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Children's thermal comfort in school classrooms: Influence of contextual factors, thermal experience, and diurnal variations

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A R T I C L E I N F O

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A B S T R A C T

In recent years, there has been growing interest in children's thermal comfort, which is partly attributed to research findings on children's lower comfort temperatures compared to adults and to the occurrence of more frequent and longer heatwaves. This paper explores the influence of contextual factors on children's thermal perception by comparing field survey results from Swedish grade school classrooms with findings from previous studies in the UK that followed the same study design. The Swedish dataset consists of 2116 questionnaires, collected from approximately 160 children aged 9–11, across 90 surveys conducted during both the heating and non-heating seasons. The results confirm the previously observed discrepancy between children's reported thermal sensation and both the Predicted Mean Vote (PMV) and the adaptive comfort models, with children's comfort temperature being lower than predicted. However, the children in this study were highly adaptive and more so than those in the UK study, with a unit change in thermal sensation vote in the non-heating season corresponding to 5 °C change in operative temperature. Regarding diurnal variation in thermal perception, children reported higher thermal sensation in the afternoon at the same operative temperature and preferred a cooler environment, with no change observed in clothing insulation. This research highlights the importance of contextual factors- such as school policies, culture and indoor climate experience- on shaping thermal comfort trends, and emphasises the need for further research on adaptive comfort of schoolchildren in different contexts.

1. Introduction

Thermal comfort is a critical aspect of indoor environmental quality, significantly impacting well-being, productivity, and overall health [1]. Research has reported lower optimal temperatures for schoolchildren than for adults, both in terms of comfort [2–8], and cognitive performance [9–11]. In a study with children at different school stages it was found that neutral, preferred, and acceptable temperatures increased with students' age [12], which makes the youngest children the most vulnerable school building occupants. Unlike adults, children have a higher surface area-to-mass ratio, which affects their heat exchange with the environment [13]. Their thermoregulation mechanisms are still developing, making them more vulnerable to temperature extremes, e.g. their underdeveloped sweat glands lead to lower sweating rates under warm conditions [14]. There is research evidence that children are more likely to be associated with heat-related morbidity [15]. In the light of the observed increase in global average temperature and the likelihood of more frequent and longer heat wave events [16], concerns for children's comfort and wellbeing under current and future climates are growing. A good understanding of children's thermal response during different periods, as well as during their school day, is therefore necessary.

1.1. Thermal adaptation of children

Recent studies have provided significant insights into how children perceive and adapt to thermal conditions. In Australia, students in locations with wider weather variations were found to have a higher adaptability compared to those in locations with steadier weather conditions [17]. In a study in Northwest China, pupils who typically experienced a warmer indoor environment during winter had greater psychological expectations [18]. It becomes clear that both indoor and outdoor climatic experiences influence thermal perception, confirming that contextual differences are important in establishing desired indoor conditions for children.

Despite their lower comfort temperatures and higher vulnerability to temperature extremes, studies showed that children exhibit high adaptive capacity as evidenced by the relationship between their thermal

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sensation and indoor operative temperature. In thermal comfort studies with school children in the UK [3], Iran [5] and Australia [17], one thermal sensation unit change corresponded to a change of 3.7- 4 °C in operative temperature. However, studies have also found differences in thermal adaptation between schools in their sample [7,17], pointing to the influence of specific indoor thermal experience in each of the schools, or other contextual factors. The relationship between reported thermal sensation and operative temperature also depends on the span of the survey period, which varies between studies. Studies that are longitudinal in nature are required for more conclusive findings [19].

Behavioural adaptation is one of the primary means of achieving comfort indoors, including adjustment of personal variables, such as clothing, or technological adjustments, such as turning on a fan or opening a window or curtain [20]. In school environments, as in all large common spaces, the presence of approximately 30 children in one space means there may be limited adaptive opportunities that suit everyone. The metabolic rate is also defined by the activity undertaken in class and there is little room for individual adjustment. In a classroom setting, the teacher is typically responsible for controlling the classroom environment [3,8], which has been identified as a potential obstacle to achieving comfort in school classrooms [21].

While adjustment of clothing is the most straightforward adaptive action for achieving comfort and one of the limited such actions the children can take during the school day, young children's response to thermal change through changing clothing levels has been found to be weak [22]. This limitation may be further exacerbated by cultural and contextual factors, e.g. school uniform policies. Clothing adjustment practice was found to be different between primary and secondary school children in subtropical Sydney, with the clothing insulation in the case of the older children remaining almost unchanged during the whole survey period and across a range of indoor and outdoor temperatures, possibly due to presence of school uniform dress code or due to peer group norms [23]. Dress codes have been discussed as an obstacle which often overrides rational thermoregulatory behaviour [20]. Besides, under the moderate thermal conditions experienced indoors, attitudes and cognitive processes have a greater influence compared to the variable outdoor conditions with extremes, where the focus is on physiological limits [24]. Attitudes and practices within the school environment can therefore influence children's thermal response.

The increasing interest in children's thermal comfort and adaptation is evident in the number of field studies in schools over the last years, which has also led to several review articles on this topic [19,25–30]. The reviews highlight the progress made, but also the gaps in our understanding of children's thermal needs and suggest future directions of research. Based on the reviews and the literature overview in the previous section, future research on children's thermal comfort should consider the influence of contextual factors, such as climate, educational levels, gender and room types among others [26]. To this purpose, a need for increased sample sizes, longitudinal and year-round studies has also been highlighted [19]. A wide variation in thermal neutralities was also observed in studies performed in the same climate zones [29], which emphasises the need for exploration of other influencing factors on children's thermal comfort. Finally, recent research on children's thermal sensitivity found age-related thermal sensitivity differences [31], questioning the applicability of currently used metrics in thermal comfort research for the case of children.

1.2. Diurnal variation of thermal perception

Within-day variations of thermal perception and adaptation are of great interest for school environments, where children spend a big part of their day. Human autonomic thermoregulatory processes follow diurnal variations regulated by the circadian clock. The body's core temperature is at its minimum early in the morning and at its highest in the late afternoon [32]. Similar diurnal variations could therefore be expected also in human thermal perception. Review studies on diversity in thermal perception found that preferred temperatures are higher in the afternoon when body core temperature is at its maximum [32,33]. These results are derived from studies conducted on adults and may therefore not be directly applicable to children. The few thermal comfort studies that included the "time of day" variable in their setup were reviewed in a recent article and were found to have contradictory results, attributed by the authors to evaluation and data analysis differences, in the investigated populations and/or in different experimental design [34]. No studies from schools were reported in the review. A subsequent study investigating diurnal variation in thermal perception found evidence that occupants prefer colder thermal conditions at 14:00 and progressively warmer ones in the rest of the day [35], whilst in an experimental investigation humans were found to have different physiological response depending on time of the day [36]. Considering children spend a large part of their day at school and are expected to perform the same throughout the day, potential diurnal variations in their thermal perception are of interest. There is currently lack of contribution on this aspect from previous research.

1.3. Aim of the paper

Building on the gaps identified in the existing literature on thermal comfort in schools, this paper contributes to current knowledge in two ways: (i) by enhancing understanding of how contextual factors and thermal experience influence children's perceptions, through a comparative analysis of studies that share the same core design but were conducted in schools with distinct contextual differences and (ii) by providing insights into diurnal variations in children's thermal perception.

To achieve this, the paper presents findings from a study that replicates a survey protocol previously applied in two UK primary schools [3,22,37] to a Swedish primary school. The Swedish context is particularly interesting due to the prevailing hypothesis that the country's generally cooler climate makes building occupants more sensitive to temperature increases [38,39], aligning with adaptive comfort theory that postulates that people adapt to the indoor and outdoor climatic conditions they normally experience. Combined with previous findings in schools, this makes Sweden a critical case for investigation. Additional contextual differences of interest between the studied samples include clothing and footwear policies, pedagogical approach, as well as school year duration.

The study's objectives are to:

- Analyse children's year-round thermal comfort in the investigated Swedish school classrooms, with a focus on children's thermal sensitivity and adaptation.
- Demonstrate the extent of inaccuracy in adult-based comfort model predictions, particularly regarding children's varying adaptations across contexts.
- Identify differences and similarities in children's adaptation across contexts, through the comparison of the results with a UK study that followed the same protocol.
- Investigate diurnal variations in thermal sensation, preference and clothing level of children.

