Proceedings of 7th Windsor Conference: ***The changing context of comfort in an unpredictable world*** Cumberland Lodge, Windsor, UK, 12-15 April 2012. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Field study on thermal comfort in a UK primary school

Despoina Teli*, Mark F. Jentsch, Patrick A.B. James, AbuBakr S. Bahaj

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

*Corresponding author. Tel: +44 (0)2380592134, E-mail: dt1e09@soton.ac.uk

Abstract

This paper presents findings from a field survey in a naturally ventilated primary school building in Southampton, UK. The study included thermal comfort surveys and simultaneous measurements of indoor environmental variables. Approximately 230 pupils aged 7-11 in all 8 classrooms of the school were surveyed in repeated survey runs outside the heating season, from April to July 2011. In total 1314 responses were gathered. The survey involved questions on the thermal sensation and preference of the pupils. This paper investigates the children's thermal sensation trends, their perception of overall comfort and tiredness. Furthermore, it compares the survey results to predictions achieved with current adult-based comfort standards, namely ISO 7730 and EN 15251. The results suggest that children have a different thermal perception than adults. Possible explanations are discussed in relation to the particularities and specific character of school environments.

Key words: School buildings, Thermal comfort, Field survey, Comfort models, School children.

1. Introduction

Research has shown that increased classroom temperatures (Mendell and Heath, 2005, Wargocki and Wyon, 2007) and low ventilation rates (Bakó-Biró et al., 2012) can have a negative impact on schoolwork performance and health of children. However, there is limited information on children's thermal perception in school classrooms and the thermal conditions deemed acceptable by them. Moreover, the majority of research in this field regards adults' thermal comfort conditions: the heat-balance model of thermal comfort was developed using data from experiments with adults in climate chambers (Fanger, 1970), while the majority of the adaptive thermal comfort surveys were undertaken in offices (de Dear and Brager, 1998, McCartney and Nicol, 2002).

Current comfort standards, such as ISO 7730 (ISO, 2005) and EN 15251 (CEN, 2007), determine design values for operative temperatures in school classrooms, based on the heat balance and the adaptive thermal comfort model respectively. However, there is no assurance

that results from comfort studies performed in climate-control chambers, offices or university classrooms reflect the thermal sensation and preference of school children. Table 1 compares the main characteristics of climate chambers, offices, university classrooms and schools. In general, climate chambers are significantly different to everyday environments and the impact of this on thermal sensation of occupants has been thoroughly discussed in the past (Humphreys and Nicol, 2002). Furthermore, the everyday environments of offices, universities and school classrooms are different to an extent, which suggests that occupants probably adapt to different thermal conditions (Table 1). Pupils' school day includes diverse activities in densely occupied classrooms where adaptive action is limited, as well as outdoor playtime at least twice a day. It is likely that pupils' thermal perception is influenced by this different daily routine.

Table 1. Typical characteristics of offices, chambers, schools and university classrooms

	Climate chamber	**Office space**	**University classroom**	**School classroom**
Occupants	Adults	Adults	Adults	Children
Occupancy density	Varies	10 m^2/person (BCO, 2009)	Depending on the class can be very high	High (approx. 2.2 m^2/person)
Occupancy profile	Only for the survey time	8am-5pm with 1h lunch break	Students visit the room for the lecture hours (usually 1 to 2h)	9am-3pm with 2 major breaks, morning and lunch break
Typical layout	Restricted and controlled space	Usually open plan large areas	Lecture theatres or seminar rooms	Classrooms of approx. 60m^2
Environmental control/ action	None	Generally possible but depends on availability/ proximity	Limited during the lectures but possible	Main users (pupils) don't take action, the teacher does
Activities	Depends on the experiment	Desk-based	Lecture or workshop	Diverse during a day: maths, arts, physical education, literacy, playtime/ sports

The above suggests that there is need for research on the thermal perception of children in school classrooms to obtain a deeper understanding of their thermal preferences. However, there are only a limited number of comfort studies in schools. Table 2 shows published field studies performed in school classrooms. Furthermore, only few of them dealt with young children under 13 years. A possible explanation for this may be the lack of confidence on the ability of very young children to use thermal comfort rating scales for the assessment of their thermal sensation. However, Humphreys investigated this prior to his fieldwork in 1971 and found that many children under 7 years were capable of understanding a simply worded thermal sensation scale (Humphreys, 1977).

Table 2. Thermal comfort field studies in school classrooms

Reference	Country	Climate	Ventilation type	Age group
(Humphreys, 1973)	United Kingdom	Temperate	NV[1]	12-17
(Humphreys, 1977)	United Kingdom	Temperate	NV	7-11
(Wong and Khoo, 2003)	Singapore	Tropical	NV	13-17 13 teachers 26-50
(Kwok and Chun, 2003)	Japan	Sub-tropical	NV+AC[2]	13-17
(Corgnati et al., 2007)	Italy	Mediterranean	NV	12-23
(Hwang et al., 2009)	Taiwan	Sub-tropical	NV	11-17
(Al-Rashidi et al., 2009)	Kuwait	Desert	MM[3]	11-17
(Mors et al., 2011)	Netherlands	Temperate	NV	9-11
(Liang et al., 2012)	Taiwan	Sub-tropical	NV	12-17

[1] NV=Natural ventilation, [2]AC= Air-conditioning, [3]MM=Mixed mode ventilation

The study presented in this paper aims at contributing to the knowledge base of the pupils' response towards their classroom's thermal environment. The main objectives of this paper are as follows:

- To investigate the ability of the participating pupils to understand thermal comfort related questions.
- To study pupils' thermal perception in classrooms and compare the results with previous research in schools.
- To compare the results with adult-based standards for thermal comfort.

2. Thermal comfort field study

The field study presented here included pupil questionnaire surveys and simultaneous measurements of the environmental variables which affect thermal comfort. It was conducted in a naturally ventilated primary school in Southampton, in the South of England. The field studies were carried out outside the heating season, from April to July 2011. The case study school and the methodology applied are described below.

2.1. The case study school

The case study primary school building is denoted as B on the left hand side of Figure 1. Building A is an infant school which was constructed in the same period and is attached to the case study school. The building is a typical example of a light-weight post war school in the UK. It was constructed in 1978 using a steel frame construction and pre-fabricated concrete panels. As shown in Figure 1, the case study building consists of two parts. The L-shaped 2-storey building part accommodates the classrooms, computer spaces and common areas, whilst the 1-storey part consists of the offices, the hall and kitchen. The two parts create an enclosed courtyard which is used for outdoor activities. The study was conducted in the L-shaped building part with the classrooms.

