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Evaluating the effect of passive cooling strategies in school buildings on children's well-being in Barcelona: A quasi-experimental, mixed methods study

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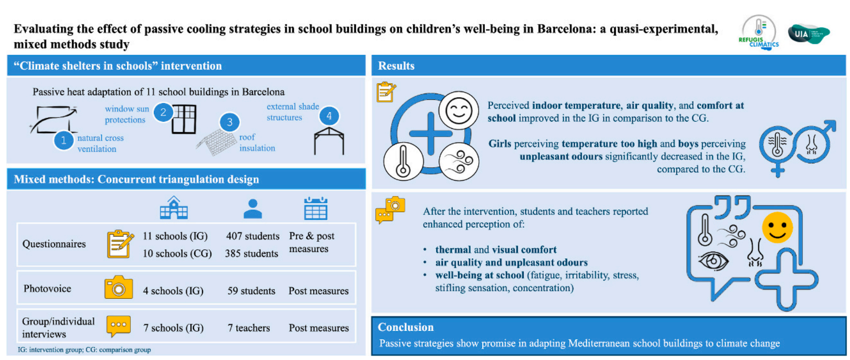
HIGHLIGHTS

- Satisfaction with temperature and air quality increased after the intervention.
- Girls perceiving school temperature too high decreased after the intervention.
- Solar protections on windows seem to reduce glare while reducing perceived heat.
- Passive cooling enhanced reported comfort and concentration and reduced reported fatigue and stress.
- There is a need to expand passive cooling strategies to other school buildings.

GRAPHICAL ABSTRACT



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ABSTRACT

Passive cooling strategies were implemented in 11 school buildings in Barcelona within a pilot project to improve thermal conditions. The present study aimed to evaluate the intervention's impact on students' comfort and well-being at school. A quasi-experimental pre-post study based on mixed methods was conducted. Quantitative data were collected through self-reported questionnaires administrated to sixth-grade students in 21 schools (11 in an intervention group, IG, and 10 in a comparison group, CG). The authors measured changes in satisfaction with indoor temperature and indoor air quality (IAQ), the presence of bothering factors (temperature too high, temperature too low, unpleasant odours, and lighting problems), and students' well-being and performance. Difference-in-difference analysis was conducted to evaluate differences between the IG and CG in pre-post changes. Qualitative data were collected through photovoice-based sessions (59 sixth grade students) and interviews (7 teachers) in the IG. A thematic content analysis identified three main categories: changes in

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perceptions of indoor environmental conditions, indoor environment-related health and well-being, and indoor environment and their reported impact on learning. Quantitative findings show positive changes among the IG in perceived indoor temperature, air quality, and well-being at school, while suggest no significant changes in perceptions of temperature too low, lighting problems, and students' performance, in relation to the CG. Compared to the CG, students in the IG perceiving temperature too high significantly decreased among girls, while unpleasant odours decreased only among boys. In the qualitative assessment, participants reported that school transformations improved their indoor thermal and visual comfort, IAQ, and unpleasant odours. Participants also reported a reduction of fatigue, stress, irritability, and stifling sensation, as well as enhanced concentration. This study highlights the benefits of school passive design for student's comfort and well-being in Mediterranean climates and suggests the need to extend these interventions to other school buildings in similar contexts.

1. Introduction

Schools in southern Europe are experiencing poor indoor thermal conditions due to inadequate ventilation and building's insulation (Alegría-Sala et al., 2022; Almeida and De Freitas, 2014; De Giuli et al., 2012; Sánchez-Torija et al., 2022; Zinzi et al., 2021; Zomorodian et al., 2016). Moreover, children are more susceptible to higher temperatures and need cooler environments than adults (Fang et al., 2023; Sadrizadeh et al., 2022; Zomorodian et al., 2016). The situation in Barcelona is especially concerning due to its high urban density, its Mediterranean climate with hot summers, and its old and poorly insulated school buildings.

In the city of Barcelona, educational community members are already calling for immediate action to mitigate the problem of heat in classrooms (Rius, 2022). However, the issue extends beyond thermal comfort, as schools also face challenges in terms of their indoor air quality (IAQ) (Rivas et al., 2014). Increased room temperature and poor IAQ have been linked to headache, fatigue, breathing and thinking difficulties, as well as ocular, nasal and throat symptoms (Fang et al., 2004; Norbäck and Nordström, 2008; Roulet et al., 2006). Previous research has confirmed that students' well-being and academic performance can be affected by environmental conditions inside school buildings (Bakó-Biró et al., 2012; Bidassey-Manilal et al., 2016; Bluyssen, 2017; Fang et al., 2023; Mazon, 2014; Savelieva et al., 2019; Vilčeková et al., 2023; Wargocki and Wyon, 2013).

As climate change intensifies, temperatures are expected to continue to rise, which will make it increasingly challenging to keep classrooms cool and comfortable and to ensure students' health, well-being, and performance (Heracleous and Michael, 2018; Heracleous et al., 2021). To tackle this issue, in 2020, the Barcelona City Council implemented a pilot project "Climate shelters in schools" with the support of the European initiative, Urban Innovative Actions (Ajuntament de Barcelona, 2020; Plazas et al., 2023). 11 primary schools in Barcelona, distributed across all city districts, were adapted with the aim of improving thermal comfort, especially during hot periods. Various passive cooling strategies were incorporated to improve indoor thermal conditions. These measures included natural cross ventilation strategies, sun protection on windows, roof insulation, and external shading structures to provide shade inside the classrooms. All transformations were made after a co-creation process with the school community and different measures were implemented in each school based on their needs and building's characteristics.

