 classes, 1P-S.SCH Short-term measurements, warm and mid-season	Dfb,Helsinki (Finland)	MV + HRR	–	–	–	–	✓	–	✓	Olf
Yang et al. [66]	5 classes, 1P.SCH Long-term measurements, cold season	Dfc,Sweeden (Umeå)	MV + HRR	✓	✓	✓	20.8 °C TSV = 0.155 • Ta–3.237	–	–	–	–

In the TC and IAQ sections, comparisons made with other indices (PMV, TPV, etc), and comparisons made with objective parameters (T, RH and CO_2) are indicated. E.SCH: Elementary School; P.SCH: Primary Education School; S.SCH: Secondary Education School; UN: University; NV: Natural Ventilation; MV: Mechanical Ventilation; MV + HR: Mechanical Ventilation + Heat Recovery; R: Radiator; AC: Air Conditioning; Olf: Olfactory.

periods, combining with field monitoring and students' surveys. It should be mentioned mid-season period was not incorporated in this study due to insufficient data from surveys. This comprehensive dataset allows a detailed analysis of thermal perception and air quality, allowing robust comparisons between environmental variables and both perceived and estimated parameters. A key innovation is the assessment of neutral temperatures derived from students' subjective impressions, bridging the gap between subjective experience and objective metrics. By integrating these findings with measurable parameters, the study provides critical insights to refine comfort models and ultimately guide the optimisation of natural ventilation protocols and mechanical HVAC system designs in educational environments. This work not only fills an important knowledge gap, but also has practical implications for improving learning spaces in similar climatic regions.

2. Methods

The methodology employed in this study is developed in distinct phases which are illustrated in Fig. 1 and described below. The field study is based on a large experimental campaign carried out intermittently between January 2022 and June 2023 in 54 classrooms of 7 educational buildings of different levels and climate zones in the south of Spain. The sample comprised 1056 surveys conducted by students, aged 12 to 18. Data acquisition has been carried out through monitoring campaigns in both heating (H) and non-heating season (NH) in naturally ventilated classrooms, as well as through student surveys. Different weeks within each period were selected for the development of surveys. Thus, to establish a direct relationship with the survey results, monitoring data was selected over the same days were selected. The data processing phase was based on a comparison between objective variables and subjective factors or factors estimated from the assigned votes. A statistical analysis has been applied to develop the comparative study, consisting of three sections. The first section evaluates the effect of the environmental variables monitored on thermal perception. The second section then assesses the effect of these variables on the perception of air quality. Finally, the third section establishes the relationships found

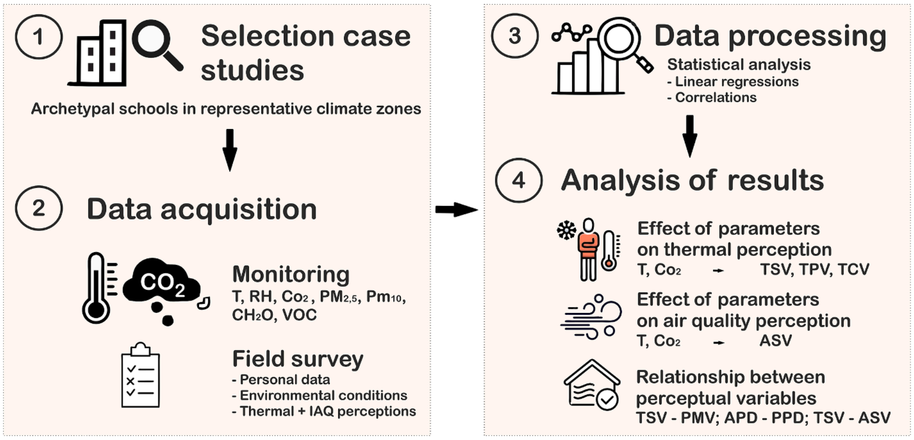

Fig. 1. Diagram of the research methodology.

between the perceptual and estimated factors.

2.1. Case study description

The process for selecting and defining the case studies of representative school in the Mediterranean climate is described in detail in the work conducted by Llanos et al. [40] and [41]. However, a summary of the primary data to be taken into account can be found in this text. The selection of the case studies is based on a multi-parametric statistical analysis, integrating criteria such as climate zone, year of construction, architectural typology, classroom orientation, and building envelope solutions. This approach allows a balanced representation of the most characteristic conditions of the region.

Based on the Köppen climate classification system [22], the Andalusian region is characterised by the Csa typology, which corresponds to a warm summer Mediterranean climate. In Spain, the Technical Building Code (CTE) [42] defines climate classification using a coding system that combines a letter for winter severity (A to E, where A indicates the mildest and E the most severe) and a number for summer severity (1 to 4, with 1 being the mildest). For this study, representative secondary schools from zones A3, B3, B4, C3, and C4 were selected, representing the three most common winter climates (A, B, and C) along with the most frequent summer climates (levels 3 and 4). The study is based on an analysis of 872 public schools, of which 200 were selected for the detailed sample. The distribution was proportional to the climatic zones defined by Spanish regulations [42]. Architectural and operational characteristics were considered, such as natural ventilation systems and regulations applicable at the time of construction. This ensures the applicability of the results to real Mediterranean school contexts. Fig. 2 shows a multiparametric parallel coordinates graph for the selection of representative secondary schools. In this Figure, the representative values for each criterion are indicated by horizontal bars in grayscale. This process yields a list of representative secondary schools (ranging from 7 to 9) for each of the five climatic zones according to Spanish regulations [42].

Table 2 presents a summary of the main characteristics of the case studies, including their size, and systems. All case studies, which were built prior to the implementation of the prevailing regulatory standard in Spain, rely on natural ventilation as mechanical ventilation only became mandatory in schools in Spain in 2007 [43]. In all case studies bar one radiators are provided as a heating system. However, for economic reasons, the activation of the system is typically reserved for days with outdoor temperatures below 12 °C. Only a limited number of selected schools have cooling systems, and their use is highly constrained.

It should be noted the construction date of a building determines the minimum requirements and performance standards for its envelope and heating, ventilation, and air conditioning (HVAC) systems. Prior to 1979, there were no mandatory regulations governing the thermal performance of building envelopes or ventilation methods to control indoor air quality. Later on, between 1979 and 2005, the first regulation to address the thermal transmittance and hygrothermal behaviour of building envelope elements and the building as a whole, as well as the air permeability of windows and doors. The main parameter limited was the overall thermal transmittance coefficient of the building.

2.2. Data acquisition

2.2.1. Monitoring campaign

The objective measurements consisted in the acquisition of environmental parameters in the classrooms during one academic year (2022–2023). Hygrothermal and indoor air quality parameters were analysed via the monitoring of the parameters of air temperature (Ta), WetBulb globe temperature (Tg), relative humidity (RH), CO_2 concentration, particulate matter ($PM_{2.5}$ and PM_{10}), and formaldehyde (CH_2O). The parameters were monitored using a properly factory-calibrated Sensonet Multisensor SW20 datalogger [44], during school hours in two classrooms with opposing orientations in each of the seven case studies. Data collection was configured to record values at 5-minute intervals. The technical information of the equipment is shown in Table 3 and outdoor variables were taken from Spanish State Meteorological Agency weather stations closest to the case study locations. Fig. 3 show a plan for a typical class setup during onsite measurements.

Measurement instruments were in the side section of the classroom in order to avoid disturbing classes and data collection distortions due to windows and doors and the use of natural ventilation.

2.2.2. Survey model

Students' subjective impressions of classroom environmental quality were collected through anonymous surveys conducted during the winter and summer seasons in the different case studies. A total of 1,056 surveys in 54 classrooms were collected during several questionnaire campaigns. The sample is balanced in terms of gender, with 52.6 % male students and 47.4 % female students. The procedure was implemented in accordance with the guidelines set forth in the Spanish Personal Data Protection Law, thereby ensuring the digital rights of the users surveyed.

As shown in Appendix A, the outline of the student survey model is divided into three blocks. After providing personal data and some basic level segmentation parameters such as position in the classroom, respondents are required to answer a series of questions relating to the natural ventilation protocol of the classroom. In the second block, students were asked to provide an overall evaluation of the environmental conditions of the classroom and to indicate the type of clothing worn in order to guarantee the basic clothing insulation [45,17]. The third block collects data on students' judgement regarding thermal impression and indoor air quality based on olfactory perception, concluding with an overall assessment. Questions regarding thermal sensations and preferences were put forward following the criteria commonly used in scales for assessing thermal environments according to ISO 10551 [46]. In order to establish neutral perceptions 5- or 7-point scales were used. Additionally, students were asked about any symptoms or illnesses they may suffer from. It should be noted that the distribution of these questionnaires has the informed consent of the relevant school authorities.

2.3. Data processing

2.3.1. Variables

The analysis of the students' perception is based on the association between objective environmental variables, obtained from onsite measurements, and subjective factors, derived from students' perceptual voting.

In relation to subjective thermal factors, and following ISO 7730 [16], individual questionnaires collect Thermal Sensation Votes (TSV) using a 7-point rating scale, from +3 (hot) to −3 (cold), where 0 is neutral, and Thermal Preference Votes (TPV), from +3 (much more hot) to −3 (much more cold), where 0 is remain unchanged. Thermal Comfort Votes (TCV) are collected with a 5-point rating scale, from 'Comfortable' to 'Extremely uncomfortable'. The overall rating of indoor air quality in classrooms was evaluated using the Air Sensation Vote (ASV) with a 5-point rating scale, from 'Acceptable' to 'Very improvable'.

The Predicted Mean Vote (PMV) index reflects the average value of the votes provided by a large group of people for a given situation on a 7-point thermal sensation scale, from +3 (hot) to −3 (cold), where 0 is neutral. PMV should be used for enclosed, climate-controlled spaces environments with constant occupancy in sedentary or low-intensity activities. To ensure the correct implementation of PMV in this work, in naturally ventilated spaces the ventilation should be controlled. Thus, the air velocity should be within a moderate range (0.1 m/s–0.5 m/s) to maintain an adequate thermal sensation. The predicted percentage of dissatisfied (PPD) index provides an estimate of the number of occupants within a space who would feel dissatisfied by the thermal conditions. For