2. Methods

The study includes long-term measurements and thermal comfort surveys in classrooms. The main sample analysed here consists of 6 classrooms in a grade school in Gothenburg, Sweden, where surveys took place during two seasons, i.e. heating season (December-April) and non-heating season (May-June) in 2015–2016. The sample from previous studies in the UK during 2011–12 is used for comparison across contexts. Details on the UK samples can be found in previous publications [3,22,37]. Although the number of classrooms investigated is rather small, the longitudinal nature of the study led to a considerable dataset. As previously highlighted, longitudinal studies with children are lacking, yet they are essential for a better understanding of thermal adaptation.

Gothenburg has marine west-coast temperate climate, with Köppen Climate Classification Cfb [40]. The school is housed in nine buildings, seven of which were built in the turn of the 18th to the 19th century and two in the end of the 20th century. The buildings where the surveys took place have a lightweight construction (Fig. 1). Three of the classrooms have exhaust-only ventilation (supply through wall inlets), one is naturally ventilated through window opening and two are equipped with mechanical ventilation with heat recovery. None of the cases involve summer cooling, and comfort at warm conditions is achieved through window opening. Previously conducted cluster analysis on indoor temperature measurements in the 6 classrooms grouped them together, confirming that their thermal conditions are similar [41], hence children's overall thermal experience. All classrooms are heated in winter with water radiators.

The study follows the main methodology as previously used in UK school surveys outside the heating season [3,22]. However, this time an extended version of the same questionnaire was used, translated into Swedish and surveys were also conducted in winter. Details of the measuring methods and the survey questionnaire are given below.

2.1. Instrumentation and measuring procedures

During the surveys, measurements of the environmental parameters affecting thermal comfort were also taken (air temperature, globe temperature, air speed, relative humidity). A handheld DeltaOhm instrument HD32.3 was used, which measures globe temperature (⌀50 mm) and air temperature (accuracy class 1/3 DIN), relative humidity [accuracy ± 2 %RH (15 - 90 %RH) @ 20 °C, ± 2.5 %RH remaining range] and air speed [accuracy ± 0.05 m/s (0–1 m/s), ± 0.15 m/s (1–5 m/s)]. The instrument was placed as centrally in the classroom as possible and at a height of 1 m, using a tripod. This was preferred to the standard height of 1.1 m according to ISO7726 [42], as this is closer to the children's level when seated. The conditions measured reflect those in the centre of the classroom and may therefore differ somewhat those at the perimeter where local effects may occur, but it is expected that they reflect those experienced by most children in the classroom. Furthermore, comparison of measured temperatures by DeltaOhm and air temperatures measured at the perimeter revealed very small differences, on average 0.2 °C (±0.5). CO_2 concentration was measured before, during and after the surveys using a Rotronic CP11 [accuracy ±(30ppm+5 % of reading)]. CO_2 measurements were logged at intervals of 30 s. All instruments were calibrated prior to this study.

Long-term monitoring of the classrooms' air temperature and relative humidity was also conducted during both seasons, using small Madgetech dataloggers. The accuracy for the temperature reading is ±0.5 °C and for the relative humidity the calibrated accuracy is ±3 %. The loggers were mounted on pinboards in the classrooms at a height of approximately 1.5 m and away from heat sources and direct solar radiation. The loggers were programmed to store measurements every 5 min.

2.2. Questionnaire survey procedure

An extended version of the previously developed UK questionnaire adapted to the age of young children [3] was used, translated into Swedish. School children aged 9–11 participated in the survey. The final version consists of 9 questions which include: 1) thermal sensation vote on a 7-point scale, 2) thermal preference vote on a 7-point scale, 3) thermal sensation on three parts of the body on a 3-point scale, 4) thermal acceptability vote 5) sensation of tiredness, 6) air quality vote, 7) assessment of air movement, 8) preferred adaptation measures and 9) clothing items worn. The questionnaire was reviewed by the schoolteachers to ensure its suitability for the different age groups of children. An excerpt from the questionnaire can be seen in Fig. 2.

Approximately 16 surveys were conducted in each classroom during class and at least 20 min after breaks or other non-sedentary activities to ensure as much as possible consistent metabolic rates throughout the study. Unlike the UK studies where one survey per classroom was conducted during each day-visit to the school, in the Swedish subsample surveys took place twice on almost every day-visit; in the morning and afternoon (pre- and at least 1 h post-lunch). The survey procedure during a typical survey day is illustrated in Fig. 3.

A total of 2177 filled-in questionnaires were collected from approximately 160 children during 90 surveys. For the analysis, inconsistent cases, i.e. strongly contradicting thermal sensation and preference votes, were excluded (3 % of the sample). More details about the exclusion criteria can be found in [22]. 2116 valid responses were used in the analysis.

2.3. Calculation of PMV, comfort temperature and running mean outdoor temperature

The PMV (Predicted Mean Vote) index was calculated for comparison with the children's reported thermal sensation, using the equation given in ISO 7730 [43]. The environmental input parameters required for the calculation (air temperature, mean radiant temperature, air velocity and relative humidity) were all measured during the surveys (see 2.1). The clothing insulation was calculated for each child from the clothing items ticked on the questionnaire. For the metabolic rate the value of 1.2 met was used, equivalent to the adult value for sedentary office activity [43], considered appropriate as the surveys took place at least 20 min after breaks or other non-sedentary activities. No adjustments for children's metabolic rates were made as previous attempts have not achieved to match PMV with children's reported thermal sensation [30], and further exploration of this is deemed outside the

Fig. 1. Two of the buildings of the school where surveys took place.

Fig. 2. Excerpt from the questionnaire including questions 1 and 2 on thermal sensation and thermal preference votes [in Swedish].

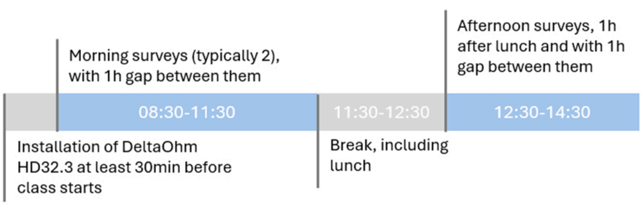

Fig. 3. Schematic of the survey procedure during a typical survey day.

scope of this paper.

Children's comfort temperature was calculated for each reported thermal sensation vote using Eq. (1) as developed by Griffiths [44] and adopted in thermal comfort literature [45].

$$T_c = T_{op} - \frac{TSV}{G} \tag{1}$$

Where T_{op} is the mean operative temperature at the time of the survey, TSV is a respondent's reported thermal sensation on the seven-point adapted ASHRAE scale and G is Griffiths coefficient, a value that denotes the maximum rate of change of thermal sensation with temperature, assuming no adaptation takes place. In the development of adaptive comfort models, G was taken to be a constant with the value of $G = 0.5/\ ^\circ C$, as estimated using extensive data from fiend studies [46]. This value was found to be appropriate for the combined UK school survey sample, though there were differences between the two schools [47]. It has also been the subject of investigation over the past few years. Rupp et al. demonstrated that the Griffiths constant used in the calculation of comfort temperature varies depending on building type (office, school, residential), ventilation mode (AC/NV), age, gender and climate [48] and that the value used influences the adaptive relationships [49]. Griffiths coefficient was also found to vary by educational stage, with a study showing that thermal sensitivity was significantly lower in primary schools and increases with children's age [31]. Analysis on the Griffiths coefficient (G) using the school sample of this study showed that it is sensitive to sample grouping and G-values per school were calculated and varied between 0.24/ °C and 0.45/ °C [41]. Given the lack of an agreed approach on the Griffiths constant, both the value 0.5 and the sample-specific G coefficients are used for comparison of the derived comfort temperatures in the analysis.

For comparison of children's thermal sensation between school samples, it was decided to use the relative temperature scale "offset from neutrality, T_{diff}" as the independent variable, proposed in previous studies [23,50], to adjust for adaptive processes within each of the samples and subsequent differences in children's thermal history across the monitoring period. T_{diff} is the temperature difference between indoor operative temperature T_{op} at a point in time and the predicted adaptive neutral temperature, which, in this study, is based on the European adaptive model in 16798–1 [51].