As suggested by previous literature, providing shade, building insulation, and increasing ventilation can potentially improve school's indoor thermal comfort (Díaz-López et al., 2022b; Heracleous et al., 2021; Zinzi et al., 2021), and may also help to enhance IAQ and visual comfort (Balador et al., 2017.; Díaz-López et al., 2022a, 2022b; Nikolaou and Meresi, 2021). Passive actions can also improve the energy efficiency of the school building (Berardi et al., 2017; Díaz-López et al., 2022b; Gil-Baez et al., 2017, 2019), while providing a healthier indoor environment compared with active measures such as air conditioning (Roulet et al., 2006; Seppänen and Fisk, 2002).

In recent years, numerous initiatives have emerged to promote energy saving in school buildings while improving indoor thermal conditions (Berardi et al., 2017; Desideri et al., 2012; Gaitani et al., 2015; RENEWSCHOOL project, n.d.; *School of the Future*, n.d.; School Vent Cool, n.d.). Yet, research has mainly focused on evaluating the potential effect of implementing retrofitting measures in school buildings using simulation-based methodologies rather than assessing the real-case impact (Baba et al., 2023; Berardi et al., 2017; Desideri et al., 2012; Gaitani et al., 2015; Grassie et al., 2022; Zahiri and Altan, 2016). Besides, limited research has evaluated the effect of this type of interventions focusing on the adaptation of school buildings to climate change, assessing different aspects of student's comfort and health, and including the participation of the educational community (Díaz-López et al., 2022b). This study presents an opportunity to explore the benefits and potential limitations of this kind of intervention in a large southern European city. The authors evaluated the effectiveness of passive cooling interventions implemented in Barcelona school buildings in improving students' indoor thermal comfort and well-being at school, using a mixed-method approach.

2. Materials and methods

This quasi-experimental pre-post study was based on mixed methods. The study is part of a broader evaluation of the project "Climate shelters in schools" (Sanz-Mas et al., 2024).

The study population consisted of sixth grade students (11- and 12-year-old schoolchildren) and teachers from 21 public primary schools in Barcelona (Spain). All 11 schools undergoing the intervention were included in the intervention group (IG). These schools were selected by the Barcelona City Council due to their higher climate change vulnerability criteria, as well as to ensure representation of all districts in the city. For school selection, a vulnerability score was developed based on 4 dimensions: potential impact, school environment, school building, and schoolyard. The study included a comparison group (CG) consisting of 10 primary schools in Barcelona with similar characteristics to the IG in terms of the eligibility criteria, but which did not undergo the intervention. Further details on school selection and the vulnerability score can be found elsewhere (Sanz-Mas et al., 2024). Data collection took place in November 2020 (quantitative data) and May 2021 (quantitative and qualitative data), after the implementation of the intervention (July–August 2020). Supplementary file Fig. S1 illustrates the data collection timeline, the methods used in the study, and the samples selected for each technique. The authors followed a concurrent triangulation design (Bryman, 2006; Creswell and Clark, 2017) by analysing quantitative and qualitative data independently and subsequently converging the results.

2.1. Quantitative evaluation

An online questionnaire was administered to a sample of sixth-grade students from the 21 primary schools included in the study (IG: 11; CG: 10) at two different time points after the implementation of the intervention: November 2020 and May 2021. All sixth-grade students from the 21 primary schools ($N = 1018$) were selected to participate in the quantitative evaluation and the questionnaire was administered to 851 students (IG: 447, CG: 404). Most non-responses were due to lack of parental consent or student absence on the administration day. Finally, 792 students (IG: 407; CG: 385) who completed both the first and second assessments were included in the study.

The schools were closed between March and June 2020, just before the intervention, due to the COVID-19 pandemic. Therefore, in the first assessment (November 2020), pre-intervention data was collected by including retrospective questions that referred to the period prior to the COVID-19 lockdown, while post-intervention measures were obtained in the second assessment (May 2021). The IG included those students who had participated in the co-creation process of school transformation.

The authors designed a self-reported questionnaire to assess the effect of the interventions on students' perception of each school's indoor environmental conditions and their well-being. Questions from the validated "MM 060 School" questionnaire (Andersson, 1998) were used. For instance, the authors assessed satisfaction with the school's indoor temperature ("*Considering the indoor area of the school, what do you think of the temperature in the school in general?*"), and with classroom IAQ ("*What do you think of the air quality in the classrooms in general, considering air cleanliness, ability to breathe properly, the presence of unpleasant smells?*"), recategorized as "very good/good" and "acceptable/poor/very poor". The authors also gathered a list of some potential bothersome indoor climate factors included in the MM060 questionnaire (temperature is too high, temperature is too low, there is an unpleasant odour, there are lighting problems) and asked students to report how often these factors bothered them at the school (yes, often/yes, sometimes/no, never). Students' well-being and performance were also analysed by including the questions "*Do you feel comfortable at school?*" and "*Do you think the indoor climate affects your school performance?*" (yes, often/yes, sometimes/no, never). These variables were dichotomized into "often" vs. "sometimes or never" (Andersson, 1998).

