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Thermal Performance Evaluation of School Buildings using a Children-Based Adaptive Comfort Model

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Abstract

This paper investigates the thermal performance of four school buildings of different ages and characteristics, using current EU overheating criteria and 'adjusted' criteria based on children's lower comfort temperature found in recent research. Data collected in Southampton, UK, between 2011-2015 are used in the analysis, which consists of two parts: a) the development of an adaptive comfort model associating children's comfort temperature to outdoor climate based on approximately 2,800 thermal comfort responses from children, and b) the thermal performance evaluation of four case study schools (built in 1894, 1929, 1978 and 2013) with the use of 5-minute air temperature measurements during spring/summer from a total of 43 classrooms. The two models, current (adult-based) and adapted to pupils, are applied to the methodology for overheating assessment based on the European standard EN 15251. Results show that there is no overheating in the schools when the classroom temperatures were assessed with the current adult-based model, while when using the children-based model overheating was identified in three out of the four schools. Interestingly, the school with the most acceptable summer performance is the oldest, an 1890s medium-weight building. The modern (2013) school had the most stable, yet high air temperatures amongst the studied schools. The study highlights the emerging issue of summer overheating in heating-dominated countries such as the UK, where this has not been traditionally a concern. The problem is exacerbated by a single-sided focus on reducing heating loads without taking appropriate measures for summer comfort, the global warming trends and children's sensitivity to high temperatures. This paper highlights the challenge of designing school buildings with acceptable year-round thermal and energy performance and the need to set higher standards in the school building design, using children-based criteria.

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Keywords: Overheating; School buildings; Adaptive comfort; Children's thermal comfort; Climate responsive design.

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1. Introduction

The recorded increase in the global average temperature over the past century[1] has raised concerns about the likelihood of overheating in buildings without mechanical cooling. Furthermore, heat waves have become more frequent and intense[1], which is of great concern as there is research evidence that children "are more likely to be associated with heat-related morbidity"[2]. Schools are particularly vulnerable to increased temperatures due to the young age of occupants, high occupancy densities and limited opportunities for behavioural adjustments to improve thermal comfort in classrooms. A further challenge is posed by recent research which has shown that comfort temperature levels are lower for children than adults [3-8]. Thermal comfort field surveys during spring and summer in naturally ventilated classrooms in the UK found this comfort temperature difference to be around 2^{o}C [4]. The same difference was recently found in a study in the much warmer climate of Shiraz in Iran[9]. This means that, irrespective of climate and location, children are more sensitive to high temperatures than adults, posing a great challenge to achieving and maintaining acceptable thermal conditions in classrooms with the current building design guidelines.

There are both physical and physiological differences between children and adults which may explain their different thermoregulation and reported thermal sensation, i.e. children's greater surface–area-to-mass ratio, greater metabolic heat production per kg body mass and lower sweating rate[10]. Under the same experimental conditions and exercise levels, children have been found to have lower evaporative sweat loss and higher skin temperature by 3^{o}C compared to adult men[11]. The children's high body surface area to weight ratio and their poorly developed sweat mechanism led to a similar heat dissipation of 51% via evaporation and 44% via radiation and convection. For adult men the corresponding percentages were 65% and 33% respectively. Although activities in classroom are less intensive compared to physical exercise, this experiment highlights that children rely more on dry heat loss (through radiation and convection) compared to adults[10]. This suggests that children's cooling potential is more sensitive to the physical properties of their surrounding space which determine the radiant and convective heat losses, highlighting the significance of school building design in order to avoid heat discomfort in children.