For the investigation of the relationship between comfort temperature and outdoor temperature the exponentially weighted running mean outdoor temperature T_{rm} is used, which accounts for the larger impact of more recent weather conditions on people's thermal experience, hence adaptation. The T_{rm} is calculated using Eq. (2) [52]:

$$T_{rm} = (1 - a) * \{T_{ed-1} + a * T_{ed-2} + a^2 * T_{ed-3} \ldots\} \tag{2}$$

where $T_{ed\ -1}$ is the daily mean outdoor temperature for the previous day; and $T_{ed\ -2}$, . . . is the daily mean outdoor temperature for the day before and so forth.

3. Results

3.1. Summary statistics and TSV-PMV comparison

Table 1 gives summary statistics of environmental parameters and observed and predicted thermal perception indices for the two investigated seasons. In the heating season (winter) operative temperatures during the surveys ranged from 20.7 to 24.4 °C while relative humidity (RH) was within 23–51 % (Fig. 4) and the air speed never exceeded 0.1 m/s. CO_2 concentration during the surveys in winter had an average of 1180 ppm and maximum 2600 ppm. However, this value is due to one classroom increasing the average (classroom ventilated through window opening). In general, CO_2 in most classrooms was kept below 1000 ppm.

The non-heating season (spring/summer) was smaller in duration as ambient temperatures stayed below 10 °C until the end of April and the school year in Sweden ends mid-June. The average operative temperature during the surveys was 25.4 °C, reaching up to 27.6 °C on the hottest day. The relative humidity was overall slightly higher than in winter (Fig. 4) and air speed levels were similarly low as in winter. CO_2 was overall lower in the non-heating season as windows were frequently opened (Table 1).

Clothing insulation was on average 0.68 clo in the heating season and 0.37 clo in the non-heating season. These values are overall lower than the values of 1 and 0.5 clo for winter and summer respectively assumed in international standards [43,53,54].

The average reported thermal sensation of the children is near 'a bit warm' in both seasons (Table 1) and the tendency towards warm sensations can be seen in the distribution of the votes by season in Fig. 5. The thermal preference votes in the non-heating season shift towards the cool side as expected with most children expressing a preference to feel cooler [Fig. 6(b)]. Interestingly, this is not the case in the heating season [Fig. 6(a)]. Even though children had on average warm sensation during the surveys, their thermal preference also shifts towards the warm side, i.e. they seem to prefer this warm sensation during winter.

Table 1
Summary statistics of the environmental measurements and thermal comfort indices during the surveys per season (HS: heating season, N-HS: non-heating season, N is number of surveys or number of respondents, depending on the variable, and SD is standard deviation).

	Season	N	Minimum	Maximum	Mean	SD
Indoor environmental parameters						
Operative temperature (°C)	HS	53	20.7	24.4	22.7	0.9
	N-HS	37	23.3	27.6	25.4	1.1
Relative humidity (%)	HS	53	23	51	34	6
	N-HS	37	26	58	40	8
Air speed (m/s)	HS	53	0.00	0.05	0.01	0.01
	N-HS	37	0.00	0.08	0.01	0.02
CO_2 (ppm)	HS	53	610	2600	1180	490
	N-HS	37	460	1690	830	290
Outdoor environmental parameters						
Outdoor daily temperature (°C)	HS	53	0.0	8.0	4.3	2.1
	N-HS	37	12.2	22.6	17.3	3.0
Outdoor running mean temp (°C)	HS	53	−3.1	7.7	3.0	3.1
	N-HS	37	12.4	19.6	15.8	2.3
Personal parameters						
Clothing insulation (clo)	HS	1244	0.3	1.2	0.68	0.1
	N-HS	860	0.1	0.8	0.37	0.1
Observed thermal perception						
Thermal Sensation vote (TSV)	HS	1212	−3	3	0.3	1.2
	N-HS	811	−3	3	0.6	1.1
Thermal Preference Vote (TPV)	HS	1246	−3	3	0.1	1.3
	N-HS	852	−3	3	−0.3	1.2
Predicted thermal perception						
Predicted Mean Vote (PMV)	HS	1243	−1.6	0.5	−0.3	0.4
	N-HS	861	−1.2	1.0	−0.1	0.4
Predicted Percentage Dissatisfied (PPD)	HS	1243	5	57	10	8
	N-HS	861	5	36	9	5

Compared to the warm tendency in the average reported thermal sensation, the Predicted Mean Vote lays in the cool side in both seasons. The comparison between PMV and $TSV_{(mean)}$ by survey can be seen in Fig. 7. $TSV_{(mean)}$ is the average thermal sensation vote of the children's reported thermal sensation votes (TSV) during a single survey. The evident discrepancy between PMV and TSV is not surprising, as the prediction accuracy of PMV has been found to be rather low, i.e. 34 % [55]. However, its prediction accuracy was typically higher at sensation votes close to neutrality, which has not been the case in this or previous studies with children. The discrepancy is almost consistent throughout the operative temperature range, i.e. 20–28 °C, and thermal sensation range experienced during the surveys. The results confirm previous findings of children's higher thermal sensation compared to the PMV model predictions.

Interestingly, the difference between PMV and $TSV_{(mean)}$ in the non-heating season for the Swedish sample is very similar to the difference previously found in the UK study (same study design, [3]). The children's neutral temperature (the temperature which corresponds to neutral thermal sensation using the regression line) is approximately 4 °C lower than predicted by the PMV/PPD model, same as in the UK study. In the heating season the difference is smaller, i.e. 2.3 °C. The mean thermal sensation votes exhibit rather large spread, as typical in thermal comfort survey results.

The neutral temperatures as derived from the regression lines should be interpreted with caution, particularly for the non-heating season, where the point lies outside the range of observed values used to fit the regression. Most importantly, extracting these neutral temperatures may give a false impression that beyond these values respondents would feel uncomfortable. As can be seen in Fig. 7, children's thermal sensation vote in the non-heating season increased by 1 scale unit for 5 ° increase in operative temperature, i.e. they felt on average slightly warm at 27 °C. This indicates a very high level of adaptation, which is further discussed in the next section.

3.2. *Thermal sensitivity and comfort temperatures*

Fig. 8 illustrates the same data as Fig. 7, with Fig. 8(a) showing the data for the entire year and Fig. 8(b) breaking it down by season. The regression coefficient of $TSV_{(mean)}$ on T_{op} for the entire dataset indicates how adaptive the children were to temperature variations over the entire survey period, throughout the year [Fig. 8(a)]. The regression coefficient $b = 0.157$ is low, suggesting a high level of long-term adaptation.

Fig. 8(b) shows the relationship between $TSV_{(mean)}$ and T_{op} by season. In the non-heating season children appear to have been much more adaptive. This may be due to several reasons, e.g. the more perceivable discomfort experienced by increasing temperatures near overheating limits that leads to higher levels of behavioural adaptation, compared to the more moderate levels of temperature in winter. Another explanation may be related to psychological adaptation, e.g. a positive disposition towards the shift to bright, warm and sunny weather. The regression coefficient for the non-heating season is $b = 0.192$, result which agrees with the 'highly adaptable' group found in Australian school classrooms during summer, with an average regression coefficient $b = 0.18$ [17].

Children's thermal response is further analysed by examining their sensitivity to changes in indoor temperature within a single day (G coefficient), assuming no adaptation takes place. The coefficient has previously been calculated for each school dataset using the day-pooling method as: 0.24/ °C (UK school 1), 0.45/ °C (UK school 2) and 0.34/ °C (Swedish school, non-heating season) [41], all of which are lower than the constant $G = 0.5/$ °C. Interestingly, children's thermal sensitivity in the Swedish school lies between the two UK schools, suggesting that children in the Swedish school were more sensitive to temperature changes on a single day than children in UK school 1, and less sensitive than children in UK school 2. As also highlighted in the previous study, the calculation of Griffiths coefficient is sensitive to sample grouping, making it challenging to determine an appropriate G value for different samples. A further challenge is the derivation of unrealistic comfort temperatures with lower values of Griffiths coefficient, as highlighted in previous studies [31,49], and confirmed by the school data in this study. Fig. 9 compares the calculated individual comfort temperatures using a constant $G = 0.5/$ °C in the calculation, with those using the G calculated with the day-pooling method for each of the three school samples. In the case of UK school 1 that has the lowest $G = 0.24/$ °C, approx. 25 % of the calculated comfort temperatures are below 16 °C, which is highly implausible. Children's average comfort temperature in the Swedish school during the non-heating season is 23.5 °C. However, with an interpercentile range of 8.3 °C (the difference between the 90th and 10th percentiles, i.e. 27.3 and 19 °C respectively), the data demonstrates substantial dispersion around this mean, indicating a wide spread of comfort temperatures over the duration of the surveys.