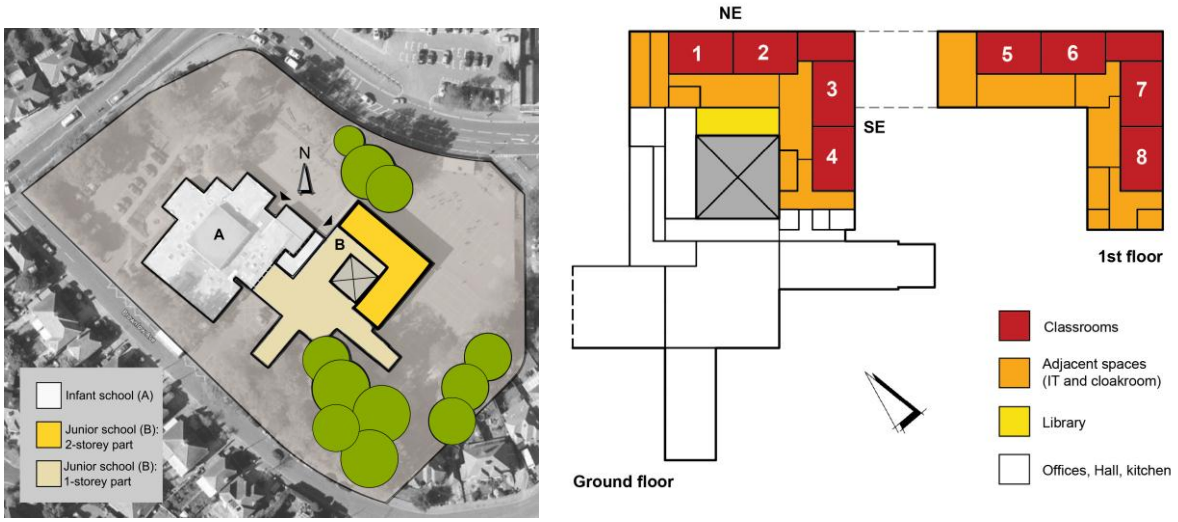

Figure 1. Left: diagrammatic plan of the school grounds- significant tree canopies shown in green (Image adapted from: Google Earth), right: schematic plans of the school

As can be seen in Figure 1, the school classrooms have North-East and South-East orientation. Other important characteristics of the building are: its light-weight construction, the top-hung outward opening windows with single glazing, reflective window film and internal shading with blinds, the flat bitumen roof, a glazing to wall ratio of ~40%, outdoor areas with hard surfacing and lack of vegetation, a low exposure to wind and lack of solar shading.

The school comprises of 8 classrooms and has around 240 enrolled pupils aged 7-11, in Years 3 to 6. Figure 2 shows a 3d model of the school and a table with the school years and age groups corresponding to each classroom. The surveys were performed in all 8 classrooms and approximately 230 pupils participated. Every classroom was surveyed 6 times and, therefore, 48 surveys were carried out in total. 4 classrooms were surveyed per day and the remaining ones were surveyed on the following day. Thus, the surveys were performed over 12 day visits to the school. For reasons of clarity, in the text the following terms will be used:

- "test": a 2-day visit to the school. 6 tests were performed in total.
- “survey”: each classroom investigation. 4 surveys per day, i.e. 8 surveys per test and 48 surveys in total.

Classrooms	Year	Age
1,2	5	9
3,4	6	10
5,6	3	6
7,8	4	7

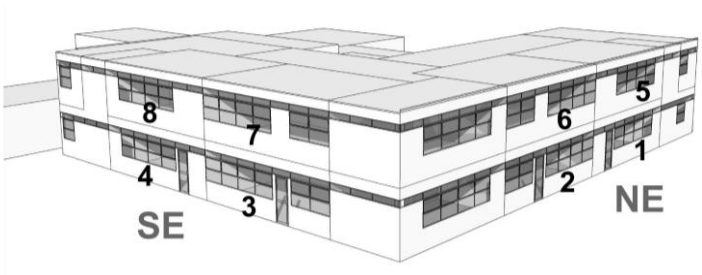

Figure 2. Left: table with the school year and age corresponding to the children of each classroom, right: 3d model of the school

2.2. Survey questionnaire

Several versions of the survey questionnaire were checked by the teachers in order to ensure that it was suitable for every age group in the school. Questions about humidity, air velocity and thermal acceptability were omitted as teachers found them difficult for young children to understand. Furthermore, it was decided not to include a checklist with clothing items for the pupils to choose from, as the teachers considered this too time consuming. Instead, a question about whether they wore their jumper was included and the various clothing combinations of the pupils were observed and noted down during the surveys. Finally, for the assessment of the pupils' thermal sensation, the ASHRAE rating scale was used but slightly amended based on the teachers' advice: "slightly cool", "slightly warm" and "neutral" were replaced with "a bit cool", "a bit warm" and "OK". A similar 7-point scale was used for the thermal preference vote for direct comparison with thermal sensation votes. The final version of the survey questionnaire is provided in the Appendix.

During the first school visits, the pupils showed a strong interest in the equipment and the survey process. However, after the second test, the children started asking why it was necessary to repeat the same process and whether they would have to do this again. In order to keep the children engaged, a sticker booklet was prepared and handed out to each pupil along with an indoor thermometer for every classroom. The booklet included individual research tasks related to the indoor climate, such as keeping a log of the classroom's air temperature on a sunny, cloudy and rainy day. These tasks were set up according to age group: i.e. Year 3 / Year 4 and Year 5 / Year 6. Each time a task was completed or a thermal comfort survey was undertaken, the children received a reward sticker. This process managed to ensure pupils' interest during the 4 remaining tests.

2.3. Measurements of environmental variables

The environmental parameters were measured during the surveys using a Testo 400 device, according to the standards of ISO 7726 "Ergonomics of the thermal environment - Instruments for measuring physical quantities" (ISO, 2001). The probes which were used included: air speed, radiant temperature (globe thermometer with diameter=150mm), ambient air temperature, relative humidity and CO_2 concentration. The above parameters were measured at a height of 1.1m, based on the recommendation of ISO 7726 (ISO, 2001). Special care was taken in order to ensure that the instruments would not disturb any class activities. Furthermore, the equipment was placed in the centre of the room and away from heat sources, such as IT equipment. The globe thermometer's response time was checked prior to the surveys and was found to be about 30 minutes. Therefore, the instruments were set up in the room about 1 hour before the survey to ensure their acclimatisation to the classroom's thermal environment.

Table 3, which is organised by classroom, gives the mean, standard deviation, minimum and maximum values of each environmental parameter measured during the surveys. Operative temperatures (T_{op}) ranged from 19.2°C to 28.9°C, relative humidity (RH) was within 40-60% and air speed rarely exceeded 0.1m/sec. CO_2 concentration was mostly within 400-2,500ppm,

except for 2 surveys where it reached 3,500 and 4,000ppm. as, due to low temperatures, the windows were shut.

Table 3. Mean, standard deviation, minimum and maximum values of the main environmental parameters and mean Thermal Sensation Votes ($TSV_{(mean)}$) of the 8 school classrooms over the survey period.

