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A field study on adaptive thermal comfort in Spanish primary classrooms during summer season

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ABSTRACT

The assessment of indoor thermal comfort in schools has become an essential object of study; however, applying existing thermal comfort criteria would assume children and adults have a similar range of thermal comfort, without considering discrepancies regarding their level of activity or their behavioural adaptation. Therefore, the objective of the present study was to investigate the thermal comfort in a school building based on an adaptive thermal comfort field study in Seville, in the southwest of Spain, during a summer season. In this study, 2 free-running and 1 air-conditioned classroom were analysed; 67 students aged 10–11 years participated and 2010 thermal questionnaires were collected. A discrepancy was observed between the predicted mean vote and the thermal sensation vote, showing the former is not a good predictor of thermal perception. Thermoneutrality was not always the desired sensation for children; a preference for coolness was detected. A neutral temperature was observed at an average indoor temperature of 24–27 °C and a widening in the thermal comfort range was detected compared with international standards. Regarding adaptive strategies, they showed a preference towards opening windows and doors over using fans or changing clothes. The results suggest that the application of the current models for adults would not be suitable for estimating the thermal comfort of children, and these data could be used to promote natural strategies for assessing thermal comfort over conditioning systems in schools, with the aim of both space ventilation and energy efficiency.

1. Introduction

People spend approximately 60%–90% of their lives in indoor environments [1]. During the schooling period in particular, students spend approximately one-third of their day inside school buildings [2]. Therefore, the assessment of indoor thermal comfort has become an essential object of study due to its relationship with the health and productivity of building occupants as well as with energy efficiency.

In order to analyse thermal comfort, several field studies based on the adaptive thermal approach have been performed in various countries, climate areas climate areas [3–8], buildings [9–11] and types of space conditioning, including naturally ventilated buildings, hybrid or mixed mode buildings, which combine natural and mechanical strategies, as well as fully air-conditioned buildings [12–14].

Based on the literature, although the number of studies considering school buildings has increased in recent decades, most have been primarily focused on office and residential buildings. Additionally, the ISO 7730 [15], ASHRAE Standard-55 [16] and EN 16798–1 [17] standards define indoor thermal comfort based on studies with adult occupants. Regarding Spanish law, the Royal Decree 486/1997 [18] establishes an acceptable indoor temperature range for workplaces and adult subjects.

Defining the same thermal comfort criteria for school buildings would assume children and adults have a similar range of thermal comfort; however, previous studies [19–21] have concluded that students' thermal preferences are not in the comfort range provided in the standards and that there are discrepancies between the thermal comfort of children and the predicted mean vote (PMV) model, as well as with current adaptive thermal comfort models. Differences in the metabolic rate [22], the level of activity, the density of the office spaces and classrooms or the limitations the children have in adapting themselves to the environment by opening or closing windows or adjusting their clothing, among others, could explain such differences. Furthermore, studies focused on educational levels typically distinguish between Kindergarten (age approximately 3–6 years), Elementary or Primary (age approximately 7–11 years), Secondary (age approximately 12–18 years) and University (age approximately 19–26 years) [23]. School children would range from 3 years to 18 years of age; thus, a further analysis regarding differences in thermal requirements within this group

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is of interest.

The relationship between an appropriate indoor environment in school classrooms and the health and ability of children to learn and solve problems has led to investigate this phenomenon with the aim of developing suitable guidance on the thermal comfort level for educational buildings [24].

Table 1 summarises thermal comfort field studies in the literature regarding the thermal comfort of school children, specifying the building typology regarding the space conditioning approach, the number of students involved, the number of surveys collected, the participants' age, the physical parameters monitored and the number of school buildings considered.

Since Humphreys (1977) [25] analysed the thermal comfort in schools for an outdoor temperature between 17 and 23 °C during 2 summer seasons, focussing on differences in terms of sex and clothing levels between students and teachers, many other studies have been performed.

In 2003, Kwok and Chun [5] investigated the applicability of the thermal comfort standard in Japan, comparing naturally ventilated and air conditioned classrooms to analyse the thermal sensation of the respondents. In 2007, Corgnati et al. [26] conducted a field study in the city of Turin, Italy, collecting information about thermal, visual and acoustic comfort and indoor air quality, and they compared the TSVs and the PMV model.

Wigö (2008) [27] focused on the effect of intermittent air velocity on students' thermal sensation, concluding that such variations could make people feel the environment as cooler and more comfortable than when the air velocity is constant. In 2009, Hussein & Rahman [6] studied thermal comfort in schools in Malaysia, determining that the respondents had a greater tolerance to heat because of the existing climate in the area. Moreover, in the same year, Hwang et al. (2009) [28] analysed the applicability of the ASHRAE-55 Standard to the thermal comfort of Taiwanese students during the autumn semester, studying their comfort range.

Over the past 10 years, the literature has shown a growing trend in field studies performed in school buildings. Although most of them have analysed naturally ventilated school buildings, they differ in the location in which they are conducted and therefore the climate, as well as in the age of the participants involved.

Given the importance of schools in children's development and learning, and because thermal comfort is affected by the local context, more evidence is needed regarding their thermal perception. In Spain, few field studies have focused on school buildings [41–44], and only 2 have addressed the students' thermal sensation [43,44]. No previous studies have therefore been performed in schools located in southwest Spain, or even in the southern area, and during a summer season. Therefore, the present study is the first to take into account these features.

Although some studies in the literature are focused on schools, not all of them have explored a comfortable temperature; also, the results are sometimes based on a set of children comprised of both elementary and secondary students. The comfort temperature varies based on the type of climate or the participant's adaptive opportunities so it is important to analyse the differences between primary and secondary students, the latter of which could have a thermal sensation closer to adults. Additionally, given a previous thermal comfort study was carried out considering office buildings in the same location, the results could be compared with the results of this study of adults in the same climatic conditions. All the above shows the relevance of the analysis presented in our study.

Therefore, the objective of our research was to expose the results of a field study based on the adaptive thermal comfort approach and performed in the southwest area of Spain, to analyse the thermal comfort of primary school children and compare it with international standards. Section 2 describes the relevant aspects related to the field study, such as the location, climate, indoor and outdoor environmental variables monitored and questionnaires considered. Section 3 shows the results obtained and our discussion of the findings, and section 4 presents the main conclusions.

Table 1
Summary of previous thermal comfort field studies in school classrooms.

Year	Paper	Ref.	Typology [a]	Students	Surveys	Age	Environmental parameters [b]	Schools
1977	Humphreys	[25]	NV, AC	641	10,000	7–9	GT-AT-RH-AV	5
2003	Kwok & Chun	[5]	NV, AC	74	–	–	AT-RH-AV-MRT-Top	2
2007	Corgnati et al.	[26]	NV, H	427	–	–	GT-AT-RH-AV	5
2008	Wigö	[27]	NV, AC	40	–	10–19	GT-AT-RH-AV	1
2009	Hussein & Rahman	[6]	NV, AC	–	–	–	GT-AT-RH-AV	2
2009	Hwang et al.	[28]	NV	1614	–	11–17	GT-AT-RH-AV	14
2011	Mors et al.	[29]	NV	79	1657	9–11	GT-AT-RH-AV	3
2012	Teli et al.	[30]	NV	230	1314	7–11	GT-AT-RH-AV-CO_2	2
2013	Montazami & Nicol	[31]	NV	–	–	–	GT-AT-RH-AV-CO_2	18
2013	d'Ambrosio et al.	[32]	NV	4000	4416	11–18	AT-AV-MRT-DP	6
2014	Dias Pereira et al.	[33]	FR	45	–	16–19	GT-AT-RH-AV-CO_2	1
2014	De Giuli et al.	[4]	NV, H	62	–	9–11	GT-AT-RH-AV	1
2015	De Dear et al.	[8]	NV, AC	–	2850	10–18	GT-AT-RH-AV	9
2016	Almeida et al.	[2]	FR	487	490	4–18	AT-AV-RH-MRT-FT-RA	6
2016	Haddad et al.	[34]	NV	–	811	10–12	GT-AT-RH-AV-CO_2	4
2017	Trebilcock et al.	[20]	NV, AC	440	5414	9–10	GT-AT-RH-AV	12
2017	Liu et al.	[35]	NV	763	–	10–15	GT-AT-RH-AV	9
2017	Wang et al.	[36]	NV	1126	–	9–16	GT-AT-RH-AV	13
2018	Jindal	[7]	NV	130	640	10–18	GT-AT-RH-AV	1
2018	Kim & De Dear	[21]	NV, MM		4866	10–18	GT-AT-RH-AV	11
2018	Yang et al.	[3]	H	150	–	8–10	GT-RH-AV–CO_2–I-DBT	1
2020	Noda et al.	[37]	AC	97	97	9–11	GT-AT-RH-AV-I	3
2020	Sadat Korsavi & Montazami	[38]	NV	805	1390	9–11	AT-RH-AV-MRT	8
2020	Heracleous & Michael	[39]	NV	317	–	12–15	GT-AT-RH-AV- CO_2-DBT-WBT	1
2021	Shrestha et al.	[40]	NV	818	2454	12–18	GT-AT-RH-AV	8

[a] Classroom typology: Free Running (FR), Naturally Ventilated (NV), Heating (H), Air-conditioned (AC), Mixed Mode (MM).