Nomenclature

T_a	Air temperature
T_{op}	Operative temperature
T_{comf}	Comfort temperature
T_{max}	Upper limit of the comfort temperature range
T_{upp}	Absolute upper limit temperature
T_{rm}	Running mean of the outdoor temperature
RH	Relative Humidity
H_e	Hours of exceedance
W_e	Weighted exceedance
TSV	Thermal Sensation Vote

1.1. Thermal performance and overheating assessment

Buildings' thermal performance during the warm seasons (spring – summer) is largely assessed according to the likelihood of overheating occurrence. Overheating has been defined as "the phenomenon of a person experiencing excessive or prolonged high temperatures" and can be assessed with respect to (i) thermal comfort, (ii) health or (iii) productivity[12]. This paper is focusing on thermal comfort and the evaluation of the likelihood of overheating in schools with the use of upper indoor temperature thresholds adapted for pupils' comfort based on empirical data collected in the UK. The overheating evaluation approach is described in the European Standard EN 15251[13] and further developed in CIBSE's Technical Memorandum TM52:2013 "The limits of thermal comfort: avoiding overheating in European buildings"[14] and CIBSE's updated Guide A- Environmental design[15]. Based on this approach, three criteria are provided in order to assess the risk of overheating for a room or building. A building is classed as overheating if any two criteria are exceeded:

- Criterion 1- Hours of exceedance (H_e): the number of hours (H_e) during which the indoor operative temperature (T_{op}) exceeds the upper limit of the comfort temperature range ($T_{comf} \pm 3°C$) by 1°C or more should not be more than 3% of the occupied hours.
  $H_e \leq 3\%$ of occupied hours, when $\Delta T \geq 1°C$ (ΔT is defined in Table 1)
- Criterion 2- Weighted exceedance (W_e): for each day the sum of the weighted exceedance for each 1°C above the upper limit of the comfort temperature range, the allowable maximum T_{max}, should be less or equal to 6.
  $W_e \leq 6$, where $W_e = (\Sigma h_e) \times WF$
- Criterion 3- Threshold/absolute upper limit temperature (T_{upp}): the indoor operative temperature should not exceed T_{max} by 4°C or more at any time ($T_{upp} = T_{max}+4°C$).
  $\Delta T \leq 4°C$

These overheating criteria are based on the 'adaptive' approach to thermal comfort, which shows that occupants' comfort temperature in naturally ventilated buildings responds to the outdoor weather conditions. This relationship has been defined through field surveys and is included in the standard EN 15251[13] [see Table 1, T_{comf} equation (2)]. The metric used for the outdoor climate is the running mean of the outdoor air temperature (T_{rm}), as this also reflects the stronger influence of recent weather experiences on comfort preferences[16].

Table 1. Calculations required for assessing against the TM52 overheating criteria[14]. The maximum acceptable operative temperature corresponds to buildings of Category II of EN 15251[13] (new buildings and renovations, adaptation strategies).

Abbreviation	Parameter	Formula	
T_{rm} [°C]	Running mean of the outdoor temperature	$T_{rm}=(1-\alpha)\cdot[T_{ed-1}+\alpha\cdot T_{ed-2}+\alpha^2\cdot T_{ed-3}\ldots]$ where T_{ed-1}=Daily mean outdoor temperature for the previous day, $T_{ed-2,\ldots}$= Daily mean outdoor temperature for the day before and so forth	(1)
T_{comf} [°C]	Comfort temperature based on EN 15251	$0.33T_{rm}+18.8$	(2)
T_{max} [°C]	Maximum acceptable operative temperature (upper limit of the comfort temperature range)	$T_{comf} + 3$	(3)
ΔT [°C]	Difference between the room operative temperature and T_{max}	$T_{op}-T_{max}$	(4)

In the UK, specific overheating criteria are provided for schools in the Building Bulletin 101[17]. However, Montazami et al. assessed the current UK criteria and found that they are too lenient and potentially underestimate the overheating risk in school buildings[18]. A new, updated version is currently being drafted based on the CIBSE TM52 assessment approach. Therefore, this study does not consider the current UK overheating criteria for schools.