In the first assessment, the authors also asked students about their sex (girl or boy), age, family socioeconomic position (SEP), migration trajectory (native child with native-born parents; native child with foreign-born parents; foreign-born child), and family structure (single parent; two-parent; stepparent; others, Currie et al., 2014). Family SEP was measured using the family affluence scale (FAS) III tool and was categorised as "low" (<7), "medium" (7–9) and "high" (>9) (Moreno et al., 2019; Torsheim et al., 2016). The study also included the school neighbourhood SEP obtained from the territorial distribution of available family income per capita in Barcelona in 2017 (Ajuntament de Barcelona, 2017).

2.1.1. Data analysis

A descriptive analysis of the sociodemographic and socioeconomic variables was performed and potential differences between the IG and CG were assessed using the chi-square or Fisher exact tests (categorical variables) and the *t*-test (continuous variables). Percentages (categorical) and means (continuous) of the study outcome variables were estimated for pre- and post-measurements. These variables were compared at baseline using the chi-square test. The McNemar test was used to estimate pre-post changes within groups. A difference-in-difference analysis was performed for each study outcome by analysing the differences between the IG and CG in pre-post changes. To do this, multilevel mixed-effects logistic regression models were built including the interaction term between intervention status (IG/CG) and period (pre/post). To account for multilevel, hierarchical data structure (students nested within schools), random effects for both individuals and schools were included in the models. The analyses were stratified by sex and adjusted for the schools' neighbourhood SEP. From these models, estimates of average adjusted predictions with random intercepts were conducted to subsequently estimate the average marginal effects for each outcome (Williams, 2012). This allowed us to calculate the real effect of the intervention. Data analysis was performed through the statistical package STATA 15.1 (*StataCorp LLC., USA*).

2.2. Qualitative evaluation

On the basis of photovoice methodology (Wang and Burris, 1997), the authors evaluated students' perception of the school buildings' transformations. From the IG, a subsample of four schools was selected by ensuring variability in the schools' neighbourhood SEP and heterogeneity in the set of measures implemented. Following a convenience sampling process, 59 students out of 170 were selected considering their availability, willingness, and motivation to participate. For each school, groups were created ensuring gender diversity and the inclusion of students with different groups of friends. There were four groups in total (one per school), with 10, 12, 12, and 25 students in each group. The percentage of girls in the groups ranged from 30 % to 58 %.

The authors conducted post-intervention (May–June 2021) photovoice-based sessions (Wang and Burris, 1997) in each school that lasted between 60 and 90 min. Research members explained the technique, camera operation and study aim in the first session, asking students to use digital cameras in groups of two or three to capture the most and least useful interventions in terms of adapting their school to climate change. Photos were taken outside the sessions, with 15 days to complete the task. In the second session and following an adaptation of the SHOWED method (Strack et al., 2004), students presented their thoughts and reflections on two of their photos to the group. The group selected the pictures that best represented their opinions.

The authors also conducted semi-structured interviews among the teachers involved in the co-creation process and other stages of the project. One teacher per school (11 IG schools) was invited to participate in online group interviews (90 min). Five of them (4 women and 1 man) attended the meeting and were interviewed as a group by a moderator assisted by an observer. Two other teachers (2 women) were interviewed individually through video or phone calls. The interviewers followed a semi-structured guide that included topics related to the intervention's impact, such as changes in children's thermal comfort at school as well as in their well-being. Four teachers could not participate in the evaluation due to high workload and lack of time.

2.2.1. Data analysis

Photovoice sessions (students) and interviews (teachers) were audio-recorded and transcribed, complemented with the students' photographs and observers' field notes. The authors performed a thematic content analysis. Common codes and topics related to the focus of the study were identified in participants' discourse. Subsequently, the codes were grouped into categories, reaching a consensus by all members of the research team. Three main categories were created: (a) changes in perceptions of indoor environmental conditions; (b) changes in indoor environment-related health and well-being; (c) changes in indoor environment and their reported impact on learning.

3. Results

3.1. Quantitative evaluation

Table 1 describes the sociodemographic characteristics of the students included in the study. In the IG, 44.7 % of the students were girls (48 % in the CG), the children's average age was 11.3 years (11.4 years in the CG), and 67.1 % had medium or high family SEP (71.7 % in the CG). No statistically significant differences were found between groups in sex, age, family SEP, migration trajectory, or family structure. The percentage of students from schools in low-SEP neighbourhoods was higher in the IG than in the CG (30 % vs 5.2 %, $p < 0.001$).

Table 2 shows IG and CG students' perceptions of their schools' indoor environmental conditions and their well-being before and after the intervention, stratified by sex. There were no significant differences between the IG and CG in baseline measurements for most of the

Table 1
Characteristics of the participants completing the questionnaires. Barcelona, 2020–2021.