Classroom	1	2	3	4	5	6	7	8
Operative temperature (^oC)								
Mean	22.8	23.3	22.5	22.1	23.6	24.4	24.1	24.1
S.D.	1.5	0.9	1.5	1.0	2.4	2.5	2.8	2.4
min	20.8	21.9	20.5	21.0	20.1	20.8	19.2	20.5
max	25.1	25.0	24.0	23.9	28.1	28.9	27.9	27.5
Relative humidity (%)								
Mean (%)	56.6	55.1	52.9	56.3	54.7	54.2	55.4	55.8
S.D.	6.5	5.5	6.9	6.9	4.9	4.6	3.9	5.0
min	46.5	47.0	39.3	40.9	47.5	46.7	48.2	46.1
max	66.5	63.1	60.4	62.0	60.9	59.6	59.2	60.8
Air speed (m/sec)								
Mean	0.07	0.08	0.06	0.07	0.09	0.09	0.08	0.12
S.D.	0.02	0.01	0.02	0.01	0.02	0.03	0.03	0.04
min	0.04	0.05	0.04	0.06	0.08	0.05	0.04	0.09
max	0.11	0.09	0.10	0.09	0.13	0.14	0.12	0.22
CO_2 (m/sec)								
Mean	1,594	1,598	932	1,093	1,070	1,097	876	916
S.D.	1141	1027	436	714	506	618	256	415
min	750	500	400	450	500	450	500	550
max	4,000	3,500	1,700	2,500	1,800	2,000	1,200	1,700
Thermal Sensation Vote (TSV)								
Mean	0.9	0.3	0.4	0.2	0.5	0.6	1.2	1.3
S.D.	1.2	1.4	1.5	1.5	1.6	1.6	1.4	1.3

3. Results

3.1. Pupils' understanding of the thermal comfort questionnaire

The children generally considered the questionnaire as straightforward and easy to fill in. However, some inconsistent responses were found in the dataset, such as cases where a pupil wished it was warmer while feeling hot. These cases were identified by adding the thermal sensation (TSV) and thermal preference (TPV) scale values (Table 4). The cases where (TSV+TPV)<-3 or (TSV+TPV)>3 were regarded as inconsistent, based on the fact that thermal sensation votes within [-3,-2] and [+2,+3] are considered to express dissatisfaction (Fanger, 1970) and one wouldn't wish to enhance that sensation. However, based on previous research, a "neutral" thermal state is not always the preferred option (Wong and Khoo, 2003, Kwok and Chun, 2003). Therefore, only the extreme cases were excluded. The above cases constituted 7% of the gathered responses (103 of 1314 responses).

Table 4. Thermal scales used in the questionnaire

TSV scale	(+3) Hot	(+2) Warm	(+1) A bit warm	(0) OK	(-1) A bit cool	(-2) Cool	(-3) Cold
TPV scale	(+3) A lot warmer	(+2) Warmer	(+1) A bit warmer	(0) No change	(-1) A bit colder	(-2) Colder	(-3) A lot colder

As can be seen in Table 5, the total incoherent cases are distributed quite uniformly within the 6 tests. This indicates that the inconsistency is not related to a lack of familiarity of the pupils with the questionnaire, as this would have led to more inconsistent responses in the first tests. In terms of their distribution within the 8 classrooms, the largest numbers of inconsistent responses appeared in classrooms 3, 6 and 8, which correspond to ages 10, 7 and 8 respectively. This eliminates the possibility that young age was responsible for the difficulty in providing coherent responses to the questionnaire. It is likely that these cases are related to individual parameters or classroom conditions, such as a difficult task prior to the survey that might had affected the ability of some pupils to match their thermal sensation with their preferred thermal condition.

Table 5. Cross-tabulation of inconsistent responses based on classroom number and test number (in brackets the total number of pupils participating in the survey)

		Test No						
		1	2	3	4	5	6	Total
Classroom number	**1**	3 (28)	0 (28)	1 (28)	2 (26)	3 (26)	1 (27)	10
	2	3 (30)	0 (26)	2 (28)	0 (26)	2 (26)	2 (27)	9
	3	2 (30)	7 (28)	4 (27)	5 (23)	2 (27)	4 (28)	24
	4	2 (28)	1 (24)	2 (27)	1 (29)	0 (28)	1 (29)	7
	5	0 (28)	0 (29)	3 (24)	2 (27)	0 (28)	1 (30)	6
	6	5 (27)	5 (27)	3 (27)	2 (28)	3 (27)	2 (29)	20
	7	1 (29)	0 (28)	2 (24)	5 (29)	1 (25)	2 (28)	11
	8	3 (30)	1 (24)	1 (27)	4 (28)	5 (28)	2 (29)	16
	Total	19	14	18	21	16	15	103

The inconsistent cases were excluded from the analysis of pupils' thermal sensation and preference as it wouldn't be possible to distinguish which answer (TSV or TPV), actually reflected the pupils' thermal response (Figure 3).

Overall, based on the limited amount of inconsistent and missing values and the pupils' general attitude during the surveys, it can be concluded that the children of all ages were capable of understanding and filling in the questionnaire, which suggests that it is suitable for primary school children.

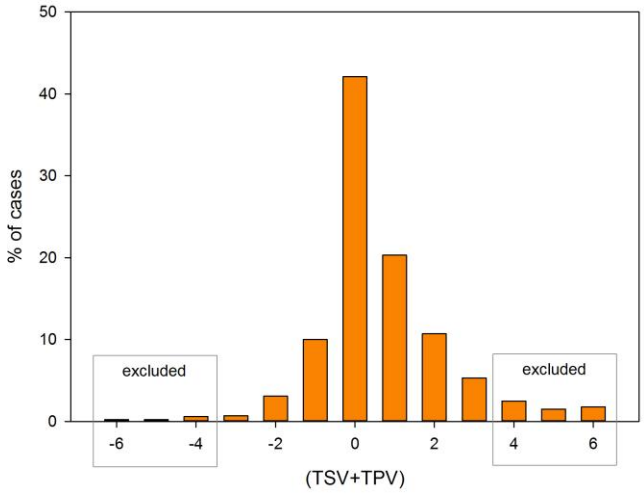

Figure 3. Excluded pupil responses from the thermal comfort questionnaire

3.2. Pupils' thermal sensation and preference

Figure 4 shows the distribution of the thermal sensation votes (TSVs) and thermal preference votes (TPVs) for the entire sample, after the exclusion of inconsistent cases. It can be seen that the TSVs are centred on 'OK' (0) with an apparent shift towards warm thermal sensations. The TPVs are centred on '0' ('No change') and '-1' ('A bit cooler') with almost symmetrical distribution of the votes around them. Overall, over the survey period the pupils evaluated their thermal environment mostly as warm, but their thermal preference was more diverse.

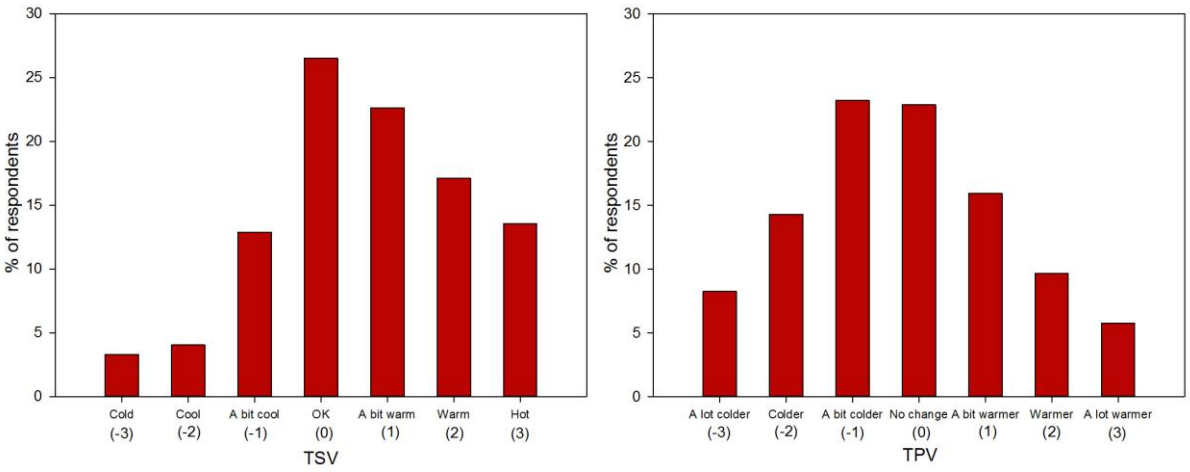

Figure 4. Relative frequency of Thermal Sensation Votes (TSVs) (Left) and Thermal Preference Votes (TPVs) (Right) from all 48 surveys