2. Methods

Four case study school buildings were used in the analysis. The four buildings were constructed in different periods and they have different thermal properties and design characteristics. School A is the most recently built school, completed in 2013 (wall U-value by 2010 regulations ≤ 0.30 W/m^2K). School B consists of two parts, one built in 1929 and an extension built in the 1970s (estimated wall U-value 1 W/m^2K). School C is a lightweight building of the 1970s, with an estimated wall U-value of 1.2 W/m^2K and school D is a medium-weight Victorian building with an estimated wall U-value of 1.4 W/m^2K. All schools are naturally ventilated through window opening and have internal shading (blinds).

2.1. Thermal comfort surveys

The comfort temperature model used in EN 15251 (Table 1) was derived from thermal comfort field surveys conducted in offices. Using the same approach, survey data were collected from 19 classrooms in two naturally ventilated schools in Southampton, UK, in 2011 and 2012[19]. The observations were used to identify the relationship between children's comfort temperature and the weather conditions. The field survey methodology for acquiring children's thermal sensation has been described in detail in previous publications[4, 5]. This study included the children's thermal sensation votes (TSV) on a 7-point thermal sensation scale (cold, cool, a bit cool, OK, a bit warm,

warm, hot) and the operative temperature measured during the on-site surveys. The comfort temperature (T_{comf}) corresponding to each thermal sensation vote (TSV) was then calculated using equation (5) [20].

$$T_{comf} = T_{op} - \frac{TSV}{b} \tag{5}$$

Where b is Griffiths constant, b=0.5 as estimated using extensive data from field studies[21] and validated for the case of school children[9, 22].

2.2. Long-term thermal monitoring

The classrooms' air temperature (T_a) and relative humidity (RH) were monitored at 5-minute intervals during the entire investigation period of each school. The monitoring in each school was conducted in different years, apart from the ones built in 1929 and 2013 (Schools B and A), which were both surveyed in 2015. This is not affecting the overheating assessment as the comfort temperature thresholds were calculated in relation to the prevailing outdoor conditions (T_{rm}) at the time of the surveys. The monitoring was undertaken using MadgeTech 2.04 miniature data loggers the size of a matchbox. The accuracy of the reading for the temperature is ± 0.5 °C.

It should be highlighted that for the overheating assessment, TM52 guidance suggests the monitoring of the operative temperature using a 40 mm globe thermometer[14], "otherwise air temperature can be used in long-term measurements and corrected for large hot or cold surfaces to estimate the operative temperature of the room". In this study only air temperatures were available for the entire monitoring period. However, a total of 565 sets of simultaneous measurements of air and radiant temperature for various outdoor weather conditions collected from three of the schools were used to assess the relationship between the measured air temperature (T_a) and the calculated operative temperature (T_{op}). The average difference between T_{op} and T_a for the newly built school A was -0.1 (σ=0.1), for the medium-weight building (school D) 0.2 (σ=0.2) and for the lightweight building (school C) it was 0.4 (σ=0.3). All of these values are lower than the manufacturer-stated accuracy of the air temperature sensor. Therefore for this analysis the monitored air temperatures were used without any correction.

3. Results

3.1. Adaptive comfort equation for school children

The dataset of the children's individual thermal sensation votes from the 2011/2012 thermal comfort surveys was 'cleaned' from missing and inconsistent values. A total of 2,784 valid thermal sensation votes and corresponding indoor operative temperatures at the time of the survey were used for the calculation of the children's comfort temperature with equation (5). These comfort temperatures were further regressed against the running mean of the outdoor air temperature in order to derive the relationship of the children's comfort temperature with the outdoor temperature. The analysis resulted in the adaptive comfort equation (6) for the surveyed children. The outdoor running means were calculated for 30 days prior to each survey date using equation (1) in Table 1 and the daily average outdoor temperatures for the survey years (2011, 2012) from the meteorological station at the National Oceanographic Centre in Southampton (NOCS)[23].

$$T_{comf\_child} = 0.26 \times T_{rm} + 18.2 \tag{6}$$

Figure 1 shows the children's comfort temperatures against 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 spread of the data points around the regression line seen in Figure 1 is common in thermal comfort research and reflects the interpersonal differences in comfort conditions[24]. As can be seen in Figure 1, the children's 'comfort regression line' lies lower than the EN 15251 'comfort line'. Based on the equations in Figure 1, for T_{rm}=

17ºC, the surveyed children's comfort temperature would be T_{comf}= 22.6ºC, whilst the adults' comfort temperature as per EN 15252 would be T_{comf}= 24.4ºC, being approximately 2ºC higher.