	IG ($N = 407$)	CG ($N = 385$)	p-Value[1]
	n (%)	n (%)	
Student characteristics			
Sex			
Girl	182 (44.7)	185 (48.0)	0.347
Boy	225 (55.3)	200 (52.0)	
Age (years)			
Age [mean (SD)]	11.3 (0.5)	11.4 (0.5)	0.246
Family characteristics			
Family SEP (family affluence scale)			
Low	134 (32.9)	109 (28.3)	0.319
Medium	189 (46.5)	185 (48.1)	
High	84 (20.6)	91 (23.6)	
Migration trajectory			
Native child with native-born parents	210 (52.6)	218 (58.6)	0.247
Native child with foreign-born parents	145 (36.4)	119 (32.0)	
Foreign-born child	44 (11.0)	35 (9.4)	
Family structure			
Single parent	87 (21.4)	70 (18.2)	0.470[2]
Two-parent	282 (69.3)	284 (74.0)	
Stepparent	32 (7.8)	27 (7.0)	
Others	6 (1.5)	3 (0.8)	
School characteristics			
Neighbourhood SEP			
Low	122 (30.0)	20 (5.2)	**<0.001**
Medium	260 (63.9)	292 (75.8)	
High	25 (6.1)	73 (19.0)	

CG: comparison group; IG: intervention group; SD: standard deviation; SEP: socioeconomic position.
Note: Missing values <5 %.
[1] χ^2-square test (categorical variables)/*t*-test (continuous variables). Bold = p-value <0.05.
[2] Fisher's exact test.

Table 2
Students' perceptions of their school's indoor environmental conditions before and after the intervention for the intervention and comparison groups, by sex. Barcelona, 2020–2021.

Girls	IG ($N = 182$)			CG ($N = 185$)			GI vs GC (pre)
	Pre (%)[1]	Post (%)[1]	p-Value[2]	Pre (%)[1]	Post (%)[1]	p-Value[2]	p-Value[3]
Satisfaction with indoor conditions							
Temperature $_{(very\ good/good)}$	51.5	76.5	**<0.001**	74.0	51.6	**<0.001**	**<0.001**
IAQ $_{(very\ good/good)}$	72.1	81.0	**0.027**	81.6	70.0	**0.006**	**0.006**
Bothersome indoor climate factors							
Temperature too high $_{(often)}$	20.0	11.7	**0.016**	17.6	19.9	0.555	0.116
Temperature too low $_{(often)}$	7.7	4.8	0.201	4.1	5.4	0.637	0.118
Unpleasant odour $_{(often)}$	5.0	3.5	0.405	4.9	4.9	1.000	0.595
Lighting problems $_{(often)}$	12.0	7.4	0.068	10.3	8.5	0.549	0.217
Comfortable at school $_{(often)}$	60.5	66.7	0.140	70.6	54.7	**<0.001**	**0.005**
School performance affected by indoor climate $_{(often)}$	11.2	9.1	0.480	9.5	9.5	1.000	0.272

Boys	IG ($N = 225$)			CG ($N = 200$)			GI vs GC (pre)
	Pre (%)[1]	Post (%)[1]	p-Value[2]	Pre (%)[1]	Post (%)[1]	p-Value[2]	p-Value[3]
Satisfaction with indoor conditions							
Temperature $_{(very\ good/good)}$	61.0	69.6	**0.046**	67.4	56.7	**0.018**	0.091
IAQ $_{(very\ good/good)}$	69.7	78.0	**0.031**	76.0	68.3	0.055	0.132
Bothersome indoor climate factors							
Temperature too high $_{(often)}$	27.2	18.0	**0.015**	25.4	24.4	0.806	0.404
Temperature too low $_{(often)}$	8.9	9.4	0.866	7.9	6.0	0.414	0.984
Unpleasant odour $_{(often)}$	13.3	8.3	0.078	6.3	9.2	0.239	**0.028**
Lighting problems $_{(often)}$	13.6	10.0	0.258	8.7	10.6	0.480	0.159
Comfortable at school $_{(often)}$	61.5	62.8	0.683	62.2	48.8	**0.002**	0.690
School performance affected by indoor climate $_{(often)}$	14.4	10.7	0.258	9.0	12.0	0.330	0.089

CG: Comparison group; IAQ: indoor air quality; IG: intervention group; pre: pre-intervention measures (November 2020); post: post-intervention measures (May 2021).
[1] Percentages estimated through average adjusted predictions with random intercepts (adjusted by SEP of school's neighbourhood).
[2] McNemar test: comparison between pre- and post-measures within groups. Bold = p-value <0.05.
[3] χ^2-square test: percentage comparison of pre-measures between IG and CG. Bold = p-value <0.05.

variable studied. However, before the intervention, girls in the IG had significantly worse perceptions of the indoor temperature (*p*-value <0.001) and IAQ (p-value = 0.006) than those in the CG. Girls in the IG often felt less comfortable at school than those in the CG (p-value = 0.005). More boys in the IG were bothered by unpleasant indoor odours in comparison with the CG (p-value = 0.028). After the intervention, satisfaction with indoor temperatures and IAQ significantly increased among girls in the IG (temperature: 51.5 % to 76.5; IAQ: 72.1 % to 81 %) and similar results were found for IG boys (temperature: 61 % to 69.6 %; IAQ: 69.7 % to 78 %). Satisfaction significantly worsened among girls in the CG in terms of temperature (74 % to 51.6 %) and IAQ (81.6 % to 70 %), while satisfaction with temperature significantly decreased in CG boys (67.4 % to 56.7 %) but did not show a significant difference for IAQ ($p = 0.055$). Likewise, the percentage of boys and girls reporting that indoor temperatures were too high decreased only in the IG (girls: 20 % to 11.7 %; boys: 27.2 % to 18 %). For both sexes, comfort at school significantly decreased in the CG (girls: 70.6 % to 54.7 %; boys: 62.2 % to 48.8 %) but not in the IG.