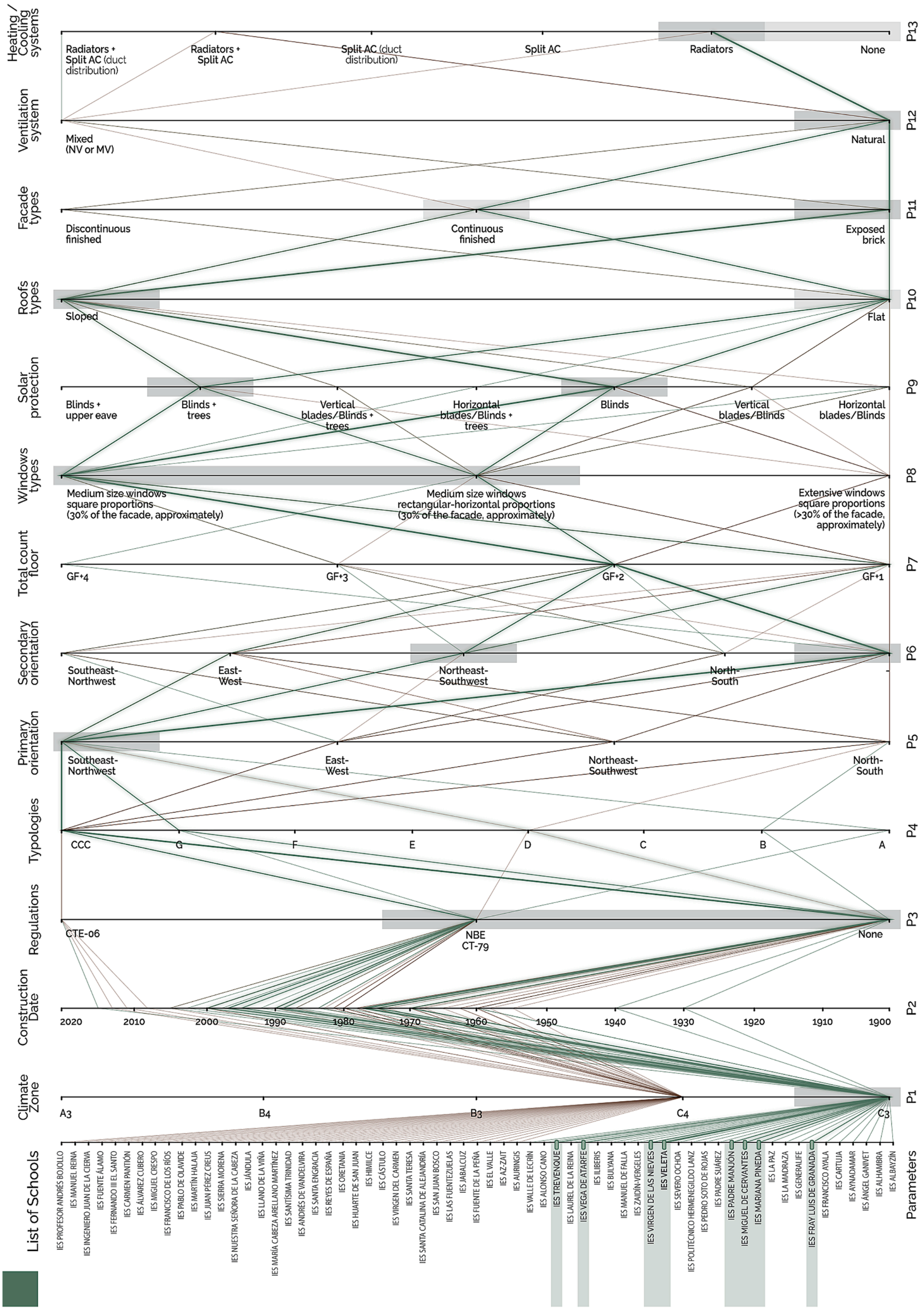

Fig. 2. Multiparametric parallel coordinates graph for the selection of representative secondary schools in one of the climatic zones according to Spanish standard [54].

Table 2
Summary of the main characteristics of the case studies.

ID	Construction period	Classroom Façade orientation	Classroom surface / volume (m^2 / m^3)	Windows: Surfacemax. aperture (m^2)	HVAC systems*	Number of students
CS 1	1979–2005	SE-NW	54.9 / 164.7	10.2 (5.1)	Radiators	30
CS 2	<1979	SE-NW	57 / 171.1	9.4 (4.7)	None	29
CS 3	1979–2006	SE-NW	45.8 / 126	13.3–9.8 (6.6–4.9)	Radiators + fans	26
CS 4	<1979	SE-NW	41.6 / 131	7.3 (3.6)	Radiators + Splits	25
CS 5	1979–2005	S-W-N	47.2 / 141.6	6.4 (3.2)	Radiators + Splits	30
CS 6	<1979	E-W	52.2 / 156.6	8.2 (4.1)	Radiators + fans	31
CS 7	1979–2005	S-N	57.7 / 173.2	8.4 (4.2)	Radiators + fans	31

* All case studies have only natural ventilation through the opening of windows (usually sliding) and doors, some of them with high windows onto the corridor.

Table 3
Monitoring equipment characteristics.

Scope	Parameters		Units	Range	Accuracy
IAQ	CO_2	Carbon dioxide	ppm	0 a 5000	±10 %
	CH_2O	Formaldehyde	mg/m^3	0 a 6.25	±0.03 mg/m^3
	$PM_{2.5}$	2.5 μm Particulate Matter	$μg/m^3$	0 a 1000	±15 $μg/m^3$ < 100 ± 15 % > 100
	PM_{10}	10 μm Particulate Matter	$μg/m^3$		
Hygro-thermal	Tg	Globe Temperature	°C	−20 a + 65	±0.5 %
	Ta	Air Temperature			
	RH	Relative Humidity	%	0 a 100	±3 %

this study a JAVA applet tool based on Fanger's parametric equation, according to ISO 7730 [16], was used to obtain PMV and PPD through iterative calculations. The Actual Percentage of Dissatisfied (APD) index was calculated according to ISO 7730 [16] from the ratio between the thermal sensation votes (−3, −2) and (+2, +3) and the total sample size [47].

The input-required recorded data relating to environmental conditions were the parameters of ambient air temperature (Ta, monitored variable), mean radiant temperature (Tr, measured with a wetbulb globe thermometer since the environment is considered uniform and the surrounding surfaces have similar temperatures), relative air velocity (v, typically estimated at range between 0.1 and 0.5 m/s, it is considered 0.3 m/s), and relative humidity (RH, monitored variable). Other parameters used in the calculation tool were: basic clothing insulation (I_{clo}), estimated and calculated [16,58] from information reported in questionnaires regarding the type of clothing according to season; metabolic energy production (M), considering sedentary work which corresponds to 1.2 met; and rate of mechanical work (W, normally 0).

2.3.2. *Neutral and comfort temperature*

The ASHRAE 55 Standard [17] provides a methodology for calculating the optimal indoor comfort temperature, taking into account the specific characteristics of the space, occupants' features, and prevailing environmental conditions. In other studies a linear regression analysis is also proposed to obtain the comfort temperature, although there are certain limitations (sample size and temperature range) which may affect the reliability of the results [48].

Other thermal comfort studies have found that the ability or degree of adaptation of the occupant may vary over time, resulting in a different average neutral temperature at each stage of the long-term studies [49]. The application of Griffith's method [50,21], which is commonly used to

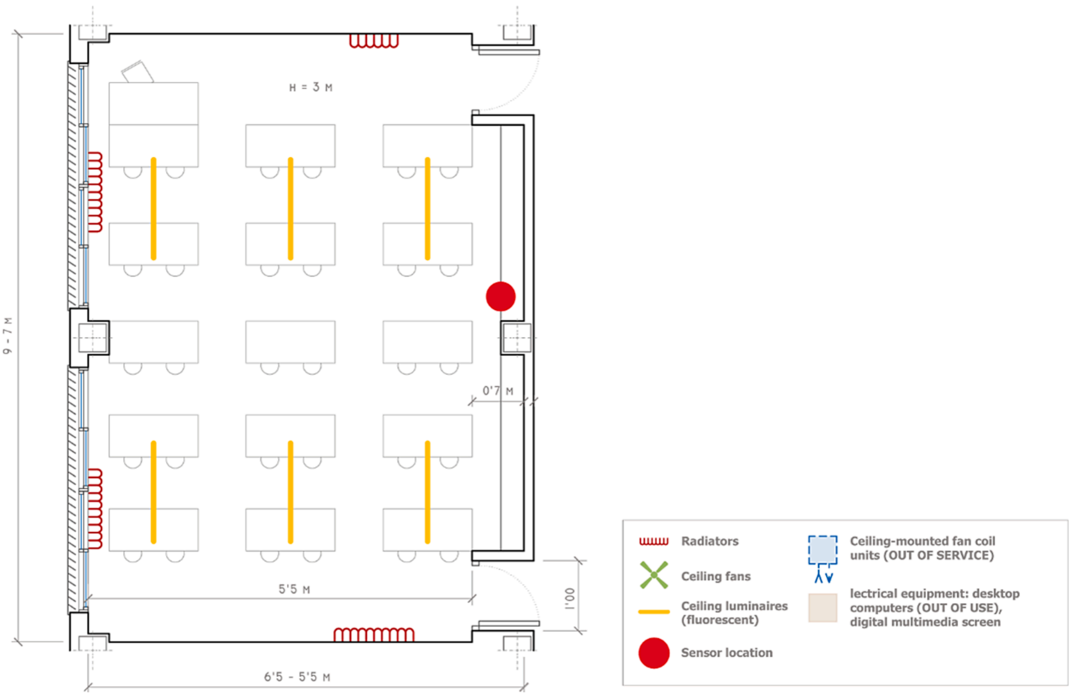

Fig. 3. Plan of a typical class setup during monitoring campaign.

derive thermal sensitivity, is based on obtaining the comfort temperature (Tc) from the following Eq. (1):

$$Tc = Top - \frac{TSV}{G} \qquad (1)$$

where Top is the operative temperature, which is obtained from the average of the air temperature (Ta) and the mean radiant temperature (Trm). TSV is the Thermal Sensation Vote and G is the Griffith constant, which is usually taken to be constant at 0.5 °C [51,21,62]. When TSV is equal to 0, the comfort temperature (Tc) obtained refers to the neutral temperature (Tn) of the occupants.

2.3.3. Statistical analysis

Data collected in the questionnaires on the subjective perception of the students was assessed by means of statistical analysis. Two main data analysis techniques were used in the study, classified as predictive and correlational assessment. Linear regression justifies and predicts the relationship between different dependent and independent variables. The R^2 coefficient of determination indicates the proportional amount of variation in the response variable explained by the regression model.

In this research, correlations and regressions are used to show how the subjective variables TSV, TPV, TCV and ASV are related to objective parameters such as T and CO_2 levels. Pearson's correlation parametric test has been used to measure the strength and direction of the linear relationship between two variables. Pearson's correlation coefficient (R) is related to the slope of the linear regression (β1) and the coefficient of determination (R^2), which measures the proportion of the variability in the *y* data that is explained by the regression model. In this study, the strength of the correlations was classified based on the following intervals for Pearson's R: very low (R = 0.00–0.19), low (R = 0.20–0.39), moderate (R = 0.40–0.59), high (R = 0.60–0.79), and very high (R = 0.80–1.00). In order to ensure reliability and accuracy of the survey results, a first step focused on a process discarding inconsistent responses. This task consisted of a correlation between responses. Three questions with slightly different approaches to thermal comfort are used to triple check the consistency of respondents' answers. The normality distribution of the data, which determines whether parametric or non-parametric tests are used, must also be verified. In this regard, graphical methods such as histogram plotting, representing the interval-scale data, are used to carry out the normality analysis.

3. Results

The results objectively recorded through continuous monitoring of parameters, as well as the subjective votes of the students regarding their thermal perception and indoor air quality in the classroom, are presented in this section. Data was depicted and organised to enable the analysis of different effects of environmental variables on the students' impressions. The data collected from the questionnaires were then classified according to climatic area and season of the year in order to provide an overview of variations resulting from the case study locations.

The environmental parameter values monitored at the time of the survey in each of the case studies, as well as the subjective indices obtained from the surveys carried out, are shown in Table 4 (heating season) and Table 5 (non-heating season). Mean vote refers to the mean value obtained individually per classroom (i.e. total sum of the votes by the number of students taking the survey).

3.1. Interaction between monitored and surveyed variables

3.1.1. Thermal perception

In Fig. 4a), percentage of votes of 'very cold/cold' (TSV = −3 and −2), 'neutral' (TSV = −1, 0 and 1), and 'hot/very hot' (TSV = 2 and 3) were plotted against indoor temperature, and Fig. 4b and c) plotted thermal sensation votes against CO_2 levels during non-heating (NH) (Fig. 4b) and heating (H) (Fig. 4c) seasons. A proportion of 100 % corresponds to all students of each survey. Similarly, Fig. 5 shows the

Table 4
Summary of data collected at the time of the survey during the heating season (H).

