

ACCEPTED FOR PUBLICATION
AUTHORS SUBMISSION VERSION

Please cite the RPG version of this paper using the following DOI: **10.1016/j.buildenv.2014.10.005**



Building and Environment

Available online 14 October 2014

In Press, Accepted Manuscript — Note to users



The role of a building's thermal properties on pupils' thermal comfort in junior school classrooms as determined in field studies

Despoina Teli^a,  , Mark F. Jentsch^b, Patrick A.B. James^a

^a Sustainable Energy Research Group, Faculty of Engineering and the Environment, University of Southampton, Southampton SO17 1BJ, United Kingdom

^b Urban Energy Systems, Faculty of Civil Engineering, Bauhaus-Universität Weimar, Coudraystrasse 7, 99423 Weimar, Germany

Received 18 July 2014, Revised 15 September 2014, Accepted 5 October 2014, Available online 14 October 2014

 [Show less](#)

DOI: 10.1016/j.buildenv.2014.10.005

 [Get rights and content](#)

The role of a building's thermal properties on pupils' thermal comfort in junior school classrooms as determined in field studies

Despoina Teli^a, Mark F. Jentsch^b, Patrick A.B. James^a

^a *Sustainable Energy Research Group, Faculty of Engineering and the Environment, University of Southampton, Southampton SO17 1BJ, United Kingdom*

^b *Urban Energy Systems, Faculty of Civil Engineering, Bauhaus-Universität Weimar, Coudraystrasse 7, 99423 Weimar, Germany*

Corresponding author: Despoina Teli

Tel: +44 (0)2380592174, E-mail: d.teli@soton.ac.uk

ABSTRACT

Recent thermal comfort research in a light-weight junior school building showed that children were more sensitive to higher temperatures than adults and subsequently that current thermal comfort standards were not appropriate for the assessment of their thermal environment. This paper presents a comparison of these survey results to those from a survey conducted in a medium-weight school building, in order to evaluate the role of the construction type on the results. Both surveys followed the same methodology, including thermal comfort questionnaires and measurements of indoor environmental variables. A total of 2990 responses were gathered. The buildings had an average difference in air temperature of 2.7°C during occupied hours in the period of investigation (June and July 2012), with the medium-weight building being cooler than the light-weight building. However, the different construction type and the cooler overall thermal environment in the medium-weight school building had little impact on the pupils' overall thermal sensitivity. The comparison showed a general agreement on the pupils' warm thermal sensation trends, interpersonal variation and undeveloped adaptive behaviour. The results further support the finding that current thermal comfort criteria lead to an underestimation of pupils' thermal sensation during summer.

Keywords: *School children, Thermal comfort, Thermal adaptation, Climate, School buildings, Thermal mass.*

1. Introduction

The adaptive approach to thermal comfort provides a method to design comfortable indoor environments controlled by occupants for much of the year [1] with the adaptive model basing on the results of thermal comfort surveys mainly in office environments [2]. Reviews on adaptive thermal comfort [2, 3] have listed numerous field studies conducted around the world and identified the lack of surveys with young children. To address this issue a number of field studies have been conducted in schools around the world which cover a range of issues related to the classroom environment at different school stages and in different climates. A number of studies conducted in tropical [4] and subtropical [5-7] locations compared the results from secondary school surveys with the ASHRAE standard 55 [8] thermal comfort model. Al-Rashidi et al. [9] investigated secondary school children's thermal sensation in classrooms in hybrid air-conditioning mode. In general, most thermal comfort studies in schools have focused on secondary schools [4-7, 10-15], differentiating the school sample in terms of climate or ventilation type. A smaller number of studies investigated children's thermal comfort in primary schools [16-19] or included primary schools in the school sample [20, 21].

However, to date no study has investigated children's thermal perception in different building construction types, which is particularly relevant for the case of primary school children which have been found to have a different thermal sensation compared to adults [17-19, 22]. This has also been highlighted in previous work by the authors in naturally ventilated classrooms of a junior school, which showed that children had a higher sensitivity to high temperatures than adults [18, 23]. Based on these findings, currently used thermal comfort standards, such as ISO 7730 [24], EN 15251 [25] and ASHRAE standard 55 [8], and guides, such as CIBSE Guide A [26], were found to be inappropriate for the assessment of classroom thermal environments [18]. Moreover, pupils' neutral temperature (the temperature which corresponds to neutral thermal sensation) was found to be approximately 4°C lower than predicted by the PMV/PPD model [24, 27] and their comfort temperature trend, calculated based on the adaptive thermal comfort model, was determined to be about 2°C lower than that underlying the EN 15251 adaptive comfort limits [25]. Recent studies in school classrooms in different climates reported similar findings in that a lower comfort temperature was observed for children compared to adults [19, 20, 28].

Further to the above, previous research in a large number of primary schools showed that existing overheating criteria for schools provided in the UK Department for Education and Skills Building Bulletins 87 [29] and 101 [30] are too lenient in their overheating assessment [31]. Recently developed overheating criteria for schools based on the adaptive thermal comfort principle [32] were also investigated and were found inadequate to reflect occupant dissatisfaction [31]. These results are alarming for pupils' thermal comfort and school work performance, suggesting that school buildings might not be currently designed according to their main occupants' thermal needs, which could impact on their health, well-being and productivity [33-35].

This paper compares the results from thermal comfort surveys in two different primary school building types. It investigates whether the results from a school survey conducted by the authors in a light-weight post-war building [18] match those from a medium-weight Victorian building. This enables an assessment of whether pupils' higher sensitivity to high temperatures compared to adults found in the first survey [18] was related to the building construction type or to its occupants. The hypothesis that the results from buildings with different thermal properties might not match is based on the fundamental observation of adaptive thermal comfort research that "over time people are usually able to match their comfort temperature to their normal environment" [1]. A particular building construction type, activity or occupant control strategy may define a 'customary temperature' in a building, determining the occupants' comfort temperature [36]. This means that buildings with different thermal properties, and subsequently different indoor thermal environments, can be expected to lead to different thermal comfort temperatures of the occupants [37].

Derived from the above, the objectives of this paper are:

- to compare the thermal environments of the two case study schools,
- to analyse the pupils' thermal comfort and preference trends in relation to the classroom thermal environment and to compare the results between the schools,
- to compare the variation between pupils' responses between the case study schools,
- to explore the impact of the different outdoor and indoor climate conditions experienced over the two survey periods on pupils' thermal perception and adaptive behaviour.
- to compare the pupils' observed thermal satisfaction against the assessment of their thermal environment based on the EN15251 operative temperature limits.

2. Methodology

The field studies were conducted in two junior schools in Southampton (50.9° N, 1.4° W), which is a port city of 250,000 people located on the southern coastline of England. The surveys, which were both carried out outside the heating season, included thermal comfort questionnaire surveys and environmental monitoring. The case study schools and the survey methodology are described below.

2.1 Case study school buildings

Post-war school (2011 survey): The case study post-war school building consists of two parts which create an enclosed courtyard (Figure 1(a)). The study was conducted in the 2-storey L shaped building area which accommodates all 8 classrooms (numbered spaces 1-8 in Figure 1). The building has single-glazed, top-hung outward opening windows with reflective window film and is internally shaded with manually operated blinds.

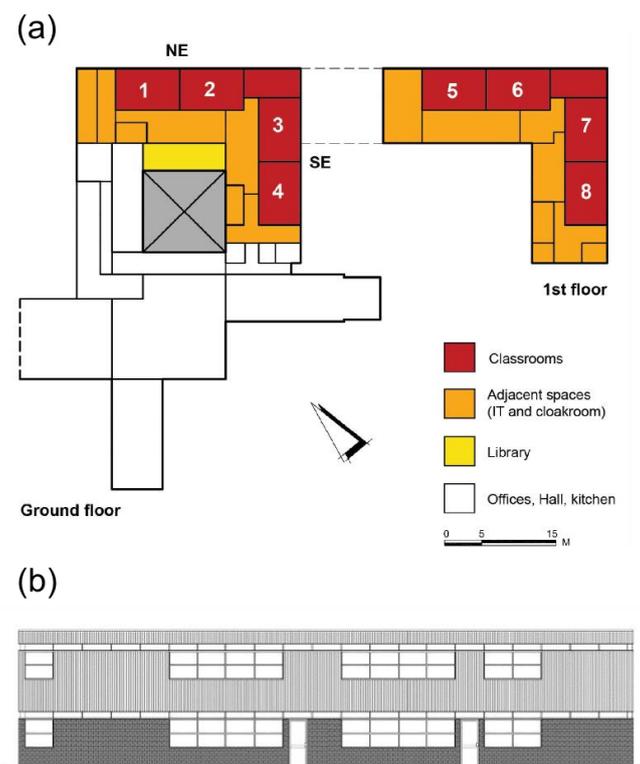
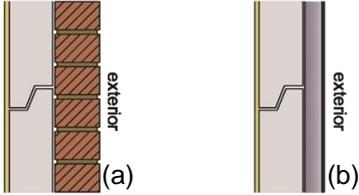
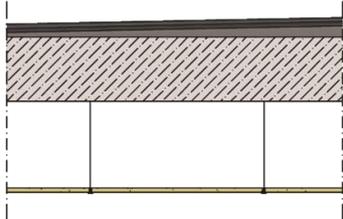
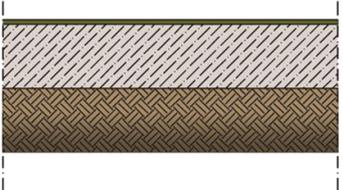
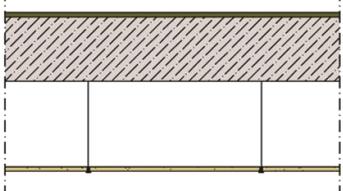


Figure 1. Post war case study school: (a) schematic plans, (b) SE elevation drawing

The building was constructed in 1978 using a steel frame construction and pre-fabricated concrete panels. The composition of each building element and its thermal properties can be seen in Table 1. The wall construction differs between the ground and upper level in terms of the outer skin, which is

exposed brick and metal sheet respectively. As can be seen in Table 1, the calculated building Thermal Mass Parameter (TMP) is 96 kJ/m²K, which is assessed as being “Low”, based on the current assessment procedures SAP and SBEM [38, 39].

Table 1. Building element properties of the post-war school building.