Table 3 shows a comparison of pre-post intervention changes between the IG and CG. Differences-in-differences analyses revealed a positive impact of the intervention on some of the variables studied. The percentage of students positively perceiving the indoor temperature increased by 47.4 % (95 % CI: 35.4 % to 59.4 %) among girls and by 19.3 % (95 % CI: 7.2 % to 31.4 %) among boys in the IG compared with the CG. The trend was similar for IAQ (girls: 20.5 %, 95 % CI 9.2 % to 31.7 %; boys: 16.0 %, 95 % CI 5.2 % to 26.9 %). The percentage of students bothered by high indoor temperatures decreased in the IG compared with the CG, with this difference being statistically significant in girls (−10.6 %, 95 % CI: −20.8 % to −0.4 %). Boys reporting unpleasant odours decreased by 8 % (95 % CI: −15.4 % to −0.5 %) in the IG after the intervention compared with the CG, whereas no differences were found in girls. In comparison with the CG, the percentage of students in the IG reporting they were comfortable at school increased by 22.1 % (95 % CI: 9.9 % to 34.4 %) in girls, and by 14.7 % (95 % CI: 2.9 % to 26.6 %) in boys.

3.2. Qualitative evaluation

Table 4 shows the list of categories, codes, and examples of quotes.

3.2.1. Changes in perception of indoor environmental conditions

Students and teachers highlighted that the interventions helped to improve thermal comfort inside the school, especially by reducing overheating in the hottest months but also by improving comfort in winter. They attributed heat reduction to the provision of shade in the classroom by sun protection on windows and external shading structures, thermal insulation of the roof, and the increase in fresh air due to solutions that allowed and improved natural cross ventilation. The latter was particularly appreciated by teachers. Teachers also noted an improvement in IAQ and a reduction in unpleasant odours due to better ventilation. Students identified sun protection on windows as a measure that enhanced visual comfort in the classroom. The provision of shade allowed them to have access to natural sunlight without being disturbed by the sun's glare. As a negative aspect, participants highlighted that in some cases the interventions were not implemented in all school facilities and some areas therefore remained hot.

3.2.2. Changes in indoor environment-related health and well-being

According to the students, sun protection on windows reduced stifling sensation inside the school and decreased their stress levels at school by providing shade and reducing the perception of heat. Teachers also highlighted that building improvements such as insulation helped children to feel less fatigued and irritable due to the increase in thermal comfort. Students reported that sun protection on windows also reduced lighting problems (i.e., sun glare) that bothered them during classroom activities.

Table 3
Percentage changes between pre- and post-intervention in the IG and CG regarding students' perceptions of their schools' indoor environmental conditions, and difference-in-difference between IG and CG. Barcelona, 2020–2021.

	Girls						Boys					
	IG (N = 182)		CG (N = 185)		Diff-in-Diff		IG (N = 225)		CG (N = 200)		Diff-in-Diff	
	Dif. post-pre[1]		Dif. post-pre[1]		(Dif. IG-CG)[2]		Dif. post-pre[1]		Dif. post-pre[1]		(Dif. IG-CG)[2]	
	%	95 % CI	%	95 % CI	%	95 % CI	%	95 % CI	%	95 % CI	%	95 % CI
Satisfaction with indoor conditions												
Temperature (very good/good)	**25.0**	**(16.6 to 33.5)**	**−22.4**	**(−30.9 to −13.9)**	**47.4**	**(35.4 to 59.4)**	**8.6**	**(0.4 to 16.8)**	**−10.7**	**(−19.6 to −1.8)**	**19.3**	**(7.2 to 31.4)**
IAQ (very good/good)	**8.9**	**(1.1 to 16.7)**	**−11.6**	**(−19.7 to −3.5)**	**20.5**	**(9.2 to 31.7)**	**8.3**	**(0.9 to 15.6)**	−7.7	(−15.7 to 0.2)	**16.0**	**(5.2 to 26.9)**
Bothersome indoor climate factors												
Temperature too high (often)	**−8.3**	**(−15.1 to −1.5)**	2.3	(−5.2 to 9.9)	**−10.6**	**(−20.8 to −0.4)**	**−9.2**	**(−16.7 to −1.8)**	−1.0	(−9.4 to 7.3)	−8.2	(−19.4 to 3.0)
Temperature too low (often)	−2.9	(−7.9 to 2.1)	1.3	(−3.0 to 5.6)	−4.2	(−10.8 to 2.4)	0.5	(−4.8 to 5.7)	−1.9	(−6.6 to 2.8)	2.3	(−4.7 to 9.4)
Unpleasant odour (often)	−1.5	(−5.1 to 2.1)	0.0	(−4.1 to 4.1)	−1.5	(−7.0 to 3.9)	−5.0	(−10.6 to 0.5)	2.9	(−2.0 to 7.8)	**−8.0**	**(−15.4 to −0.5)**
Lighting problems (often)	−4.6	(−10.1 to 0.8)	−1.8	(−7.6 to 4.0)	−2.8	(−10.8 to 5.1)	−3.6	(−9.6 to 2.4)	1.9	(−3.7 to 7.6)	−5.5	(−13.8 to 2.7)
Comfortable at school (often)	6.2	(−2.5 to 14.9)	**−15.9**	**(−24.6 to −7.2)**	**22.1**	**(9.9 to 34.4)**	1.3	(−6.7 to 9.4)	**−13.4**	**(−22.2 to −4.7)**	**14.7**	**(2.9 to 26.6)**
School performance affected by indoor climate (often)	−2.1	(−7.9 to 3.7)	0.0	(−6.0 to 6.0)	−2.1	(−10.4 to 6.2)	−3.7	(−9.8 to 2.4)	3.0	(−3.0 to 9.0)	−6.7	(−15.2 to 1.9)