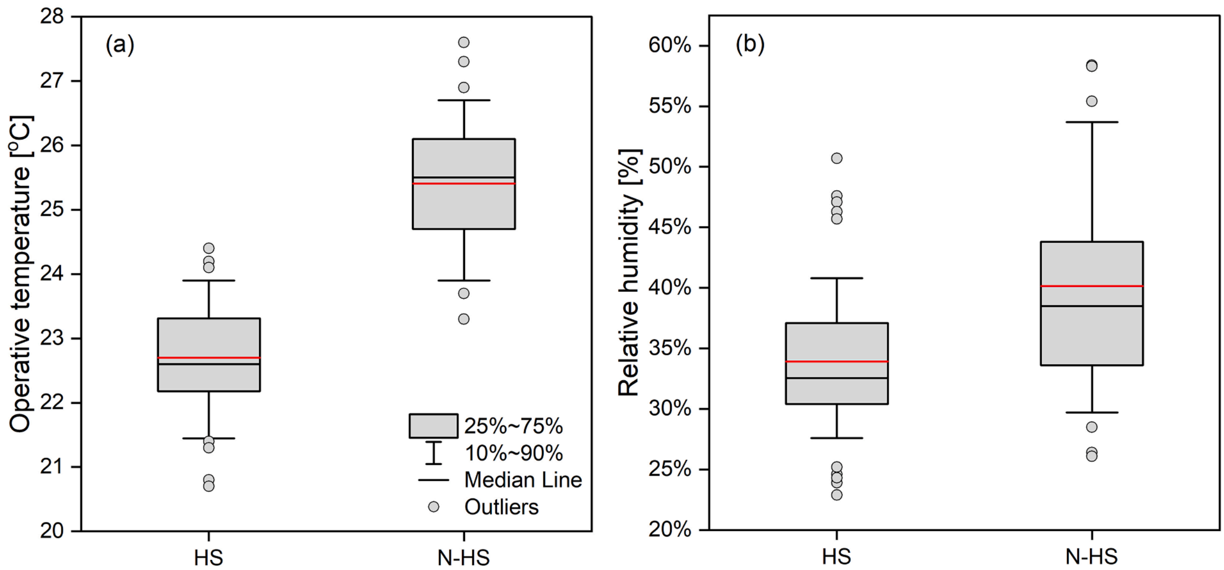

Fig. 4. Boxplots of (a) the operative temperature and (b) relative humidity during the surveys. The red line represents the mean.

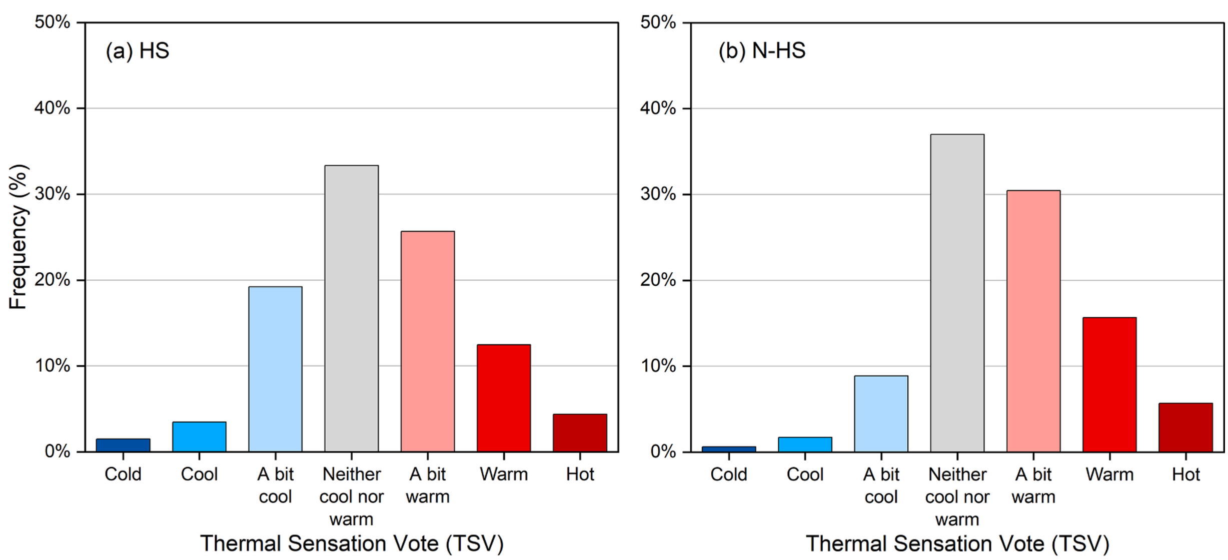

Fig. 5. Distribution of thermal sensation votes, (a) during the heating season (N = 1212), (b) during the non-heating season (N = 811).

3.3. Adaptive comfort and influence of outdoor climate

Fig. 10 shows the relationship between the average thermal sensation vote per survey [$TSV_{(mean)}$] and the temperature offset from neutrality, which was calculated based on the European adaptive model. The UK schools were combined since the relationship between $TSV_{(mean)}$ and the operative temperature was previously found to be nearly identical [37], as well as with the T_{diff} in this analysis. It can be seen that, at the same T_{diff}, children in the UK reported warmer thermal sensations compared to the children in the Swedish classrooms. Furthermore, the shallower slope of the regression line for the Swedish classrooms (0.19 units/K compared to 0.31 units/K) suggests much higher adaptation of the Swedish children during the survey period. According to the regression lines, at T_{diff}=4 °C there is a difference of nearly 1 scale point in thermal sensation between samples. The children's neutral operative temperatures can be obtained by solving the equations for TSV = 0, resulting in T_{diff}=−2.3 °C and T_{diff}=−1.8 °C for the UK and Swedish samples respectively, i.e. the children's neutrality corresponds to an operative temperature approximately 2 °C lower than the neutral temperature derived by the European adaptive model for both samples.

Fig. 11 shows the relationship between the calculated comfort temperatures in the Swedish school (with G = 0.34) and the running mean of the outdoor temperature. The size of the circles is scaled based on the number of thermal sensation votes corresponding to each comfort temperature. The European adaptive comfort line used in EN 16798–1 is also included for comparison. At running mean outdoor temperatures up to 15 °C there is rather good agreement between the regression line of the Swedish children's individual comfort temperatures and the adaptive comfort line, while at T_{rm}=20 °C the difference reaches 1.2 °C. This is different to the UK samples, where there was a difference of approximately 2 °C throughout the T_{rm} range. A similar difference has been found in Iran [5], whilst a higher difference (3 °C) was found in another UK-based study [6].