[b] Environmental parameters: Globe temperature (GT), Air Temperature (AT), Relative Humidity (RH), Air velocity (AV), Illuminance (I), CO_2 concentration (CO_2), Mean radiant temperature (MRT), Operative temperature (Top), Dew point (DP), Floor temperature (FT), Radiant asymmetry (RA), Dry bulb temperature (DBT), Wet bulb temperature (WBT).

2. Field study and methodology

The methodology included recording environmental variables over 21 days in a summer season and collecting questionnaires for analysing thermal comfort during the scholastic period with the same group of students. The field study included 1 school building located in Seville, Spain, comprising 67 students and 3 teachers from 2 free-running (FR) classrooms provided with fans and 1 mixed-mode classroom provided with a heating, ventilation and air-conditioning (HVAC) system.

2.1. Location and description of the building and the classrooms

The building analysed was a public primary school building (Fig. 1) in which 3 classrooms on the top floor were included in the field study.

The school was a freestanding construction surrounded by sports facilities and streets. The classrooms were 50 m^2 on average [45], with a theoretical occupation of 25 students, approximately 9 × 6 m with ceilings 3 m in height. The classrooms were arranged in a V-shaped configuration along internal corridors, leaving a covered central courtyard in the middle.

The elements of the school building were as follows: The external wall, from inside to outside, featured double plasterboard (15 mm), a self-supporting metal structure (48 mm), rock wool insulation (60 mm, 0.037 W/mK), an air chamber (40 mm), a polyurethane thermal insulation layer (40 mm, 0.035 W/mK) and exposed brick. Inside the classroom, there were plasterboard ceiling tiles, the floor was 40 × 40 cm terrazzo tile and the internal wall (partition) consisted of double plasterboard (15 mm), a polyurethane thermal insulation layer, a self-supporting metal structure (48 mm), rock wool insulation (45 mm) and perforated brick. In general, the school had aluminium windows with a thermal break and glass is 4 + 10 + 6 with vertical adjustable slats of anodised aluminium.

All the classrooms had operable windows and blinds that could be opened or closed manually. Two of them (classroom A and classroom B) were FR spaces provided with 2 fans. The third classroom (classroom C) was provided with a HVAC system as a back-up component that could be turned on when needed. This system was not used continuously, but at certain times during the sampling period, which explains the trend in the results considering the free-running mode and the cooling mode.

In total, 67 primary students from 10 to 11 years of age (typically termed pre-adolescent) and 3 teachers participated in the study. Borgers et al. [46] had shown that children develop formal thinking at approximately the age of 10 or 11, which was necessary for an optimal completion of our surveys about thermal comfort. Numerous previous investigations have selected a similar minimum age to participate in field studies, as explained in section "1. Introduction". In addition, the teachers explained the questionnaires to their students before they began to complete them, and all questions they had were clarified.

The distribution of the participants was as follows: 19 students from classroom A (northeast orientation), 42% boys and 58% girls; 22 students from classroom B, 45% boys and 55% girls, (east orientation); and 26 students from classroom C, 46% boys and 54% girls (northwest orientation).

2.2. Climatic factors

The school building included in the field study is located in the Southern region of Spain, in Seville (37°N, 5°W). Spain's geographical location explains its climatic diversity, given up to 4 climate types can be identified in the territory, with the Mediterranean climate predominating.

However, its geographic diversity makes it possible to determine significant differences in the weather according to the region considered. Particularly, Seville is characterised by mild winters, rainy springs and autumns and hot and sunny summers. The maximum temperature in the summer season is approximately 35–36 °C and up to 40–45 °C in July. Its climate is considered as temperate, based on the climatic classification of Köppen-Geiger [47], and the Spanish Technical Building Code [48] highlights the climatic severity during the summer period.

Table 2 shows the climate during the field study, between 1st and 21st June.

Fig. 1. School building, solar period and layout of the classrooms.

Table 2
Climate in Seville between 1st and 21st June.

Data		1 June – 21 June
Temperature (°C)	Mean	22.5
	Min	13.9
	Max	37.8
Dew point (°C)	Mean	12.5
	Min	6.1
	Max	17.7
Humidity (%)	Mean	56.7
	Min	18
	Max	98
Wind speed (mph)	Mean	6.9
	Min	0
	Max	21
Pressure (in)	Mean	29.9
	Min	29.8
	Max	29.9

2.3. Environmental parameters

In general, the indoor environment can be characterised by 4 parameters: air temperature, air velocity, radiant temperature and relative humidity. Given these parameters play an important role in determining the thermal comfort requirements of the human body [49], they have been used in many studies in the literature, along with others, such as CO_2 or luminosity, which are also typically considered.

In the present field study, the monitored variables were air temperature, relative humidity, globe temperature and air velocity. The black globe thermometer is a good predictor of the combined effect of air temperature, long-wave radiation and air movement on human heat stress [50]; thus, globe thermometers of 40-mm diameter were installed to monitor the radiant temperature. Additional devices were also included in the field study to measure the illuminance and to identify whether the doors of the classrooms were open or closed.

Table 3 shows the variables monitored and information about the devices used, according to the conditions of instruments for measuring physical quantities in ergonomics of the thermal environment (ISO 7726:1998) [51].

The sensors were evenly distributed between the 3 classes. Within each classroom, they were placed in the middle of the classroom, and additional devices were also located at the beginning and at the end of the room at a height of 1.1 m above the floor. They were placed far away from heat sources (Fig. 1).

Wireless technology was used to automate the process of recording environmental variables, so all the sensors sent the measurements to an Ethernet Gateway and then to an external server. Given the devices recorded a new value every 15 min, approximately 70,560 environmental data were collected during the sample period.

2.4. Thermal comfort surveys

To evaluate the thermal sensation of primary school children, a longitudinal survey was created based on the previous work by Teli et al. [30] and Trebilcock et al. [20]. Each student received a book with the questionnaires, on which a colourful cover was added, as well as an identification number to locate the classroom and the student. Moreover, the questionnaires themselves were also colourful and pictures were included in order to make the process easier and more interesting for the children.

A 7-point thermal sensation scale was used (hot, warm, slightly warm, neutral, slightly cool, cool, cold), with Spanish translation. Additionally, a 7-point scale was considered for collecting the thermal preference (much colder, colder, a bit cooler, no change, a bit warmer, hotter, much hotter) and the thermal acceptance was categorised into acceptable or unacceptable. Moreover, the students were asked in the longitudinal survey if they were wearing jumper, sweater or jacket while they were answering the questionnaire (Fig. 2).

The children were asked to complete the longitudinal survey twice a day and 15 min after sitting down at their desks [52]: The first time was prior to the morning school break when, in general, the school operated in the free-running mode; the second time was after the morning school break, when it was possible to use the fan or HVAC, depending on the classroom. The students did not report feeling bored when answering the questions, given the questions were brief and age-appropriate. The teachers were also asked to complete a questionnaire regarding their thermal comfort at the same time as the children. Additional questions on possible adaptive actions, as well as the students' level of activity and emotional state, were included in their questionnaires. The information collected was revised, and all the data considered in the analysis were consistent. A total of 2010 responses were collected over the sampling period, 570 responses in classroom A, 660 responses in classroom B and 780 responses in classroom C.

Generally, wearing a uniform is not mandatory for children during the summer season in Spain. Therefore, an extra questionnaire regarding clothing was also completed based on the standard EN 16798–1 [17].

2.5. Data analysis method

Based on the information about the selected location, monitored indoor and outdoor variables and thermal comfort data collected through the comfort surveys specified, an analysis of the data and a discussion based on the results obtained in previous studies can be found in section "3. Results and discussion".

First, a summary regarding the environmental variables monitored by the sensors during the field study is presented. Second, based on thermal comfort surveys, the evolution of thermal sensation and thermal preference votes as well as the relationship between them is considered. Additionally, the mean actual thermal sensation vote based on the thermal comfort surveys and on the predicted mean vote model is analysed.

Considering thermal sensation votes and indoor environmental variables, a comfort temperature and a preferred temperature were proposed and were compared with existing standards as well as with previous studies. Finally, the adaptive behaviour and the activity level of the participants in the study are analysed.