Case study	Orientation	Tout (°C)	Ta (°C)	Trm (°C)	HRm (%)	CO_2 (ppm)	N° of students	Mean Vote				PMV
								TSV	TCV	TPV	ASV	
CS1	NW(*)	7.7	18.3	17.7	37	1364	22	−0.8	1.7	0.9	2.14	−0.88
	SE	9	19.3	18.9	34	997	21	−1.5	2.8	1.0	2.76	−0.67
CS3	NW(*)	12.2	18.9	20.9	44	756	23	−0.6	1.7	0.6	1.91	−0.84
		12.2	18.9	20.9	44	756	21	0.4	1.4	0.1	2.48	−1.03
	SE	12.2	20.2	20.2	43	857	28	−0.4	1.5	0.7	1.82	−0.88
		12.2	20.2	20.2	43	857	20	−0.2	1.3	0.3	2.55	−1.31
CS4	NW(*)	7.9	18.9	18.9	39	430	21	−0.3	1.6	0.6	1.86	−1.04
		7.8	18.8	18.8	38	400	13	−0.3	1.3	0.8	1.69	−1.50
	SE	7.8	21.6	21.6	36	751	17	−0.1	1.4	0.2	1.71	−0.73
		7.9	21.5	21.5	36	746	16	−0.5	1.6	0.7	1.69	−0.14
	NW(*)	17.5	23.1	21.5	57	723	19	0.2	1.4	−0.3	1.84	−0.32
	SE	17.5	23.2	24.4	59	897	20	0.0	1.4	−0.2	2.25	0.01
	NW(*)	3.8	15.5	18.6	37	678	15	−0.5	1.5	1.1	1.87	−1.24
		4.9	17.9	16.1	40	1590	22	−0.5	1.4	0.8	1.86	−1.07
	SE	3.8	16.9	17.7	35	605	16	−0.9	1.8	0.8	2.56	−1.29
		4.9	19.2	15.3	36	1481	28	−0.6	1.6	1.1	1.96	−0.96
CS5	N	10.6	19.3	24.2	36	557	15	−0.1	1.4	0.3	2.47	−0.69
	W	10.6	19.3	24.2	36	557	19	−0.6	1.6	0.7	1.68	−0.69
	S	10.6	20.2	23.1	34	416	20	−0.2	1.3	0.2	1.70	−0.65
		10.6	20.5	22.7	35	570	21	−0.1	1.5	0.2	2.29	−0.47
CS6	E	3.5	15.2	17.0	43	606	17	−0.9	1.8	0.8	2.29	−1.38
		3.5	15.2	17.0	43	606	19	−0.2	1.4	0.5	2.00	−1.38
	W	3.1	14.1	16.3	46	624	17	−0.8	1.5	0.5	1.35	−1.79
		3.5	15.4	15.0	45	771	22	−0.2	1.1	0.4	2.36	−1.70

Table 5
Summary of data collected at the time of the survey during the non-heating season (NH).

Case study	Orientation	Tout (°C)	Ta (°C)	Trm (°C)	HRm (%)	CO_2 (ppm)	N	Mean Vote				PMV
								TSV	TCV	TPV	ASV	
CS1	NW(*)	21.2	24.7	24.5	59	406	24	0.5	1.5	−0.4	2.58	−0.75
	SE	20.4	25.5	25.5	54	769	14	0.4	1.6	−0.2	2.14	−0.44
CS2	NW(*)	30.4	28.6	28.0	37	447	10	1.2	1.8	−1.1	2.20	0.56
	SE	32	29.2	29.4	35	424	10	1.1	1.7	−0.8	2.10	0.90
CS3	NW(*)	34.3	32.5	38.2	31	503	26	2.3	3.0	−1.6	2.77	3.11
		34.3	32.6	38.1	33	495	30	2.6	3.5	−1.7	3.60	3.15
	SE	34.3	32.6	32.6	31	484	24	2.4	3.3	−1.5	3.79	2.41
		34.3	32.9	32.9	33	475	25	2.5	2.8	−1.3	3.08	2.31
CS4	NW(*)	34.9	34.6	34.0	29	585	12	2.7	3.6	−1.8	3.08	2.90
	SE	34.9	33.4	33.8	32	545	11	0.8	1.6	−0.9	2.18	2.60
		34.9	33.4	33.8	33	546	24	2.0	2.8	−1.4	2.33	2.62
CS5	N	26.3	28.5	29.7	38	1470	11	1.7	2.2	−1.2	3.27	0.63
	W	26.3	25.8	32.5	38	1470	10	1	1.7	−1.1	2.20	0.50
	S	26.3	29.5	30.7	39	831	15	1.2	1.9	−1.2	3.00	1.08
CS6	E	23.5	26.1	26.1	34	618	27	0.5	1.5	−0.3	2.22	−0.37
		23.9	26.1	26.1	34	618	29	0.6	1.4	−0.6	2.28	−0.65
		23.9	26.1	26.1	35	600	18	1.8	2.5	−1.1	2.78	−0.64
	W	2.5	25.1	25.1	34	600	32	0	1.1	0	1.97	−1.08
	E	28.6	26.5	26.5	43	509	30	−0.1	1.4	0.1	3.00	0.09
	W	28.6	25.5	25.5	41	509	27	0.3	1.2	−0.1	2.44	−0.08
CS7	N	29	28.8	27.2	31	517	23	0.7	1.5	−0.5	2.35	0.22
	S	29	29.8	28.2	34	814	22	1.5	2.1	−1	2.27	1.67
	N	24.8	23.3	22.7	50	786	23	0.3	1.9	−0.2	2.78	−0.84

proportion of students who described themselves as feeling 'comfortable' (TCV = 1), 'uncomfortable' (TCV = 2 and 3) or 'very uncomfortable' (TCV = 4 and 5) plotted against Ta (Fig. 5a) and CO_2 levels (Fig. 5b and c). In parallel, the relationships between parameters observed in Figs. 4 and 5 are supported by the statistical metrics listed in Tables 6 and 7. These data allow quantitative confirmation of the existence of statistically significant relationships.

Based on linear regressions of the sensation proportions, plotting the results in Fig. 4a) illustrates how temperature variations affect the user's perception of heat. It can be seen that the increase in temperature in the classroom leads to a significant increase in 'hot' votes, reaching almost 70 % of the proportions. This impact can be quantified from the R^2 value, which suggests that 64 % of the variations in 'hot/very hot' votes are due to the increase in temperature, while conversely, the decreasing slope of the neutral votes suggests that 48 % of the variations are caused by the variation in the thermal parameter. The relationship between sensation vote and temperature show a strong significant correlation ($p < 0.05$, Table 6).

The intersection between the linear regression models shows that at a temperature of 30.5 °C the percentages of hot and neutral votes are the same, which means that half of the students perceive a neutral environment while the other half perceive a hot environment. The intersection between regressions of hot and cold votes at a temperature of 20.5 °C can be seen from the joint representation of winter and summer outcomes, the results of which appear in the same figure. Temperature ranges vary between 14.1–23.2 °C during the H season and 23.3–34.7 °C during the NH season. In this regard, the type of clothing worn in the different seasons may determine a small percentage of the votes (10 %) feeling warm in winter and cool in summer.

The effect of varying CO_2 concentration on TSV can be analysed in Fig. 4b. The results show no meaningful relationship between the two factors, as can also be confirmed in view of the Pearson R values, which show a low or very low correlation ($R < 0.40$) in the Table 6. A high concentration of more than 70 % 'neutral' votes is observed irrespective of the CO_2 concentration. A decrease in the feeling of warmth during NH and a slight increase in the feeling of cold is observed as the CO_2 concentration increases during H season. Based on students's responses, it can be confirmed that on the coldest days (Tout between 3 and 4.9 °C) windows were closed and heating system was not activated (Ta between 14 and 16 °C). During these days CO_2 concentrations were higher, which is why an increase of "cold votes" is observed. On the other hand, during the NH season the windows were open, even on days with Tout above 33 °C, and no HVAC systems were activated, so "hot votes" increased with low CO_2 concentrations.

When assessing the relationship between environmental variables and the TCV, a clear relationship between occupant comfort and temperature variation is identified (Fig. 5a). As the temperature increases, the feeling of comfort decreases, reaching 21 % 'very uncomfortable' when temperatures exceed 34 °C. Similarly, thermal discomfort and temperature increase proportionally. It can be seen that 40 % of students are 'comfortable' at a temperature of 27 °C, and the linear regression of the 'comfortable' model intersects with the 'uncomfortable' model at a temperature of 25.5 °C, with a proportion of 44 %, and with the 'very uncomfortable' model at a temperature of 34.2 °C, with a proportion of 23 %.

As with TSV, there is no relationship with TCV as the CO_2 level increases. Thermal comfort is maintained at a rate of 50 %, even at levels above 1300 ppm during H season (Fig. 5c). This confirms the independence of thermal perception in relation to CO_2 levels (strength of correlation low or very low with R below 0.25, Table 7).

When ranking the TCVs at different temperature ranges directly related to the temperature of the static comfort models [16]. Fig. 6a) shows that at a temperature below 23 °C, 57.36 % of the 'comfortable' votes are maintained. It is only above 27 °C, considered discomfort in

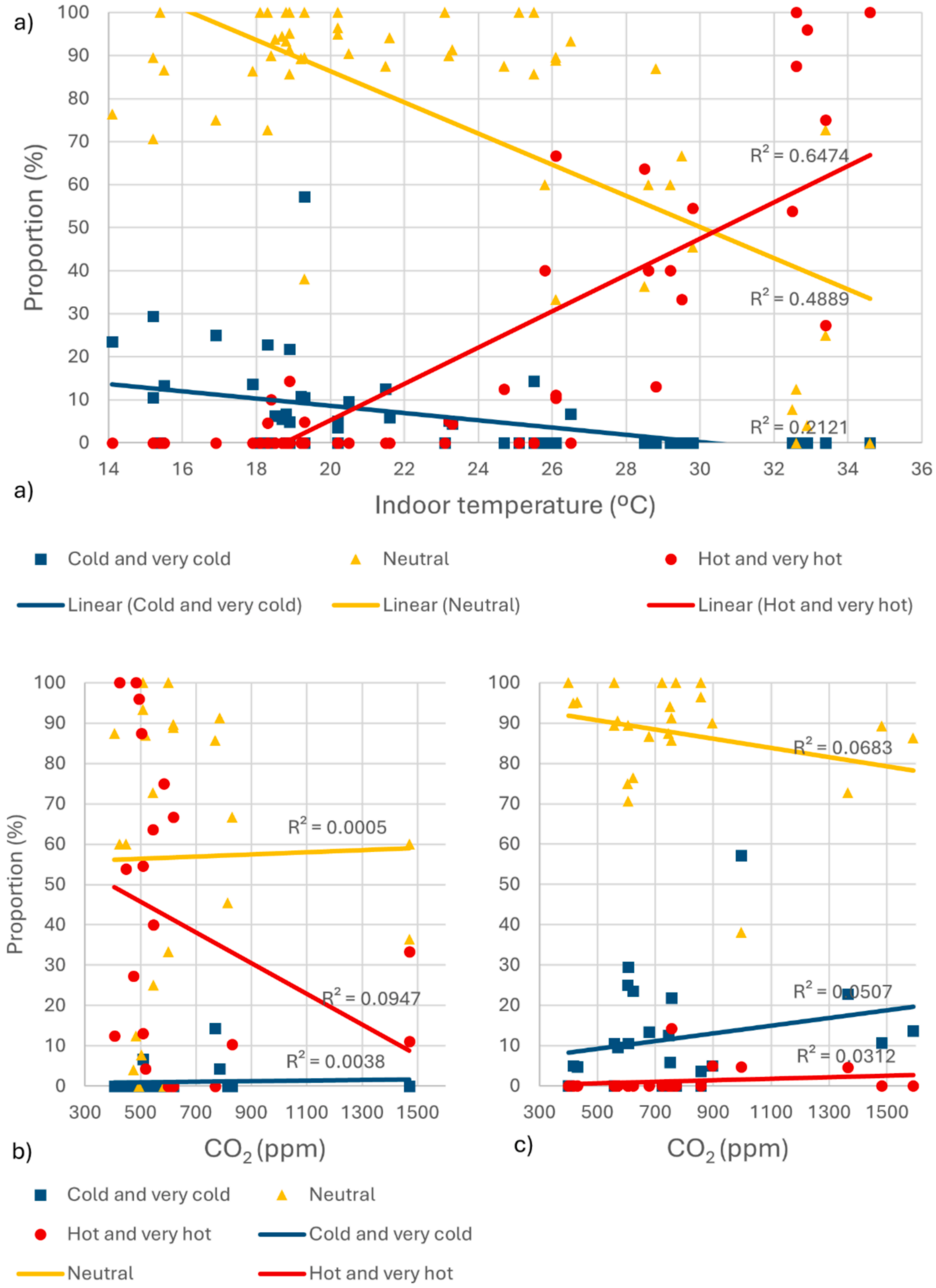

Fig. 4. Proportion of Thermal Sentation Votes (TSV) according to environmental variables (a) air temperature and CO_2 levels during NH (b) and H(c) seasons.

standards [16], that students' comfort level drops significantly, with 21.45 % of occupants expressing that they feel very uncomfortable. As mentioned above, the type of the garment used explains why, at a temperature below 19 °C, the discomfort votes (uncomfortable + very uncomfortable) are close to 39 %. The independence of CO_2 levels from TCV is also confirmed, as shown in Fig. 6b).