The mean thermal sensation vote of the pupils, $TSV_{(mean)}$, was calculated for every survey. Figure 5 shows the $TSV_{(mean)}$ in relation to the operative temperature of the classroom. As shown in the graph, for the same operative temperature, $TSV_{(mean)}$ may differ for as much as 2 scale points. The scatter is generally quite large for operative temperatures of 20-24^{o}C but the correlation is satisfactory, with r^2=0.545 which means that the mean thermal sensation of the pupils is affected by the room temperature variations. The regression gradient is 0.27 scale units/$^{\circ}$C, which is lower than the mean value from recent field data with adult subjects (0.37

scale units/°C) (Humphreys et al., 2007), derived from the de Dear (de Dear, 1998) and the SCATs (McCartney and Nicol, 2002) databases. This suggests that children are slightly less sensitive to temperature changes, which agrees with the outcome of Humphreys (Humphreys, 1977). However, it can also be attributed to the prolonged survey period of this study which might have led to more complete thermal adaptation (Humphreys et al., 2007). This conclusion is strengthened by the relation of the survey mean clothing insulation with the classroom's operative temperature, as demonstrated in Figure 6. There is an apparent decrease in mean clothing insulation at warmer operative temperatures, which is mostly related to the number of pupils deciding not to wear their jumper (pullover).

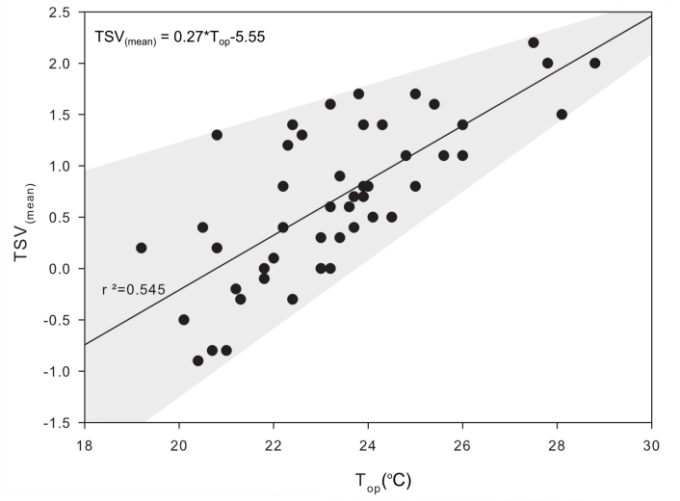

Figure 5. Mean Thermal Sensation votes per survey (TSV(mean)) against the classroom's operative temperature

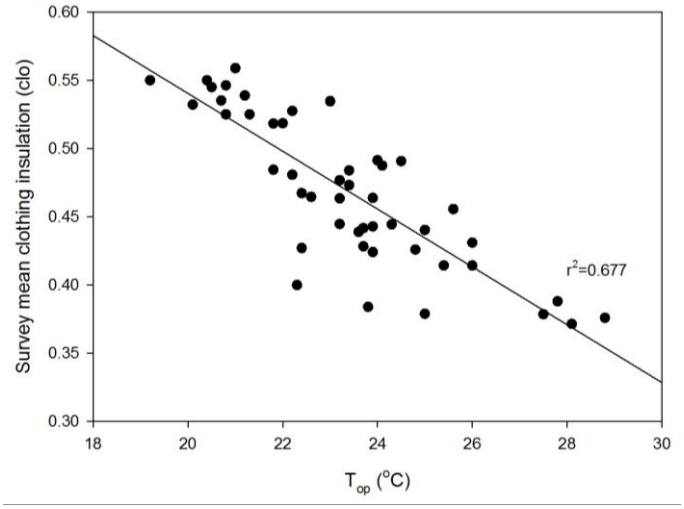

Figure 6. Survey mean clothing insulation (clo) against the classroom's operative temperature (T_{op})

Looking at the thermal sensation votes more in detail, a large variation can be identified within surveys. The standard deviation of the TSV was calculated for all surveys and ranged from 0.7 to 1.8 scale units, with a mean of 1.5, which is larger than a mean value of 1.07 scale units, calculated from studies with adults (Humphreys et al., 2007). The variation within

the surveys can be seen in Figure 7 which shows the distribution of individual votes per survey of test 1. In most classrooms the votes cover the whole range of the sensation scale (from hot to cold). Similar observations were made by Humphreys, who suggested as a possible explanation the different activity levels of different children over the school day (Humphreys, 1977). This argument is strengthened by the fact that, during breaks, children engage in different activities which may have an impact on their thermal perception.

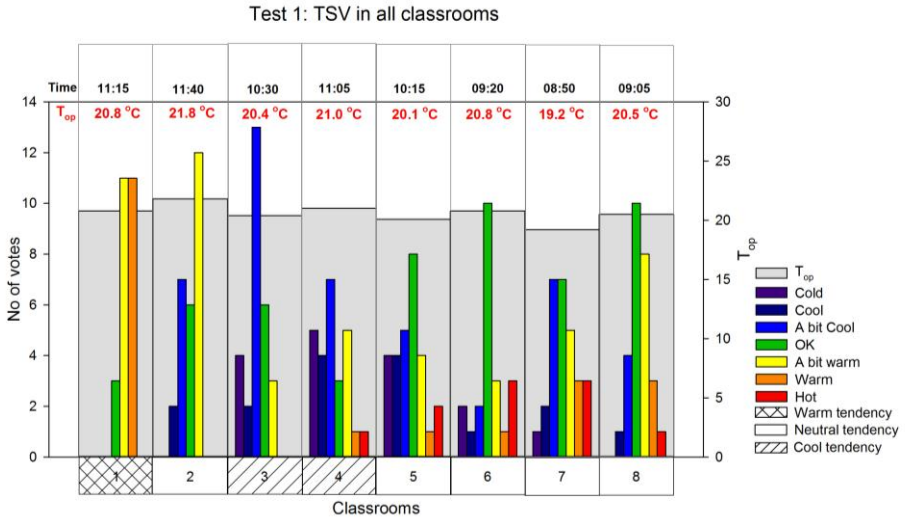

Figure 7. Distribution of Thermal Sensation votes (TSV) of Test 1

Figure 8 shows the distribution of thermal preference votes in relation to thermal sensation for all 6 tests. As can be seen, the majority of children voting for a specific thermal sensation preferred the conditions which would bring them to neutrality, as would be expected.