Table 3
Data acquisition systems and characteristics.

	Classroom A	Classroom B	Classroom C			
Sensors	Number of sensors	Number of sensors	Number of sensors	Corridor inside	Operative range	Accuracy
Globe temperature (°C)	2	2	2	–	−40 °C to +125 °C	±0.25 °C
Temperature (°C)	3	3	3	2	−40 °C to +125 °C	±0.25 °C
Humidity (%)	2	2	2	–	0 to 100	±3% under normal conditions
Illuminance (lux)	2	2	2	–	0 to 1000	±0.5%
Air velocity (m/s)	1	1	1	–	0–5 m/s	±0.2 m/s
Open-closed (door)	1	1	1	–	0–1	–
Motion	1	1	1	–	Sensing Range 5 m.	–

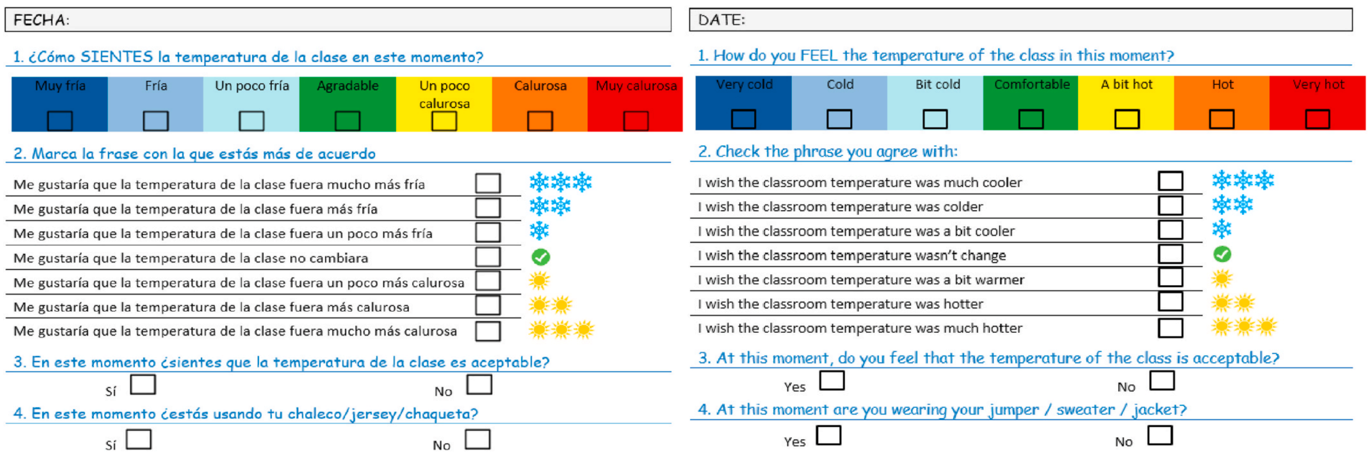

Fig. 2. Actual questionnaire used in Spanish (left) and a translation into English (right) (based on [30]) for children.

3. Results and discussion

Once the description of the climatology, the information regarding the devices, the questionnaires and the methodology used have been previously exposed, in the present section, the main results of the field study are analysed and discussed.

3.1. Indoor environmental conditions

The average, minimum and maximum values of the indoor variables recorded during the field study are shown in Table 4.

Regarding the globe temperature and the air temperature, similar values were monitored in the 3 classrooms, although the average temperature was lower in Classroom C due to the availability of a HVAC system. During class hours, 9:00 to 14:00, the difference between the indoor and the outdoor temperature could be almost 10 °C. No significant differences were observed in the average indoor relative humidity in the 3 classrooms. Due to the influence of lighting on productivity and wellbeing [53,54], the illuminance level was monitored but it was not analysed in the present study. The average value was above 200 Lux, a suitable value for moderate vision, according to the Spanish Law RD 486/1997.

Table 4
Indoor variables during the field study.

Classroom		Classroom A	Classroom B	Classroom C
Globe Temperature (°C)	Mean	28.1	28.0	27.1
	Min	24.4	23.3	23.7
	Max	34.7	34.4	33.8
Temperature (°C)	Mean	27.4	27.5	26.7
	Min	24.5	24.3	24.0
	Max	33.1	33.0	32.0
Temperature difference between 9:00 and 14:00 (°C)	Mean	3.9	4.0	3.2
	Min	−3.5	−3.1	−4.3
	Max	9.3	8.8	8.8
Temperature difference at 9:00 (°C)	Mean	7.6	7.7	7.2
	Min	6.5	6.9	5.9
	Max	9.3	8.6	8.8
Temperature difference at 14:00 (°C)	Mean	0.8	0.8	0.1
	Min	−3.5	−3.1	−4.3
	Max	6.8	6.9	6.4
Humidity (%)	Mean	43.7	43.4	44.3
	Min	30.0	29.3	31.4
	Max	59.3	61.9	63.0
Illuminance (Lux)	Mean	264.9	356.7	325.9
	Min	11	10	47
	Max	1.2	1.0	695

3.2. Thermal responses: thermal sensation and thermal preference votes

The percentage distribution of the thermal sensation votes (TSVs) and the thermal preference votes (TPVs) collected is represented in Fig. 3. The data were divided into 2 groups: if the HVAC system was in use at the time of the survey, the data were classified as being in the cooling mode (CL). If it was not, the data were classified as being in the FR mode [55]. Fig. 3-a shows the distribution of the TSVs and the TPVs for the FR mode and Fig. 3-b shows that for the CL mode.

In general, the average thermal sensation vote shows that most of the students were comfortable, with the neutral sensation predominating, and based on their thermal preference votes, they preferred no change or cooler environments.

Some 64% of the students' TSVs were in the comfort range (between −1 and 1), and 57.3% of the TPVs were between "no change" and "slightly cooler/warmer" for the FR mode. For the CL mode the results were similar: 56% of the students were in the comfort range and 60% of the TPVs were between "no change" and "slightly cooler/warmer".

The distribution of the students' TPVs in relation to their TSVs is shown in Fig. 3-c for the FR mode and in Fig. 3-d for the CL mode, and the results showed a greater tolerance to higher temperatures than to lower temperatures for both modes. Considering the FR mode, for a "cold" TSV, students would prefer a much warmer temperature (85%); nevertheless, for a "warm" TSV they would prefer "colder" (43%) and "a bit colder" (57%) temperature. Moreover, for the "a bit warm" vote the children would mostly prefer "no change" or "a bit colder/warmer" environment (92%). This percentage was similar (93%) for a "neutral" TSV but decreases down to 70% for "a bit cool". For the CL mode, for a "cold" TSV, students would prefer a much warmer temperature (83%), and for a "warm" TSV they would prefer a "a bit colder" (57%) temperature. For the "a bit warm" vote the children would mostly prefer "no change" or "a bit colder/warmer" (95%), and this percentage was similar for a "neutral" TSV.

Table 5 shows the average TSV and TPV considering the indoor environment under the FR and the CL modes. Regarding the FR mode, the average TSV shows that most children felt comfortable and that they preferred neutral environments and slightly cooler environments. Regarding the CL mode, the average TSV vote was near the thermal comfort range, with a preference for a bit cooler and cooler environments. Analysing the acceptability of the thermal environment (TA), the temperature was considered acceptable for the majority of students (56%).

In order to further analyse the correlation between the thermal sensation votes and the thermal preference votes, Fig. 4 shows the average TPV for each value on the thermal sensation scale.