The high adaptive capacity to high temperatures evidenced in Swedish classrooms may be seen as surprising, based on the general notion of a colder climate experienced on average in Sweden. However, the average outside temperatures for the period 01 May- 30 June for the three schools were 14.4 °C, 14.2 °C and 15.8 °C for the UK school 1

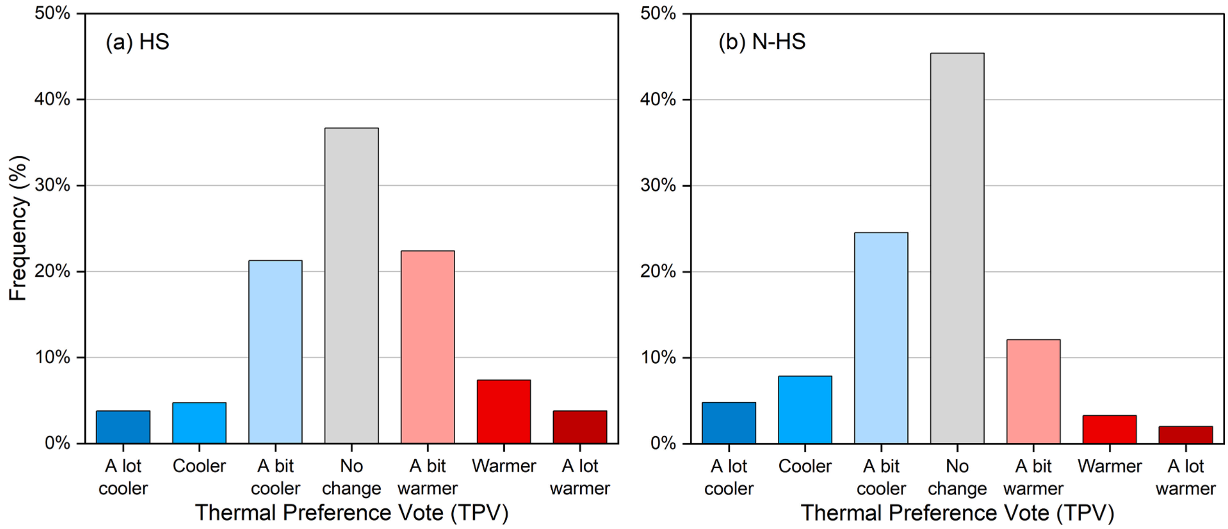

Fig. 6. Distribution of thermal preference votes, (a) during the heating season ($N = 1246$), (b) during the non-heating season ($N = 852$).

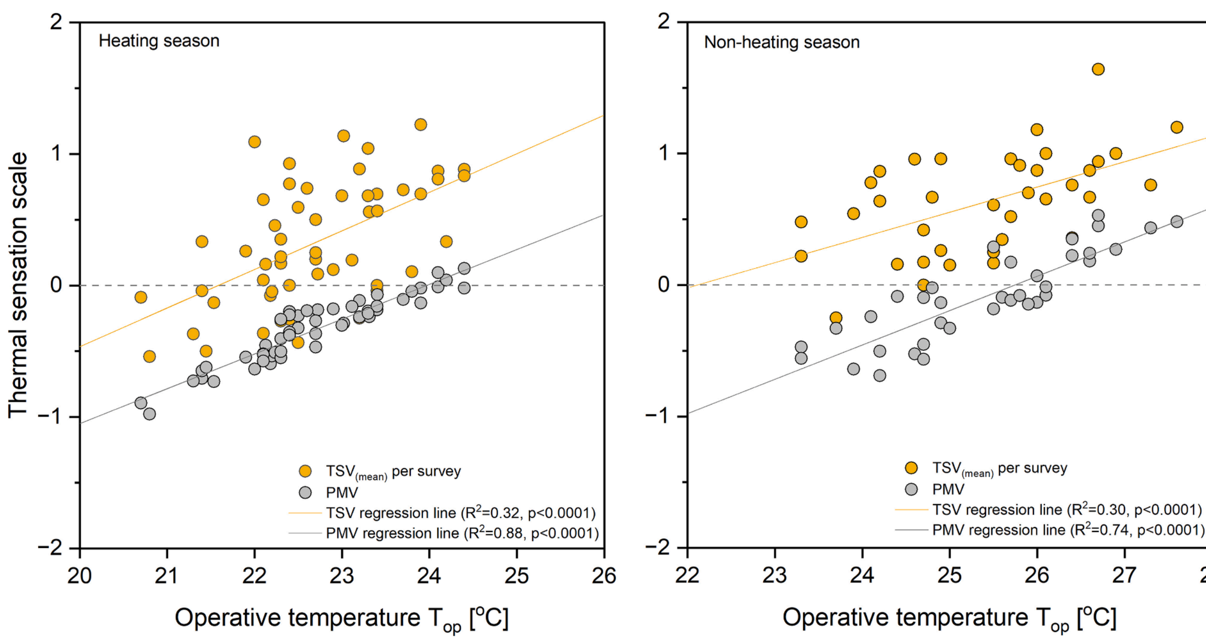

Fig. 7. Survey average thermal sensation vote ($TSV_{(mean)}$) and predicted mean vote (PMV) against operative temperature at the time of the survey.

(2011), UK school 2 (2012) and the Swedish school (2016) respectively. The weather during the survey period was therefore somewhat warmer in the Swedish sample compared to both UK samples, as can be seen also in the daily outdoor temperatures in Fig. 12. Fig. 12 also demonstrates that high outdoor temperatures occurred earlier in the survey period in Sweden, likely instigating adaptive mechanisms earlier than in the UK samples, e.g. clothing adjustments and psychological adaptation.

3.4. Influence of indoor thermal experience

Fig. 13 shows the distribution of the 5-minute air temperature measurements during occupied hours (8:30–15:00, weekdays, holidays excluded) in all classrooms where the thermal comfort surveys took place in the UK and Sweden, depicting the indoor thermal conditions experienced by the children in the three schools. The measurements cover the school period from May until early July in the UK and early June in Sweden, as the school year in Sweden ends in June. Children in the Swedish classrooms experienced on average warmer temperatures during the survey period than the children in both UK schools, with an average air temperature of T_{a3}=24.5 °C (σ=2.1), while the UK schools had average air temperatures of T_{a1}=23.5 °C (σ=1.6) and T_{a2}=20.7 °C (σ=2.0). A one-way ANOVA revealed that these differences were statistically significant.

Fig. 14 shows the relationship between the mean thermal sensation vote of each class with the classroom's average air temperature during occupied hours of the examined season, i.e. the mean air temperature the children experienced during the survey period as calculated using the 5-minute air temperature measurements taken in each classroom. Overall, within the range of the average experienced temperatures, 20–25 °C, the average classroom thermal sensation remained between 'neutral' and 'slightly warm', with the exception of three UK classrooms. Children in most classrooms could therefore overall adapt to the conditions they typically experienced, although it becomes more challenging for them at higher experienced temperatures, such as those in the Swedish classrooms during the non-heating season.

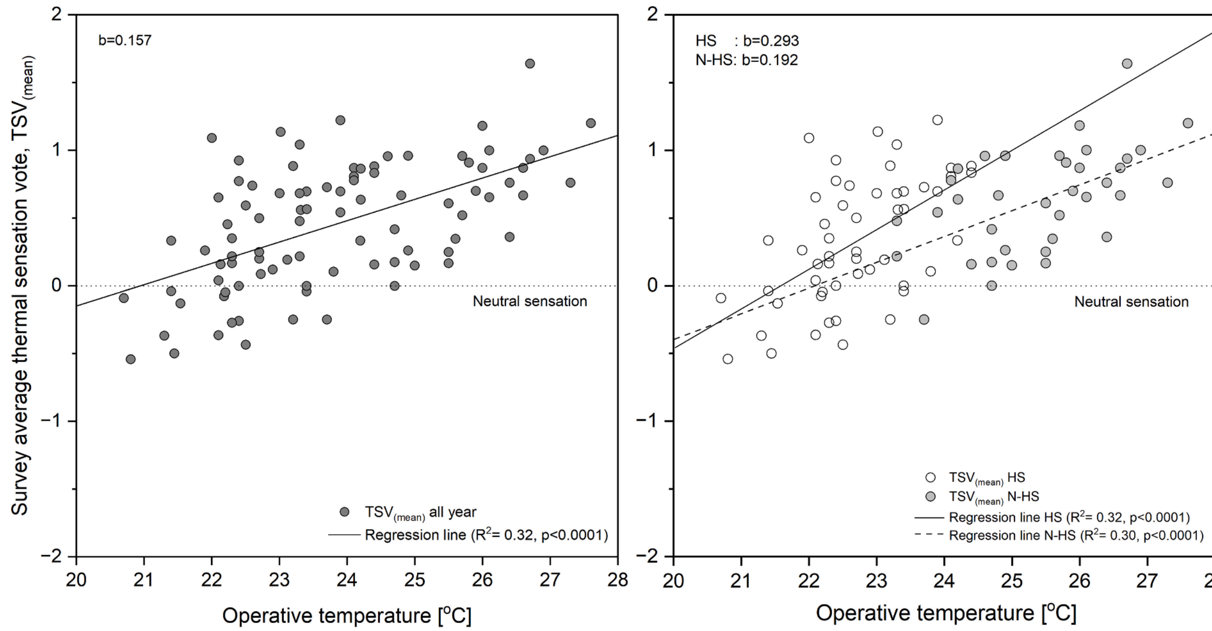

Fig. 8. Average thermal sensation vote per survey [$TSV_{(mean)}$] against operative temperature (T_{op}) for a) the entire period and b) by season (HS: heating, N-HS: non-heating).