Element	Composition layers	Properties
External wall 	<i>Inside to outside:</i> Plaster Prefab concrete panel (AAC) (a) Brick, (b) Corrugated metal panels	Thickness: (a) 215 mm (b) 116 mm Total surface area: (a) 500 m ² (b) 200 m ² U-Value: (a) 1.17 (b) 1.15 W/m ² K κ-value ¹ : (a) 70 (b) 41 kJ/m ² K Time lag ² : 0.8 h TMP _{element} ³ : (a) 35,000 (b) 8,200 kJ/K
Roof 	Asphalt bonded with bitumen Sand cement screed Prefab Concrete slab Air gap (for services) Plasterboard ceiling tiles	Thickness: 220 mm Total surface area: 1,250 m ² U-Value: 0.9 W/m ² K κ-value: 13 kJ/m ² K Time lag: 0.7 h TMP _{element} : 16,250 kJ/K
Ground floor 	Carpet Prefab Concrete slab Soil	Thickness: 160 mm Total surface area: 1,250 m ² U-Value: 1 W/m ² K κ-value: 66 kJ/m ² K Time lag: n/a TMP _{element} : 82,500 kJ/K
Internal wall (partition) 	Plasterboard Air gab (within steel frame) Plasterboard	Thickness: 95 mm Total surface area: 500 m ² U-Value: n/a κ-value: 7 kJ/m ² K Time lag: n/a TMP _{element} : 3,500 kJ/K
Internal floor 	Carpet Prefab Concrete slab Air gap (for services) Plasterboard ceiling tiles	Thickness: 160 mm Total surface area: 450 m ² U-Value: n/a κ-value: 40 kJ/m ² K Time lag: n/a TMP _{element} : 18,000 kJ/K

Building Thermal Mass Parameter= $TMP_B^4 = \Sigma(TMP_{element}) / (\text{total floor area}) = 96 \text{ kJ/m}^2\text{K}$
LOW THERMAL MASS

Notes:

- ¹ κ -value: the element's thermal capacity per square metre in $\text{kJ/m}^2\text{K}$.
 Thickness used to calculate the κ -value: 100mm starting with the internal layer, as in SAP [38].
 The κ -value was calculated using the 'Dynamic thermal property calculator' [40].
- ² Time lag: time for heat to pass from one side of the element to the other.
- ³ $TMP_{element}$: the element's Thermal Mass Parameter in kJ/K .
- ⁴ TMP_B : The building's thermal mass per square metre total floor area in $\text{kJ/m}^2\text{K}$, calculated based on the calculation method used in SAP [38] and SBEM [39].

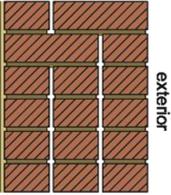
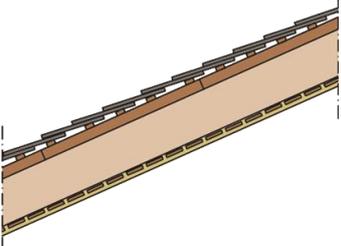
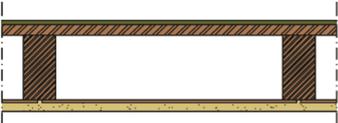
Victorian school (2012 survey): The second case study school building is shown in Figure 2. It comprises of 11 classrooms. As can be seen, most school spaces and 7 classrooms are located on the ground floor and only 4 classrooms and the staff room are on the 1st floor (Figure 2(a)). The study was conducted in all 11 junior school classrooms (numbered spaces 1-11). The classrooms have single-glazed, wooden sash windows with vertically sliding panels and, above them, one row of top-hung outward opening windows (Figure 2(b)). Only one classroom (classroom 10) has internal shading blinds and in 4 classrooms (classrooms 3, 5, 6, 9) improvised shading solutions have been applied, such as sheets of card and canvas posters on parts of the glazing area. The classrooms have ceilings with a height of 3.7 m at the lowest point and 5.6 m at the highest point.



Figure 2. Victorian case study school: (a) schematic plans, (b) NE elevation drawing

The building was built in 1884 using a solid wall system of three courses of brick and a pitched roof covered with slate tiles. Table 2 gives the thermal properties of each building element and the overall thermal mass of the building. The calculated building Thermal Mass Parameter is 235 kJ/m²K, which corresponds to a “Medium” thermal mass.

Table 2. Building element properties of the Victorian school building.

Element	Composition layers	Properties
External wall 	<i>Inside to outside:</i> Plaster Brick masonry	Thickness: 340 mm Total surface area: 1,766 m ² U-Value: 1.4 W/m ² K κ-value ¹ : 169 kJ/m ² K Time lag ² : 8 h TMP _{element} ³ : 298,454 kJ/K
Roof 	Slate Timber board Air gap (between rafters) Lath and plaster	Thickness: 160 mm Total surface area: 2,550 m ² U-Value: 1.6 W/m ² K κ-value: 34 kJ/m ² K Time lag: 2 h TMP _{element} : 86,700 kJ/K
Ground floor 	Carpet Suspended timber floor Floor void (with joists) Soil	Thickness: 235 mm Total surface area: 2,020 m ² U-Value: 1 W/m ² K κ-value: 31 kJ/m ² K Time lag: n/a TMP _{element} : 62,620 kJ/K
Internal wall 	Plaster Brick masonry Plaster	Thickness: 130 mm Total surface area: 1,450 m ² U-Value: n/a κ-value: 109 kJ/m ² K Time lag: n/a TMP _{element} : 158,050 kJ/K
Internal floor 	Carpet Timber floor Air gap with joists Lath and plaster	Thickness: 212 mm Total surface area: 640 m ² U-Value: n/a κ-value: 31 kJ/m ² K Time lag: n/a TMP _{element} : 19,840 kJ/K

$$\text{Building Thermal Mass Parameter} = \text{TMP}_B^4 = \frac{\sum(\text{TMP}_{\text{element}})}{(\text{total floor area})} = 235 \text{ kJ/m}^2\text{K}$$

MEDIUM THERMAL MASS

Notes:

- ¹ κ -value: the element's thermal capacity per square metre in $\text{kJ/m}^2\text{K}$.
Thickness used to calculate the κ -value: 100mm starting with the internal layer, as in SAP [38].
The κ -value was calculated using the 'Dynamic thermal property calculator' [40].
- ² Time lag: time for heat to pass from one side of the element to the other.
- ³ $\text{TMP}_{\text{element}}$: the element's Thermal Mass Parameter in kJ/K .
- ⁴ TMP_B : The building's thermal mass per square metre total floor area in $\text{kJ/m}^2\text{K}$, calculated based on the calculation method used in SAP [38] and SBEM [39].

Table 3 summarises the main thermally relevant characteristics of the two schools with their potential impact on the classrooms' thermal environment as well as differences between the two buildings that may affect their thermal performance. The microclimatic conditions of the areas surrounding the schools are similar, with mostly residential buildings, limited vegetation and mainly tarmac on the outdoor spaces. The classroom design characteristics and furniture layout are also similar between the schools. The U-values of both buildings are similarly high and there is no external shading, which means that high surface temperatures can be expected in both schools. Overall, the main differences between the case study schools are their thermal mass, classroom form and available indoor environment controls.

Table 3. Summary of the thermally relevant characteristics of the two case study buildings.

Characteristic	Post-war school	Victorian school	Impact on indoor environment/differences between the buildings
Building fabric properties	Light-weight construction ($\text{TMP}=96$), low to medium albedo building envelope materials, mean wall U-value= $1.2 \text{ W/m}^2\text{K}$	Medium-weight construction ($\text{TMP}=235$), low albedo building envelope materials, mean wall U-value= $1.4 \text{ W/m}^2\text{K}$	Rapid thermal response of building elements of post-war school, time-delayed response of the Victorian school
Classroom height/ size/ density	2.3m/ 46.2m^2 on average/ $1.7\text{m}^2\text{pp}$	4.7m on average/ 73.5m^2 on average/ $2.7\text{m}^2\text{pp}$	Higher internal gains through occupancy in the densely occupied post-war school classrooms
Glazing to wall ratio/ average window area per classroom	40%/ 7.0 m^2	25%/ 11.4 m^2	Larger glazed areas in the Victorian classrooms: more direct sunlight and solar radiation, but lower % of glazing
Shading	Internal blinds	Variable: none/ internal blinds/ improvised shading	Less shading in the Victorian school

Occupant (teacher) controls and availability

Window and door opening, blinds, fans

Window and door opening, in some classrooms blinds and fans, old window frames: some not openable

Similar controls, in the Victorian school more limited availability

Notes: pp=per person

2.2 Thermal comfort survey methodology

The pupil questionnaire surveys and simultaneous measurements of the indoor environmental variables (as per ISO 7726 [41]) were conducted in both schools in line with standard methods used in adult surveys [1, 2]. Further to this, the dry bulb temperature and relative humidity were monitored at 5 minute intervals during the survey period, from March to July (2011 in the post-war school and 2012 in the Victorian school) using miniature data loggers. The accuracy for the temperature reading is ± 0.5 °C and for the relative humidity the calibrated accuracy is $\pm 3\%$. Two loggers were placed in each classroom and were mounted on the wall, 2m above floor level. The measuring equipment used during the surveys comprises of a multi-functional instrument with probes measuring the air temperature, relative humidity, air speed, radiant temperature and CO₂ concentration. The equipment was placed as centrally in the classroom as possible. The survey questionnaire, which was specifically tailored towards children [18], contained questions looking at the thermal sensation vote (TSV), thermal preference vote (TPV), feeling of comfort, clothing level (jumper on or off), feeling of tiredness and the children's activity level prior to the survey [18]. It was administered to the children and then read out loud slowly, to ensure that the pupils were comfortable filling it out. The surveys were carried out during 2-day visits to the schools, approximately every two weeks depending on the planned school activities. For reasons of clarity and for consistency with previous work [18, 23], the following terms are used in the text:

- "test": a 2-day visit to the school,
- "survey": each classroom investigation.

In total, approximately 560 pupils participated in the surveys and 2990 responses were gathered.

Details on the number of surveys and the data gathered are listed below:

(a) Post-war school (2011): Approximately 230 pupils aged 7-11 in all 8 classrooms were surveyed 6 times (6 tests) and a total of 1314 responses were gathered. The field studies were carried out on 12 days outside the heating season, from April to July 2011. 4 surveys were conducted per day, i.e. 8 surveys per test and 48 surveys in total.

(b) Victorian school (2012): Approximately 330 pupils aged 7-11 in 11 classrooms were surveyed a minimum of 6 times, while some were surveyed 7 times (7 tests). A total of 1676 responses were gathered on 14 survey days from March to July 2012. However, in 3 of the tests the heating was on for a limited time during the day, due to the exceptionally wet and dull summer in 2012 [42]. Overall, 36 surveys were conducted in free-running classrooms and 33 in classrooms with the heating on during parts of the day, equalling 69 surveys in total.