Although the most desired sensation was "neutral", other answers were also given, which shows that children usually do not like to feel

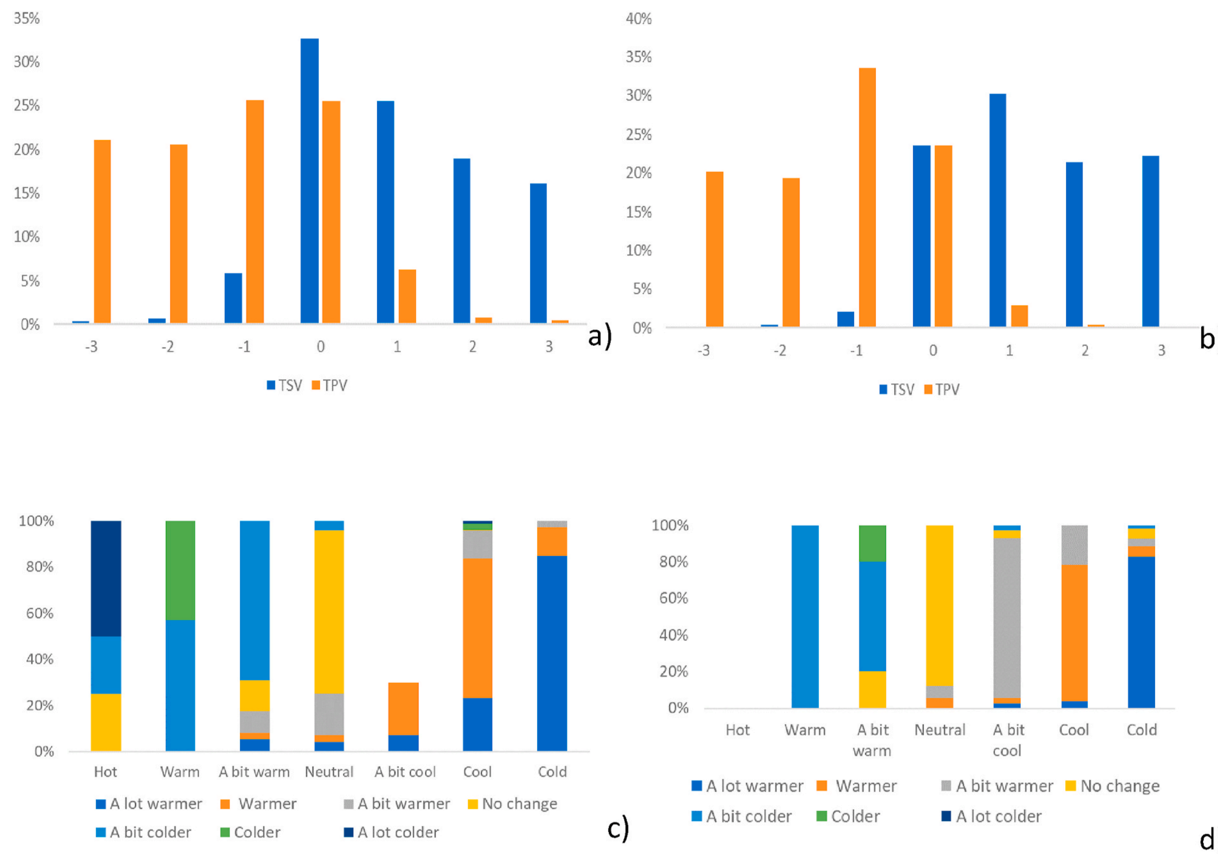

Fig. 3. Evolution of thermal sensation votes (TSV) and thermal preference votes (TPV).

Table 5
Average values and standard deviations for thermal sensation vote and thermal preference.

Mode		TSV	TPV	TA
FR	Mean	1.03	−1.21	0.09
	SD	1.23	1.28	1.00
CL	Mean	1.37	−1.29	0.29
	SD	1.15	1.15	0.96

neutral. For an actual sensation of “neutral”, they preferred a thermal sensation ranging from “slightly warmer” to “colder”. This result agrees with the study by Humphreys and Hancock [56], therefore in terms of the relationship between the TPV and the TSV, there is similarity between adults and children.

For both the FR and CL modes, the results were statistically significant ($p < 0.001$). A negative correlation was observed between these variables; i.e., users mostly preferred a thermal sensation diametrically opposed to the current one. For the actual thermal sensations “neutral”, “slightly warm” and “warm”, their preferred thermal sensations were respectively “neutral”, “slightly cool” and “cold”, and this tendency was more significant for the warmest area of the thermal sensation scale. These results indicate children’s preference for coolness in hot climates, both in the FR and CL modes. This preference is similar to that of adults, based on a previous study performed in Seville in office buildings [13].

3.3. Predicted mean vote and thermal sensation vote

To compare the thermal sensation (obtained based on the surveys collected) and the predicted mean vote (PMV), the evolution of the data were analysed considering the whole range of indoor operative

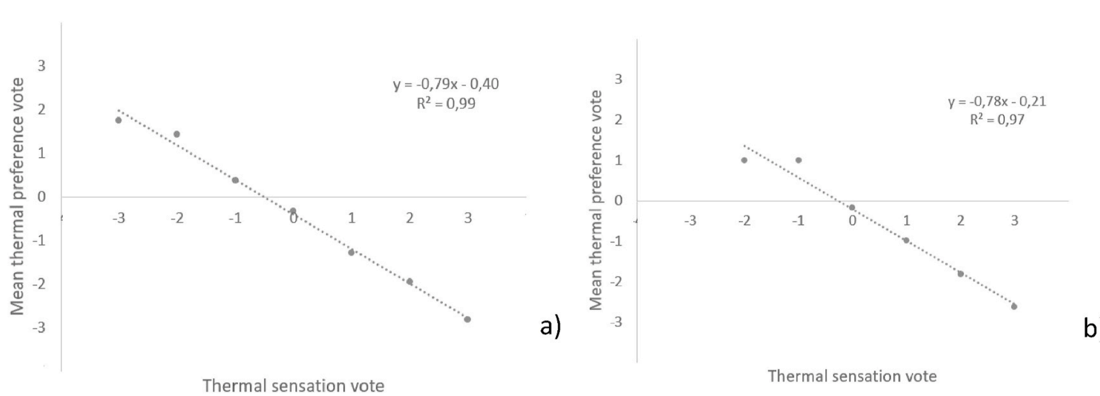

Fig. 4. Average thermal preference votes and thermal sensation votes for the FR mode (a) and CL mode (b).

temperatures. The data were analysed independently for indoor environments under the FR mode (Fig. 5-a) or the CL mode (Fig. 5-b) and intervals of 1 °C were defined for the operative temperature. The equations in the ISO 7730 Standard [15] were considered for calculating the PMV and the predicted percentage of dissatisfaction. The parameters for this calculation were estimated based on the variables monitored through the devices installed and the data collected through surveys. Given questions regarding the clothing that students were wearing during the sample period were included in the questionnaires, the clothing insulation for the estimation of the PMV was calculated based on these data collected.

Given there are differences between the metabolic rate of children and adults for the same activity level, the PMV was adjusted based on the study by Teli et al. [30], in which the value of 58.15 W/m^2 for the resting metabolic rate (RMR) of adults was corrected 48.8 W/m^2 for 10-year-old children. They demonstrated that this value is more suitable to predict the thermal sensation of pupils considering the PMV model; therefore, in the present work a value of 48.8 W/m^2 for the RMR was employed. Moreover, we selected a value of 1.2 met based on the standard ISO 7730 [15] and the type of activities in the classrooms analysed.

Analysing the FR mode, for the entire operative temperature range, the average PMV was much lower than the TSV, which shows that the PMV index does not adequately predict the thermal sensation [57]. The slope of the PMV linear regression line is lower than the slope of the TSV linear regression model, which indicates the PMV index assumes a greater sensitivity to indoor operative temperatures compared with the data collected. The PMV model underestimates the students' thermal sensation, given that for the whole range of indoor operative temperatures, the PMV predicted colder thermal sensations than the actual vote. Students are not as sensitive to changes in indoor temperature as the PMV predicts, and they easily adapt to heat environments. These differences between PMV values and TSV values ranged from 2 points for the lowest operative temperatures to 0.5 points for the highest operative temperatures. The underestimation of the PMV regarding the children's actual thermal sensation was previously concluded in other studies [3, 30,43].

For the CL mode, the results were similar, but the difference between the TSV and the PMV was less, ranging from 1 point for the lowest operative temperatures to 0.1 points for the highest operative temperature. Although a greater similarity between the average PMV and the average TSV was observed considering CL mode conditions, the PMV index was still not a good predictor for the actual TSV.

