Winter thermal comfort and indoor air quality in Swedish grade school classrooms, as assessed by the children

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SUMMARY

This paper presents results from a pilot thermal comfort study in five Swedish grade school classrooms in three different buildings during winter 2015/16. The study includes measurements of environmental parameters (air temperature, globe temperature, relative humidity, air speed, CO_2) and questionnaire surveys designed to match the children's cognitive level. The questionnaire includes questions about thermal perception, air quality and air movement, as well as the children's clothing level. The aim of this study is to investigate whether recently found differences in thermal sensation between children and adults outside the heating season also apply to the winter season. Children's assessment is compared to the objective measurements during the surveys, to winter design criteria for school classrooms and to comfort temperatures from previous studies. The results agree with the previously found warmer sensation of children compared to adults' predicted thermal sensation based on the currently used PMV model, although this time the difference is smaller. Regarding air quality, no relationship was found between children's assessment and CO_2 levels.

PRACTICAL IMPLICATIONS

This study is part of a project which aims to inform guidelines and standards for the indoor environment based on children's assessment of their thermal conditions. This will help designers and other stakeholders involved in school building design and management to create spaces that meet children's needs.

KEYWORDS

School buildings, air quality, thermal comfort, heating demand, indoor temperature.

1 INTRODUCTION

Thermal comfort in school classrooms is essential for the pupils' productivity (Wyon, 1970). "Even though the human organism is highly adaptive, a student cannot attend, perceive, or process information easily when his or her physical environment is uncomfortable" (Knirk, 1979). The combined effect of temperature and humidity has been proved to impact on performance and attention (Mendell and Heath, 2005). It has been shown that the impact of the indoor environmental conditions is stronger on children's schoolwork performance than on adults' office work (Wargocki and Wyon, 2013). Therefore, children appear to be more sensitive to the indoor environment than adults. Clearly, sustaining classroom temperatures within acceptable limits for children is crucial for their wellbeing and learning ability.

Temperature design criteria for school environments

Table 1 summarizes the indoor operative temperatures recommended for teaching spaces by International and European standards (ISO7730, ASHRAE 55, EN15251). In Sweden, recommended operative temperature ranges are issued by the Work Environment Authority (Arbetsmiljöverket, 2009) and the Public Health Agency (Folkhälsomyndigheten, 2014), and are included in Table 1. The absolute minimum operative temperature is specified by Swedish building regulations at 18°C, or 20°C in spaces with vulnerable people (Boverket, 2011). A working group of the National Board of Housing, Building and Planning of Sweden (Boverket) published a report which recommends the use of ISO7730 and suggests general operative temperature ranges, to be used also for schools (Boverket, 1998). The Swedish guidelines for the indoor environment also recommend ISO7730 and set an acceptability level of PPD<10% (SWEDVAC, 2013). Specific guidelines for school classrooms are also provided in a 1990s document (Boverket och Arbetarskyddsstyrelsen, 1996). The recommended design temperatures in these specific Swedish guidelines are also shown in Table 1. For comparison, the UK guidelines for the thermal conditions in schools have been included, as determined in Building Bulletins (BB) 87 (DfES, 2003) and 101 (DfES, 2006).

Table 1. Design values of the operative temperature for teaching spaces

Standard/ Guide	Type	Met[1]	Clo[1]		Category/ acceptability	Operative temperature T_{op} range (°C)	
			C-s[1]	H-s[1]		C-s[1]	H-s[1]
ISO 7730	ALL	1.2	0.5	1.0	A (PPD<6)	24.5±1.0	22.0±1.0
					B (PPD<10)	24.5±1.5	22.0±2.0
					C (PPD<15)	24.5±2.5	22.0±3.0
ASHRAE 55[2]	AC[1]	1.1	0.5	1.0	PPD<10	PMV-based range of T_{op} and RH	
	FR[1]	-	-	-	90% accept	$0.31T_m+17.8\pm2.5$	Same as AC
					80% accept	$0.31T_m+17.8\pm3.5$	
EN 15251	AC[1]	Same as ISO 7730			-	Same as ISO 7730	
	FR[1]				I (strictest)	$0.33T_{rm}+18.8\pm2$	Same as AC
Arbetsmiljöverket[3]	ALL	-	-	-	PPD<10	23.0±3.0	22.0±2.0
Folkhälsomyndigheten[3]	ALL	-	-	-	-	23.0±3.0	21.5±1.5
Swedish Guide/schools	ALL	-	-	-	Classroom	24.5±1.5	20.0±2.0
UK BB87, BB101	ALL	-	-	-	Low activity	24±4	21
					Normal	24±4	18
					High activity	24±4	15