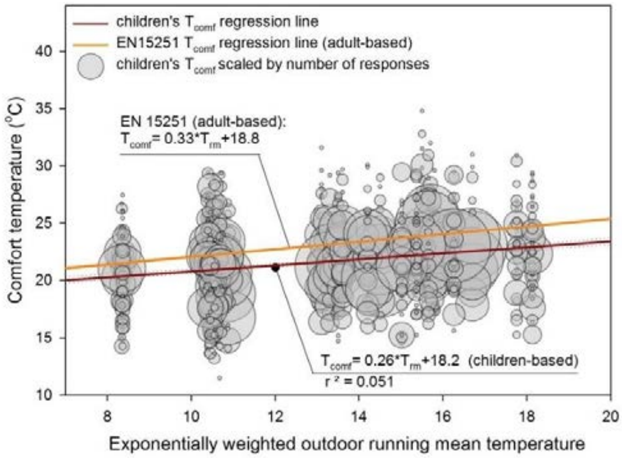

Fig. 1. Relationship between the children's comfort temperature and the running mean of the outdoor temperature with regression line. The line used in the European standard EN 15251 is also included for comparison.

3.2. Thermal performance evaluation of the case study schools

The evaluation of the thermal performance of the case study school buildings follows the methodology outlined in section 1.1, using both the EN 15251 T_{comf} model (adult-based) and the $T_{comf\text{-}child}$ model derived from this study [equation (6), children-based]. For each of the monitoring years only the classroom temperatures during school days for the period from May to July were used. All the holidays, weekends and out-of-term dates were removed. The final datasets were analysed to derive the occupancy profiles for the classrooms. In general, the hours that classrooms were almost fully occupied were between 8:00-16:00. TM52 guidance specifies that the selected period for overheating assessment should be of "typical weather" for the season. This was tested here through comparison with the Test Reference Year (TRY, average weather data used in energy analysis and compliance with building regulations) and is overall fulfilled for the years in question (Table 2).

Table 3 summarizes the results of the overheating assessment, after evaluating the monitoring data against all of the criteria outlined in section 1.1. As can be seen, using the current adult-based comfort model (EN 15252) none of the 43 classrooms is evaluated as overheating. As can be seen in Figure 2, most of the data points lie within the comfort range (green area) and even to the cool side of the spectrum. This means that the schools overall meet the current criteria for acceptable thermal conditions in summer. The upper limit of the comfort temperature range (T_{max}) is exceeded only in a few occasions, whilst the absolute maximum (T_{upp}) is never exceeded. However, as can be seen in Table 3 the result is different when using the children-based comfort model, with almost half of the classrooms overheating: 64% of the classrooms in school A, 62% in school B (43% and 83% in the 1929 and 1970s building parts respectively) and 50% in school C.

Table 2. Summary statistics of the daily outdoor temperature during the monitoring period for each year compared to TRY.

	2011	**2012**	**2015**	**TRY**
Average of daily outdoor temperature (May-July)	15.17	15.00	15.41	15.04
Standard deviation of daily outdoor temperature (May-July)	2.17	3.18	2.68	2.95
Maximum daily temperature (May-July)	21.54	23.08	23.24	22.17
Minimum daily temperature (May-July)	10.65	7.54	9.63	8.92

Table 3. Percentage of classrooms overheating using both the adult-based and children-based models.