The linear regression considering the average TSV in the FR mode

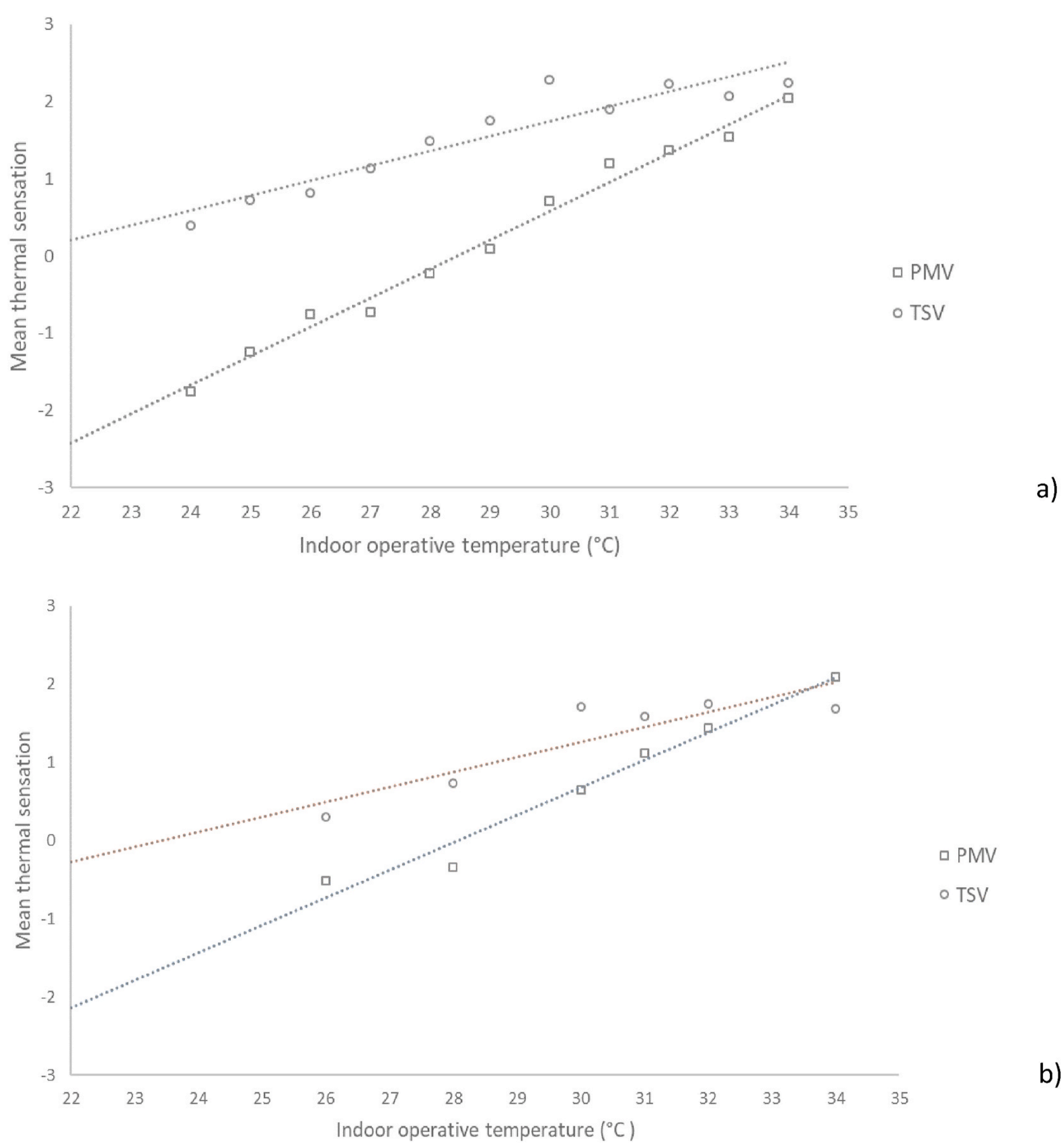

Fig. 5. Observed thermal sensation votes and predicted thermal sensation votes for the FR (a) and CL mode (b).

(Fig. 5-a) was 0.19x-4.07 ($R^2 = 0.88$) and for the PMV was 0.37x-10.68 ($R^2 = 0.99$), in which PMV and TSV were the dependent variable and the operative temperature were the independent variable. In the case of the CL mode (Fig. 5-b) it was 0.19x-4.49 ($R^2 = 0.79$) for the TSV and 0.32x-8.95 ($R^2 = 0.94$) for the PMV. The statistical significance of the results was tested for each operating mode ($p < 0.05$).

To further investigate the effect of the metabolic correction factor on the results, the PMV with a value of 58.15 W/m^2 for the RMR was also calculated (PMV_58.15). The linear regression considering the average PMV_58.15 was 0.31x-8.18 ($R^2 = 0.99$) for the FR mode and 0.29x-7.45 ($R^2 = 0.97$) for the CL mode. The statistical significance was also tested for both cases ($p < 0.05$).

Considering the FR mode and comparing the PMV and the PMV_58.15 models, a similar tendency was observed for the entire operative temperature range. A difference in the slope of both models was detected as well as a shift on the y-axis for the PMV_58.15 model with respect to the PMV model. The difference between them ranged between 0.2 points for the lowest operative temperature and 0.9 points for the highest operative temperature. Just as with the PMV model, the PMV_58.15 model predicted colder thermal sensations than the actual vote, which shows that the PMV_58.15 does not adequately predict thermal sensation; it assumes greater sensitivity to indoor operative temperatures compared with the data collected and underestimates the students' thermal sensation.

Similar results were obtained for the CL mode, given a difference in the slope of both models was detected as well as a shift on the y-axis for the PMV_58.15 model regarding the PMV model. The difference between them ranged between 0.2 points for the lowest operative temperature and 0.7 points for the highest operative temperature. Although a greater similarity was observed between the average PMV_58.15 and the average TSV, the PMV_58.15 is still not a good predictor for the actual mean vote.

3.4. Comfort and preferred temperature

The comfort temperature was calculated using Griffith's method, and the preferred temperature was obtained for analysing the difference between them.

3.4.1. Comfort temperature

To estimate the temperature at which the children felt comfortable, the comfort temperature ($T_{comfort}$) was calculated using the Griffith method (Eq. (1)), based on the globe temperature (T_g), the *TSV* and a standard value, the Griffith constant (*G*). A value of 0.5 was considered for the Griffith constant, based on previous studies in the literature [10, 58].

$$T_{comfort} = T_g - TSV/G \quad (1)$$

The comfort temperature for the FR mode was 24.5 °C (standard deviation 2.7 °C; 95% confidence limits were 24.3 °C and 24.6 °C), which is similar to that calculated in previous studies for naturally ventilated classrooms during a nonheating season. Regarding the CL mode, the comfort temperature was approximately 27.4 °C (SD = 3 °C; 95% confidence limits were at 27.1 °C and 27.7 °C).

3.4.2. Preferred temperature

The students' preferred temperature was also calculated for the FR mode and the CL mode, to compare it with their comfort temperature. To this end, a probit analysis was conducted for the TPVs and their corresponding indoor operative temperature. Given that the probit analysis is a dichotomous study, the TPVs were grouped considering preferences for cooler or warmer environments. The results are shown in Fig. 6, determining the intersection between the "cooler" preference curve (bold line) and the "warmer" preference curve the preferred temperature. The statistical tests indicated that the fitted models were significant for both modes ($p < 0.001$).

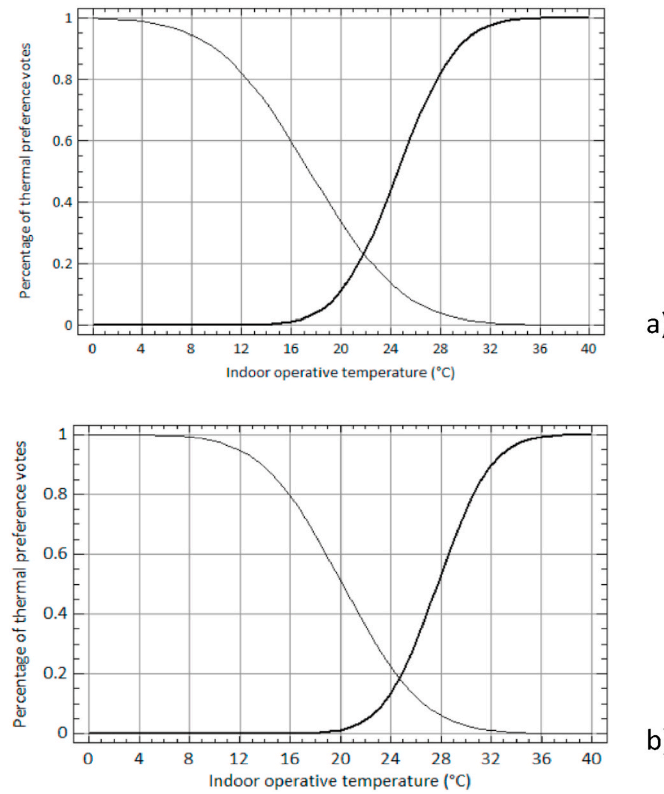

Fig. 6. Preferred temperature for the FR mode (a) and the CL mode (b).

Considering the FR mode (Fig. 6-a), a preferred temperature of 22 °C was calculated. This value was obtained in previous studies in the literature review for college students [8]. For CL environments (Fig. 6-b), the preferred temperature was 25 °C. The 95% confidence limits for the preferred temperature were 20 °C and 23 °C for the FR mode. For the CL mode, the 95% confidence limits for the preferred temperature were 20 °C and 26 °C.

The analysis of the comfort temperature and the preferred temperature showed a difference between them, with the comfort temperature approximately 2 °C higher than the preferred temperature. A similar degree difference between the thermal comfort temperature and the thermal preference temperature was identified in previous research in the literature [30,35,59], which reinforces the results we obtained.