Fig. 7 shows the close association between the mean thermal sensation (MTS), and the sensitivity to the outdoor temperature. The results of the linear regression are significant, as R^2 coefficient increases are observed as the outside temperature increases. That is, there is a conclusive tendency for the thermal preference to decrease as the outdoor temperature increases, indicating the influence of high T_{out} on the thermal perception of a space.

3.1.1.1. Air quality perception. Figs. 8 and 9 represent the votes of 'acceptable' (ASV = 1), 'improvable' (ASV = 2 and 3) and 'very improvablevery improvable' (ASV = 4, no registration of "unacceptable" data (ASV = 5)) against indoor temperature during the non-heating (NH) and

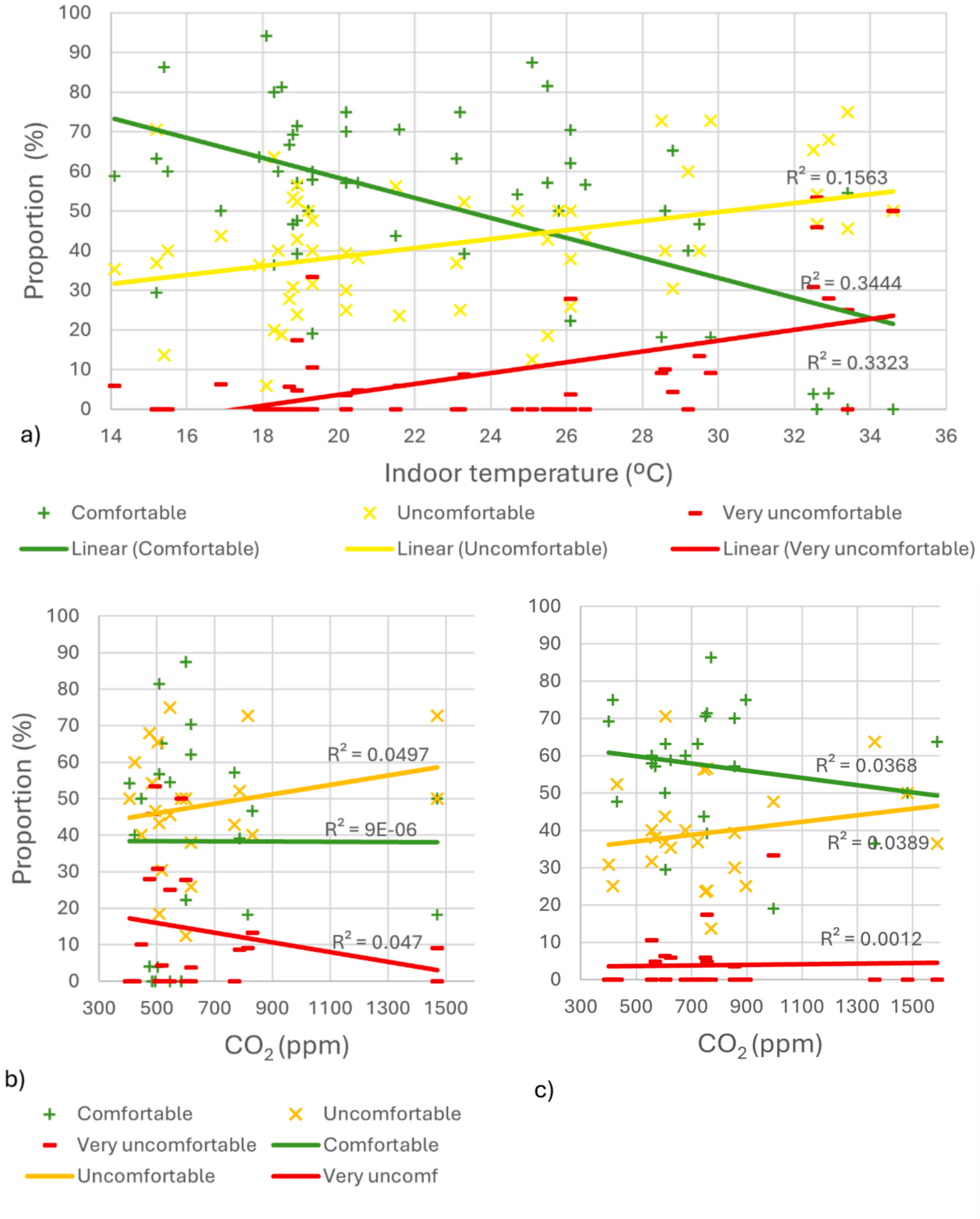

Fig. 5. Proportion of Thermal Comfort Votes (TCV) according to environmental variables (a) air temperature and CO_2 levels during NH (b) and H (c) seasons.

heating (H) seasons provided for each survey. It should also be noted that the standard [52] for categories I and II and ASHRAE standards recommend CO_2 levels below 1000 ppm for maintaining good IAQ in educational buildings.

The increasing linear regression trend (Fig. 8) of the 'very improvable' model explains the influence of temperature on ASVs. The R^2 value suggests that 34 % of the variation in the 'very improvable' judgement is due to the increased operative temperature of the classroom. This is directly related to the drop in the 'acceptable' linear model, which intersects with 'very improvable' at a temperature of 27.5 °C, indicating an equal proportion of votes in both models.

Similarly, Fig. 9 shows the proportion of students who expressed votes from 'acceptable' to 'very improvable' against CO_2 levels for summer (Fig. 9a) and winter (Fig. 9b), separately. As the NH and H results are plotted independently, the hot and cold regressions do not intercept each other. Interestingly, regardless of the season, the proportion of 'acceptable' and 'very improvable' votes increase in both cases, with the worst ASV rating being 10 % higher in the H season than in the NH season. The low R^2 values (below 0.2 in all cases) suggest that the effect of CO_2 concentration on ASV is not relevant. To complement the graphical correlations observed in Figs. 8 and 9, Table 8 shows the statistical metrics extracted from the relationships observed in the figure. These data show a low or moderate correlation ($0.21<R<0.59$) correlation between the ASV and temperature.

The distribution of ASV percentages in different temperature ranges (Fig. 10a) confirms previous observations in Fig. 8 about the influence of

Table 6
Statistical metrics extracted from the observed relationships in Fig. 4.

Seasons	Relationship	Vote	R^2	R^2 adjusted	R	p
Heating and Non-heating	TSV – T	Cold and very cold	0.21	0.20	−0.46	<0.05
		Neutral	0.49	0.48	−0.70	<0.05
		Hot and very hot	0.65	0.64	0.80	<0.05
Non-heating	TSV – CO_2	Cold and very cold	0.004	−0.04	−0.06	0.77
		Neutral	0.000	−0.04	−0.02	0.92
		Hot and very hot	0.094	0.05	0.31	0.14
		Cold and very cold	0.050	0.01	0.23	0.29
Heating	TSV – CO_2	Neutral	0.068	0.03	0.26	0.22
		Hot and very hot	0.031	−0.01	0.18	0.41

temperature on ASVs. At a temperature of above 27 °C there is a drastic increase in 'very improvable' votes, which reach 30 % of the total, while 'acceptable' values are reduced to half of those recorded at T < 18 °C. No meaningful conclusions can be drawn from the proportions of votes with respect to CO_2, as the variations do not follow a common pattern. Even the highest vote acceptance is recorded at CO_2 levels above 1400 ppm (Fig. 10b).

Fig. 11 plotted a three-variable relationship in order to comprehensively assess how both environmental parameters can affect the perception of air quality (ASV). Confirming previous observations, the distribution of results indicated the perception of a bad quality environment at temperatures above 27 °C, regardless of CO_2 levels. Other studies carried out in countries with a Mediterranean climate [21,53] have also confirmed this finding, highlighting the importance of temperature in the subjective perception of thermal comfort.

3.2. *Comparative between thermal and air quality assessments*

In order to establish correlations for the perceptual factors obtained from the questionnaires, the relationship between TSV and ASV indices is presented in Fig. 12.

In the NH season, the students express a directly proportional relationship between TSV and ASV, as can be seen in Fig. 12. This is in line with previous findings suggesting that the conditioning effect of temperature on both perceptual factors is even higher than that of CO_2 concentration in the case of ASV. This is not the case for the students' ratings during the H season, where the TSV = −2 rating for cold is rarely exceeded and where the highest concentration of votes is concentrated between TSV = 0 and −1.

Similarly, it is observed that the relationship between TSV and TCV is more relevant during the NH season, given that as the wind chill votes approach very hot (TSV = 2 and 3), the perception of thermal comfort worsens (TCV = 4 and 5). In winter, the ratings for 'a little uncomfortable' are below TSV = −2.

3.3. *Calculation of neutral temperature*

In order to find out the extent to which students' thermal perception is related to the variation of environmental variables such as temperature, the linear regression model between the thermal sensation vote (actual-TSV and estimated-PMV) and the air temperature inside the classroom is applied. Table 9 shows a summary of TSV and PMV regression equations and neutral temperature calculated for each season and considering the measurements for the whole year, and separately for the heating and non-heating seasons. The results, which are plotted in Fig. 13, show the degree of dispersion between them.

With the exception of winter (R^2 = 0.17 and p-value = 0.1), the results show that when considering the global annual average in summer, the variation in the actual perception of the occupants is accounted for by the variation in thermal conditions. In the case of the vote estimated from environmental variables, the relationship adapts more closely to the recorded temperature, exceeding 70 % in all cases and with a p-value of less than 0.05, which determines a statistical significance. As previous sections show, the average PMV for the whole temperature range is lower than the TSV. Neutral operative temperature (Tn) was obtained from the regression equations resulting in 22.9 °C for TSV, and 26.6 °C for the PMV during the warm season. Regarding the use of Griffith's method, the average global Tc obtained in this study was 22.3 °C, 1 °C higher than that obtained through linear regression. It is worth noting that the estimated comfort temperature by this method during the non-heating season reached 26.3 °C, is more than 3 °C higher than that obtained by the regression method. There are other studies carried out in the south of Spain that also obtain similar values [21]. High outdoor temperatures are recorded in both studies during summer. This fact may justify the discrepancy in results between the two calculation methods, as well as the differences with respect to the comfort temperatures obtained in other studies carried out in Mediterranean climates [35,54]. These results are in line with the Predicted Percentage of Dissatisfied (PPD), which is higher than the Actual Percentage of Dissatisfied (APD) calculated from the students' responses.

4. Discussion

An analysis was carried out on the overview of the collected data from different approaches. Firstly, the impact of environmental parameters such as air temperature and CO_2 was assessed in terms of thermal perception. This was followed by an analysis on the influence on indoor air sensation of the same objective variables. Finally, a comparative study was carried out on the different subjective and estimated

Table 7
Statistical metrics extracted from the observed relationships in Fig. 5.