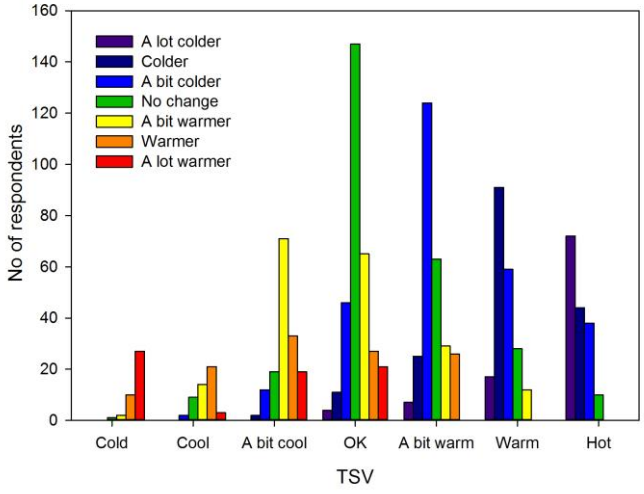

Figure 8. Thermal preference vote (TPV) by thermal sensation vote (TSV)

3.3. Perception of overall comfort and tiredness

The pupils were asked whether they were feeling comfortable during the survey (Question 3 in the Appendix). The aim of this question was to identify the perceived impact of the thermal sensation on the overall comfort of the pupils. Figure 9 shows their responses in relation to their thermal sensation votes. The distribution is centred around "OK" with about 70% of the pupils who voted "OK" feeling comfortable, which suggests that a thermal sensation around "OK" was generally associated with overall comfort. Of the children that would be considered as cold dissatisfied, i.e. voting -2 and -3, 45% and 25% respectively felt comfortable. Furthermore, 43% of those who voted TSV=+3 ("hot"), which is generally considered to express warm dissatisfaction, stated that they were feeling comfortable. Similarly, 30% of the pupils that felt thermally satisfied (TSV: 0, "OK") said that they are not feeling comfortable. This does not appear to be plausible. This means that some pupils may feel hot but still say that they are comfortable. This finding could have several explanations, such as, that children may not associate extreme thermal sensations with overall discomfort. Furthermore, it is possible that children's perception of overall comfort is strongly affected by other parameters, such as the class activity, their psychological condition or time of the day, rather than their thermal sensation. Also, it could be related to a tendency of children not to express dissatisfaction when they feel thermal discomfort, which was reported by teachers in a previous survey (Teli et al., 2011).

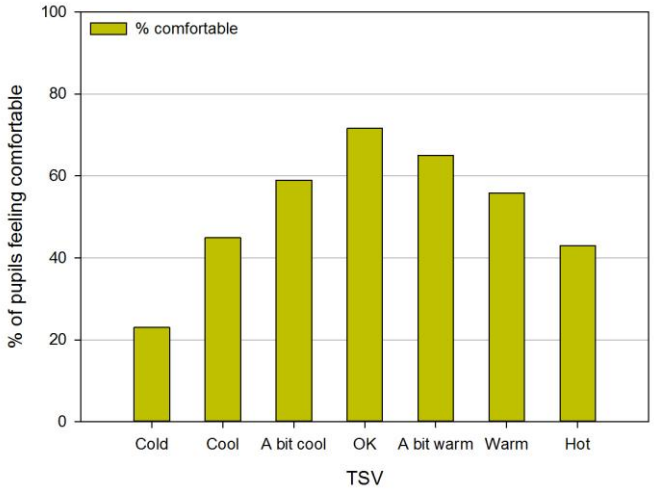

Figure 9. Percentage of pupils feeling comfortable per thermal sensation vote

Figure 10 shows the relative frequency of the pupils' feeling of tiredness ('very tired', 'a bit tired', 'not tired') per survey, in relation to the CO_2 concentration at the survey time, the operative temperature (T_{op}), the mean Thermal Sensation Vote ($TSV_{(mean)}$) of the pupils and the time of the day the survey took place. Overall, as can be seen in Figures 10(a), (b) and (c), there is a large scatter and a weak correlation of the percentage of pupils feeling tired with the above factors. The weakest correlation can be seen with the CO_2 concentration and can be attributed to the fact that the CO_2 measurements reflect the instant CO_2 level during the surveys while the feeling of tiredness often results from a more prolonged exposure to an influential factor. The percentage of pupils stating that they felt 'very tired' is within 0-40% and appears to be independent of the mean thermal sensation, but positively-although

weakly- correlated with the CO_2 level and operative temperature. The strongest correlation is found to be with the operative temperature (b): when the operative temperature increases the percentage of pupils that stated that they were feeling ‘a bit tired’ decreases, which is offset by the increase in the percentage of pupils feeling ‘very tired’ and ‘not tired’. The increase of pupils voting for ‘not tired’ at higher temperatures could be related to the fact that under warm conditions windows are usually opened, keeping the CO_2 concentration at lower levels. This highlights the interrelation of the factors affecting pupils’ perception of tiredness.

As can be seen in Figure 10(d), the distribution profiles of the votes in relation to breaks are similar, which suggests that the pupils’ feeling of tiredness was not related to the time of the day the survey was conducted. Overall, the majority of the pupils felt “a bit tired” regardless of the time of the day, which could be attributed to a general predisposition towards school activities and tasks. The results indicate that the pupils’ feeling of tiredness is weakly related to the factors examined here, although the operative temperature appears to have a more profound impact on tiredness, compared to CO_2, thermal sensation and time of the day.