[1] C-s =Cooling season, H-s= Heating season, Met=Metabolic rate, Clo=Clothing insulation, AC=Air conditioned, FR=Free running (neither heated nor cooled)

[2] ASHRAE- Standard 55 does not provide criteria by building type, therefore the general criteria are considered applicable for school environments

[3] Arbetsmiljöverket: Swedish Work Environment Authority, Folkhälsomyndigheten: Public Health Agency

As can be seen in Table 1, in the heating season (highlighted in grey) the PMV-based acceptable operative temperatures for teaching spaces span from 18 to 25°C. The recommended operative temperature zones of Table 1 vary significantly, which reveals a lack of a well-defined comfort zone for children. Furthermore, the PMV-based criteria in the standards are similar or even the same as those suggested for office spaces. Therefore, there is essentially no differentiation for the building and occupant type. There is a reference to very young children in the categories of EN 15251 (Category I- high level of expectation) but there is no definition of what ages are considered as “very young” (CEN, 2007). On the other hand, as can be seen in Table 1, the specific guidelines for schools recommend lower operative temperatures in winter, 20^{o}C and 18^{o}C in Sweden and UK respectively. However, these lower values may be based on outdated information and assumptions, as there are no recent research data to support these criteria.

In terms of air quality, CO_2 concentration is the most common indicator and a critical parameter in school classrooms where occupant density is high. The recommended limit for school classrooms is 1000 ppm (Boverket och Arbetarskyddsstyrelsen, 1996).

Children’s thermal comfort in winter

There is a growing interest in schools’ thermal environment over the last years, which is associated with recent findings on children’s thermal perception. Results from thermal comfort surveys in primary school classrooms conducted mainly outside the heating season highlighted that pupils had warmer thermal sensation than adults and preferred lower temperatures (Mors et. al. , 2011, Teli et. al. , 2012, Teli et. al. , 2014, Trebilock and Figueroa, 2014, Haddad et. al. , 2014, de Dear et. al. , 2014). There are several physical and physiological differences between children and adults that affect thermoregulation and could explain such differences in thermal sensation, i.e. children’s greater surface–area-to-mass ratio; hence increased heat gain or loss, greater metabolic heat production per kg body mass and lower sweating rate (Falk, 1998). Therefore, the hypothesis investigated in this study is that children’s warmer thermal sensation indoors; hence lower comfort temperature, extends to the winter season.

Using Fanger’s PMV model, Zeiler and Boxem (2009) calculated children’s neutral temperature in winter at 24^{o}C, based on a metabolic rate of $M=53W/m^2$ (Havenith, 2007), instead of adults’ $M=70W/m^2$ for office activity. This led to a higher calculated neutral temperature compared to that of adults, suggesting that children need higher temperatures to be comfortable in winter. However, research has found discrepancies between PMV and children’s reported thermal sensation even when adjustments to the metabolic rate were applied to the PMV model (Mors et. al., 2011, Teli et. al., 2012, Haddad et. al., 2014). Therefore, a higher comfort temperature for children based on PMV should not be assumed as valid. Overall, as can be seen in Table 2, there is contradictory information across literature regarding children’s neutral temperature in winter and field studies with young children as subjects are scarce. It should be noted that this study is focused on primary (grade) schools, as secondary school children are closer to adulthood both physiologically and behaviorally. Therefore, data or literature from secondary schools are not included.

Table 2. Winter neutral temperatures of young children from published studies

Researcher	Location	Season/month	Neutral temperature	Estimation method	Adults’ equivalent
Auliciems (1975)	Brisbane[1]	winter	24.2	Field surveys	N/C[2]
Zeiler and Boxem (2009)	Netherlands	winter	24.0	PMV calculation with $M=53W/m^2$	21.4
Liang et. al. (2012)	Taiwan	Coldest month (January)	22.4	Field surveys, linear regression	23 (ASHRAE55)
Trebilock and Figueroa (2014)	Chile	winter	16.7	Field surveys, linear regression	N/C[2]

[1] Very mild winters (average ambient temperature during the sampling season: 19.2^{o}C)

[2] N/C: not calculated

This study uses a previously tested methodology for surveying young children with a new, updated questionnaire for capturing the children's own assessment of their classroom's environment for comparison with the recommended temperatures of Table 1 and the neutral temperatures of Table 2. This paper reports on a pilot field study and aims to present initial results and highlight the aspects of children's thermal comfort in winter that require further investigation.