Seasons	Relationship	Vote	R^2	R^2 adjusted	R	p
Heating and Non-heating	TCV – T	Comfortable	0.344	0.33	−0.59	<0.05
		Uncomfortable	0.156	0.14	0.40	<0.05
		Very uncomfortable	0.332	0.32	0.58	<0.05
Non-heating	TCV – CO_2	Comfortable	0.000	−0.05	−0.01	0.96
		Uncomfortable	0.050	0.01	0.22	0.30
		Very uncomfortable	0.047	0.00	0.22	0.31
		Comfortable	0.037	−0.01	−0.19	0.37
Heating	TCV – CO_2	Uncomfortable	0.039	0.00	0.20	0.36
		Very uncomfortable	0.001	−0.04	0.03	0.87

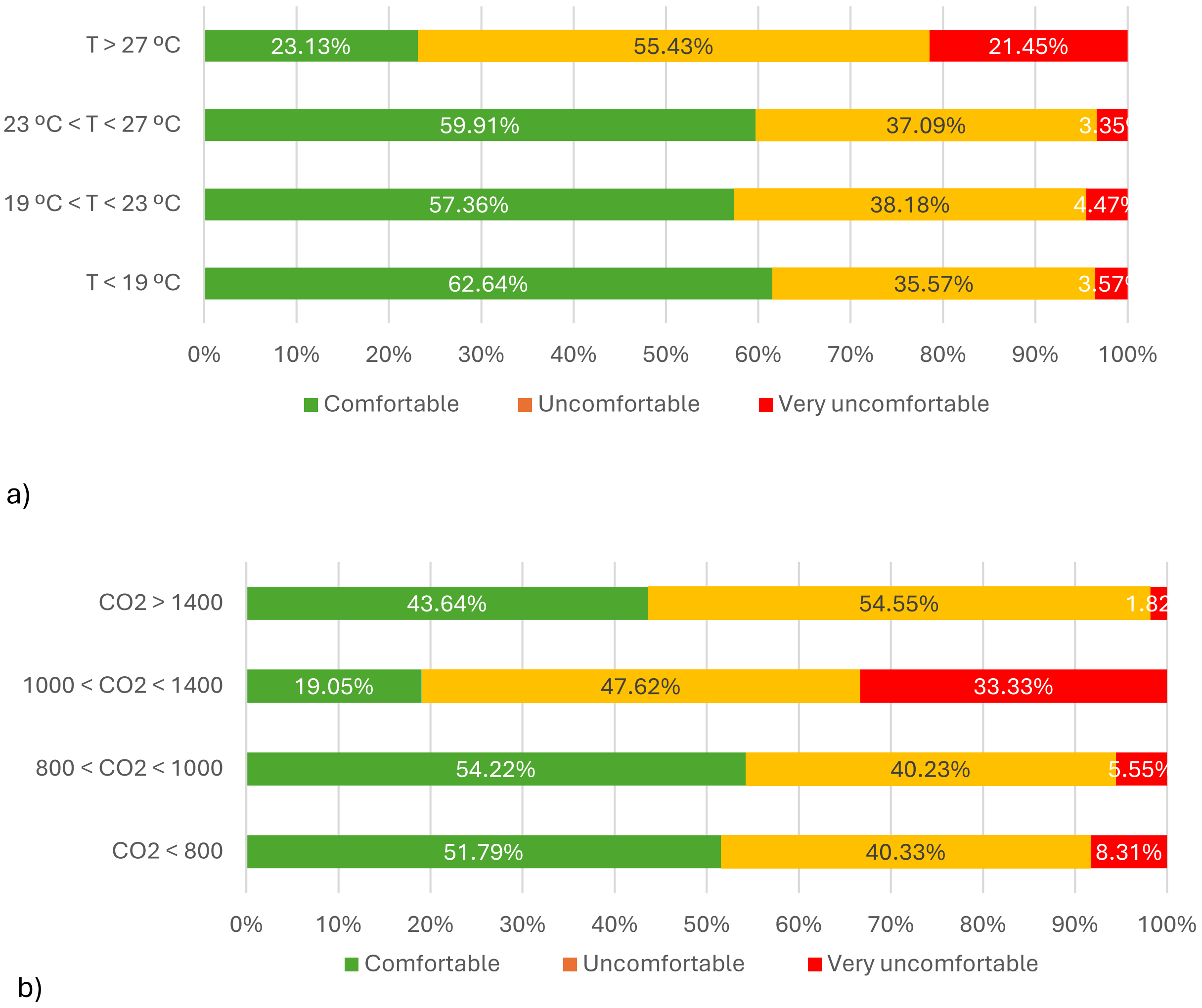

Fig. 6. a) Proportion (%) of TCVs for various air temperature (t) ranges; b) proportion (%) of TCVs for CO_2 (T) for different ranges of CO_2 level.

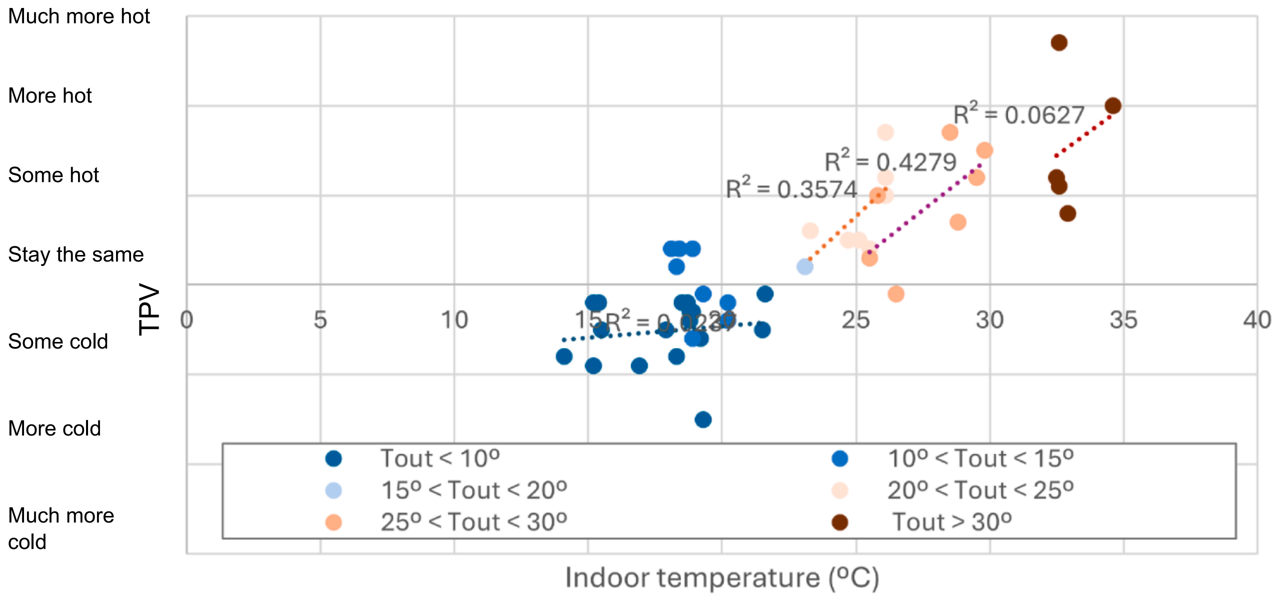

Fig. 7. Mean thermal preference vote (MTP) in relation to indoor and outdoor temperature.

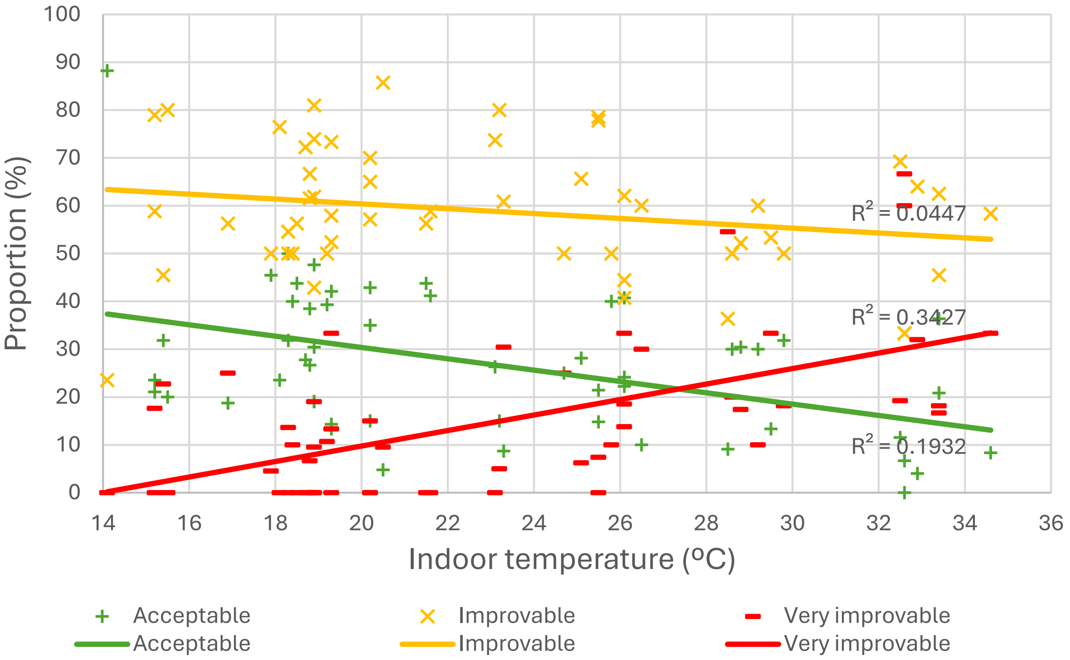

Fig. 8. Proportion of Air Sensation Votes (ASV) according to air temperature during NH and H seasons.

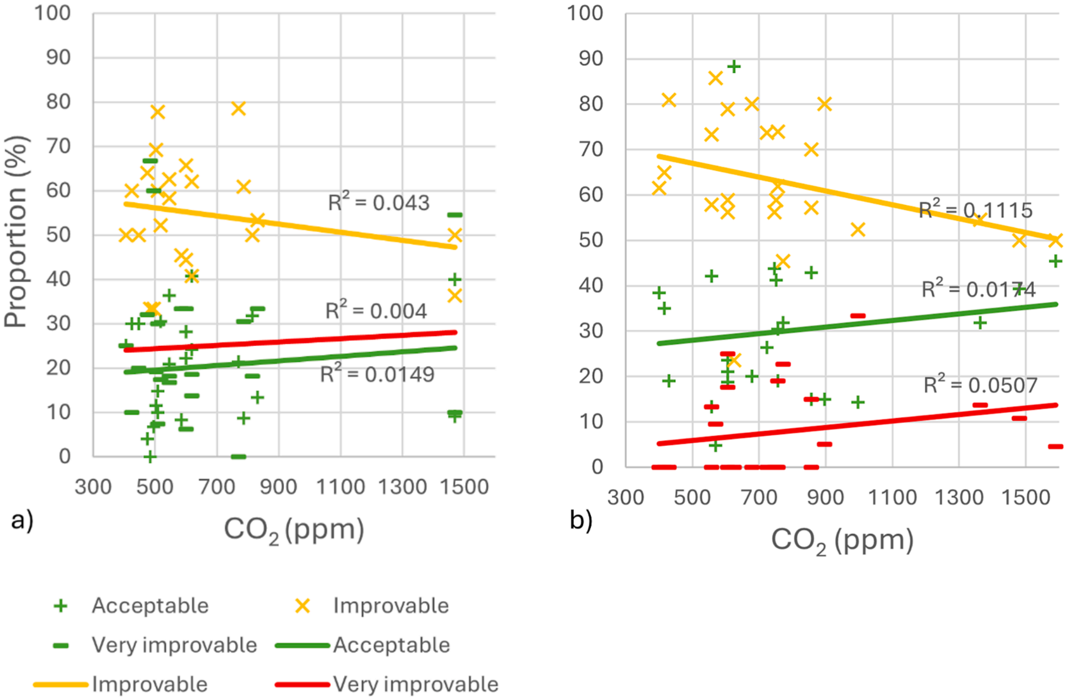

Fig. 9. Proportion of Air Sensation Votes (ASV) according to CO_2 levels during a) NH season; b) H season.

factors to review the correlation of students' actual vote and estimated values according to international standards.

4.1. Effect of environmental variables on thermal perception

The focus of the analysis of the survey results is to assess the influence of both air temperature (Ta) and CO_2 concentration on students' judgement of thermal sensation and thermal comfort. The cross-regressions made it possible to quantify the values of the environmental parameters as a function of the assigned vote.

The comfort temperature calculated using Griffith's method during the non-heating season was found to be 26.3 °C, over 3 °C higher than the value derived from the regression model. Similar findings were observed in other studies conducted in southern Spain [21], which also report higher comfort temperatures in warmer climates. These findings align with the Predicted Percentage of Dissatisfied (PPD) being higher than the Actual Percentage of Dissatisfied (APD) based on students' responses, suggesting a potential gap between theoretical comfort models and real-world perceptions.

An interesting observation is that, at a temperature as high as 30.5 °C, the number of "hot" and "neutral" votes is the same. This is particularly interesting because this temperature is significantly higher

Table 8
Statistical metrics extracted from the observed relationships in Figs. 8 and 9.