CI: confidence interval; CG: Comparison group; IAQ: indoor air quality; IG: intervention group; pre: pre-intervention measures (November 2020); post: post-intervention measures (May 2021).

[1] Percentage (%) difference of the average marginal effect estimates of the intervention or comparison group, with 95 % CI = %post - %pre. Bold = p-value <0.05.

[2] Percentage difference in differences of the average marginal effect estimate between IG and CG = [(%post_IG - %pre_IG) - (%post_CG - %pre_CG)]. Bold = p-value <0.05. Models included random effects for individuals and schools and were adjusted by SEP of school's neighbourhood.

Table 4
Perceptions of the scholar community (students and teachers) about the effects of building adaptation. Barcelona, 2021.

Categories	Code	Intervention	Source	Quotes
Changes in perception of indoor environmental conditions	Providing shade in classrooms	SP, ESH	Students & teachers	"[*The pergola*] *provides plenty of shade in the classroom and we appreciate it very much.*" (*teacher*)
	Improving indoor thermal comfort (summer and winter)	SP, RI, NCV	Students & teachers	"*We have noticed the effect of natural cross ventilation during winter, and especially in summer when the temperature has dropped compared to before the intervention.*" (*teacher*)
	Improving IAQ (e.g. smells, fresh air)	NCV	Teachers	"*Before the intervention, the school gym was so hot or so cold and it smelled really bad because windows were closed. We noticed a positive change after cross ventilation.*" (*teacher*)
	Improving visual comfort	SP	Students	"*We think* [*solar protection on windows*] *is a good addition since it provides enough shade inside the classroom to be able to properly see sheets of paper but not be disturbed by sunlight.*" (*student*)
	Not implemented in all school facilities	SP	Students	"*On the negative side, I think there are classrooms that are still very hot.*" (*student*)
Changes in indoor environment-related health and well-being	Reducing stifling sensation	SP	Students	"*Sometimes, when I was working, I had to stop for a moment, go out and get some air because I couldn't continue due to the heat in class.*" (*students*)
	Decreasing stress levels	SP	Students	"*I used to be hot and stressed in class but not anymore because now I'm cooler.*" (*student*)
	Reducing fatigue and irritability levels	RI	Teachers	"*Before* [*roof insulation*], *students needed to drink water, they were tired, and very irritable. Now, the classroom atmosphere is different.*" (*teacher*)
Changes in indoor environment and their reported impact on learning	Improving working environment	SP	Students	"*Now, we are more comfortable, and we can work better.*" (*student*)
	Enhancing students' concentration capacity	SP	Students	"[*Solar protections on windows*] *don't make the environment either too hot or too cold, and that helps you focus.*" (*student*)
	Promoting new type of activities	RI	Teachers	"*We can do other types of activities that we didn't even think about before.*" (*teacher*)

IAQ: indoor air quality; NCV: natural cross ventilation; ESH: external shade structures; RI: roof insulation; SP: sun protection on windows.

3.2.3. Changes in indoor environment and their reported impact on learning

As mentioned by participating students, the sensation of heat reduction, along with the enhancement of visual comfort in the classroom, helped to improve their concentration and enhanced their working environment during classroom activities. Some teachers pointed out that the improvement in indoor thermal comfort enabled them to perform new activities during learning hours that had been impossible to carry out before the intervention.

4. Discussion

This study suggests that, after the implementation of passive cooling measures in the school buildings, students and teachers improved satisfaction with their indoor school environment, including perceived temperature, air quality, and visual comfort. Qualitative data also points to a reduction of students' levels of fatigue and stress as well as enhanced concentration after the school transformations.

The results of this study strengthen findings of previous simulation-based studies (Gil-Baez et al., 2019; Grassie et al., 2022; Heracleous et al., 2021; Zinzi et al., 2021) that found passive design strategies could potentially improve thermal comfort inside school buildings. According to the quantitative results, after the intervention, overall satisfaction with school indoor temperatures increased and the percentage of students who were bothered by "too high" temperatures decreased in the IG, in contrast with the CG. In the qualitative evaluation, students and teachers consistently reported a decrease in indoor heat perception due to the implementation of shading devices, thermal roof insulation, and natural cross ventilation. These findings suggest that passive solutions could be a potential viable alternative solution to less sustainable measures (e.g. air conditioning) for maintaining thermal comfort in schools.