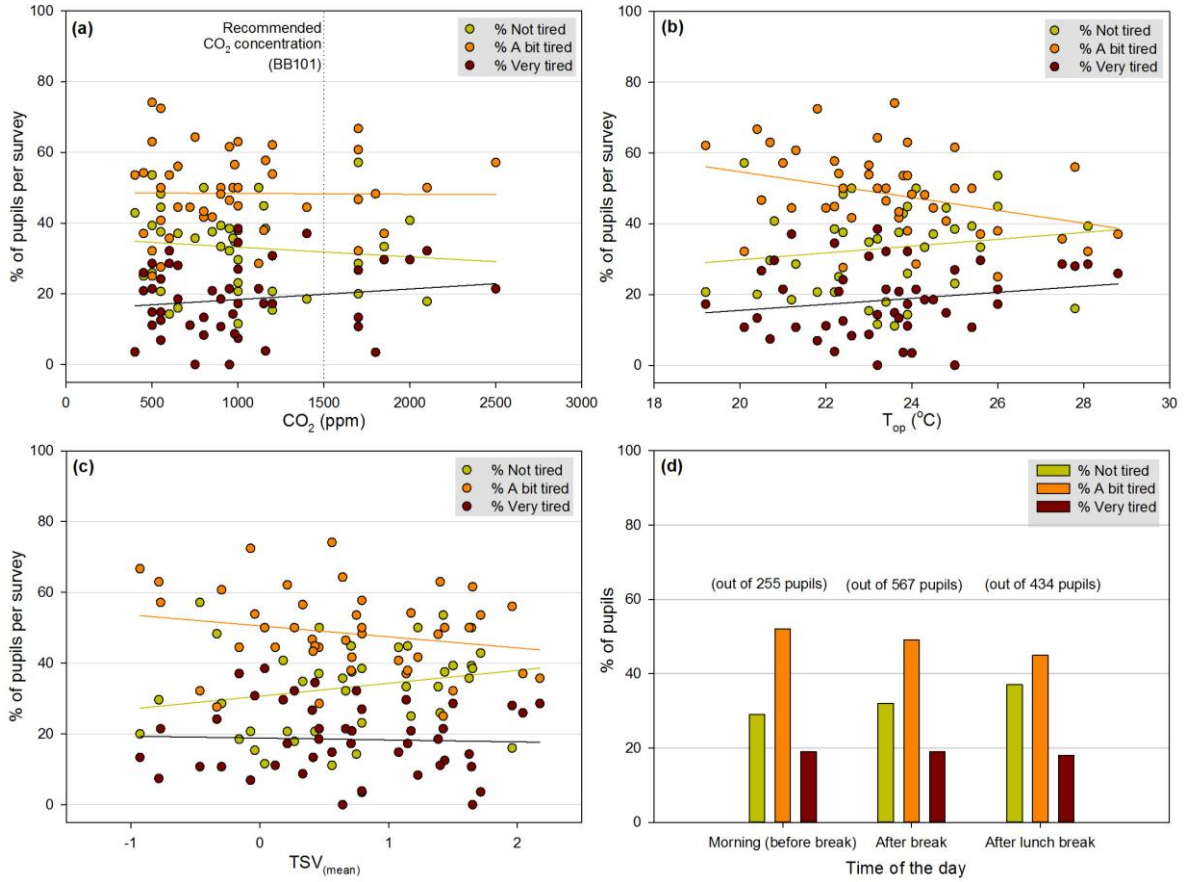

Figure 10. Percentage of pupils feeling ‘very tired’, ‘a bit tired’ and ‘not tired’ per survey, in relation to (a) CO_2 concentration, (b) Operative temperature (T_{op}) and (c) Thermal sensation vote (TSV) and (d) distribution of votes for ‘tired’, ‘a bit tired’ and ‘not tired’ in relation to time of the day.

3.4. Survey results and PMV model predictions (as per ISO 7730)

ISO 7730 (ISO, 2005) provides criteria for thermal comfort in moderate thermal environments based on the PMV and PPD indices. The environmental input parameters required for their calculation (ambient air temperature, mean radiant temperature, air velocity and relative humidity) were all measured during the surveys (see section 2.3). The metabolic rate and clothing insulation of children had to be estimated.

Compared with adults, children have a higher resting metabolic rate per kilogram body weight (Holliday, 1971). In recent thermal comfort studies with children several adjustments have been made to the PMV model in order to address the difference in metabolic rates between adults and children, but the corrected PMVs failed to predict the actual thermal sensations (Wargocki and Wyon, 2007, Mors et al., 2011, Al-Rashidi et al., 2009). Here, the PMV model is applied unchanged, as presented in ISO 7730, in order to compare the actual thermal sensation votes of children to the adult based predictions.

The metabolic rate and clothing insulation values were determined based on ISO 7730 (ISO, 2005). In the surveys presented here the questionnaires were handed out after at least 15 minutes of classroom activities therefore the metabolic rate was set at 1.2 met (sedentary activity). The clothing values of all possible combinations observed during the surveys were determined and were found to be within a range of 0.30-0.49 clo without jumper. The jumper adds 0.25 ‘clo’ to the insulation value. For the calculation of the PMV/PPD indices a weighted average ‘clo’ value was deduced for each survey, using mean values of 0.35 and 0.40 clo for girls and boys respectively and the responses to the questionnaires regarding the jumper.

Figure 11 shows the actual mean thermal sensation vote ($TSV_{(mean)}$) against the calculated PMV. The dashed line corresponds to the ideal case where the actual thermal sensation would be equal to the predicted, $TSV_{(mean)}$=PMV. As can be seen, the actual thermal sensation votes are higher than the calculated PMV, which agrees with another study in the UK that used the same met value (1.2) and clo=0.9 (Bakó-Biró et al., 2012). This outcome means that the children felt warmer than adults would feel based on the predictions of the PMV model. The discrepancy ranges from 0.1-2.7 scale points. Based on the regression line, for a predicted neutral sensation (PMV=0) the actual mean thermal sensation is about 1.1 scale points higher. This means that thermal conditions that adults would find neutral would be assessed by children as ‘slightly warm’. The critical cases however are those of higher thermal sensation votes as, for instance, for PMV values around +1 (slightly warm), which would be considered as acceptable, the actual mean thermal sensation of children in the survey discussed here is around +2.

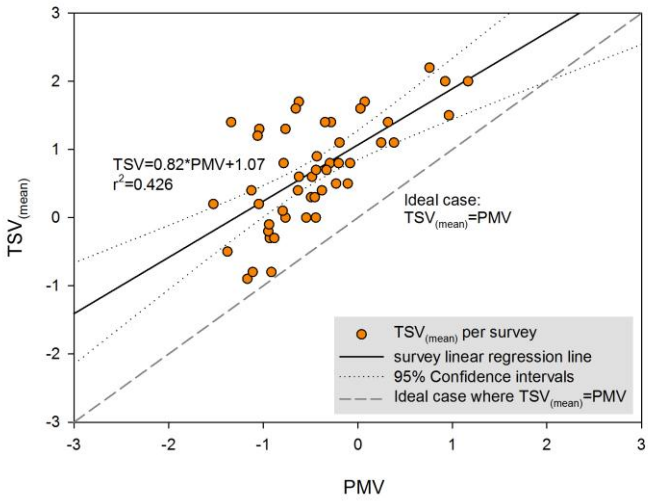

Figure 11. Actual mean thermal sensation vote ($TSV_{(mean)}$) for each survey against the calculated PMV

Figure 12 compares the predicted percentage of dissatisfied (PPD) with the actual percentage of dissatisfied (APD) plotted against the predicted mean vote (PMV). The actual percentage of dissatisfied (APD) was calculated from the share of the [-3, -2] and [+2, +3] thermal sensation votes to the overall sample size, based on the PPD definition used in common thermal comfort standards (ISO, 2005, CEN, 2007, ASHRAE, 2010). As can be seen in the graph, there is a clear mismatch as the APD is generally higher than the PPD.

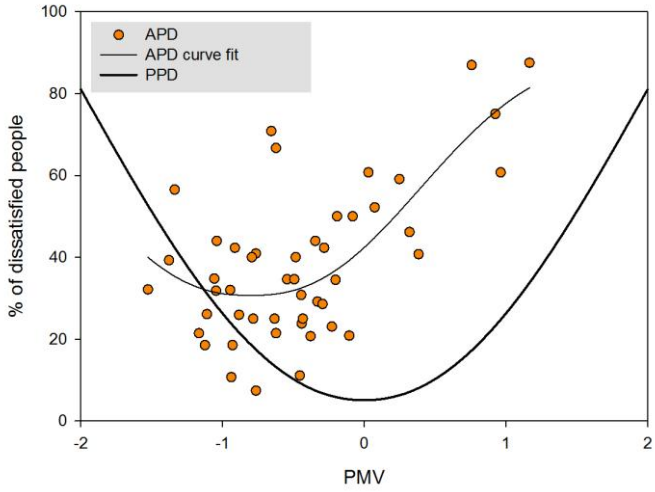

Figure 12. Actual percentage of dissatisfied (APD) and calculated PPD as a function of PMV

Figure 13 shows the relationship between the actual percentage of dissatisfied (APD) and the actual mean thermal sensation vote per survey. It can be seen that in most cases where the mean thermal sensation vote is within the 3 central categories (-1,0,+1) the APD is between 20 and 40%. This suggests that even when the thermal sensation was on average assessed as neutral, slightly warm or slightly cool, there were a number of pupils who gave a more extreme evaluation, voting within (-3,-2) or (+2, +3). This reinforces the findings of section 3.2 that there is a large variation in children's thermal responses.