Seasons	Relationship	Vote	R^2	R^2 adjusted	R	p
Heating and Non-heating	ASV − T	Acceptable	0.193	0.018	−0.44	<0.05
		Improvable	0.044	0.03	−0.21	0.12
		Very imrovable	0.342	0.33	0.59	<0.05
Non-heating	ASV − CO_2	Acceptable	0.014	−0.03	0.12	0.57
		Improvable	0.043	0.00	−0.21	0.33
		Very imrovable	0.004	−0.04	0.06	0.77
		Acceptable	0.017	−0.03	0.13	0.54
Heating	ASV − CO_2	Improvable	0.111	0.07	−0.33	0.11
		Very imrovable	0.050	0.01	0.23	0.29

than typical comfort model thresholds, which usually suggest a more noticeable discrepancy between thermal comfort perceptions at such high temperatures. In most comfort models, temperatures above 27 °C tend to push most individuals towards perceiving discomfort. In this regard, ISO 7730 [16] indicates that 25 °C-27 °C is often seen as the upper limit for comfort in indoor environments without causing discomfort in the general population, while ASHRAE Standard 55 [17] also suggests that 28 °C is commonly regarded as the upper end of the comfort range for many individuals in moderate humidity conditions.

Additionally, a slight decrease in temperature recorded along with the increase in CO_2 concentration may be linked to the closing of windows and the resulting lack of natural ventilation during the H season. Similarly, the higher accumulation of heat votes at low CO_2 levels could be justified by the opening of windows in summer when outdoor temperatures are high.

Based on the findings of this subsection and their comparison with studies conducted in colder climates, where users reported a sensation of warmth starting at 23.5 °C [52], it can be concluded that respondents from warmer climates exhibit a slightly greater tolerance to elevated temperatures.

4.2. *Effect of environmental variables on indoor air quality perception*

This section examines the influence of air temperature (Ta) and CO_2 levels on the perception of air quality in classrooms. The analysis of the relationship between objective and subjective data reveals that a significant portion of the variation in perceptions of an "very improvable" classroom environment is linked to increases in operative temperature. This is evident in the distribution of "acceptable" and "very improvable" votes, where a threshold temperature of 27 °C is identified, marking a clear shift in perception.

Temperature appears to have a stronger influence than other factors, such as CO_2 levels, which show minimal or negligible effects, even on the assessment of indoor air quality (IAQ) during periods of extreme heat. In the absence of noticeable olfactory stimuli (such as dust, moisture, or chemicals), research suggests that IAQ perceptions are primarily influenced by high temperatures, contributing to discomfort and a perception of stuffiness in the environment. Other studies have also linked IAQ ratings to temperature, including those by Mishra et al. [56] and Romero et al. [21]. In fact, research by Torriani et al. [24,30], Korsavi et al. [38], and Wu and Wagner [29] found an inverse relationship between temperature and perceived IAQ, with worsening IAQ perceptions as temperatures rise.

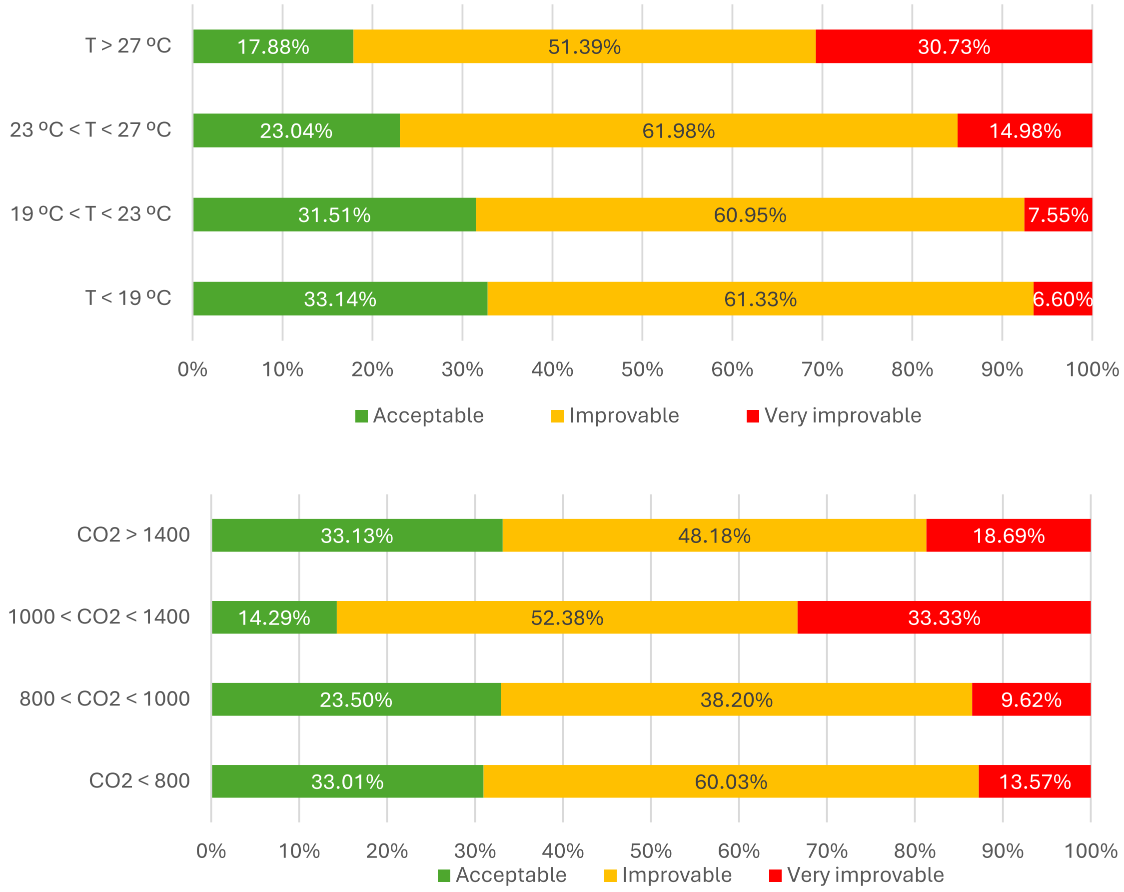

Fig. 10. a) Proportion (%) of ASVs for various air temperature (T) ranges; b) proportion (%) of ASVs for CO_2 (T) for different ranges of CO_2 level.

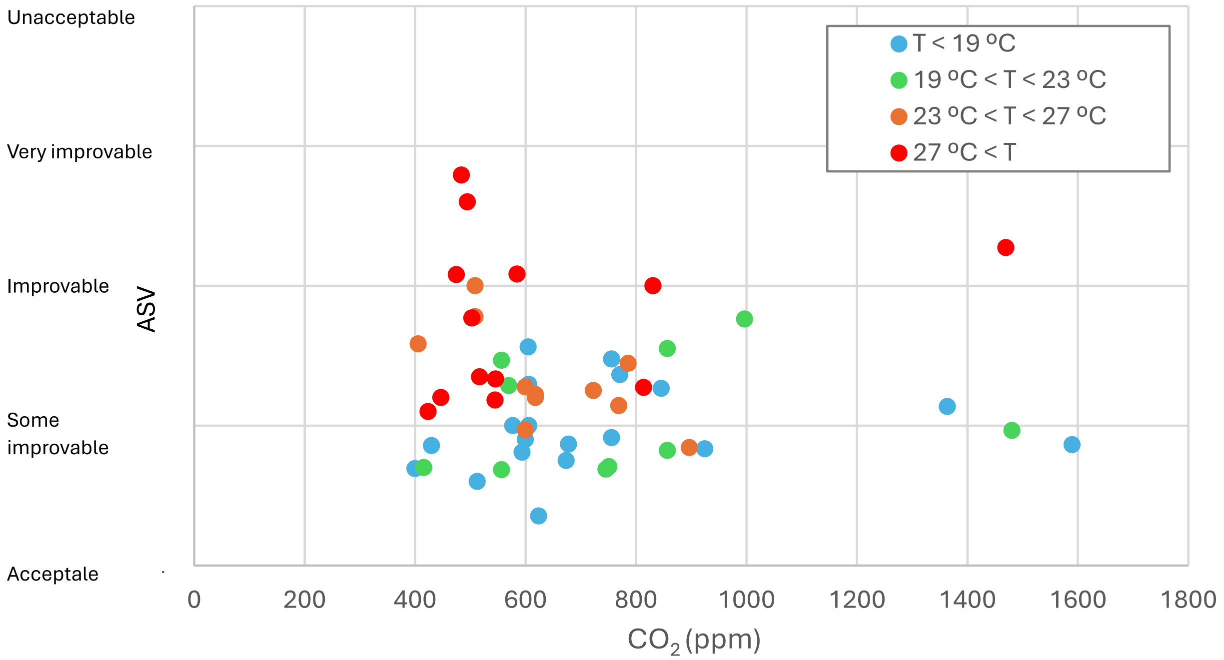

Fig. 11. Analysis of parameters affecting ASV.

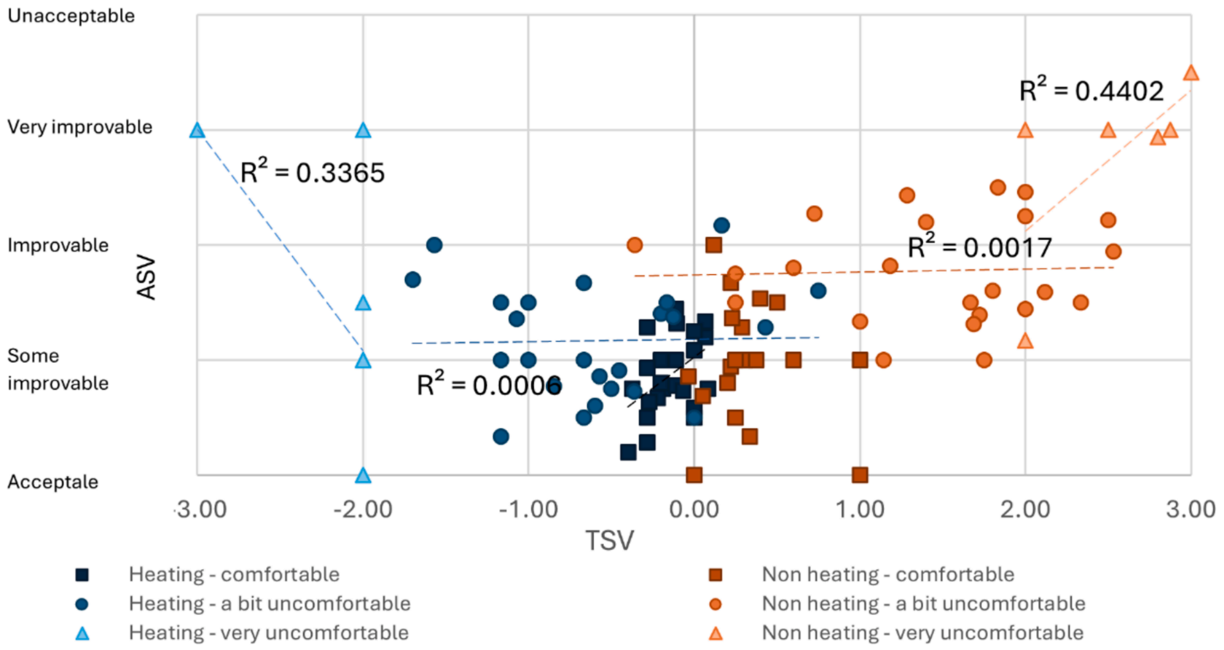

Fig. 12. Air Sensation Votes (ASV) vs. Thermal Sensation Votes (TSV) according to Thermal Comfort Votes (TCV) for each season.

4.3. *Students' perceptions versus predictive comfort indices*

A comparison of the mean values of thermal preference and thermal sensation revealed a low dispersion of results. The correlation index between both factors is 0.92, which means that only 8 % of the results are not in perfect agreement (Fig. 14 a). The correlation between the two parameters is more pronounced when the wind chill is hot. In this case, a general preference for slightly cooler environments was observed, as MTS = −1.5 corresponds to the thermal preference MTP = 2.5.