2.3 Weather conditions during the survey periods

A comparison of the weather conditions during the two survey periods (March-July, 2011 and 2012) highlights important differences. Figure 3 shows the mean, maximum and minimum daily dry bulb temperatures for the period of March - July 2011 and 2012 in Southampton, UK (Data from the meteorological station of the National Oceanographic Centre, Southampton [43]). The 10-year averages for the period 2002-2012 of the mean, maximum and minimum daily dry bulb temperatures for the same months are also plotted on the graphs for comparison.

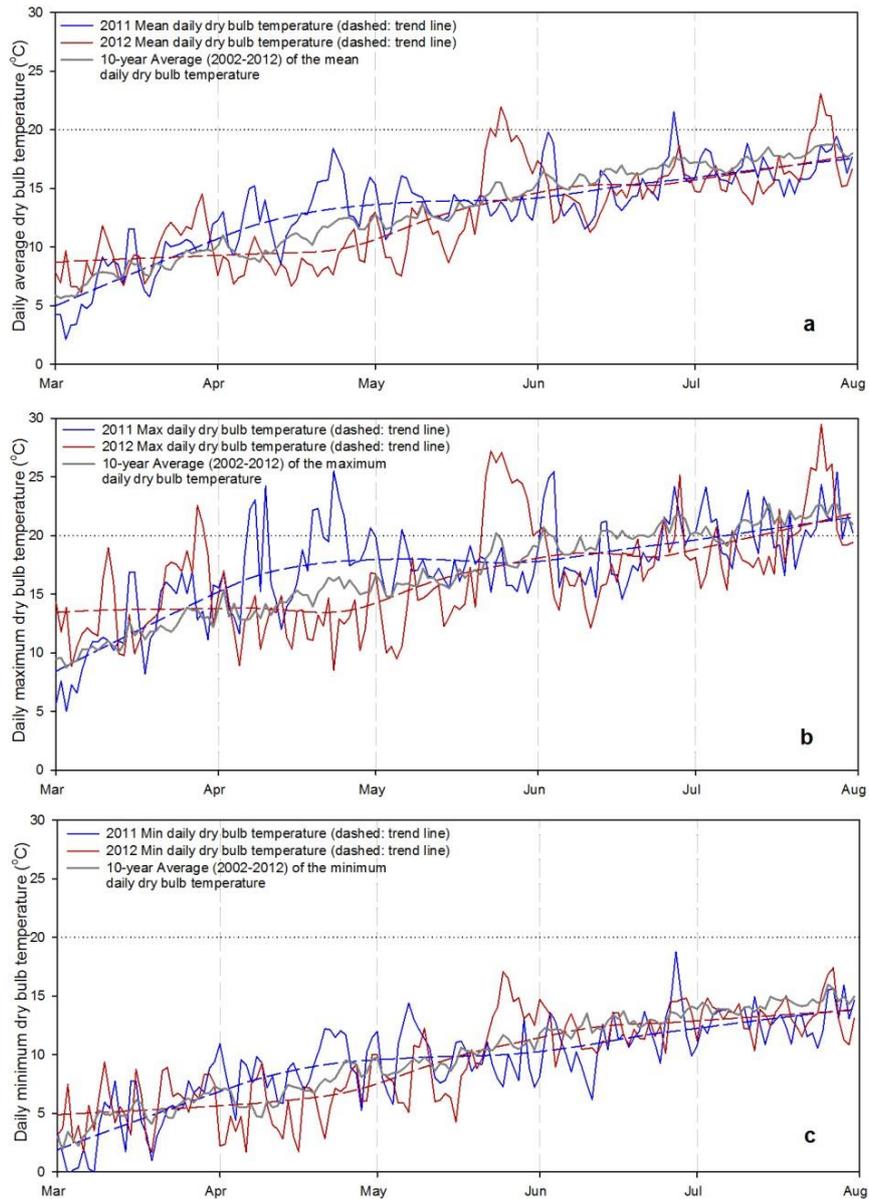


Figure 3. (a) Average, (b) maximum and (c) minimum daily outdoor dry bulb temperature from March to July in 2011 and 2012, with 10-year averages (data from [43])

It can be seen that the outdoor temperature profile of the two years was very different until the beginning of June, with generally lower temperatures in 2012. Furthermore, while in 2011 there was a gradual temperature increase from March to May, in 2012 the temperature trend remained almost flat until May. This may have had an impact on pupils' thermal adaptation, which will be discussed in this paper.

As can be seen in Figure 3(b), the maximum daily dry bulb temperature in 2012 exceeded 20°C on 27 days from March to end of July. In 2011 this occurred on 40 days. Even though the trend lines almost

match from around mid-June onwards, in 2011 the maximum daily dry bulb temperature exceeded 20°C every week in July, which was not the case in 2012.

Figure 4 compares the daily mean outdoor temperatures in 2011 and 2012 with the 10-year average of the daily mean outdoor temperature for Southampton from March to July. It can be seen that in most of April and May, the mean daily temperature was way below the average in 2012 and above the average in 2011. The comparatively cooler April and May of 2012 also led to the heating system being switched on over several days until the end of May.

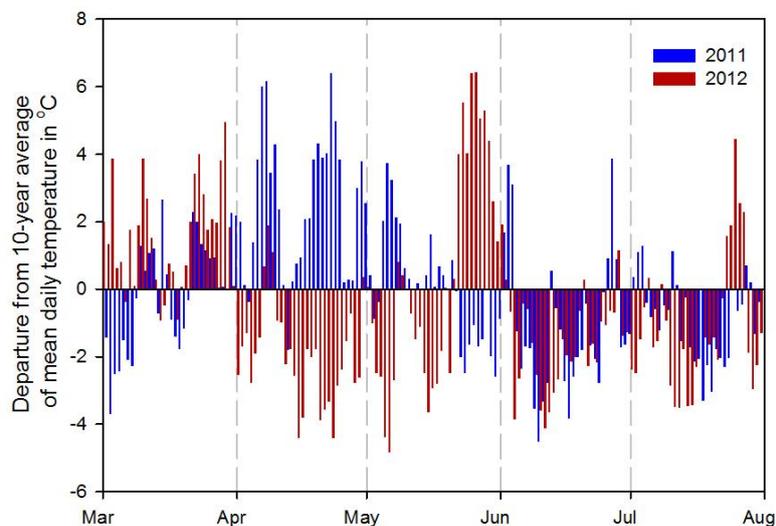


Figure 4. Departure of the 2011 and 2012 daily means of the outdoor temperature from the 10-year average of the mean daily (24h period) temperature, for the period March-July (data from [43])

Apart from the relatively low temperatures in particular in April and early May, June and July 2012 were wetter than normal, with rainfall being almost twice the 1981-2010 monthly average during June 2012 (198%) and 148% of the average during July 2012 [42]. Furthermore, sunshine levels were also significantly below normal in 2012 (70% of the average during June and 81% of the average during July). Overall, June and July 2012 have been considered as “generally cool, wet and dull” [42].

The above analysis shows that, besides the distinctive differences between the two buildings in terms of their construction, there were strong differences in the weather conditions that determined the indoor thermal environment and thermal adaptation during the two case study periods. Inevitably, the

weather anomalies which occurred during the survey period in 2012 affected the Victorian school's indoor thermal environment and determined the operation time of the manually operated heating system. Figure 5 shows the relationship between the measured air temperature in the Victorian school classroom 1 (see also Figure 2) and the ambient temperature, per month and at four time-steps of a day. Only one classroom was investigated for this analysis since the heating system is centrally controlled and therefore the results can be considered as representative of the heating regulation profile of all classrooms for the survey period. The system was designed to meet winter loads and therefore it is reasonable to assume that it can easily meet the heating demand in the entire school for the examined period.

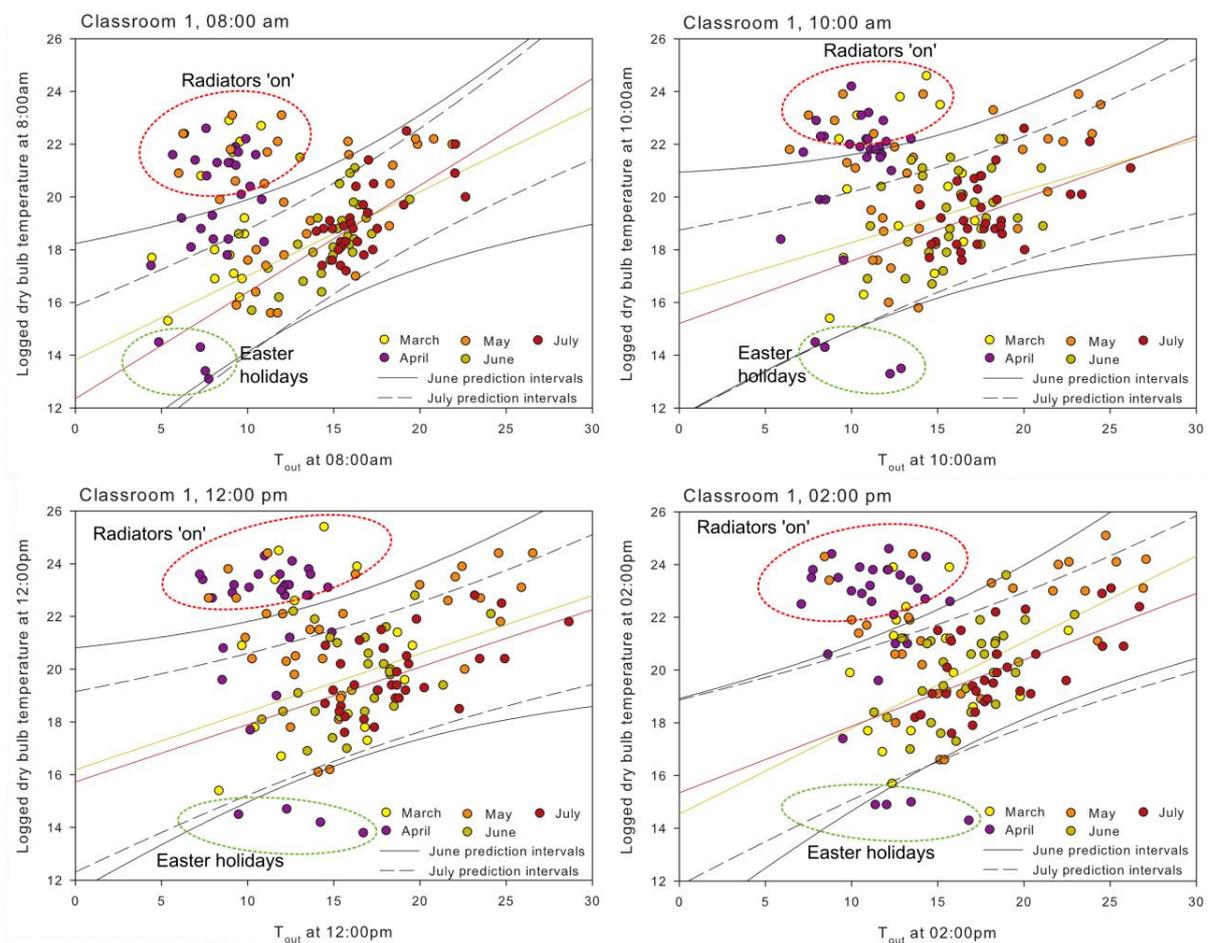


Figure 5. Logged dry bulb temperature of classroom 1 in the Victorian school against the ambient dry bulb temperature at four time-steps: 08.00am, 10.00am, 12.00pm and 02.00pm, plotted for each day of the month from March to July 2012.