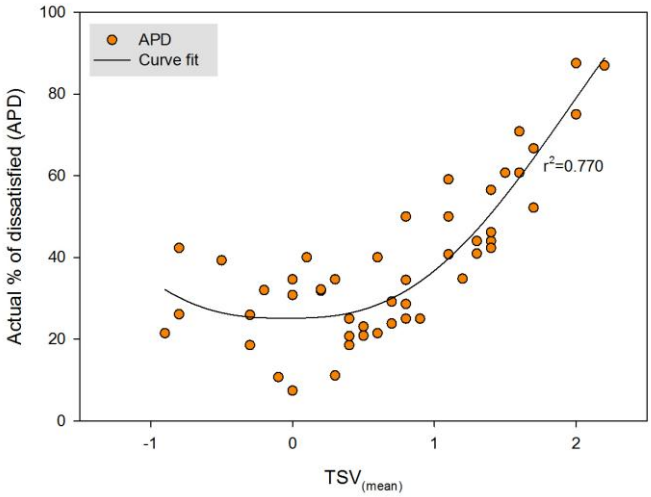

Figure 13. Actual percentage of dissatisfied as a function of $TSV_{(mean)}$

3.5. Assessment of the classroom's thermal environment based on the adaptive model of thermal comfort

Figure 14 shows for all 6 tests the operative temperatures determined during the surveys compared to the recommended temperature limits given in Annex A of EN 15251 for buildings without mechanical cooling (CEN, 2007). The outdoor running mean temperature (T_{rm}) for the survey days was calculated using the outdoor daily mean temperatures, which were calculated from hourly meteorological data of Southampton (NOCS). The operative temperature limits for mechanically cooled school buildings were also included in the graphs as they are used for non-mechanically cooled buildings, when T_{rm}<10 °C for the upper limits and when T_{rm}<15 °C for the lower limits (CEN, 2007). The black dashed-dotted line in the graph is the comfort temperature in relation to the outdoor running mean which was the base for deriving the upper and lower comfort zone limits of the EN 15251 diagram (Nicol and Humphreys, 2010). Each of the 6 graphs in Figure 14 includes an inlay figure with the actual $TSV_{(mean)}$ per classroom of the corresponding test, in order to facilitate comparison between the EN 15251 comfort diagrams and the survey results.

According to the diagrams, in most surveys the classrooms' operative temperature fell within the acceptability range for category I buildings of EN 15251. However, the actual tendency of the mean thermal sensation was warmer than would be expected as a result of the EN 15251 assessment. For instance, in test 2, 6 out of 8 classrooms fall within the comfort limits of the EN 15251 diagram and only 2 exceed the upper limit for category I. However, the $TSV_{(mean)}$ in most classrooms is above +1. In test 1, the thermal conditions were mostly assessed by EN 15251 as unacceptably cold, whilst in most surveys the pupils' mean thermal sensation vote was around neutral. The results indicate that the EN 15251 underestimated the actual thermal sensation of the pupils, which agrees with the outcome of Mors et al. (Mors et al., 2011) in their comfort study in 3 primary school classrooms.

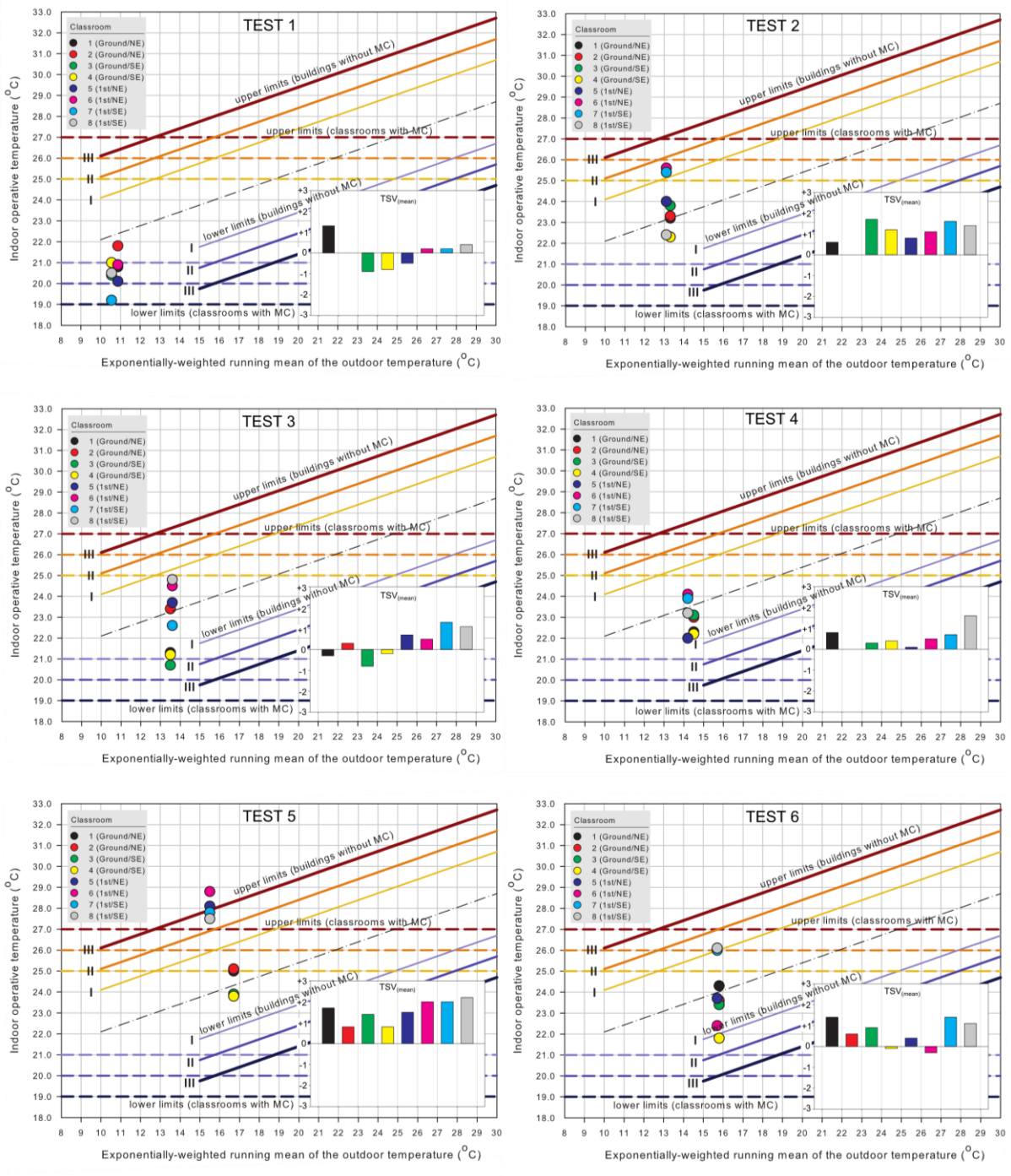

Figure 14. Operative temperatures of the surveys per test, plotted on the EN 15251 diagram for acceptable indoor temperatures in buildings without mechanical cooling (I, II and III correspond to the EN 15251 building categories).

4. Conclusions

The main outcomes from the thermal comfort study presented here are the following:

- The surveyed primary school children aged 7-11 were capable of understanding simplified thermal sensation and preference rating scales.
- There is a large variation in pupils' thermal sensation votes which could be related to their diverse activity schedule.
- The pupils' perceived overall comfort is not always related to their thermal state, i.e. some may feel hot but state that they are feeling comfortable. Their feeling of tiredness has a weak correlation with the mean thermal sensation, CO_2 and time of the day and slightly stronger correlation with the classroom's operative temperature.
- The actual mean thermal sensation vote is higher than the PMV predictions. Similarly, for most surveys, the actual mean thermal sensation indicates warmer conditions than the EN 15251 assessment of the corresponding operative temperatures would suggest.