Fig. 14 b) shows the relationship between the estimated mean vote PMV and the actual thermal sensation MTS. Although the slope of the models follow a similar trend, the relationship is far from perfect, especially for a neutral estimated vote (MTS between −1 and 1), where the results are quite scattered towards a cold thermal sensation (PMV −2). According to the correlation index, under 30 % of the votes match their estimate. This results in a cooler vote being estimated than what is actually expressed by the occupants, that is to say, the TSV model has overestimated the predicted sensation. This finding is in agreement with the conclusions obtained in studies carried out in other areas with the same climatic conditions [21].

5. Limitations and further work

The geographical scope of this study refers to representative

Table 9
Proposed TSV and PMV regression equations and neutral temperatures.

Season	Indices	Equation	R^2	p-value	Tn	Average	
						TSV/PMV	APD/PPD (%)
All year	TSV	$TSV = 0.1625*T_a-3.3458$	0.79	<0.05	21.3	0.34	24.00
	PMV	$PMV = 0.2163*T_a-5.1731$	0.83	<0.05	23.9	−0.20	34.22
Non-Heating	TSV	$TSV = 0.2084*T_a-4.7735$	0.65	<0.05	22.9	1.22	41.50
	PMV	$PMV = 0.4017*T_a-10.681$	0.92	<0.05	26.6	0.87	40.97
Heating	TSV	$TSV = 0.0676*T_a-1.6769$	0.17	0.1	24.8	−0.40	13.05
	PMV	$PMV = 0.1613*T_a-3.9777$	0.73	<0.05	24.7	−0.94	27.46

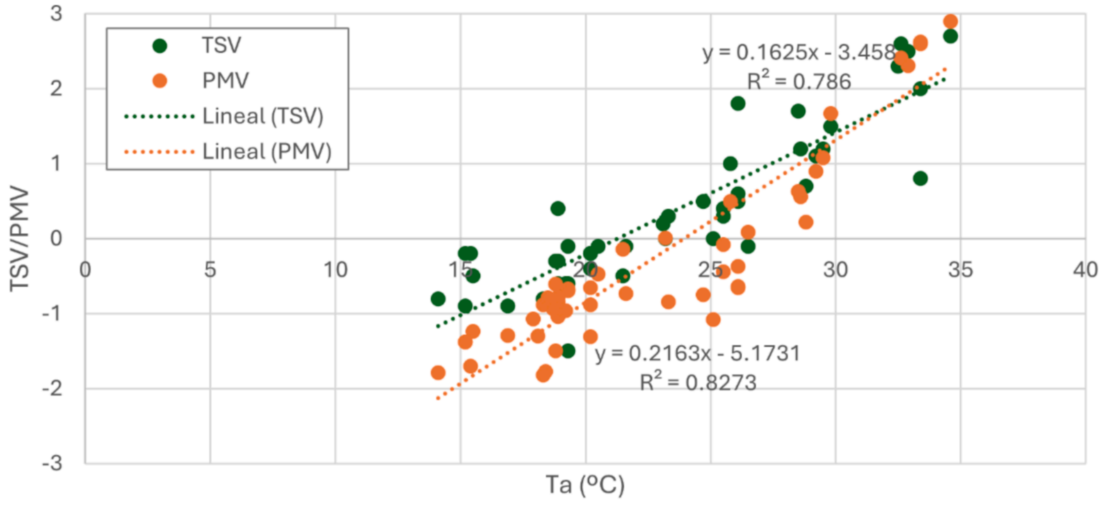

Fig. 13. Relationship between indoor operative temperature (Ta) and students' perception (TSV-PMV).

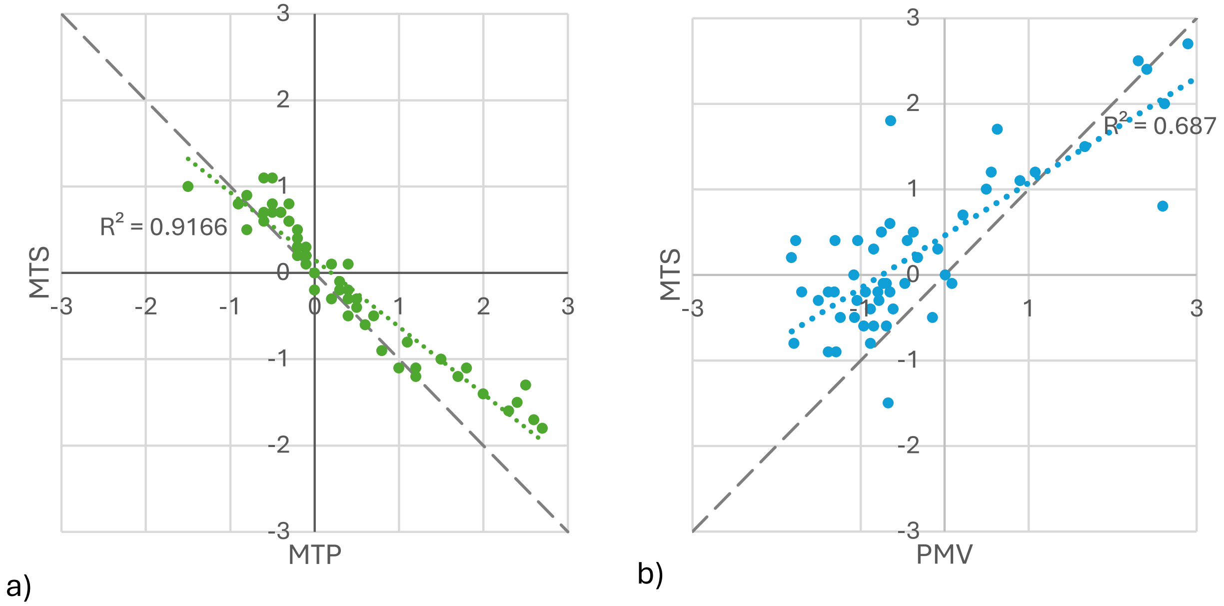

Fig. 14. a) Thermal sensation vs. thermal preference mean values (MTS and MTP); b) thermal sensation mean values (MTS) vs. Predicted Mean Values (PMV).

secondary schools in Andalusia. Expanding the study to schools in diverse regions could provide broader insights into the interplay between environmental factors and student comfort. Additionally, factors such as building orientation, educational level, and long-term exposure to varying conditions can be extensively explored in further work.

The study's reliance on the PMV model exposed discrepancies between predicted and actual comfort sensations. This underlines the need to refine comfort models to better reflect local climates and the adaptability of populations.

In alignment with EU sustainability goals, future research should explore energy-efficient adaptive comfort strategies and evaluate their resilience under climate change scenarios. By addressing these limitations, future work can contribute to developing sustainable and healthy indoor environments in schools.

6. Conclusions

This study conducted a comprehensive assessment of students' thermal and indoor air quality perception in representative secondary schools in the Andalusian region. The results are based on a monitoring campaign carried out over an entire year and questionnaires collected during intermittent periods of warm and cold seasons. Linear regression models were used to analyse the effect of environmental variables on the actual subjective indices, calculated from the responses collected in the surveys. The relationships between perceptual and estimated factors (PMV) were also assessed. Based on the findings of this work, the following conclusions can be highlighted:

- Regarding thermal perception:
  - o A higher tolerance to extreme temperatures during non-heating season is observed, as 60 % of occupants remain thermally comfortable up to a temperature of 27 °C, and only 23 % described their perception as very uncomfortable at 34 °C. During heating season, discomfort values are close to 40 % at a temperature below 19 °C.
  - o Variations in CO_2 levels do not affect the thermal perception of the occupants.
- Regarding indoor air quality perception:
  - o High temperatures recorded during non-heating season has a significant effect on air quality, since at a temperature above 27 °C there is a drastic increase in 'very improvable' votes, which reach 30 % of the total.
  - o Variations in CO_2 levels were considered irrelevant, especially during periods of extreme heat. Even the highest vote acceptance is recorded at CO_2 levels above 1400 ppm.
- Regarding the relationship between actual and predicted factors:
  - o The predicted vote underestimated the actual vote with PMV values lower than thermal sensation. This determined a poor prediction of students' actual wind chill during cold season in warm climates.
  - o High outdoor temperatures led to higher neutral temperatures being obtained than in other studies carried out in a Mediterranean climate. Neutral temperature values were quantified at 22.9 °C for thermal sensation, and 26.6 °C for the PMV during warm season.

In view of the conclusions, interesting observations are made regarding the strong influence of climate on the environmental perception, both thermal and indoor air quality. This finding raises an important point about how real-world conditions, such as high outdoor temperatures and acclimatization to warmer climates, may lead to deviations from the established comfort models. This suggests that comfort thresholds might be more flexible in warmer environments, especially in regions where individuals are exposed to high temperatures regularly. This observation could be useful for refining comfort models to better account for local climate conditions and the adaptability of the population.

In summary, while the results exceed typical comfort model predictions, they provide valuable insights into how comfort perceptions can vary in specific climatic conditions, suggesting a need to adapt existing models to reflect real-world thermal experiences.

All authors have read and agreed to the published version of the manuscript.

CRediT authorship contribution statement

Alicia Alonso: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rafael Suárez:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Jesús Llanos-Jiménez:** Writing – review & editing, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Carmen M. Muñoz-González:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2025.115479.

Data availability

Data will be made available on request.

References

[1] A. Alonso, J. Llanos, J. Sendra, R. Escandón, Effects of the COVID-19 pandemic on indoor air quality and thermal comfort of primary schools in winter in a Mediterranean climate, Sustainability 13 (5) (2021) 2699, https://doi.org/10.3390/su13052699.

[2] A. Monge-Barrio, M. Bes-Rastrollo, S. Dorregaray-Oyaregui, P. González-Martínez, N. Martin-Calvo, D. López-Hernández, A. Arriazo-Ramos, A. Sánchez-Ostiz, Ecouraging natural ventilation to improve indoor environmental conditios at schools. Case studies in the north of Spain before and during COVID, Energy Build 252 (2022) 111567, https://doi.org/10.1016/j.enbuild.2021.111567.

[3] A. Kabirikopaei, J. Lau, J. Nord, J. Bovaird, Identifying the K-12 classrooms' indoor air quality factors that affect student academic performance, Sci. Total Environ. 786 (2021) 147498.

[4] H.W. Brink, M.G.L.C. Loomans, M.P. Mobach, H.S.M. Kort, The influence of indoor air quality in classrooms on the short-term academic performance of students in higher education; a field study during a regular academic course, Indoor Air (2021) 32. https://research.tue.nl/en/publications/the-influence-of-indoor-air-quality-in-classrooms-on-the-short-te. Accessed July 15, 2024.

[5] T.M. Stafford, Indoor air quality and academic performance, J. Environ. Econ. Manage. 79 (2015) 34–50.

[6] C. Tribuiani, L. Tarabelli, S. Summa, C. Di Perna, Thermal performance of a massive wall in the Mediterranean climate: experimental and analytical research, Appl. Sci. 10 (13) (2020) 4611, https://doi.org/10.3390/app10134611.

[7] C. Wang, F. Zhang, J. Wang, et al., How indoor environmental quality affects occupants' cognitive functions: a systematic review, Build Environ. 193 (2021) 107647.

[8] W. Zeiler, G. Boxem, Effects of thermal activated building systems in schools on thermal comfort in winter, Build Environ. 44 (2009) 2308–2317.

[9] M.K. Singh, R. Ooka, H.B. Rijal, S. Kumar, A. Kumar, S. Mahapatra, Progress in thermal comfort studies in classrooms over last 50 years and way forward, Energy Build. 188–189 (2019) 149–174.

[10] UN. Educación – Desarrollo Sostenible. https://www.un.org/sustainabledevelopment/es/education/. Accessed July 10, 2024.

[11] J. Sundell, On the history of indoor air quality and health History, Indoor Air 14 (Suppl 7) (2004) 51–58, https://doi.org/10.1111/j.1600-0668.2004.00273.x.

[12] WHO, Coronavirus disease (COVID-19): how is it transmitted? https://www.who.int/news-room/questions-and-answers/item/coronavirus-disease-covid-19-how-is-it-transmitted. Accessed July 12, 2024.

[13] UNE 171380, Continuous measurement of CO2 indoors to improve the health and well-being of users, 2024.

[14] U. Haverinen-Shaughnessy, R.J. Shaughnessy, A. Nevalainen, Indoor environmental quality and health in schools: a review of the literature, Int. J. Environ. Res. Public Health 12 (2) (2015) 304–318, https://doi.org/10.3390/ijerph120100304.