In June and July 2012 the building was in free-running mode. Therefore, the classroom temperature profiles of these months were used as a baseline in order to establish when the heating was switched

on in the school. It can be seen that there are indoor temperatures in April and on a few days in March and May which were exceptionally high at ambient temperatures below 15°C, compared to the baseline profiles of June/July. This means that the radiators were switched 'on' over several days in April and on some days in March and May. However, this was not consistently the case but depended on the weather conditions and in some cases the radiators were 'on' only for 1-3 hours each day, in order to bring the school temperatures to an acceptable level. Figure 6 gives an example of the partial use of heating by showing a comparison of the air temperature profile in classroom 1 over two survey days, one early in May and one in the end of June. It can be seen that on the day in May there was a significant temperature rise from 6am to 8am which means that the heating was switched on for those 2 hours. (Solar gains can be excluded as a reason due to the North-West orientation of the classroom as highlighted by Figure 2.) This effect was observed across all 'partial heating' days.

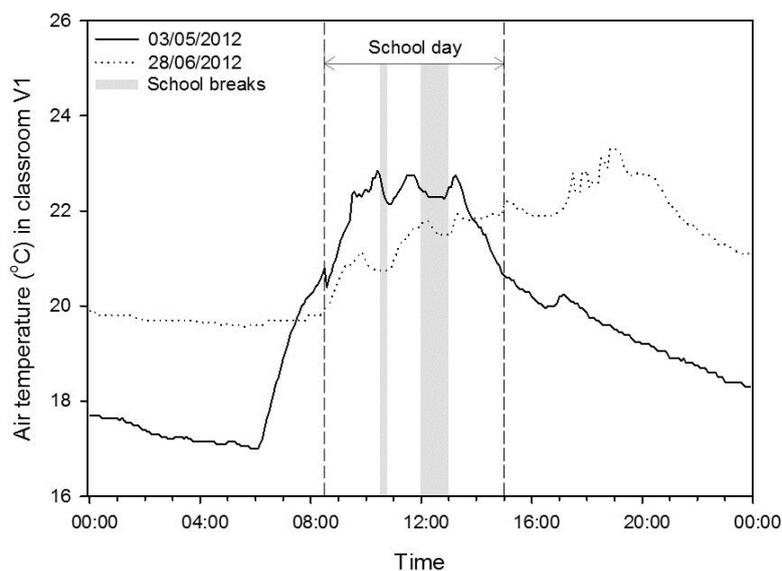


Figure 6. Measured air temperature at 5 minute intervals in classroom 1 of the Victorian school on two days, one when heating was on in the morning (03/05) and one in free-running mode (28/06).

Evidently, due to the manual operation mode of the heating system the end of the heating season or the exact free-running period of the building is not clearly defined. However, based on Figure 3, the rise in outdoor temperature after the first week of May could be considered to mark the starting point of the free-running period, since this also agrees with the results of Figure 5 and the difference in classroom temperature profiles as shown in Figure 6. Therefore, the 2 survey tests conducted in

March and April and the first one in May could be attributed to a transitional period, where the radiators were occasionally switched on.

3. Comparative analysis of the survey results from the two schools

The school surveys are compared in the following sections regarding the classrooms' thermal environment and the pupils' thermal sensation trends, looking at their thermal sensation votes (TSV) and their thermal preference votes (TPV).

3.1 Summary statistics of the two school surveys

From the 1676 survey responses in the Victorian school, 165 were found to be inconsistent, with $TSV+TPV < -3$ or > 3 . These were excluded from the analysis in order to be consistent with the analysis of the post-war case study school as discussed in [23] and [18] where 103 responses were found to be inconsistent. Overall, 9.8% of the gathered responses were excluded from the analysis in the 2012 survey, which is slightly more than that in the 2011 survey (7%).

Figure 7 shows, for each school, box plots of the environmental parameters measured during the surveys as well as the pupils' thermal sensation votes (TSV). The black and red lines inside each box represent the median (50th percentile) and mean values respectively. The boxes' lower and upper limits are the 25th and the 75th percentiles respectively. The whiskers mark the 10th and 90th percentiles and the data points mark the extreme values. The mean air temperature (T_{air}) and mean radiant temperature (T_r) were overall higher in the post-war school (mean $T_{air} = 23.0 > 21.7$ °C and mean $T_r = 23.9 > 22.0$ °C) with a greater difference being determined for the radiant temperature (Figure 7 (a,b)). The relative humidity (RH) in the post-war school ranged from 40-67%, whilst in the Victorian school it varied between 47 and 82% (Figure 7 (c)). Given the high rainfall during the survey period these relatively high RH values for the classrooms in the Victorian school are to be expected. Mean air speeds in the Victorian school's classrooms ranged from 0.07 to 0.12m/s, which is overall slightly higher than in the post-war school classrooms where air speeds rarely exceeded 0.1m/s (Figure 7 (d)).

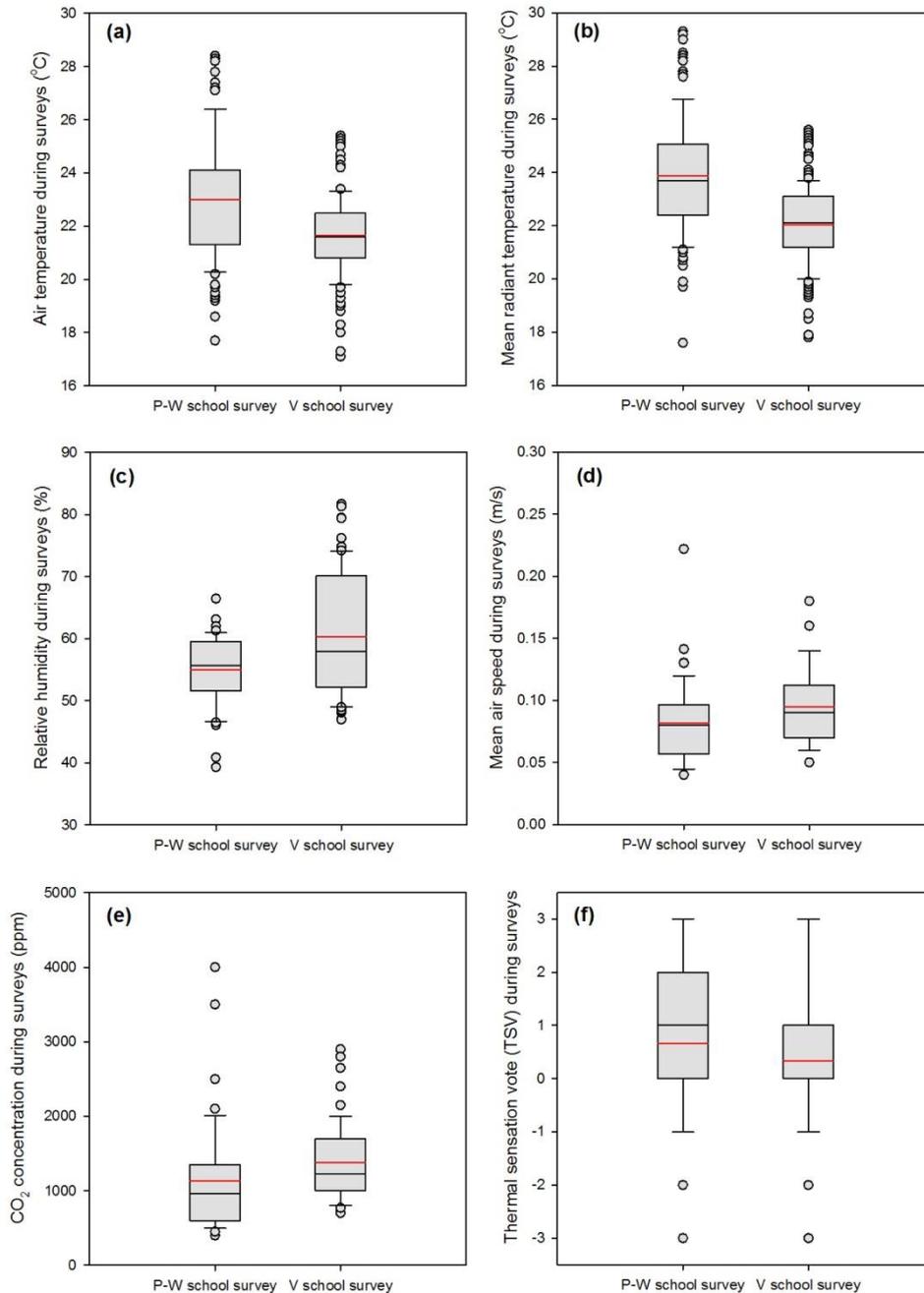


Figure 7. Box plots with the median (black lines), 25th and 75th percentiles (box edges), 10th and 90th percentiles (whiskers), mean values (red lines) and extreme values (dots) of (a) air temperature, (b) mean radiant temperature, (c) relative humidity, (d) air speed, (e) CO₂ concentration and (f) thermal sensation vote during the surveys in the post-war (P-W) and the Victorian (V) school.