Percentage of monitored classrooms overheating (%)	A (2013)	B (1929)	B (1970s)	C (1978)	D (1894)
Adult-based model	0 %	0 %	0 %	0 %	0 %
Children-based model	64 %	43 %	83 %	50 %	0 %

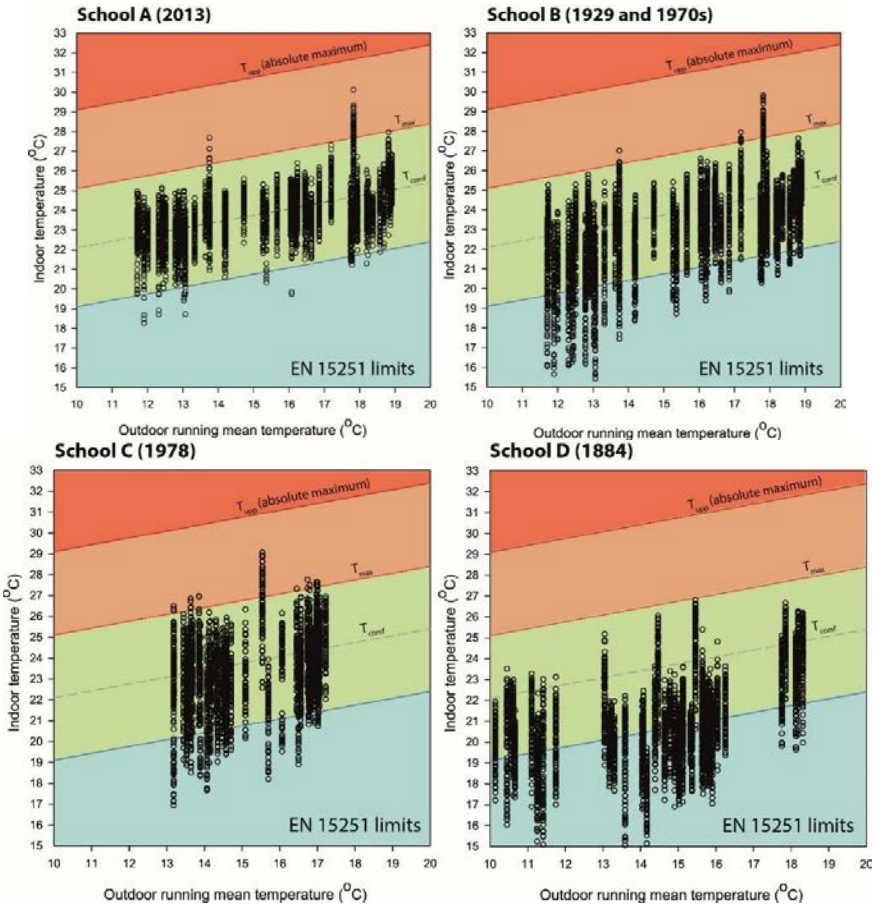

Fig. 2. Measured hourly air temperatures during occupied hours in each school against the outdoor running mean temperature. The EN 15251 temperature limits used for the overheating assessment are also illustrated.

The 1978 lightweight building, the 1970s extension of school B and the newly built school A have the highest percentage of overheating likelihood based on the introduced children's comfort limits, especially at the top floor classrooms. As seen in Table 3, the old medium-weight Victorian building (D) appears to have the best summer performance without any overheating occurrence under both threshold scenarios. School A appears to have quite stable and high air temperatures, suggesting that there is not enough opportunity for heat dissipation (Figure 3 left).