[15] P. Wargocki, D.P. Wyon, P.O. Fanger, The effects of indoor air quality on performance and productivity in schools, Indoor Air 10 (5) (2000) 277–283, https://doi.org/10.1034/j.1600-0668.2000.010005277.x.

[16] ISO 7730, Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, 2005.

[17] ASHRAE, ANSI/ASHRAE Addenda O, P, and Q, Standard 55. Thermal Environment Conditions for Human Occupancy, 2023.

[18] J. Van Hoof, Forty years of Fanger's model of thermal comfort: comfort for all? Indoor Air 18 (2008) 182–201.

[19] S. Carlucci, L. Mazzarella, R.F. de Masi, Human thermal comfort and socio-economic factors in office environments: a review of the literature, Build. Environ. 92 (2015) 22–32, https://doi.org/10.1016/j.buildenv.2015.04.026.

[20] Environmental Protection Agency (EPA), Climate Change and the Health of Socially Vulnerable People, 2020. https://www.epa.gov/climateimpacts/climate-change-and-health-socially-vulnerable-people.

[21] P. Romero, V. Valero-Amaro, R. Isidoro, M.T. Miranda, Analysis of determining factors in the thermal comfort of university students. A comparative study between Spain and Portugal, Energy Build. 308 (2024) 114022.

[22] F. Rubel, M. Kottek, W. Köppen, Köppen-Geiger Climate Classification. Meteorologische Zeitschrift. 2011. http://koeppen-geiger.vu-wien.ac.at/. Accessed April 9, 2022.

[23] M. Kottek, J. Grieser, C. Beck, B. Rudolf, F. Rubel, World map of the Köppen-Geiger climate classification updated, Meteorol. Z. 15 (3) (2006) 259–263, https://doi.org/10.1127/0941-2948/2006/0130.

[24] G. Torriani, G. Lamberti, F. Fantozzi, F. Babich, Exploring the impact of perceived control on thermal comfort and indoor air quality perception in schools, J. Build. Eng. 63 (2023) 105419.

[25] L. Dias Pereira, D. Raimondo, S.P. Corgnati, M. Gameiro da Silva, Assessment of indoor air quality and thermal comfort in Portuguese secondary classrooms: methodology and results, Build Environ. 81 (2014) 69–80.

[26] C. Heracleous, A. Michael, Thermal comfort models and perception of users in free-running school buildings of East-Mediterranean region, Energy Build. 215 (2020) 109912.

[27] P. Aparicio-Ruiz, E. Barbadilla-Martín, J. Guadix, J. Muñuzuri, A field study on adaptive thermal comfort in Spanish primary classrooms during summer season, Build. Environ. 203 (2021) 108089.

[28] R.M.S.F. Almeida, N.M.M. Ramos, V.P. De Freitas, Thermal comfort models and pupils' perception in free-running school buildings of a mild climate country, Energy Build. 111 (2016) 64–75.

[29] Z. Wu, A. Wagner, Thermal comfort of students in naturally ventilated secondary schools in countryside of hot summer cold winter zone, China, Energy Build. 305 (2024) 113891. 2023;63:105419.

[30] G. Torriani, G. Lamberti, G. Salvadori, F. Fantozzi, F. Babich, Thermal comfort and adaptive capacities: differences among students at various school stages, Build Environ. 237 (2023) 110340.

[31] ASHRAE, ANSI/ASHRAE Standard 62.1-2022. Ventilation and Acceptable Indoor Air Quality, 2022. https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2.

[32] BB 101, Building Bulletin 101: Ventilation, Thermal Comfort and Indoor Air Quality. United Kingdom: Department for Education. Design, Education and Skills Funding Agency (ESFA); 2018, 2018. https://www.gov.uk/government/publications/building-bulletin-101-ventilation-for-school-buildings.

[33] B. Cabovská, G. Bekö, D. Teli, L. Ekberg, J.O. Dalenbäck, P. Wargocki, T. Psomas, S. Langer, Ventilation strategies and indoor air quality in Swedish primary school classrooms, Build. Environ. 226 (2022) 109744, https://doi.org/10.1016/j.buildenv.2022.109744.

[34] N.G. Vásquez, G. Bekö, P. Wargocki, B. Cabovska, D. Teli, J.-O. Dalenbäck, L. Ekberg, T. Psomas, S. Langer, Ventilation strategies and children's perception of the indoor environment in Swedish primary school classrooms, Build. Environ. 240 (2023) 110450.

[35] P.V. Dorizas, M.N. Assimakopoulos, M. Santamouris, A holistic approach for the assessment of the indoor environmental quality, student productivity, and energy consumption in primary schools, Environ. Monit. Assessment 187 (5) (2015) 1–18, https://doi.org/10.1007/s10661-015-4503-9.

[36] G. Smedje, D. Norback, E. Christer, Subjective indoor air quality in schools in relation to exposure, Indoor Air 7 (2) (1997) 143.

[37] J. Wang, G. Smedje, T. Nordquist, D. Norbäck, Personal and demographic factors and change of subjective indoor air quality reported by school children in relation to exposure at Swedish schools: A 2-year longitudinal study 508 (2015) 288–296. https://doi.org/10.1016/j.scitotenv.2014.12.001.

[38] S.S. Korsavi, A. Montazami, D. Mumovic, Perceived indoor air quality in naturally ventilated primary schools in the UK: Impact of environmental variables and thermal sensation, Indoor Air 31 (2021) 480–501, https://doi.org/10.1111/ina.12740.

[39] Y. Al-Dmour, Beyond academia: Investigating indoor environmental quality and its impact on postgraduate student satisfaction, Results Eng. 24 (2024) 103190, https://doi.org/10.1016/j.rineng.2024.103190.

[40] J. Llanos, R. Suárez, A. Alonso, J. Sendra, Archetypes of public secondary schools in Mediterranean climate. Indoor air quality and comfort field studies, in: AIVC 2022 Conference: 42nd AIVC-10th TightVent & 8th Venticool Conference, 2022. Rotterdam, pp. 808–817.

[41] J. Llanos, R. Suárez, A. Alonso, J. Sendra, Objective and subjective indoor air quality and termal comfot indices: characterization of Mediterranean climate archetypal schools after the COVID-19 pandemic, Indoor Air 1 (2024) 2456666, https://doi.org/10.1155/2024/2456666.

[42] CTE, Código Técnico de la Edificación - Documento Básico de Ahorro Energético (DB HE-0). Climas de referencia, Madrid, 2006. https://www.codigotecnico.org/DocumentosCTE/AhorroEnergia.html (accessed January 28, 2024).

[43] RITE, Reglamento de Instalaciones Térmicas En Los Edificios. Madrid, Spain: Ministerio de Industria, Energía y Turismo, 2021. https://www.boe.es/buscar/doc.php?id=BOE-A-2021-4572. Accessed March 31, 2024.0.

[44] Sensonet Multisensor SW20 datalogger. https://sensonet.com/nuevo-multisensor-datalogger-wifi/.

[45] ISO 9920, Ergonomics of the thermal environment—Estimation of thermal insulation and water vapour resistance of a clothing ensemble, 2007.

[46] ISO 10551, Ergonomics of the Physical Environment – Subjective Judgement Scales for Assessing Physical Environments, 2019.

[47] E.E. Broday, A.A. de Paula Xavier, A method for predicting the actual percentage of dissatisfied (APD) through a simple proposition of thermal comfort zones in a working environment, Work 67 (2020) 599–609. https://doi.org/10.3233/WOR-203215.

[48] G. Guevara, G. Soriano, I. Mino-Rodriguez, Thermal comfort in university classrooms: an experimental study in the tropics, Build. Environ. 187 (2021) 107430, https://doi.org/10.1016/j.buildenv.2020.107430.

[49] F. Nicol, M. Humphreys, Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251, Build. Environ. 45 (2010) 11–17, https://doi.org/10.1016/j.buildenv.2008.12.0135.

[50] L.A. López-Pérez, J.J. Flores-Prieto, C. Ríos-Rojas, Adaptive thermal comfort model for educational buildings in a hot-humid climate, Build. Environ. 150 (2019) 181–194, https://doi.org/10.1016/j.buildenv.2018.12.011.

[51] M.K. Singh, S. Kumar, R. Ooka, H.B. Rijal, G. Gupta, A. Kumar, Status of thermal comfort in naturally ventilated classrooms during the summer season in the composite climate of India, Build. Environ. 128 (2018) 287–304, https://doi.org/10.1016/j.buildenv.2017.11.031.

[52] EN 13779:2018 Ventilation for non-residential buildings – Performance requirements for ventilation and room-conditioning systems.

[53] A. Montazami, M. Gaterell, F. Nicol, M. Lumley, C. Thoua, Impact of social background and behaviour on children's thermal comfort, Build. Environ. 122 (2017) 422–434, https://doi.org/10.1016/j.buildenv.2017.06.002.

[54] G. Zhang, C. Zheng, W. Yang, Q. Zhang, D.J. Moschandreas, Thermal comfort investigation of naturally ventilated classrooms in a subtropical region, Indoor Built Environ. 16 (2007) 148–158, https://doi.org/10.1177/1420326X06076792.

[55] L.V. Abreu-Harbich, L.A. Chaves, M.C. Brandstetter, Evaluation of strategies that improve the thermal comfort and energy saving of a classroom of an institutional building in a tropical climate, Build. Environ. 135 (2018) 257–268, https://doi.org/10.1016/j.buildenv.2018.03.017.

[56] A.K. Mishra, M. Ramgopal, A thermal comfort field study of naturally ventilated classrooms in Kharagpur, India, Build Environ. 92 (2015) 396–406.

[57] J. Kim, R. de Dear, Thermal comfort expectations and adaptive behavioural characteristics of primary and secondary school students, Build. Environ. 127 (2018) 13–22.

[58] S. Haddad, A. Synnefa, M.A. Padilla-Marcos, R. Paolini, S. Delrue, D. Prasad, M. Santamouris, On the potential of demand-controlled ventilation system to enhance indoor air quality and thermal condition in Australian school classrooms, Energy Build. 238 (2021) 110838, https://doi.org/10.1016/j.enbuild.2021.110838.

[59] S. Miao, M. Gangolels, B. Tejedor, A comprehensive assessment of indoor air quality and thermal comfort in educational buildings in the Mediterranean climate et al., Indoor Air (2023) 6649829. https://doi.org/10.1155/2023/6649829.

[60] D. Teli, M.F. Jentsch, P.A.B. Jjames, The role of a building's thermal properties on pupils' thermal comfort in junior school classrooms as determined in field studies, Build. Environ. 82 (2014) 640–654.

[61] C.M. Calama, A.L. León-Rodríguez, R. Suárez, Indoor air quality assessment: comparison of ventilation scenarios for retrofitting classrooms in a hot climate, Energies 12 (2019) 4607, https://doi.org/10.3390/en12244607.

[62] A. Dhalluin, L. Karim, Comparison of natural and hybrid ventilation strategies used in classrooms in terms of indoor environmental quality, comfort and energy savings, Indoor Built Environ. 23 (4) (2014) 527–542, https://doi.org/10.1177/1420326X12464077.

[63] C. Di Perna, E. Mengaroni, L. Fusel, A. Stazi, Ventilation strategies in school buildings for optimization of air quality, energy consumption and environmental comfort in mediterranean climates, Int. J. Vent. 10 (1) (2011) 61–78, https://doi.org/10.1080/14733315.2011.11683935.

[64] A. Cablé, H.L. Hammer, M. Mysen, Comparison of two ventilation control strategies in the first passive house standard norwegian school, Int. J. Ventilation 14(4) (2016) 371–382.

[65] C. Vornanen-Wingvist, H. Salonen, K. Järvi, M.A. Andersson, R. Mikkola, T. Marik, L. Kredics, J. Kurnitski, Effects of ventilation improvement on measured and perceived indoor air quality in a school building with a hybrid ventilation, System 15 (7) (2018) 1414.

[66] B. Yang, T. Olofsson, F. Wang, W. Lu, Thermal comfort in primary school classrooms: a case study under subarctic climate area of Sweden, Build. Environ. 135 (2018) 237.