The CO₂ concentration was on average higher in the Victorian school, ranging from 700-2,900ppm, compared to 400-2,500ppm in the post-war school (Figure 7 (e)). This is due to the lower outdoor temperatures during the surveys which led to the windows remaining shut. However, there were no extreme readings such as those of around 4,000ppm that occurred in the post-war school when the

windows were shut. This is probably due to the large volume of the Victorian school classrooms (Table 3) and the higher air-change rate, as indicated by the higher airflow measurements (Figure 7 (d)). Overall, the thermal environment in the Victorian school was cooler during the surveys, which is also reflected in the lower thermal sensation votes of the pupils, as can be seen in Figure 7 (f).

3.2 Long-term measured thermal performance

During June and July 2012 temperature monitoring using miniature data loggers was conducted in both schools for comparison of their thermal performance under the same weather conditions. These 2 months corresponded to the time when the Victorian school was in free-running mode. Figure 8 shows the air temperature variation in 8 classrooms (4 in each of the two schools) in relation to ambient temperature and solar radiation during two days in June 2012. It can be seen that, as would be expected, the air temperature in the Victorian school classrooms was significantly lower and had a smaller variation compared to the post-war school classrooms. Classrooms with the same orientation (e.g. PW2 and V5) had an approximately 2°C difference throughout the day. Furthermore, on the 29th of June, when the total horizontal solar radiation was high (800W/m² at around 2 pm) and the ambient temperature reached 26°C, the Victorian school classrooms were cooler (22-24°C) than the outside temperature, whilst in two post-war school classrooms the air temperature almost reached 28°C.

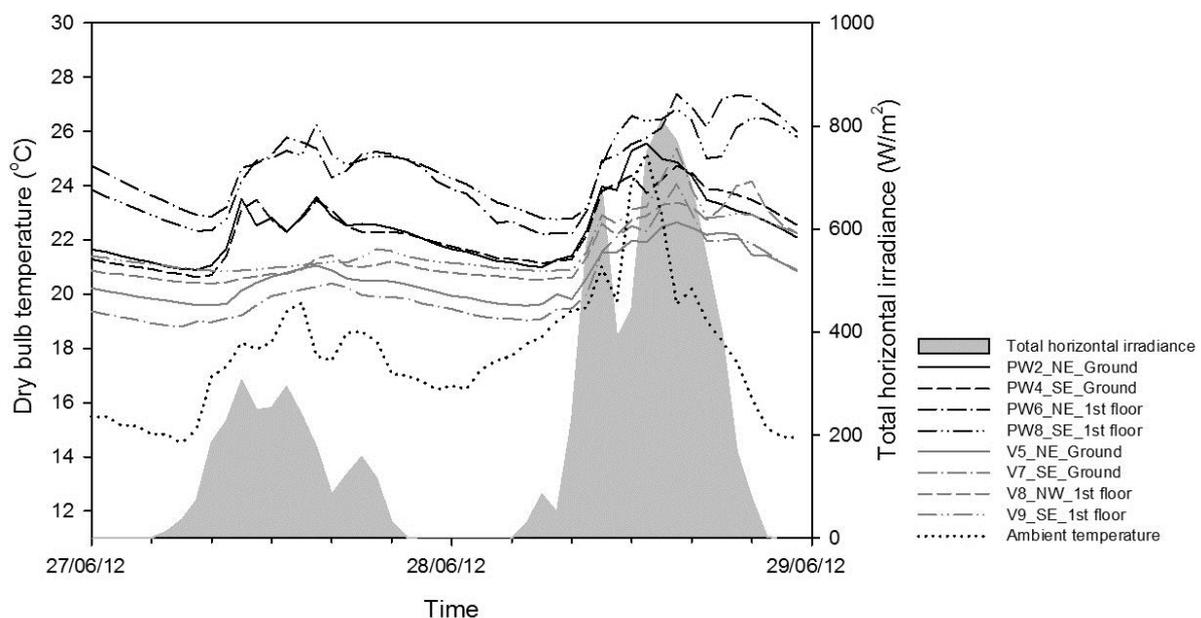


Figure 8. Dry bulb temperature in 4 classrooms of the post-war school and 4 of the Victorian school over a two-day period, in relation to ambient temperature and total horizontal irradiance

Based on the findings presented in Tables 1 and 2, the main reason for this difference is to be attributed to the higher thermal mass of the Victorian school building. The building fabric has the ability to absorb heat during the day, keeping the indoor spaces cooler. The heat is then released with a time delay, when the ambient temperature drops. This ability of the medium-weight Victorian school building helps to stabilise the indoor thermal environment, whilst the light-weight school building has a short response time to weather changes. Therefore, as can be seen in Figure 8, the post-war school is more vulnerable to high ambient temperatures and solar radiation impacts. Further to its light-weight construction, the post-war building has less exposed thermal mass (ceilings) compared to the Victorian building, lower indoor air velocities (Figure 7(d)) and a higher occupancy density (Table 3). These characteristics of the two building types, which led to the different thermal performance of their classrooms as illustrated by Figure 8, can be seen in Figure 9 which shows two typical classrooms. Clearly, pupils in the two schools have been experiencing different thermal environments which is likely to have had an impact on their thermal sensation.



Figure 9. Interior view of two classrooms in the two case study schools, left: post-war school classroom, right: Victorian school classroom

The measured thermal conditions of the warmest classrooms of the two case study schools during summer 2012 were also compared to the adaptive thermal comfort limits of EN 15251 [25] in order to assess the classrooms' performance against current thermal comfort criteria. The two classrooms under investigation are classroom 6 of the post-war (P-W) school (Figure 1), and classroom 9 of the Victorian (V) school (Figure 2).

The classrooms' logged thermal conditions were investigated using the maximum daily temperature, in order to capture the level of exceedance from the EN 15251 comfort limits. The EN 15251 limits correspond to operative temperature limits, accounting for the combined effect of the air and radiant temperatures in a room. However, the long-term monitoring in the classrooms included only the air temperature. Therefore, in order to account for the radiant effect, an approximation for the radiant temperature was used to be able to determine the operative temperature. This was based on the air and radiant temperatures measured during the surveys. This approach does not result in a "calculated" radiant temperature but rather an "estimated" value which provides a better representation of the indoor thermal conditions in the classrooms than using the air temperature alone. For the approximation of the required radiant temperatures at 5 minute intervals, the correlation between the measured air temperatures (T_{air}) and radiant temperatures (T_r) during the surveys in the two schools was taken (i.e. 136 and 218 sets of measurements for the post-war and Victorian school respectively). The linear correlations were strong with $r^2=0.939$ and $r^2=0.935$ respectively, which means that the equations reflect well the general relation of the air temperature to the radiant temperature during school hours and under conditions similar to those encountered during the surveys. The corresponding equations are (1) and (2), for the post-war and the Victorian school respectively.

$$T_{r(P-W)} = 0.93 * T_{air} + 2.53 \quad (1)$$

$$T_{r(V)} = T_{air} + 0.30 \quad (2)$$

The daily maximum operative temperature (T_{op}) was then calculated using the logged maximum air temperatures and the estimated radiant temperatures, for the period from mid-March to the end of July 2012 for classroom 9 (V) and for June-July 2012 for classroom 6 (P-W) taking the average of T_{air} and T_r , which applies for indoor air speeds below 0.1 m/s [26]. This approach can be considered as valid as the measurements during the surveys rarely exceeded 0.1 m/s (Figure 7(d)).

Figure 10 shows the resulting classroom operative temperatures for the Victorian school survey period (March-July 2012). The operative temperature limits as per EN 15251 for the same period were also calculated using the actual outdoor running means (T_{rm}) of Southampton for 2012 as input in the equations given in Annex A2 of EN 15251 [25]. For the comparison with the schools' operative

temperatures, the category III thermal environment of EN 15251 was used, which is defined as “an acceptable, moderate level of expectation and may be used for existing buildings”.

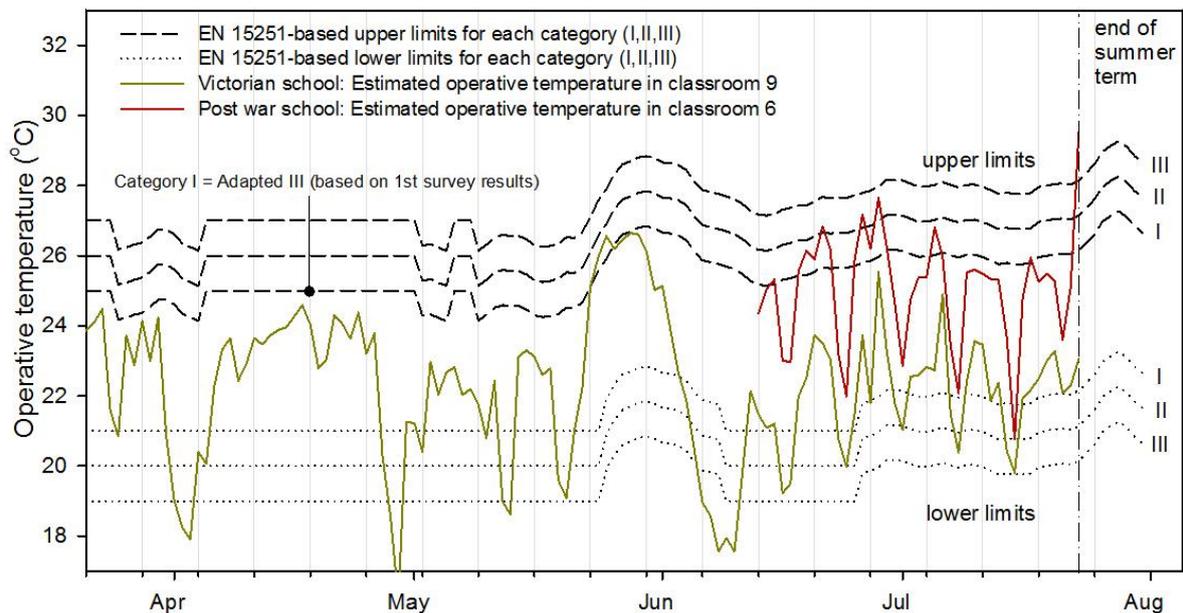


Figure 10. Estimated maximum daily operative temperature for classroom 9 of the Victorian school and classroom 6 of the post-war school in relation to the operative temperature limits for the period of March-July 2012 as calculated from Annex A of EN 15251 [25], using the actual T_{m} .

It can be seen that the Victorian school classroom performs well according to the EN 15251 limits, always falling within the category III comfort zone (only on weekends T_{op} occasionally falls below the lower limit). Based on the results of the post-war school pupil survey [18, 23], a stricter limit that lies 2°C lower than the original limit would be required for children, which essentially represents an EN 15251 category I thermal environment. Even when using that stricter upper limit (current Category I), the Victorian school classroom remains within the acceptability limits and only slightly exceeds the line during the hot spell at the end of May. In contrast, classroom 6 of the post-war school appears to frequently exceed the adapted stricter upper limit (current Category I), which agrees with the observations from the 2011 survey described in [18].