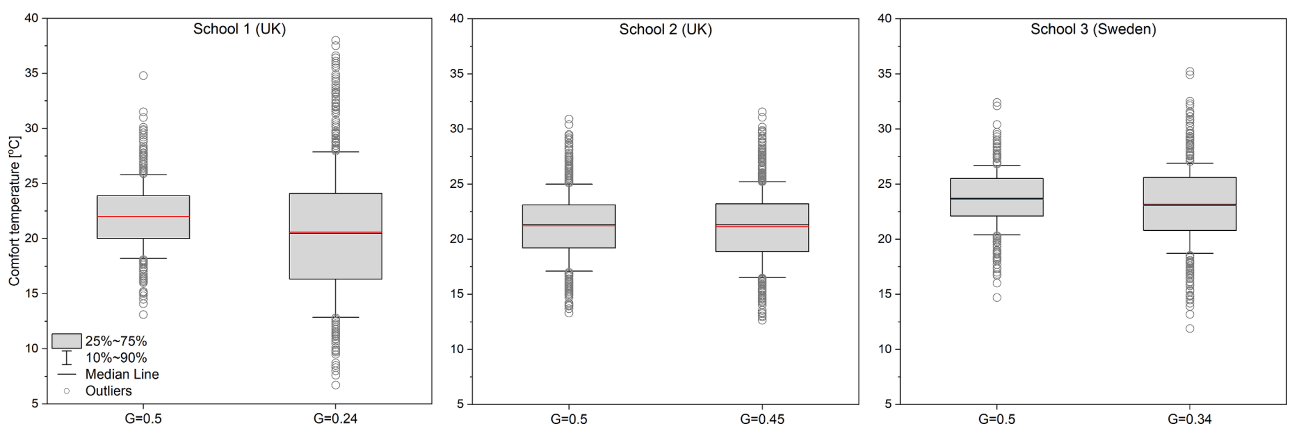

Fig. 9. Boxplots of children's calculated individual comfort temperatures with constant G and school-specific G. The red line represents the mean.

3.5. Within-day changes in TSV, TPV and clothing insulation

For the analysis of diurnal changes, the dataset was split in two groups, morning (N_m=1142) and afternoon (N_a=974). Children's perception responses (TSV, TPV), clothing insulation and the operative temperature at the time of the survey are used in this analysis.

Wilcoxon signed-rank tests for paired groups and ordinal variables showed a statistically significant change in children's thermal sensation ($Z = -7.361$, $p < 0.0001$) and thermal preference ($Z = -7.618$, $p < 0.0001$) from morning to afternoon. The median thermal sensation vote was 0 (neutral) in the morning and 1 (slightly warm) in the afternoon.

For further analysis of the changes from morning to afternoon, the unit of analysis is set to survey, as the questionnaires were anonymised to comply with ethical requirements and therefore the morning responses cannot be linked to the afternoon ones of individual pupils. For each survey day and each classroom that was surveyed twice, the morning and afternoon averages of the variables TSV, TPV, clo and T_{op} were calculated. This resulted in 41 morning/afternoon data pairs. Fig. 15(a)-(c) show the 41 morning and afternoon classroom mean TSV, TPV and clo against the classroom's operative temperature. As can be seen, in the afternoon the mean thermal sensation votes are overall higher and the preference votes lower at the same operative temperature, while the clothing insulation is on average the same.

Table 2 gives the average and standard deviation of the 41 values of the investigated variables for each group (morning/afternoon) and their difference. The operative temperature was on average 0.3 °C warmer in the afternoon surveys. The average clothing insulation change is only 0.01 clo/ °C, confirming findings previously reported on the minor clothing changes occurring during a working day in offices and schools [46]. Therefore, minimal adaptation took place during survey days. On the other hand, an average change of 0.39 is seen for the thermal sensation vote (TSV). This corresponds to an average increase of 1.3 scale points/ °C difference from morning to afternoon, which is high. The change in average thermal preference vote aligns with the TSV change, i.e. indicates preference for cooler environment in the afternoon compared to the morning.

4. Discussion

4.1. Thermal adaptation

This study confirmed the high adaptive capacity of children, even in

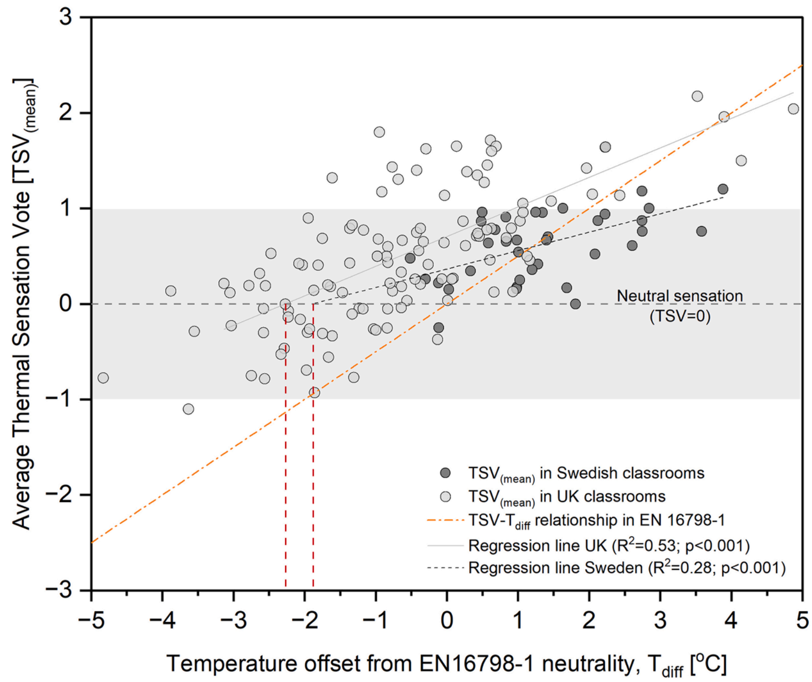

Fig. 10. Average thermal sensation vote per survey [$TSV_{(mean)}$] against temperature offset from neutrality (T_{diff}) during the non-heating season for the UK and Swedish classrooms.

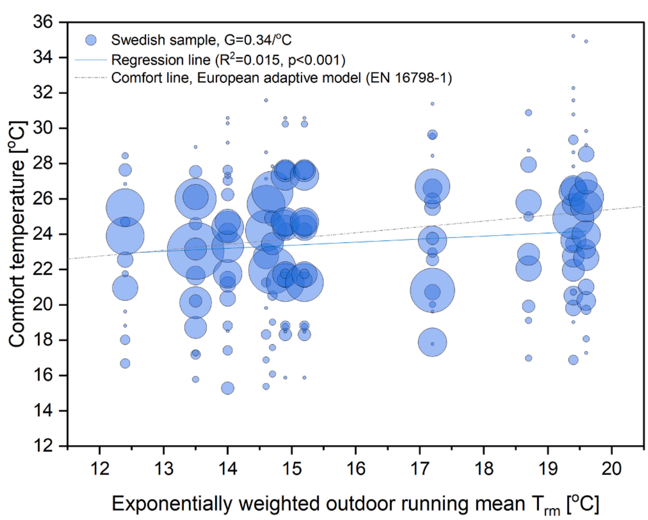

Fig. 11. Comfort temperature of all subjects in the Swedish school against the exponentially weighted outdoor running mean temperature. The comfort temperature line in EN 16,798–1 also included.