Earlier work has reported that an increase in building insulation could lead to a risk of overheating if done disproportionately (Díaz-López et al., 2022b). Also, some cooling measures such as fixed shading devices has been found to potentially increase heating demands because they block solar gains (Heracleous et al., 2021). Notably, no overheating problems due to increased roof insulation were reported in the present study. Also, qualitative and quantitative data suggest that participants' thermal comfort did not worsen on cold days after the intervention. This is relevant since it suggests that the implemented measures have the potential to effectively create a comfortable school environment during both hot and cold seasons.

According to previous reviews (Haselsteiner, 2021; Karjalainen, 2012), females tend to be more critical of thermal conditions than males, as they are more sensitive to temperatures that are too warm or too cold. This phenomenon has been attributed to physiological, cultural, and psychological factors. These differences could explain why, in the present study, the perception of being bothered by high temperatures significantly decreased in the IG compared with the CG only among girls. However, while most of previous studies exploring differences between male and female in thermal comfort have focused on adults and youth (Karjalainen, 2012; Nico et al., 2015; Wang et al., 2018), there is a gap in knowledge regarding primary school children. More research is needed to understand how passive cooling interventions might impact girls and boys differently in this specific age group.

Quantitative findings in the present study reveal that, after the intervention, students' satisfaction with general classroom IAQ was enhanced in the IG, compared with the CG, among both sexes. The qualitative analysis suggests that natural cross ventilation might be partly responsible for this improvement, as teachers reported that such measure provided fresh air and reduced indoor smells. In this line, previous literature suggest that provision of adequate ventilation rates can potentially enhance air quality inside buildings by reducing pollution and odour generated indoors (Ahmed et al., 2021; Díaz-López et al., 2022b). Also, a previous study showed that students value classroom ventilation as an important element of indoor air quality (Domínguez-Amarillo et al., 2020). In line with these previous studies, the results of the present study support the idea that increasing ventilation rates can be effective in improving the perception of IAQ in school buildings. However, natural ventilation strategies in school buildings situated in areas with high air pollution may facilitate penetration of harmful outdoor pollutants into indoor environments (Grassie et al., 2022; Rivas et al., 2014; Vilčeková et al., 2023). Alternatively, filters can be incorporated when using natural ventilation (Ahmed et al., 2021) or such strategies can be combined with interventions that aim to reduce air pollution in school surroundings (Honey-Rosés et al., 2023). Indeed, as part of the "Climate shelters in schools" project, schoolyards in the IG schools were also adapted by introducing measures such as vegetation (Sanz-Mas et al., 2024), which might have also positively impacted students' perceptions of IAQ in the IG. In addition, previous literature suggests that improving indoor thermal conditions might help to increase satisfaction with IAQ (Deng et al., 2024; Fang et al., 2004; Jia et al., 2021). Therefore, installing shading structures and building insulation could also be partly responsible for the improvement observed in the present analysis.

When analysing specific bothersome factors in this study, a decrease was found in the reporting unpleasant odours by boys in the IG compared with the CG, while no differences were observed among girls. Earlier investigations concluded that women might be more sensitive and concerned about IAQ (Haselsteiner, 2021) and more likely to report unpleasant odour (Wang and Norbäck, 2022). Consequently, the authors would expect a greater impact on girls, but the study results suggest the opposite. The sex differences observed in the present study are likely due to the increased percentage of boys in the CG reporting unpleasant odours. In this regard, it is important to recognize that a variety of factors, beyond air pollutants, can contribute to unpleasant odours inside school buildings, including sewage smells, building humidity, personal body odours, chemical cleaning products, and food preparation. In addition, the perception of unpleasant odours could have been intensified during the data collection period since students were using masks as a preventive measure against COVID-19. Further research should be conducted to understand potential sex differences in the impact of this type of intervention on students, particularly regarding this issue.

Contrary to what was previously suggested in prior research (Balador et al., 2017; Díaz-López et al., 2022b), the authors did not find a statistically significant decrease on reported lighting problems in the quantitative analysis after the intervention. However, in the qualitative results, students revealed that external shading structures and sun protection on windows reduced their perception of excess light and glare inside the classroom, improving the working environment and comfort during learning hours. This finding confirms the importance for urban planners to incorporate this type of measures in building renovations, promoting not only enhanced thermal comfort but also improved visual comfort at school. An explanation for the lack of significance in the quantitative analysis might be that shading structures were not implemented in all transformed schools or in all classrooms. Consequently, not all students who completed the questionnaires would have benefited from this modification and they would not therefore perceive its effects.