The fact that the preferred temperature was lower than the comfort temperature in both types of environment indicates that, although there is a trend towards colder environments regarding the thermal preference of children, they have greater flexibility regarding indoor conditions [30]. Also, thermoneutrality might not always determine the optimal indoor temperature, which reinforces the results previously obtained by comparing the TSV and TPV votes.

3.5. Comparison of the comfort temperature with adaptive models

The comfort temperature based on the questionnaires collected during the sample period was compared with the EN 16798-1 Standard [17], the ASHRAE-55 Standard [16] and other previous thermal comfort field studies performed in schools.

3.5.1. Comparison with standards

Fig. 7 shows the evolution of the comfort temperature with the outdoor temperature (black line) and the comfort range of +2 K/-3 K (dashed line) based on the EN 16798-1 Standard. The outdoor temperature is represented in terms of the running mean temperature (T_{rm}),

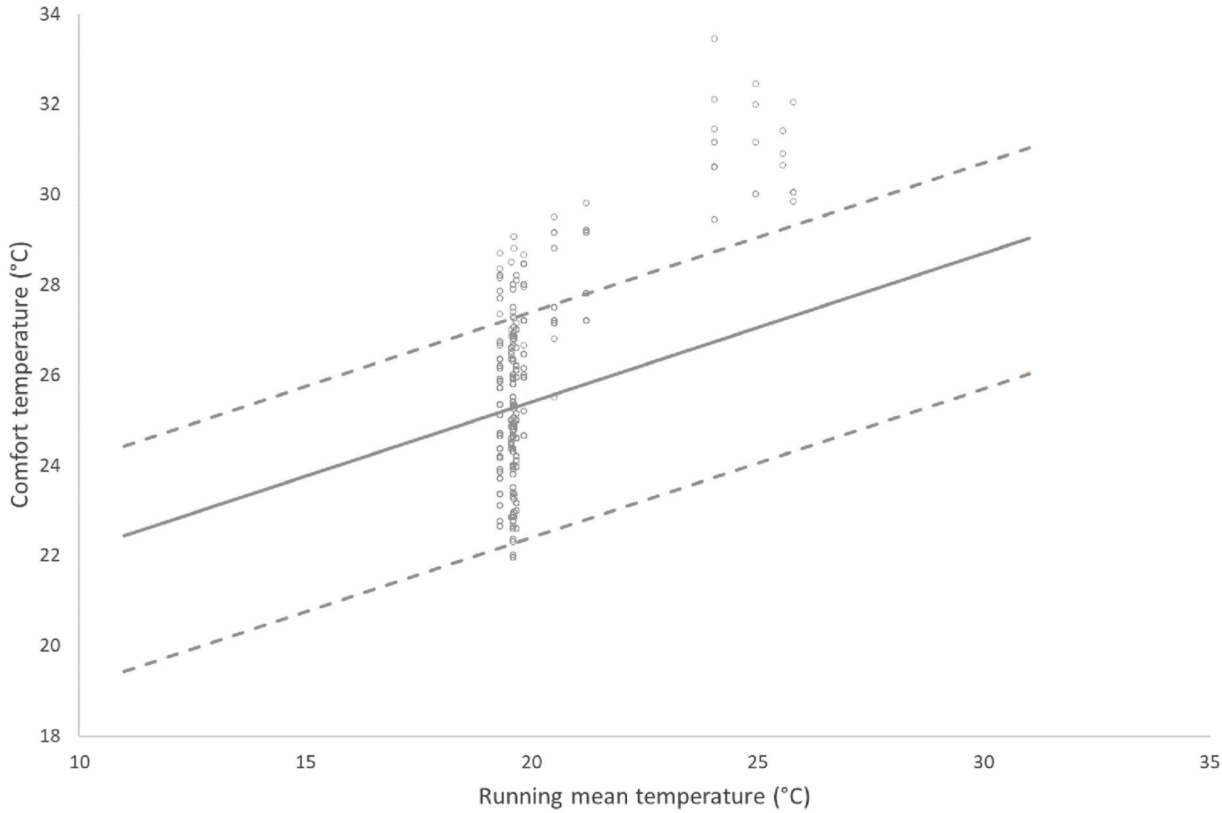

Fig. 7. Comparison of the present study and the EN 16798-1 Standard.

which exponentially weights the average daily outdoor temperatures (Eq. (2)) [17] based on the running mean temperature of the previous day ($T_{rm\ -1}$) and the average temperature of the previous day ($T_{od\ -1}$). The α is a constant that represents how the running mean temperature varies with the outdoor temperature, and it is usually equal to 0.8 [58].

$$T_{rm} = \alpha \cdot T_{od\ -1} + (1 - \alpha) \cdot [T_{rm\ -1}] \tag{2}$$

Similarly, the values of comfort temperature versus the running mean temperature for the present study (white solid dots) are shown in Fig. 7.

Given the sample period categorised in the present study was considered a summer season, the R squared obtained from the regression between the comfort temperature and the outdoor temperature was lower; however, there was a statistically significant relationship between both variables for the period considered ($p < 0.05$).

There are a significant number of values observed for the comfort temperature in the upper half of the comfort range defined by the EN 16798-1 Standard and outside it. This fact reveals the greater acceptability of heat by students, and that the application of current models for adults in nonresidential buildings would not be suitable for estimating the thermal comfort of children. Likewise, the broader range of thermal comfort for students should be noted, which shows a better adaptability to higher outdoor temperatures.

A comparison of the thermal comfort temperatures observed in the present study with the thermal comfort range as defined by the ASHRAE-55 Standard [16] was also performed. Most of the comfortable TSVs are grouped near the upper limit of the comfort range defined by the ASHRAE-55 Standard, which shows a greater acceptability of the indoor temperature for a certain outdoor temperature for students than for adults.

For classroom C, which was equipped with a backup HVAC system, the data collected were compared with the adaptive comfort equation for mixed-mode office buildings based on a field study performed in the city of Seville [13]. The results of this comparison were similar to those obtained when comparing with the EN 16798-1 Standard and the ASHRAE-55 Standard.

Based on the previous analysis, considering higher outdoor temperatures, we conclude that a significant percentage of students did not want a change in the indoor temperature or they wanted it to change slightly, given they were within their comfort range. This fact is especially evident in warmer areas in which students are able to easily adapt to a broader indoor temperature range during a nonheating season [21, 37,60] compared with adults and with indoor temperature variations [8].

Moreover, a widening in the thermal comfort range for children was observed compared with the thermal comfort range for adults; that is, children have a greater acceptability of indoor temperatures than adults do for a certain outdoor temperature.

3.5.2. Comparison with previous studies in schools

Due to the fact that the TSVs in a thermal comfort field study depend on the season, the climate or the thermal history of the participants, different neutral temperatures have been proposed in previous studies performed in school buildings. Therefore, we performed a comparative analysis regarding the comfort temperature proposed and that of previous research. We included studies presented in the literature that were similar to the present study in terms of season and the age of the participants.

Considering the FR mode, the comfort temperature obtained in the present study, 24.5 °C, is higher than that of studies from other European locations, such as the study by Teli [30] et al. during spring and summer (20.5–23 °C) or by Korsavi & Montazami [38] during a summer season (20.5 °C) in the UK with children aged 7–11 years. It is also slightly higher than that proposed by Trebilcock et al. in Chile [20] during a spring season (22.5–23.1 °C) with children between 9 and 11 years of age, and similar to the neutral temperature range proposed by Haddad et al. (23.2–24.4 °C) for a spring season [34] including participants aged 10–12 years.

Regarding the classroom with a HVAC system and in the air-conditioned operating mode, the comfort temperature agrees with the study by Noda et al. in Brazil [37].

3.6. Considering the clothing insulation, the level of activity and adaptive opportunities

3.6.1. Clothing insulation

The clothes people wear have a high correlation with indoor and outdoor temperatures and is an important factor for achieving thermal comfort. In the present study, clothing insulation (clo) level data were collected through questionnaires.

Fig. 8 shows the variation of the clothing insulation. Most of the clo levels were concentrated in the range between 0.29 and 0.32, with the mean clothing insulation approximately 0.3 for the summer season considering FR conditions as well as CL conditions. These values are similar to a previous study performed in a school in Spain [44], in which it was concluded that the clo level was 0.34 for boys and 0.32 for girls.

To investigate clothing behaviour, the evolution of clo with regard to the outdoor temperature was analysed based on the previous work by Kim and de Dear [21]. Fig. 9 shows the mean value of the clothing level and ± 1 standard deviation for the running mean temperature and the average daily outdoor temperature under the FR and CL modes.