2 MATERIALS/METHODS

The pilot study included thermal comfort surveys with 124 children aged 8-11 in a grade school in Gothenburg, Sweden. The school is housed in 9 buildings, seven of which were built in the turn of the 18th to the 19th century and two in the end of the 20th century, which have all been refurbished. The surveys took place in 5 classrooms located in 3 of the 9 buildings over three days in December 2015.

The study follows the main methodology as previously used in UK school surveys outside the heating season (Teli et. al., 2012, Teli et. al. , 2013). However, this time an extended version of the same questionnaire was used, translated into Swedish. Details of the measuring methods and the survey questionnaire are given below.

Instrumentation and measuring procedures

For the measurement of the indoor environmental parameters a handheld DeltaOhm instrument HD32.3 was used, which measures globe temperature (∅50mm) and air temperature (accuracy class 1/3 DIN), relative humidity [accuracy ± 2%RH (15 - 90 %RH) @ 20°C, ± 2.5%RH remaining range] and air speed [accuracy ± 0.05 m/s (0-1 m/s), ± 0.15 m/s (1-5 m/s)]. The instrument was placed as centrally in the classroom as possible and at a height of 1m, using a tripod (see Figure 1). This was preferred to the standard height of 1.1m according to ISO7726 (ISO, 2001), as this is closer to the children's level when seated. Figure 1 shows the placement of the instrument in a classroom prior to children's arrival. CO_2 concentration was measured before, during and after the surveys using a Rotronic CP11 [accuracy ±(30ppm+5% of reading)]. Measurements were logged at intervals of 30 seconds to enable detailed investigation of CO_2 variation. All instruments were calibrated in 2015.

Figure 1. (a and b) Thermal comfort instrument placed in a classroom.

Questionnaire design

The questionnaire was based on a previously designed version for children (Teli et. al., 2013) and was revised based on Humphreys et. al. (2016), addressing issues of wording and translation of thermal comfort scales. The presented pilot study helped to confirm the suitability of alterations and added questions. The final version consists of 9 questions which include: 1) thermal sensation vote on a 7-point scale, 2) thermal preference vote on a 7-point scale, 3) thermal sensation on three parts of the body on a 3-point scale, 4) thermal acceptability vote 5) sensation of tiredness, 6) air quality vote, 7) assessment of air movement, 8) preferred adaptation measures and 9) clothing items worn. Colours and sketches are used in the questionnaire, as previously, to keep children's interest.

3 RESULTS

Thermal sensation: preliminary results

The children's thermal sensation vote is first compared to the predicted mean vote (PMV), calculated based on ISO7730 (ISO, 2005) using the measured environmental parameters at the time of the survey. The average measured operative temperature in the five classrooms was 22.4±0.6^{o}C and the average thermal sensation vote was 0.13±1.2 scale points. The clothing insulation was calculated using tabulated values from ISO 9920 (ISO, 2009) and children's selected items on the questionnaire's checklist. The average clothing insulation for the entire sample was 0.66clo ±0.16, which is significantly lower than the assumed value of 1clo for winter used in standards (ISO, 2005, ASHRAE, 2013, CEN, 2007) and that found in Dutch school classrooms 10 years ago (Havenith, 2007), although the corresponding indoor temperatures in that study were not reported. This study's average clo, however, is close to the median winter clothing insulation value of 0.69clo, which was derived from analysis of 2949 field observations, mainly from office buildings (Schiavon and Lee, 2013). For the metabolic rate, a met value of 1.2 was used, corresponding to adults' office activity (70 W/m^2 and basal metabolic rate 58 W/m^2). Figure 2(a) shows the calculated average PMV and average reported thermal sensation vote (TSV$_{(mean)}$) per survey in relation to the operative temperature at the time of the survey. As can be seen, children's thermal sensation was slightly higher than the PMV in agreement with studies outside the heating season, by an average of 0.6 scale points. However, the difference in this case is smaller.