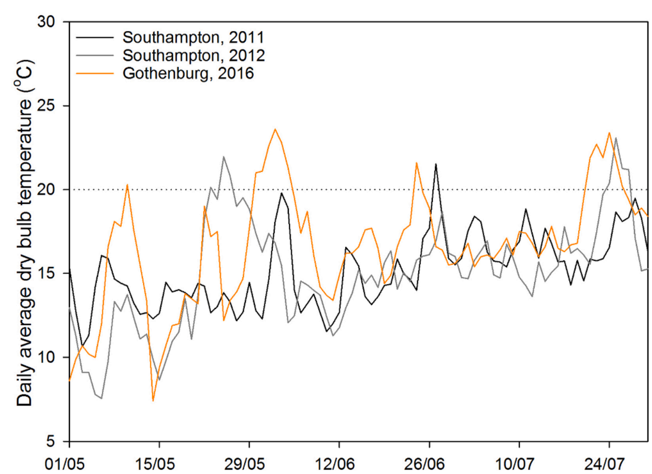

Fig. 12. Daily outdoor temperature during the study period (non-heating season, May-July), Data from the official Meteorological institutes in UK and Sweden.

a country with a cooler climate. There is a possibility that the higher tolerance to warm conditions that the children in Sweden showed is related to cultural and psychological factors. As Shipworth et al. highlight [56]: “a sunny day in a climatic context with a majority of days being rainy might lead to […] emotions of happiness or joy and a distinctive acceptance of an overheated room” which is supported by psychology literature [57] and the concept of thermal pleasure and alliesthesia [58,59]. Furthermore, Knez and Thorsson [60] found in a field study that culture and environmental attitude influenced people’s thermal, emotional and perceptual assessments of a park by comparing responses of Swedish and Japanese participants. Swedish participants evaluated the weather as cooler and better for outdoor activities than the Japanese participants, even though they experienced similar thermal conditions. This kind of psychological and cultural responses may have led to Swedish children’s high acceptance of warm conditions in their classrooms, as these are associated with sunny, bright days and more time spent on outdoor activities, which is comparatively a small part of their school year. Either way, the results demonstrate that, despite their underdeveloped thermoregulatory system that makes them more susceptible to thermal stress, children have a high adaptive capacity, such that it may even compensate for their physiological limitations. However, for the latter to happen, children need to be provided with adaptive opportunities.

4.2. Comparison with model predictions and other studies

The comparison of children’s neutral temperatures with both the PMV and the adaptive model predictions confirmed the discrepancies found by previous studies. In this study however, there was a better agreement of the children’s comfort temperature regression line with

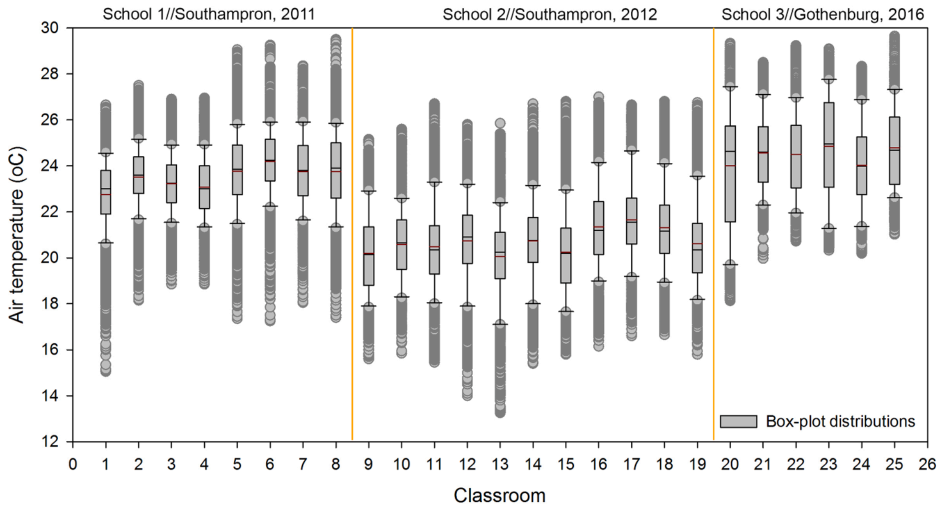

Fig. 13. Distribution of the 5-minute measurements of the air temperature during school operating hours (non-heating season only). Box: the 50 % of the values; whiskers: the 10th and 90th percentile; dots: outliers; black line: median, red line: mean.

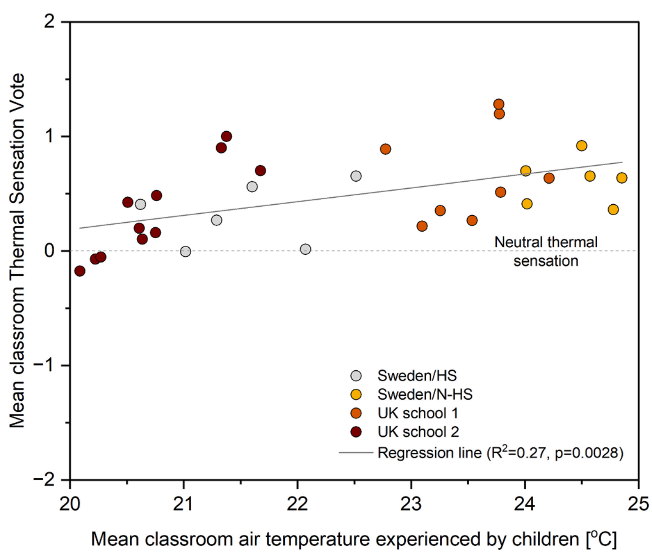

Fig. 14. Relationship between the mean thermal sensation vote by classroom and the mean classroom air temperature experienced by children during occupied time.

the adaptive comfort model. This could be attributed to the fact that the adaptive model does not include individual parameters, which are most likely the main source for the differences between adults and young children, especially the metabolic rate. The adaptive model relies solely on the adaptive capacity of the occupants and the relationship of their comfort temperature to the outdoor temperature, which in the examined sample was very high.

In this study, during the non-heating season, the neutral temperature - determined from the regression of $TSV_{(mean)}$ on T_{op} - was 22.3 °C. The average comfort temperature, calculated using the sample-specific G coefficient, was 23.5 °C. This is higher than in the UK sample also investigated here, yet closer to the neutral temperatures reported from Spain [2], Iran [5], Australia [17] and Italy [12]. This finding underscores the significant influence of contextual factors beyond climate on children's thermal adaptation.

4.3. Contextual influences

The comparison between the UK and Swedish samples confirmed that thermal perception is highly contextual. During the non-heating season, the children in the Swedish study had higher neutral temperature and demonstrated a more complete adaptation. This could be due to differences between the UK and Swedish context, e.g. absence of uniform and no-shoes-indoors policy in Sweden, different expectations due to the shorter summer period in the Swedish school year, overall thermal history and possibly cultural perception in relation to summer and warmth. A further aspect that may have some role in these results is that the investigated Swedish school follows a Montessori pedagogy, but such an association would require a different type of expert analysis. Overall, it is important that designers, authorities and policy makers address the specific context in question when using or developing thermal criteria, especially when dealing with sensitive population groups such as children. Based on the results from this study, contextual factors such as clothing and footwear policies, pedagogical approach, school year duration and attitude towards summer may influence thermal adaptation, potentially overriding expectations based on the overall climatic context.

The contextual nature of thermal perception presents a significant challenge in thermal comfort research, particularly in developing predictive models. Future research should focus on integrated models that combine physiological, behavioural, climatic, psychological and other influencing factors. The inclusion of more contextual data in field studies, beyond building type and ventilation mode, would help to enhance empirical models. In the case of school buildings, such variables could be school policies, availability of adaptive opportunities, cultural perception, pedagogical approach and more. A better aligned methodology for field data collection is also necessary, if we aim to combine datasets from different contexts in the development of thermal comfort models. Finally, interdisciplinary collaboration is essential for understanding the full variability of thermal perception and improving model accuracy.