The mean value of the clothing insulation and its standard deviation were similar to those obtained by Kim and de Dear [21] for the range of outdoor temperatures considered in the present study and the FR operating mode. Actually, the average value of the clothing insulation level was slightly lower in the present study than in the study by Kim and de Dear [21], mainly due to the climate in Seville.

The results show that the adaptation behaviour regarding the clo in a summer season with warmer outdoor temperatures is less than in a winter season. Moreover, the clo level decreases in both FR and cooled environments as the outdoor temperature increases and that such a reduction is more significant in naturally ventilated environments than in spaces with a HVAC system.

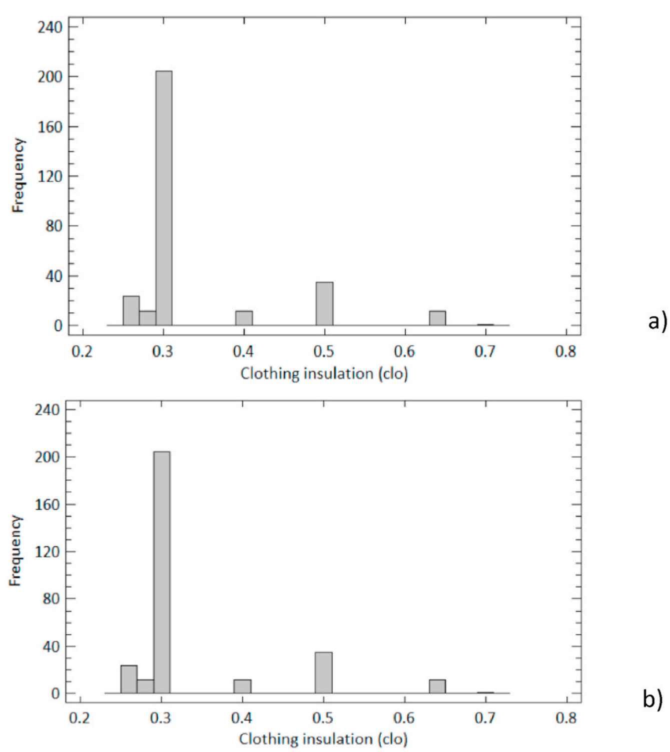

Fig. 8. Clothing insulation considering the FR (a) and the CL (b) mode.

3.6.2. Level of activity

During the field study, the students' level of activity was collected through questionnaires. Fig. 10 shows this distribution in term of percentages, for both the FR mode (Fig. 10-a) and the CL mode (Fig. 10-b), according to whether the surveys were completed during the morning or during the afternoon. In both cases, most of the answers were concentrated in the 3 central categories: the FR mode was concentrated between "good" and "active" and the CL mode concentrated between "tired" and "good". For the FR operating mode, during the morning, the level of activity increased towards "active"; however, during the afternoon, it increased towards "tired". In the CL mode, the percentages of the activity level were similar during both the morning and the afternoon.

Due to the extreme outdoor temperatures that occur in summer, with gradient differences higher than 10 °C with respect to the interior, students experience a sudden variation regarding the temperature and physiological conditions, which causes greater fatigue in CL mode compared with that produced in FR mode. In this sense, for HVAC spaces, a gradual change would be recommended when going from FR mode to CL mode when entering the classroom, which could help prevent the high numbers of tired and very tired students.

To further investigate the students' level of activity, a logistic regression analysis was performed to analyse its evolution with the average daily outdoor temperature. For the FR mode, an increasing percentage can be observed for the levels of activity "tired" and "very tired" with the outdoor temperature, whereas this percentage decreases for the "active" level of activity (Fig. 11). All logistic models depicted in Fig. 11 were statistically significant ($p < 0.001$). No significant results were found for the conditioning mode.

The majority of the students had a level of activity ranging from "good" to "very active". Moreover, a relationship can be observed between the students' level of activity and the average daily outdoor temperature, mainly based on the time of day (morning or afternoon).

3.6.3. Adaptive strategies during the field study

During the survey, various thermal adaptive strategies were investigated based on the questionnaires, which included opening windows and doors, adjusting blinds, turning on/off fans and turning on/off the light. Fig. 12 shows the percentage distribution of such adaptive opportunities, distinguishing the time they took place (morning or afternoon).

In FR classrooms we observed a preference for opening the windows and opening the doors as adaptive strategies, more than the use of fans, which were mainly turned on in the afternoon.

Fig. 13 shows the participants' preference for adaptive actions to feel more comfortable. Once again, the use of windows predominates, and in FR classrooms there is a preference for having and using a HVAC system over the use of a fan.

Logistic regression analysis is commonly adopted in thermal comfort research for predicting the preference for adaptive opportunities in naturally ventilated environments [61]. Therefore, a logistic regression analysis was performed to analyse the evolution of these preferences regarding the outdoor temperature at the time the surveys were completed (Thour). Fig. 14 illustrates the logistic models that achieved a significance level ($p < 0.01$). A tendency towards opening windows as an adaptive strategy was mainly observed for lower outdoor temperatures, decreasing for higher temperatures. Regarding the use of a HVAC system versus the use of fans, the former prevailed, which followed a pronounced upward trend from an outdoor temperature of 25 °C.

4. Conclusions

This paper examines the results of a thermal comfort field study performed in 3 classrooms, 2 FR and 1 provided with a HVAC system, of a school in Seville, Spain, during a summer season. The results are based on indoor and outdoor environmental measures and thermal comfort

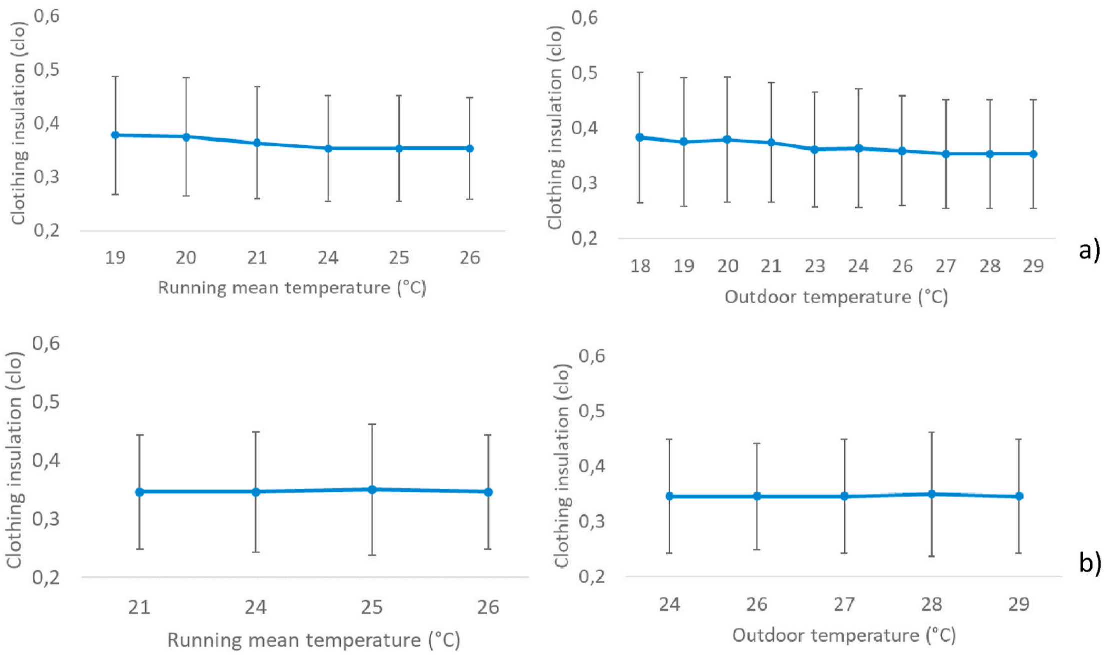

Fig. 9. Clothing insulation regarding the running mean temperature and the mean daily outdoor temperature for the FR (a) and the CL (b) mode.