Previous research has established a link between poor indoor school environment and symptoms such as fatigue, thinking difficulties, and headaches (Bidassey-Manilal et al., 2016; Norbäck and Nordström, 2008; Savelieva et al., 2019; Vilčeková et al., 2023). However, a significant knowledge gap remains in understanding how passive school building design strategies can positively impact students' health and well-being by improving indoor environment conditions. The present study contributes to addressing this gap by providing valuable evidence for the benefits of passive cooling interventions in promoting healthier learning environments. Quantitative data suggest a significant improvement in students' comfort at school in the IG in comparison to the CG. Qualitative analysis further suggests these interventions, particularly solar protections and roof insulation, can contribute to reductions in student's stress, fatigue, irritability, and stifling sensation and can help them to increase focus by reducing indoor heat perception at school. Notably, quantitative pre-post changes were not found in the percentage of students reporting their school performance was affected by indoor climate. This discrepancy between quantitative and qualitative findings might be due to the fact that school performance is a broader term encompassing more than just concentration or focus capacity.

This study has some limitations. The main limitation is related to the COVID-19 outbreak. Due to school closures at the beginning of the pandemic, the authors were unable to collect questionnaire data prior to the intervention, as originally intended. The study design was adapted by adding retrospective questions for pre-intervention indicators, which could have led to recall and social desirability biases. However, these potential limitations are minimized by the inclusion of a CG. Additionally, to decrease the risk of SARS-CoV-2 spread, mask-wearing became mandatory in schools, coinciding with the data collection period of this study. Such measure could have negatively affected students' perception of the indoor environment, comfort, and well-being at school (Lang et al., 2024; Liu et al., 2020) and was probably more noticeable in CG schools. This could explain why students' perception of temperature, IAQ and comfort worsened in the CG, and could also have limited the improvements in the IG. Again, these potential limitations are reduced by the availability of qualitative data to complement and contrast the quantitative results, as well as by the inclusion of a CG.

Another limitation is that pre- and post-intervention measurements were conducted in different seasons (November vs May). The results could be under- or overestimated as thermal comfort perceptions are influenced by seasonality and recent thermal experience. In addition, data collection at specific time points could also limit the results' generalizability to other seasons. Again, potential biases were minimized by the inclusion of a CG.

Notably, in this study the authors did not measure changes in school's objective environmental conditions, such as temperature and air quality parameters. However, the effect of the intervention was assessed on subjective perceptions, which provide in-depth insights into participants' experiences. Moreover, prior research has reported that measured indoor temperature is related to perception of indoor temperature, suggesting that subjective reports of poor thermal conditions may indicate an objectively inadequate indoor thermal environment (Wang and Norbäck, 2022).

Finally, since study participants were involved in the co-creation process, they might be more enthusiastic and motivated about the intervention, potentially leading to an overestimation of its effectiveness. However, these students can provide more insightful results due to their deeper understanding of the intervention. Likewise, for the photovoice sessions, we recruited volunteers, so those involved were highly motivated and willing to participate, limiting the diversity of perspectives captured. However, the motivation of participants resulted in highly engaged photovoice sessions from which we could obtain rich qualitative information about their perceptions and experiences. Also, the interview sample included 7 teachers, potentially limiting the generalizability of the findings to all schools. Yet, teachers were selected from those involved in the project from the beginning, enabling for in-depth interviews and reaching data saturation.

There is a lack of quasi-experimental studies on the real effect of adapting school buildings to climate change using passive solutions and focusing on students' health and well-being. This study allowed us to assess the impact of a novel urban intervention intended to help schools adapt to climate change in a large southern European city with an increasing impact of high temperatures over time. One of the strengths of this study is the inclusion of students in the evaluation through interactive participatory techniques, allowing us to include their viewpoint concerning an urban program that significantly impacted them. Moreover, this evaluation extended beyond thermal comfort to encompass a wider range of factors such as indoor air quality, visual comfort, well-being at school, and student's performance, allowing for a more holistic assessment. Another important factor is the mixed methods design and the inclusion of a CG to reduce potential threats to internal validity. Given the heterogeneity of the interventions, the collection of qualitative data enabled us to conduct an in-depth examination of participants' perceptions and experiences, revealing changes that would have remained undetected through quantitative analysis alone. In certain cases, qualitative data also allowed the observed changes to be attributed to specific interventions.

5. Conclusions

This study examined the effectiveness of passive cooling actions as a strategy to adapt primary school buildings to climate change in urban areas with a Mediterranean climate. The study shows the benefits of such interventions on perceived thermal comfort but also on perceived IAQ, visual comfort, students' well-being, and concentration at school. This is important as children, who are particularly vulnerable to heat, spend long periods of time in school classrooms. The findings of the present study also suggest potential different impact between girls and boys but need further investigation. This research provides valuable results for urban planners and policymakers to improve school building climate resilience in warm regions. The positive results encourage the implementation of passive climate adaptations in other schools in similar contexts. Future research should focus on confirming that these passive systems, alone or combined, remain effective against worse future climate scenarios.

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Ethical considerations

The study was conducted in accordance with the Good Clinical Practice Guidelines of the Declaration of Helsinki. The protocol study was approved by the Parc de Salut Mar Clinical Research Ethics Committee (2019/8820/I). All the schools participating in the project signed a document of commitment that included the study information. Written informed consent was obtained from students' families and teachers.

CRediT authorship contribution statement

Marta Sanz-Mas: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Xavier Continente:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Sílvia Brugueras:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Marc Marí-Dell'Olmo:** Writing – review & editing, Methodology, Conceptualization. **Laura Oliveras:** Writing – review & editing, Validation, Investigation. **María José López:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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