In summary, the study presented here suggests that children have a different thermal perception to adults. Possible explanations for this may be the following:

- The higher metabolic rate per kg body weight.
- The limited available adaptive opportunities in classrooms. Children cannot control their classroom's thermal environment, e.g. open or close windows/doors/blinds. The teacher is responsible for any action taken.
- The variation of activity levels and the strong relationship with the outdoor climate that children experience, since their daily school schedule includes outdoor playing, which is different to adult office activities.
- Children take limited adaptive action with regards to clothing during the day. Furthermore, in the UK there is a school uniform policy which means that the available clothing choices are limited.

Based on the results presented here, school environments require special consideration with regards to occupant thermal comfort. However, more information is needed on children's thermal comfort, over a wider range of conditions. Furthermore, adjustments appear to be required to current comfort criteria in order to address the thermal perception of children. Overall, more research is needed in order to verify the observations of this study and to obtain a better understanding of children's thermal perception.

5. Acknowledgments

The authors are grateful to the teachers and pupils who participated in this survey.

References

Al-Rashidi, K. E., Loveday, D. L. & Al-Mutawa, N. K. (2009). Investigating the Applicability of Different Thermal Comfort Models in Kuwait Classrooms Operated in Hybrid Air-Conditioning Mode. *In:* Howlett, R. J., Jain, L. C. & Lee, S. H. (eds.) *Sustainability in Energy and Buildings.* Springer Berlin Heidelberg.

ASHRAE (2010). ANSI/ASHRAE Standard 55- Thermal Environmental Conditions for Human Occupancy. Atlanda: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Bakó-Biró, Z., Clements-Croome, D. J., Kochhar, N., Awbi, H. B. & Williams, M. J. (2012). Ventilation rates in schools and pupils' performance. *Building and Environment,* 48**,** 215-223.

BCO (2009). *BCO Guide to Specification*, British Council for Offices.

CEN (2007). 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. Brussels: CEN (European Committee for Standardization).

Corgnati, S. P., Filippi, M. & Viazzo, S. (2007). Perception of the thermal environment in high school and university classrooms: Subjective preferences and thermal comfort. *Building and Environment,* 42**,** 951-959.

de Dear, R. J. (1998). A global database of thermal comfort field experiments *ASHRAE Transactions,* 104 (1b)**,** 1141-1152.

de Dear, R. J. & Brager, G. S. (1998). Developing an Adaptive Model of Thermal Comfort and Preference. *ASHRAE Transactions,* 104 (1)**,** 145-167.

Fanger, P. O. (1970). *Thermal Comfort: Analysis and Applications in Environmental Engineering*, New York, Mc Graw-Hill.

Holliday, M. (1971). Metabolic rate and organ size during growth from infancy to maturity and during late gastation and early infancy. *Pediatrics,* 47**,** 169–79.

Humphreys, M. A. (1973). Classroom temperature, clothing and thermal comfort-A study of secondary school children in summertime. *Building Services Engineer,* 41**,** 191-202.

Humphreys, M. A. (1977). A study of the thermal comfort of primary school children in summer. *Building and Environment,* 12**,** 231-239.

Humphreys, M. A. & Nicol, J. F. (2002). The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. *Energy and Buildings,* 34**,** 667-684.

Humphreys, M. A., Nicol, J. F. & Raja, I. A. (2007). Field Studies of Indoor Thermal Comfort and the Progress of the Adaptive Approach. *Advances in Building Energy Research,* 1**,** 55-88.

Hwang, R.-L., Lin, T.-P., Chen, C.-P. & Kuo, N.-J. (2009). Investigating the adaptive model of thermal comfort for naturally ventilated school buildings in Taiwan. *International journal of biometeorology,* 53**,** 189-200.

ISO (2001). EN ISO 7726:2001 Ergonomics of the thermal environment- Instruments for measuring physical quantities. Brussels: International Standardisation Organisation.

ISO (2005). 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. Geneva: International Standardisation Organisation.

Kwok, A. G. & Chun, C. (2003). Thermal comfort in Japanese schools. *Solar Energy,* 74**,** 245-252.

Liang, H.-H., Lin, T.-P. & Hwang, R.-L. (2012). Linking occupants' thermal perception and building thermal performance in naturally ventilated school buildings. *Applied Energy,* 94**,** 355-363.

McCartney, K. J. & Nicol, F. (2002). Developing an adaptive control algorithm for Europe. *Energy and Buildings,* 34**,** 623-635.

Mendell, M. & Heath, G. (2005). Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. *Indoor Air 2005. The 10th International Conference on Indoor Air Quality and Climate.* Beijing, China.

Mors, S. t., Hensen, J. L. M., Loomans, M. G. L. C. & Boerstra, A. C. (2011). Adaptive thermal comfort in primary school classrooms: Creating and validating PMV-based comfort charts. *Building and Environment,* 46**,** 2454-2461.

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

NOCS. *Meteorological station. National Oceanographic Centre, Southampton. A collaboration between NOCS & Met Office* [Online]. Available: http://www.noc.soton.ac.uk/noc_intranet/metstation/index.html [Accessed: 15/10/11].

Teli, D., Jentsch, M. F., James, P. A. B. & Bahaj, A. S. (2011). Overheating risk evaluation of school classrooms. *World Renewable Energy Congress.* Linköping, Sweden, 8-13 May.

Wargocki, P. & Wyon, D. P. (2007). The Effects of Moderately Raised Classroom Temperatures and Classroom Ventilation Rate on the Performance of Schoolwork by Children (RP-1257). *HVAC&R Research,* 13**,** 193-220.

Wong, N. H. & Khoo, S. S. (2003). Thermal comfort in classrooms in the tropics. *Energy and Buildings,* 35**,** 337-351.

APPENDIX A

1

Comfort in classroom-pupil survey

UNIVERSITY OF Southampton
School of Civil Engineering and the Environment

I am a: Girl ☐ Boy ☐

1) How do you feel at the moment?

Cold	cool	A bit cool	OK	A bit warm	Warm	Hot
☐	☐	☐	☐	☐	☐	☐

2) Tick the box of the phrase you agree with:

AT THE MOMENT, IN THE CLASSROOM:

I wish it was a lot colder	☐	❄❄❄
I wish it was colder	☐	❄❄
I wish it was a bit colder	☐	❄
I don't want any change	☐	
I wish it was a bit warmer	☐	☀
I wish it was warmer	☐	☀☀
I wish it was a lot warmer	☐	☀☀☀

3) At the moment, do you feel comfortable?

Yes ☐ No ☐

4) At the moment, are you wearing your jumper?

Yes ☐ No ☐

5) Do you feel tired?

Very tired ☐ A bit tired ☐ I am not tired ☐

Please turn the page

Classroom No:……|Date:…/…/11

Thank you very much!

6) What were you doing in the last 30 minutes before the survey?

Class activity (reading, writing, maths, science, etc.) ☐

PE (Physical education, games) ☐

ICT (Computers) ☐

Playing outside/ running during break ☐

Relaxing during break ☐

Having lunch ☐

Thank you very much!