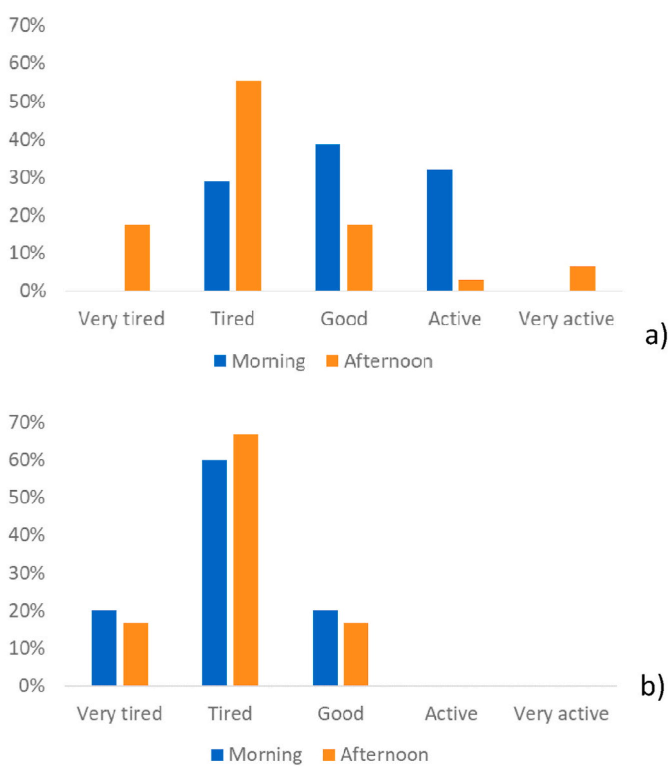

Fig. 10. Students' level of activity for the FR (a) and the CL mode (b).

questionnaires collected during 21 days. The main conclusions are as follows:

1) According to the TSVs, most children were comfortable, in both FR and CL environments.
2) Although the most desired sensation was "neutral", thermoneutrality was not always the desired sensation for children, which agrees with the results obtained for adults. A negative correlation between thermal sensation and thermal preference votes was observed, which

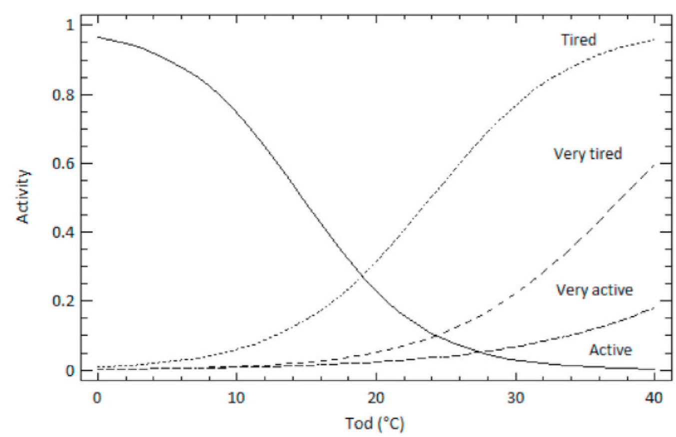

Fig. 11. Students' level of activity and the daily outdoor temperature.

shows children's preference for coolness in hot climates in both FR and CL modes. It also agrees with previous studies considering adults in the same location.

3) The PMV index is not a good predictor of children's actual TSV, either for the FR or the CL mode, given it underestimates the students' thermal sensation. For the entire operative temperature range and both the FR and CL modes, the average PMV was much lower than the TSV, and this deviation was more significant for naturally ventilated environments.
4) The mean comfort temperature was approximately 24 °C for the FR mode and 27 °C for the CL mode, based on the Griffith method. The proposed comfort temperature is higher than that calculated for students of the same age range from other European countries. The preferred temperature was lower than the comfort temperature in both cases.
5) The current models for adults in nonresidential buildings would not be suitable for estimating the thermal comfort of children. Compared with EN 16798–1 and the ASHRAE-55 Standard, a widening in the thermal comfort range for children was observed in the present study. The same tendency was observed compared with a previous study performed in Seville in office buildings. A greater similarity

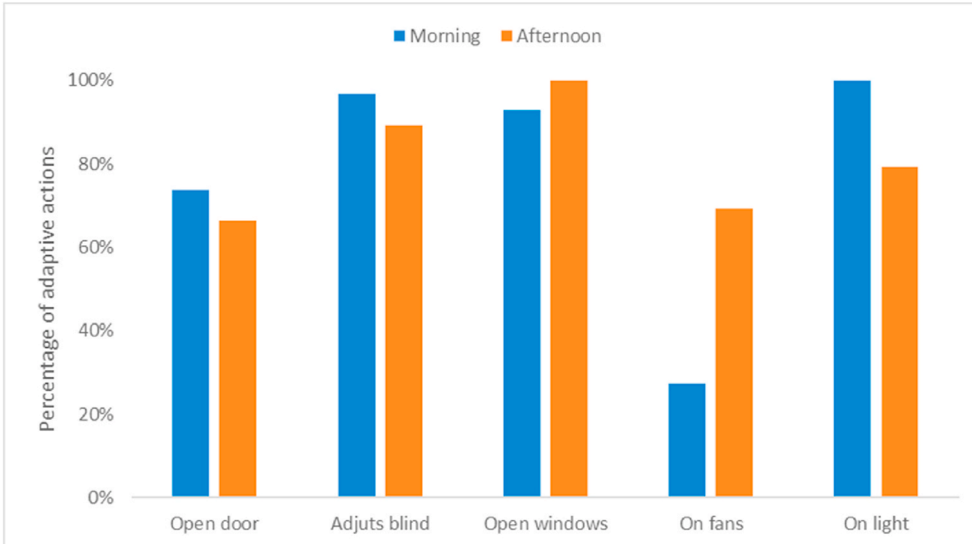

Fig. 12. Distribution of thermal adaptive strategies (morning and afternoon).

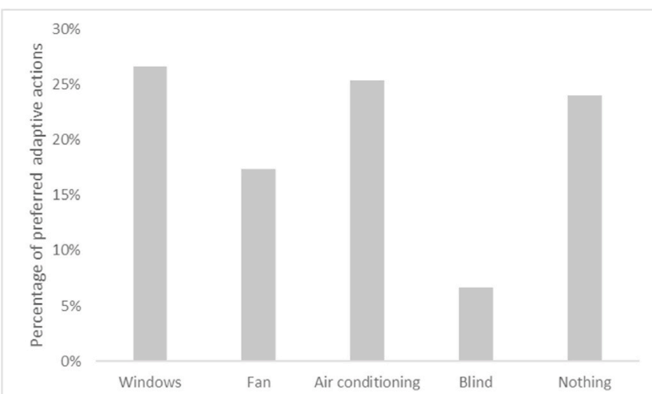

Fig. 13. Distribution of preferred thermal adaptive strategies.

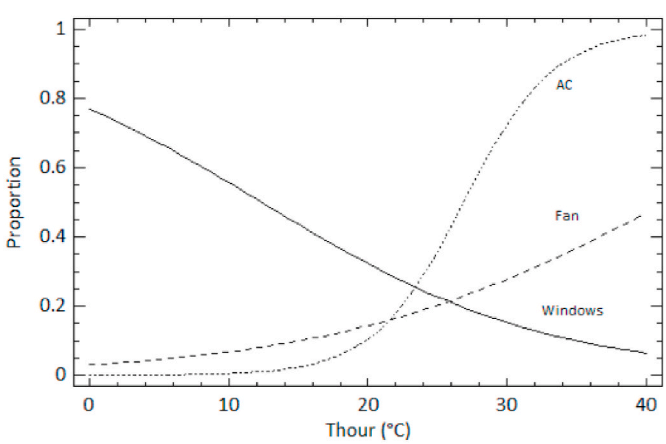

Fig. 14. Logistic analysis of preferred thermal adaptive strategies.

was detected with previous studies in school buildings in the literature.

6) Adaptive behaviour regarding the clo level in a summer season with warmer outdoor temperatures is less than in a winter season. The clo level decreased in both the FR and cooled environments as the outdoor temperature increased. Such reduction is more significant for the former situation.
7) The students' level of activity was categorised based on the time of day the corresponding survey was completed; generally, higher percentages were detected during the morning than during the afternoon for the "good", "active" and "very active" levels of activity. Based on the logistic regression analysis performed, an increasing percentage was observed for the "tired" and "very tired" levels of activity with the outdoor temperature. A relationship was detected between the students' level of activity and the average daily outdoor temperature, and mainly with the time of day (morning or afternoon), given the results show that higher average daily outdoor temperatures, especially during the second part of the day, influenced children's activity levels.
8) In naturally ventilated environments, there was a preference towards opening windows and doors as adaptive strategies compared with the use of fans, and this preference decreased along with the outdoor temperature. Of all methods, schools indicated a preference for using HVAC systems.

The study shows that the majority of students felt comfortable with FR indoor thermal environments and that this percentage was similar in cooled environments. Moreover, the results reinforce the idea of extending the investigation of thermal comfort in schools, given the differences in thermal comfort detected between children and adults.

The present paper focused on a summer season; therefore, further studies are needed, considering a winter season as well as widening the age range of the participants.

After this study was completed, a passive solution was applied to improve the roof insulation in the building. An active solution could be applied in terms of night ventilation, which is a very effective strategy in hot climates, and it can also provide effective cooling that is not usually applied in schools.

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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