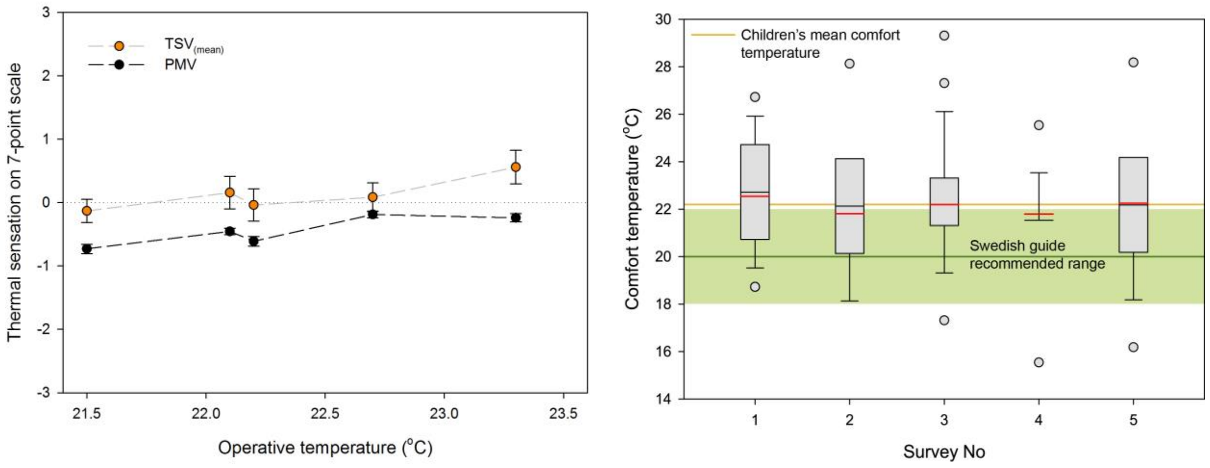

Figure 2. a) Mean thermal sensation vote (TSV(mean) and mean PMV per survey with standard error bars, against operative temperature at the time of the survey, b) Children's comfort temperature distribution per survey. Box: the 50% of the comfort temperatures; whiskers: the 10th and 90th percentile; dots: outliers; black line: median, red line: mean.

Children’s comfort temperature was calculated for each reported thermal sensation vote using equation (1) (Humphreys et. al., 2016).

$$T_{comf} = T_o - TSV/G \qquad (1)$$

Where T_o is the mean operative temperature at the time of the survey, TSV is a respondent’s reported thermal sensation on the seven-point adapted ASHRAE scale and G is Griffiths constant, G=0.5 as estimated using extensive data from fiend studies (Humphreys et. al. , 2013) and validated for the case of school children (Teli et. al. , 2015).

As can be seen in Figure 2(b) the majority of comfort temperatures, based on the 10th and 90th percentiles, range on average between 18.7^{o}C and 24.7^{o}C. The average comfort temperature calculated from the 123 valid responses is 22.1±2.4^{o}C, for an average clothing insulation of 0.66clo. Using the calculated PMVs instead of the observed TSV in equation (1), the average comfort temperature derived is 23.3±0.7^{o}C. Therefore, the PMV method used in ISO7730 and recommended by most guidelines for winter overestimates children’s comfort temperature by approximately 1^{o}C. The Swedish guidelines for schools however, appear to underestimate children’s comfort zone (Boverket och Arbetarskyddsstyrelsen, 1996).

Air quality: CO_2 concentration

Achieving good air quality and at the same time thermal comfort is one of the major challenges in winter, especially in naturally ventilated spaces. From the five investigated classrooms, two are naturally ventilated-NV (one due to system failure) through window opening (1 and 5 of Figure 3) and the remaining three are mechanically ventilated-MV. As can be seen in Figure 3, children’s assessment of the air quality appears to have no relation to CO_2 levels, with the majority of responses being “neither stuffy nor fresh’ regardless the CO_2 concentration in the classroom. However, this may be due to the moderate CO_2 concentrations registered during the surveys. Interestingly, the lowest percentage of children assessing the air as being ‘stuffy’ was in the naturally ventilated classroom. Surveys under more variable conditions are needed in order to evaluate whether children can perceive air quality issues.