4.4. Diurnal variations

The analysis of diurnal variation in children's responses showed that their thermal sensation was overall higher in the afternoon at the same operative temperature with a preference for cooler environment, and this is not attributed to higher clothing levels. The finding agrees with previous research where occupants preferred colder thermal conditions at 14:00 [35]. A higher metabolic rate related to the circadian rhythm may be a contributing factor to the children's warmer sensation in the afternoon, or other psychological influences. Either way, this finding is important for school building design and operation, since it means that

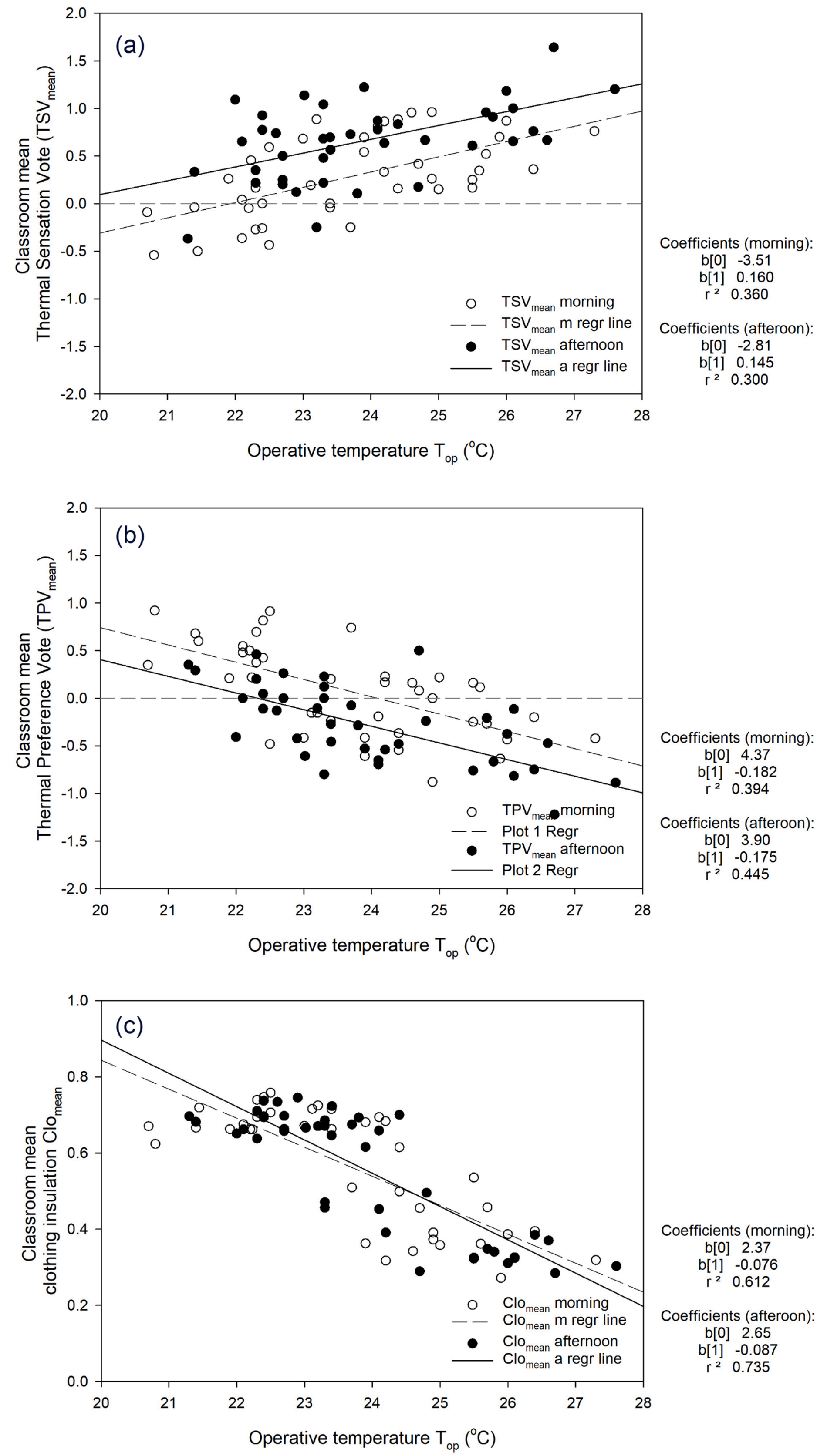

Fig. 15. Relationship of (a) mean thermal sensation vote, (b) mean thermal preference vote and (c) mean clothing insulation with the operative temperature by time of the day (morning/afternoon).

Table 2
Average value and standard deviation of Top, TSV, TPV and Clo by time of day (morning/afternoon).

	T_{op} (SD)	TSV (SD)	TPV (SD)	Clo (SD)
Morning	23.7 (1.6)	0.28 (0.43)	0.08 (0.46)	0.56 (0.16)
Afternoon	24.0 (1.6)	0.67 (0.43)	−0.29 (0.42)	0.55 (0.17)
Difference	−0.3	−0.39	0.37	0.01

varying conditions during a day may be preferred. However, this could be challenging to achieve, since the preference for cooler temperatures coincides with the typically warmest time of the day.

4.5. Limitations

The datasets analysed are relatively old. However, the study aimed at comparing different contexts and therefore selecting a similar time period, even if dated, is considered a valid approach for obtaining meaningful results. Moreover, the results presented are derived from a sample of 160 children in one school and do not represent the conditions encountered across the Swedish school stock and population. The paper does not attempt to provide a representation of the thermal comfort conditions in Swedish schools, but aims to highlight differences and similarities across contexts through a comparative analysis of studies in schools with distinct contextual differences.

Another limitation of the study is that classrooms have different ventilation systems, since ventilation mode may influence thermal perception due to potential differences in adaptation. This could be due to difference in thermal experience, i.e. different thermal conditions experienced, or due to differences in adaptive opportunities. However, none of the cases involved summer cooling, and comfort at warm conditions is achieved through window opening in all classrooms. Also, all classrooms are heated in winter with water radiators. Previously conducted cluster analysis on indoor temperature measurements in the 6 classrooms grouped them together, confirming that their thermal conditions are similar, and therefore overall thermal experience of the children in the classroom was similar. Finally, the Swedish questionnaire was somewhat longer than the one used in the UK study, which may have affected the children's attention span. However, this is not expected to have influenced the results.

5. Conclusions

This paper aimed to shed light into the influence of contextual differences and thermal experience on children's thermal sensitivity and adaptation, as well as on diurnal changes in children's thermal perception.

In relation to adult-based predictions, discrepancies were found with both widely used models. In agreement with previous studies and the UK study, the observed neutral temperature was lower compared to that derived from the PMV (temperature corresponding to neutral sensation), with a difference of 2.3 °C and 4 °C in the heating and non-heating seasons respectively. Similarly, children's neutral sensation corresponded to an operative temperature approximately 2 °C lower than the neutral temperature calculated based on the European adaptive model for both the UK and the Swedish samples. However, despite Sweden's generally cool climate, the children in this study were found to be highly adaptive- more so than those in the UK study. Their thermal sensation vote in the non-heating season increased on average by 1 scale unit for 5 °C increase in operative temperature.

Regarding diurnal changes in thermal perception, children's thermal sensation was overall higher in the afternoon at the same operative temperature with a preference for cooler environment, while clothing insulation remained on average unchanged. The physiological and/or psychological processes behind such a result need to be further explored in future studies.

From a methodological perspective, the analysis identified two key limitations in current practices. First, neutral temperatures, derived from the regression of thermal sensation votes against temperature, should be reported alongside the regression coefficient, which reflects the rate of change in thermal sensation with temperature variation. This prevents overemphasizing a single value, particularly when occupant acceptability and adaptation are high. Second, the Griffiths coefficient significantly influences the outcomes of thermal comfort analyses, presenting a major, unresolved challenge in the field of thermal comfort research.

The results highlight the complexity of addressing contextual differences in establishing guidelines for the indoor thermal environment. The diversity of conditions experienced by children due to different countries, climates, building types, ventilation modes, school policies, or other contextual characteristic, could strongly influence their thermal perception. While research findings from school studies challenge the use of specific common comfort conditions, they agree on the differences between children and adult-based predictions, and on children's high adaptive capacity even in cooler climates. A way forward in addressing contextual differences in the provision of thermal comfort may be the adoption of thermal zones or clouds, instead of single neutral temperature target values. It appears that we need to explore new ways of thinking to appropriately address diversity in thermal comfort perception.

CRediT authorship contribution statement

Despoina Teli: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, 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.

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Data availability

Data will be made available on request.

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