Figure 10 further highlights the different long-term thermal performance of the investigated schools, with the estimated operative temperature in the post-war school classroom being constantly about 2°C higher than in the Victorian school classroom. Based on the existing EN 15251 comfort limits for a category III thermal environment, both schools perform well with operative temperatures within the

limits. However, if an adapted upper limit is used to reflect the higher thermal sensitivity of children observed in the post-war school survey in 2011 [18], then the light-weight school building presents an alarming exceedance during the months of the monitoring. Considering that more extreme radiant temperatures could have occurred, compared to those estimated with equations (1) and (2), exceedance of the limits and henceforth thermal discomfort may have been even more intense. Given the large number of this type of school in the UK, it is likely that many pupils in the UK frequently experience unacceptably warm thermal conditions in classrooms outside the heating season. However, the medium-weight Victorian building appears to provide acceptable thermal conditions, based on the current EN15251 comfort limits as well as those adapted for children's thermal sensation according to the previous findings from the post-war school survey [18].

The air temperature difference between the two schools was determined as on average 2.7°C during occupied hours (weekdays 9am-3pm) in the free running period of 2012, with the average measured air temperatures being 23.4°C and 20.7°C for the post-war and Victorian buildings respectively. Evidently, the pupils in the post-war school have been experiencing higher air temperatures in classrooms than pupils in the Victorian school. Based on the basic adaptive relationship between neutral temperature and mean indoor temperature [1], this difference could potentially lead to different comfort temperatures between the schools.

3.3 Interpersonal differences and adaptive behaviour

The interpersonal differences within surveys were determined using the standard deviations of the $TSV_{(mean)}$ calculated for each survey. The results for the Victorian and the post-war school survey were found to be consistent, with the standard deviation values ranging from 0.8 to 2.0 scale units in the Victorian school, which was slightly higher than those in the post-war school (0.7-1.8). However, the average of 1.5 was identical for both school surveys. This result supports the argument that, in a school environment, occupants may engage in different activities which may impact on their individual thermal perception [16, 23]. On the contrary, in other everyday environments, such as offices, occupants experience mostly the same activity level throughout a day, which can explain the lower mean standard deviation of 1.07 scale units found from studies with adults [2]. This highlights the invalidity of generalised criteria for everyday environments without taking into account the

particularities involved, especially with regards to the occupants and the variability in the activities they undertake.

Further to the variable schedule, the clothing change behaviour of pupils could also be a cause of interpersonal differences in thermal sensation. As previously discussed with respect to the post-war school, pupils' response to thermal change through changing clothing levels was often not as immediate as it would ideally have been in order to avoid thermal discomfort [18]. As can be seen in Figure 11 this finding is also supported by the Victorian school survey responses on whether respondents were wearing their jumper (pullover) during the surveys. In fact, the results are more critical than those from the post-war school survey since 51% of the children who voted 'hot' and 58% of those who voted 'warm' still wore their jumper, while in the post-war school survey the percentages were 15% and 25% respectively (Figure 11). A possible explanation for this may be the lower ambient temperatures experienced in 2012 compared to 2011. Indeed, most of these responses were given in surveys conducted in April and May, after the lunch break. This means that children had stayed outside, at much lower temperatures than indoors, for up to one hour before the survey and they most probably did not think of changing their clothing after coming back inside.

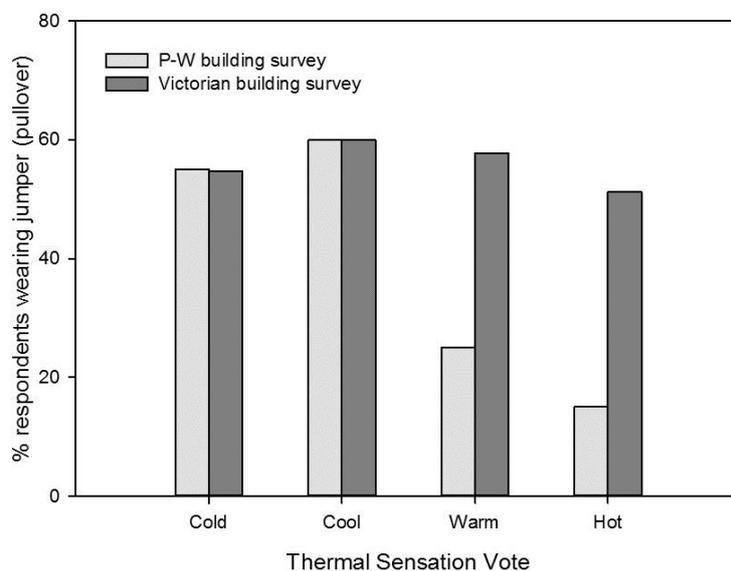


Figure 11. Percentage of subjects wearing their jumper (pullover) voting for thermal sensations expressing dissatisfaction [-3, -2, +2, +3] in the post-war (P-W) and the Victorian (V) school

Overall, immediate behavioural thermoregulation, which is an important aspect of human interaction with the environment [1], appears to be underdeveloped in primary school children. This highlights the

importance of maintaining acceptable thermal conditions in classrooms, as, based on the results of this study, children's adaptive action may not be as immediate as required in order to avoid thermal discomfort.

Figure 12 shows the survey mean clothing insulation (clo) values in relation to the classroom operative temperature (T_{op}) of both school surveys. Children in both schools wear uniforms, with similar clothing combinations. As can be seen in Figure 12, the scatter of mean 'clo' values is larger in the Victorian school surveys which can be attributed to the cooler weather conditions that occurred in 2012 and the lower average T_{op} in the Victorian school. However, it can be seen that, the mean 'clo' regression slopes are identical ($= -0.02 \text{ clo}/^{\circ}\text{C}$) and therefore the rate of average 'clo' decrease as a function of the classroom operative temperature was generally the same between the two schools. However, there is a constant mean 'clo' difference of 0.15 as pupils in the Victorian school were generally dressed with slightly warmer clothing than in the post-war school. This cannot be associated with the outdoor temperature, as for the same operative temperature inside the schools, the outdoor temperature would be expected to be higher in the case of the Victorian school survey and therefore would have led to the pupils wearing fewer clothes, rather than more. This means that the warmer clothing in the Victorian school is related to a perceived cooler thermal environment, as compared to the post-war school, for identical operative temperatures, which may be due to lower radiant temperatures, especially at the start of the school day. Figure 13 shows the measured mean radiant temperature against the air temperature during the surveys in both schools. It can be seen that the mean radiant temperature in the Victorian school is overall lower than in the post-war school building for the same air temperature. The warmer clothing could be therefore a long-term adaptation, i.e. a 'learned behaviour', relating to low winter radiant temperatures pupils experience in Victorian buildings.

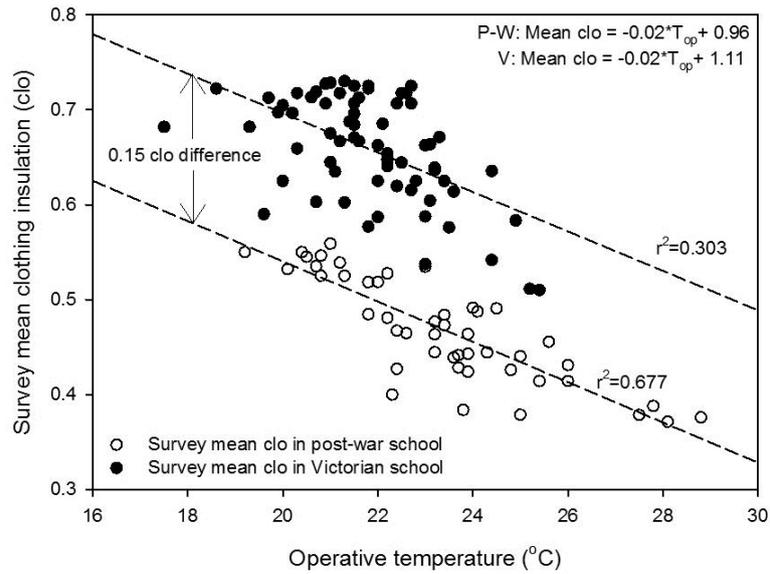


Figure 12. Mean clothing insulation (clo) per survey and by school, against the operative temperature.

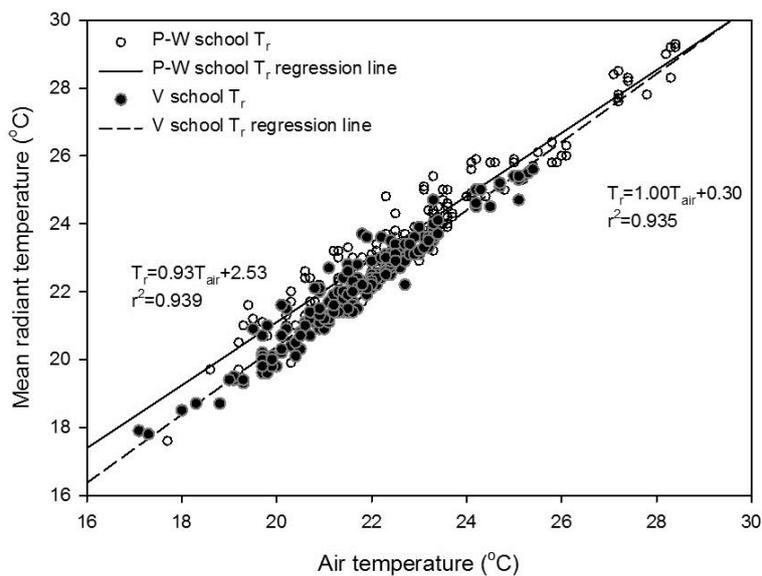


Figure 13. Mean radiant temperature measured during the surveys in the post-war (P-W) and the Victorian (V) school.

3.4 Thermal sensation, preference and comfort temperature

The mean thermal sensation votes ($TSV_{(mean)}$) and mean thermal preference votes ($TPV_{(mean)}$) were calculated for all surveys in both schools. Figure 14 shows the $TSV_{(mean)}$ and $TPV_{(mean)}$ of the 69 Victorian school surveys plotted against the operative temperature (T_{op}). Strong agreement was found between the two school surveys in the resulting linear regressions. Similarly, the survey values for the neutral (T_n) temperature (corresponding to a $TSV_{(mean)}=0$) and the preferred (T_p) temperature

(corresponding to a $TPV_{(mean)}=0$) were almost identical for both surveys. As can be seen in Figure 14, the pupils of the Victorian school survey furthermore appear to have had a preference towards a warmer than their neutral thermal state ($T_n < T_p$). This is again the same as for the pupils in the post-war school [18] and appears to be an indication for the representativeness of the data for primary school children's thermal sensation and preference.