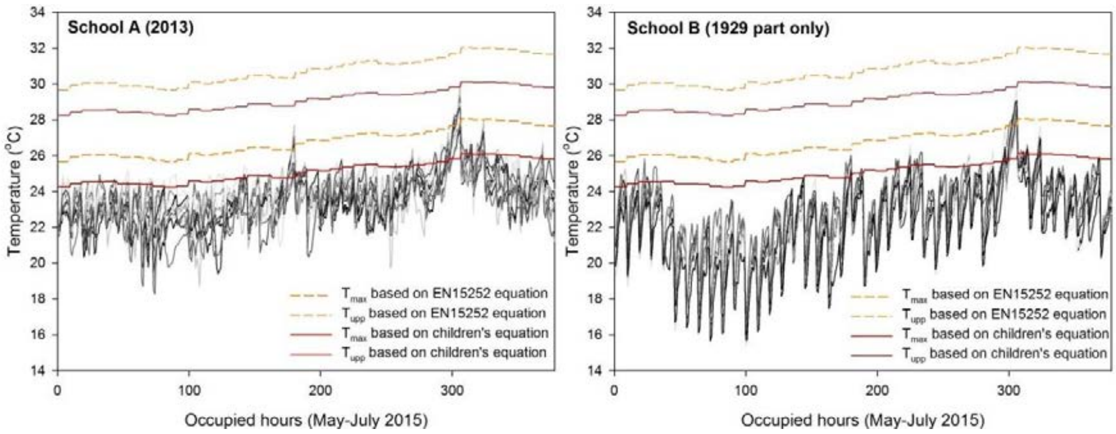

Fig. 3. Measured hourly air temperatures of the occupied hours in schools A (2013) and B (1929 part) against both the EN 15251 temperature limits (dashed orange lines) and the children-based limits (solid red lines).

4. Discussion and conclusions

There is growing evidence regarding the children's lower comfort temperatures and therefore the focus of regulations and industry should shift on addressing this challenge in terms of building design, refurbishment and evaluation of schools' indoor environment. In particular, there are a number of issues that need to be considered when assessing schools' thermal performance during summer: 1) Unlike offices, which have in principle a continuous year-long occupancy and individually determined holiday breaks, the annual school schedule is nationally determined and differs between countries. For example, in Greece due to the climate the school year ends in June followed by a 2 month summer break. In the UK, where hot summers were not traditionally an issue, breaks are distributed throughout the school year, with a smaller summer break. However, increasing global warming and heat wave events suggest that school buildings in the UK (and other Northern European countries) may be more susceptible to overheating now due to the extended occupancy until July and the warmer than historical summers. 2) The overheating assessment periods typically start in May. In locations at high latitudes the early afternoon solar gains can be significant during warm weather. 3) Most importantly, any thermal assessments of the environmental conditions in school buildings and occupant responsive design should use thermal comfort criteria adapted to reflect children's thermal sensation.

This paper used empirical data from thermal comfort surveys in UK primary schools to create an adaptive thermal comfort model for children. The empirical model was subsequently used to evaluate the indoor thermal conditions and the likelihood of overheating occurrence in 43 classrooms in four case study schools. The results suggest that the business as usual practice of using the adult-based overheating thresholds fails to highlight discomfort in classrooms that would be classed as overheating if assessed with the children-based temperature thresholds. When the children-based thresholds are used, approximately 45% of the classrooms were assessed as overheated in comparison to none with the current adult-based comfort model.

From the four schools assessed, the oldest medium-weight building had the best thermal performance during summer under both comfort assessment scenarios. However, its poor thermal insulation suggests that the building is likely to be highly energy inefficient in winter. On the other hand, 64% of the newly built classrooms of school A were found to have a high risk of overheating. This could be explained with the improved air-tightness and insulation of the building in conjunction with safety-related constrained window opening and the lack of external shading and night-purge ventilation. This study highlights a potential 'rebound effect' from a single-sided view on reducing heating loads without taking appropriate measures for thermal comfort in summer. This effect is expected to pose a greater challenge in the following years in lieu of persistent global warming trends and extreme weather events. The challenge that needs to be addressed is to design buildings with year-round acceptable thermal and energy performance and to set higher standards in school building design and other buildings with vulnerable occupants. Passive and low-energy cooling solutions need to be incorporated in the design phase, in order to avoid post-occupancy retrofitting of energy-intensive mechanical cooling systems in countries where cooling has not been an issue before.

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