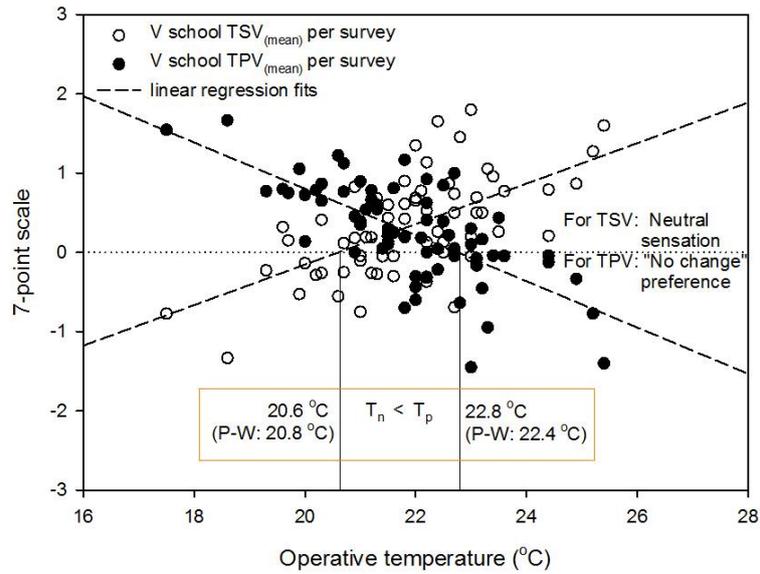


Figure 14. Mean thermal preference vote ($TPV_{(mean)}$) and mean thermal sensation vote ($TSV_{(mean)}$) for each survey in the Victorian school plotted against the operative temperature (T_{op}). The regression lines are also included.

In addition to the above, the mean comfort temperature (T_{comf}) was calculated for each survey from the pupils' mean thermal sensation votes using equation (3) [2] below:

$$T_{comf} = T_{op} - \frac{TSV}{b} \quad (3)$$

where T_{op} is the operative temperature, TSV the thermal sensation vote and $b=0.5$ the Griffiths constant [44]. The Griffiths constant has been previously investigated for the school sample and was found to overall correspond to pupils' response to indoor temperature changes, assuming minimal adaptation throughout the day [45]. Furthermore, the Griffiths constant was used for derivation of the EN 15251 adaptive comfort equation [44] which is used in this paper for comparison with the survey results.

Figure 15 shows the mean comfort temperatures of all surveys per school against the operative temperature during the survey. It can be seen that the data points generally fit well between the schools and that the regression lines are nearly identical. This means that the pupils' mean comfort temperature in response to the indoor temperature was very similar between the two schools and that the pupils appear to have had the same sensitivity to indoor temperature changes (almost identical regression slope). Therefore, even though the pupils in the two schools had experienced different thermal environments, they had the same overall response to indoor temperature changes over the prolonged survey period. This indicates that the building's thermal environment appears to have a limited impact on the general correlations in terms of the thermal perception of primary school children.

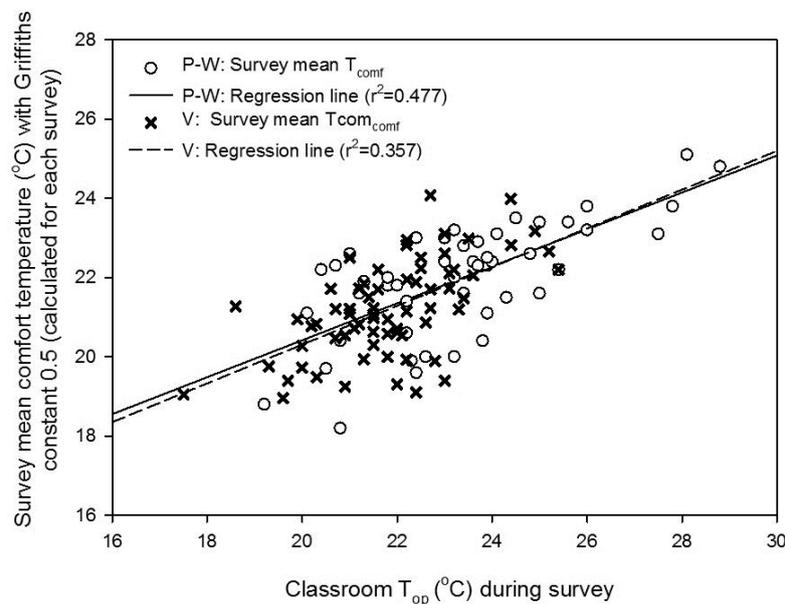


Figure 15. Mean comfort temperature for each survey in both schools (P-W: post-war school, V: Victorian school) plotted against the operative temperature (T_{op}) during the survey. The regression lines are also included.

Overall, it is evident that the results of the two school surveys agree well in terms of pupils' general sensation trends, interpersonal differences, neutral and preferred temperatures and clothing adaptation. The Victorian school survey results indicate that pupils have a different thermal perception to adults, lower neutral and preferred temperatures, higher interpersonal variation and underdeveloped immediate behavioural thermoregulation. This also agrees with the findings of the 2011 post-war school survey.

3.5 Pupils' thermal satisfaction in relation to the EN15251 assessment for buildings without mechanical cooling systems

Figure 16 shows the operative temperatures during all 117 surveys conducted in the two schools in relation to the EN 15251 temperature limits for buildings without mechanical cooling [25]. The required outdoor running mean was calculated as described in [44] using data from the National Oceanographic Centre in Southampton [43]. The operative temperatures of the Victorian school surveys were grouped in two categories based on whether the surveys were conducted when the building was in free-running mode or in the transitional mode with the radiators occasionally switched on. For the assessment of the classrooms' thermal environment during the transitional period the dashed limits were used, which apply for the heating season [25]. These temperature limits are PMV-based and are calculated with an assumed clothing insulation of 1.0 clo, which is higher than the 'clo' value of 0.75 mostly encountered during the surveys in the transitional period (Figure 12).

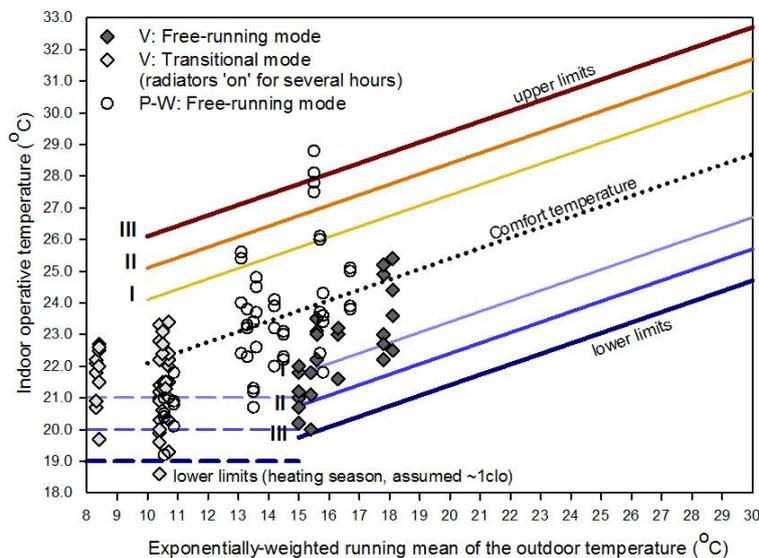


Figure 16. Survey operative temperatures in both schools on the EN 15251 diagram for acceptable indoor temperatures in buildings without mechanical cooling systems [25] (P-W: post-war school, V: Victorian school).

As can be seen in Figure 16, the majority of the data points are within the temperature limits for category III of EN 15251, which denotes “an acceptable, moderate level of expectation and may be

used for existing buildings” [25] and is considered to correspond to 85% of thermally satisfied people. Based on the Victorian school survey results, in all but 1 survey the operative temperature lies within the limits. However, only in 6 out of 69 surveys the actual percentage of satisfied (pupils who voted ‘-1’, ‘0’ or ‘+1’) exceeded 85%, similar to the post-war survey results [18]. Furthermore, most indoor operative temperatures during the surveys fall below the EN 15251 ‘comfort temperature’ line, within the lower temperature limits (Figure 16). However, as can be seen in Figure 17, the ‘warm dissatisfied’ votes were more than the ‘cold dissatisfied’ votes. Therefore, the assessment of the Victorian school classrooms’ thermal environment as per EN 15251 shows an underestimation of pupils’ thermal sensation, similar to the results of the post-war school survey. Given the differences in the underlying weather conditions in spring and early summer 2011 and 2012 (see section 2.3) this is an interesting result as it reinforces the notion that children in school classrooms appear to have a different thermal sensation to adults in offices. As previously highlighted [16, 18, 20] this could be related to the children’s limited access to classroom controls (i.e. windows, blinds, doors) and their limited clothing adaptation over a day.

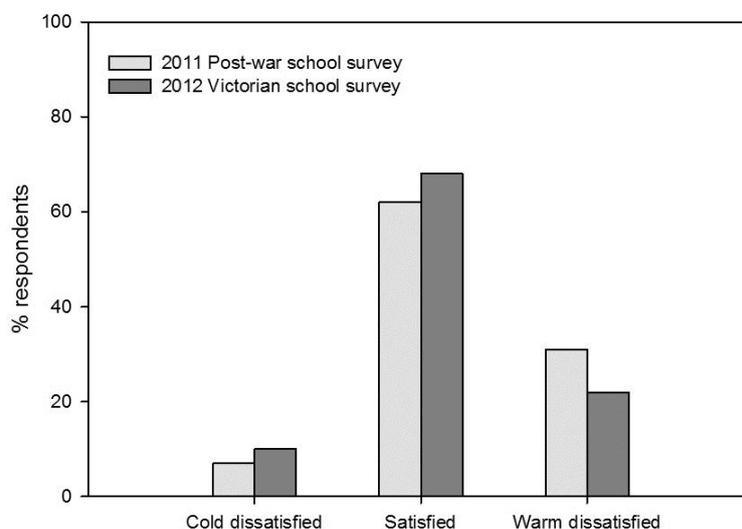


Figure 17. Percentage of thermally satisfied (pupils who voted -1, 0, +1 on the thermal sensation scale) and dissatisfied respondents (Cold dissatisfied: -3, -2/ Warm dissatisfied: +2, +3) in both school surveys.

4. Conclusions

In this paper, the results from a Victorian school thermal comfort survey conducted in 2012 were compared with those from a survey in a post-war school in 2011. This helped to investigate whether the warmer thermal sensation of pupils found in the post-war school survey compared to adults was related to the specific type of school building and/or past experiences of the pupils in the school. The results of the comparative analysis highlight the following:

- The medium-weight Victorian school classrooms were overall cooler than the light-weight post-war school classrooms, by an average of 2.7°C during occupied hours. The estimated operative temperatures were always within the EN 15251 comfort limits for both the existing and the adapted limits based on pupils' higher thermal sensitivity than adults as determined in the post-war school survey.
- The surveys highlighted the strong interpersonal differences between pupils due to their variable activities. Furthermore, it was shown that maintaining acceptable thermal conditions in classrooms is critical, as pupils' immediate adaptive action to avoid discomfort appears to be limited.
- The pupils' mean thermal sensation in relation to the operative temperature during the surveys was very similar between the two schools suggesting that, overall, the different thermal environments did not lead to different comfort temperatures.
- The operative temperatures of both the Victorian and the post-war school building surveys lie within the EN 15251 comfort limits, suggesting a high level of thermal satisfaction, which did not match with the survey results. A higher warm dissatisfaction than predicted was observed in the Victorian school survey results, which agrees with the observations from the post-war school survey.

Overall, the results from the Victorian school survey show that, even though the school performs well outside the heating season and there was no concern about summer overheating occurrences, the pupils felt warmer than would be expected. This finding of a higher sensitivity towards feeling warm concurs with the findings from the post-war school survey, which was however conducted under different weather conditions with higher ambient temperatures [18]. This suggests that the different

construction type and, more importantly, the overall cooler thermal environment in the Victorian school had little to no impact on the general thermal sensation trend of the school children. In essence, the 2012 Victorian school survey results validate the finding of a higher sensitivity of pupils to higher indoor temperatures as determined in the 2011 post-war school survey, as well as in other surveys conducted under various climate conditions [17, 19, 20, 28]. It is therefore clear that further guidance is required in school building design and refurbishment based on thermal comfort research with children in order to achieve environmental conditions which reflect children's thermal preferences.

Acknowledgements

The authors are grateful to the teachers and pupils of Bitterne CoE Junior school (year 2011) and St. Mark's CoE primary school (year 2012), Southampton, for their participation in this research.

References

- [1] F. Nicol, M. Humphreys, S. Roaf, Adaptive thermal comfort: Principles and practice, Routledge, London, 2012.
- [2] M.A. Humphreys, J.F. Nicol, I.A. Raja, Field Studies of Indoor Thermal Comfort and the Progress of the Adaptive Approach, *Advances in Building Energy Research*, 1 (1) (2007) 55-88.
- [3] A.K. Mishra, M. Ramgopal, Field studies on human thermal comfort — An overview, *Building and Environment*, 64 (0) (2013) 94-106.
- [4] N.H. Wong, S.S. Khoo, Thermal comfort in classrooms in the tropics, *Energy and Buildings*, 35 (4) (2003) 337-351.
- [5] A.G. Kwok, C. Chun, Thermal comfort in Japanese schools, *Solar Energy*, 74 (3) (2003) 245-252.
- [6] R.-L. Hwang, T.-P. Lin, C.-P. Chen, N.-J. Kuo, Investigating the adaptive model of thermal comfort for naturally ventilated school buildings in Taiwan, *International journal of biometeorology*, 53 (2) (2009) 189-200.
- [7] H.-H. Liang, T.-P. Lin, R.-L. Hwang, Linking occupants' thermal perception and building thermal performance in naturally ventilated school buildings, *Applied Energy*, 94 (0) (2012) 355-363.
- [8] ASHRAE, ANSI/ASHRAE Standard 55- Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 2010.
- [9] K.E. Al-Rashidi, D.L. Loveday, N.K. Al-Mutawa, Investigating the Applicability of Different Thermal Comfort Models in Kuwait Classrooms Operated in Hybrid Air-Conditioning Mode, in: R.J. Howlett, L.C. Jain, S.H. Lee (Eds.) *Sustainability in Energy and Buildings*, Springer Berlin Heidelberg, 2009, pp. 347-355.
- [10] S.P. Corgnati, M. Filippi, S. Viazzo, Perception of the thermal environment in high school and university classrooms: Subjective preferences and thermal comfort, *Building and Environment*, 42 (2) (2007) 951-959.
- [11] M.A. Humphreys, Classroom temperature, clothing and thermal comfort-A study of secondary school children in summertime, *Building Services Engineer*, 41 (1973) 191-202.
- [12] F.R. d'Ambrosio Alfano, E. Ianniello, B.I. Palella, PMV–PPD and acceptability in naturally ventilated schools, *Building and Environment*, 67 (0) (2013) 129-137.
- [13] A. Auliciems, Thermal requirements of secondary schoolchildren in winter, *Epidemiology & Infection*, 67 (01) (1969) 59-65.

- [14] A. Auliciems, Thermal sensations of secondary schoolchildren in summer, *Epidemiology & Infection*, 71 (03) (1973) 453-458.
- [15] L. Dias Pereira, D. Raimondo, S.P. Corgnati, M. Gameiro da Silva, Assessment of indoor air quality and thermal comfort in Portuguese secondary classrooms: Methodology and results, *Building and Environment*, 81 (0) (2014) 69-80.
- [16] M.A. Humphreys, A study of the thermal comfort of primary school children in summer, *Building and Environment*, 12 (4) (1977) 231-239.
- [17] S.t. Mors, J.L.M. Hensen, M.G.L.C. Loomans, A.C. Boerstra, Adaptive thermal comfort in primary school classrooms: Creating and validating PMV-based comfort charts, *Building and Environment*, 46 (12) (2011) 2454-2461.
- [18] D. Teli, M.F. Jentsch, P.A.B. James, Naturally ventilated classrooms: An assessment of existing comfort models for predicting the thermal sensation and preference of primary school children, *Energy and Buildings*, 53 (0) (2012) 166-182.
- [19] M. Trebilock, R. Figueroa, Thermal comfort in primary schools: a field study in Chile, *Counting the Cost of Comfort in a changing world*, 10-13 April 2014, Cumberland Lodge, Windsor, UK, 2014.
- [20] R. de Dear, J. Kim, C. Candido, M. Deuble, Summertime Thermal Comfort in Australian School Classrooms, *Counting the Cost of Comfort in a changing world*, 10-13 April 2014, Cumberland Lodge, Windsor, UK, 2014.
- [21] A. Auliciems, Warmth and comfort in the subtropical winter: a study in Brisbane schools, *Epidemiology & Infection*, 74 (03) (1975) 339-343.
- [22] R.J. de Dear, G.S. Brager, The adaptive model of thermal comfort and energy conservation in the built environment, *International journal of biometeorology*, 45 (2) (2001) 100-108.
- [23] D. Teli, P.A.B. James, M.F. Jentsch, Thermal comfort in naturally ventilated primary school classrooms, *Building Research & Information*, 41 (3) (2013) 301-316.
- [24] ISO, EN ISO 7730:2005 Ergonomics of the thermal environment- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, International Standardisation Organisation, Geneva, 2005.
- [25] CEN, EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, CEN (European Committee for Standardization), Brussels, 2007.
- [26] CIBSE, Guide A-Environmental design, Chartered Institution of Building Services Engineers, London, 2006.

- [27] P.O. Fanger, Thermal Comfort: Analysis and Applications in Environmental Engineering, Mc Graw-Hill, New York, 1970.
- [28] S. Haddad, P. Osmond, S. King, S. Heidari, Developing assumptions of metabolic rate estimation for primary school children in the calculation of the Fanger PMV model, Counting the Cost of Comfort in a changing world , 10-13 April 2014, Cumberland Lodge, Windsor, UK, 2014.
- [29] DfES, Building Bulletin 87. Guidelines for Environmental Design in Schools, UK Department for Education and Skills, 2003.
- [30] DfES, Building Bulletin 101. Ventilation of School Buildings, UK Department for Education and Skills, 2006.
- [31] A. Montazami, F. Nicol, Overheating in schools: comparing existing and new guidelines, Building Research & Information, 41 (3) (2013) 317-329.
- [32] Johnston and Partners, EFA PSBP Natural Ventilation Strategy, 2012.
- [33] D.P. Wyon, I. Andersen, J. Sundell, e. al, The effects of moderate heat stress on mental performance, Scand J Work Environ Health, 5 (4) (1979) 352-361.
- [34] A. Enander, S. Hygge, Thermal stress and human performance, Scandinavian Journal of Work, Environment & Health, 16 (suppl 1) (1990) 44-50.
- [35] D. Clements-Croome, Creating the productive workplace, Second ed., Spon-Routledge, 2006.
- [36] J.F. Nicol, M.A. Humphreys, New standards for comfort and energy use in buildings, Building Research and Information, 37 (1) (2009) 68-73.
- [37] M.A. Humphreys, H.B. Rijal, J.F. Nicol, Updating the adaptive relation between climate and comfort indoors; new insights and an extended database, Building and Environment, 63 (0) (2013) 40-55.
- [38] BRE, The Government's Standard Assessment Procedure for Energy Rating of Dwellings, 2014.
- [39] BRE, SBEM: Simplified Building Energy Model, BRE, 2014.
- [40] ARUP, Dynamic Thermal Properties Calculator, MPA-The Concrete Centre, 2010.
- [41] ISO, EN ISO 7726:2001 Ergonomics of the thermal environment- Instruments for measuring physical quantities, International Standardisation Organisation, Geneva, 2001.
- [42] Met Office, <http://www.metoffice.gov.uk/>, 11/10/11.

[43] NOCS, Meteorological station. National Oceanographic Centre, Southampton. A collaboration between NOCS & Met Office, http://www.noc.soton.ac.uk/noc_intranet/metstation/index.html, 20/06/14.

[44] J.F. Nicol, M.A. Humphreys, Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251, *Building and Environment*, 45 (1) (2010) 11-17.

[45] D. Teli, P.A. James, M.F. Jentsch, Do the constants used in adaptive comfort algorithms reflect the observed responses of children in junior school classrooms?, *Proceedings of 8th Windsor Conference: Counting the Cost of Comfort in a changing world*, 2014.