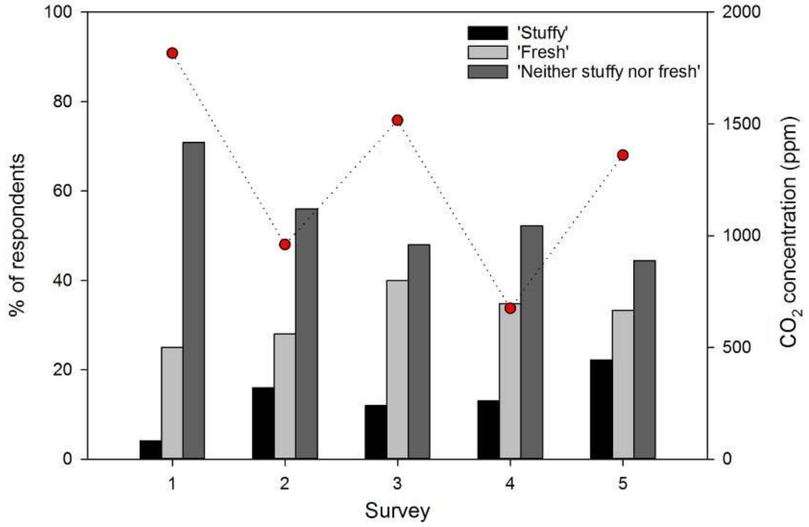

Figure 3. Children’s assessment of the air quality in the 5 investigated classrooms in relation to the CO2 concentration (red dot) during the survey.

Although the recommended limit was exceeded in both NV and MV classrooms, the increase did not occur at the same rate, as would be expected. Survey 1 in Figure 4 was conducted in one of the NV classrooms with one window partly open whilst survey 2 in one of the MV classrooms. In survey 1, the CO_2 level rises sharply after children's arrival and continued rising towards 1500ppm. In survey 2 the increase was more gradual. The recommended limit was exceeded within 30 minutes from children's arrival but remained very close to the guideline value of 1000ppm. The airflow rate per person was approximately 60% higher in Survey 2, which is a substantial difference. Overall, it seems that in both cases ventilation rates were adequate, considering the high number of occupants (average 25 children and one adult). Furthermore, the percentage of children assessing the air quality as 'stuffy' was low, below 20% in both cases. However, as highlighted above, children's evaluation of air quality needs to be investigated further.

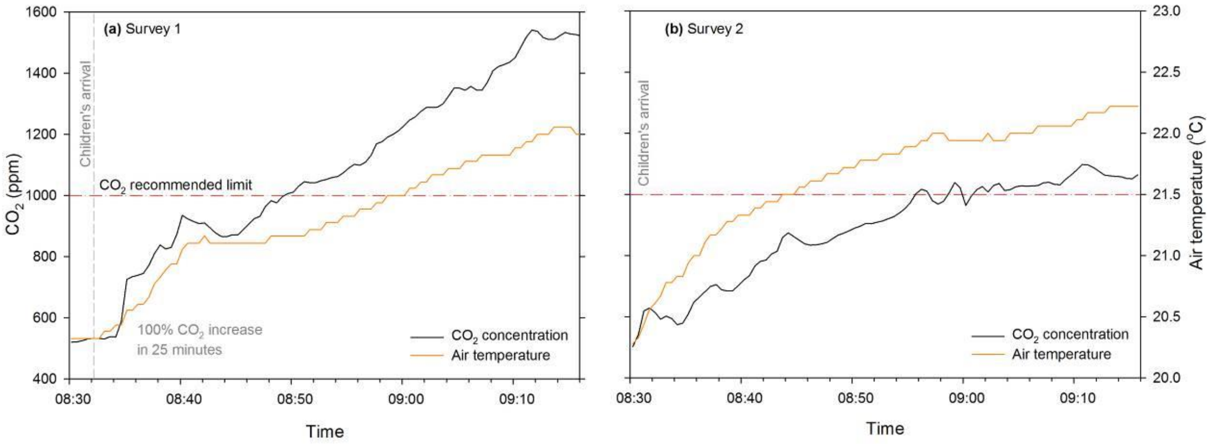

Figure 4. CO2 concentration and air temperature at 30-second intervals during 45 minutes of class time in two of the 5 investigated classrooms: (a) Naturally ventilated through window-opening, (b) Mechanically ventilated.

4 DISCUSSION

There are numerous studies throughout the world which have reported thermal and air quality conditions in schools that were not complying with standards and guidelines for the indoor environment. Furthermore, recent field surveys in schools showed that these standards and guidelines may not be applicable to the case of young children. There is clearly a need to take these observations further and update current design criteria and practices based on children's observed thermal perception and comfort trends. The pilot study presented here further supports this, as it indicates that the differences in thermal comfort conditions between adults and children previously found may not be limited to the non-heating season. The pilot study also highlights a behavioral factor in indoor temperature development. The children's average clothing insulation was much lower than what is assumed in standards for the winter season. This poses the question of whether clothing choices led to the temperatures experienced in the classroom or, conversely, whether children adapted their clothing to their classroom environment. Either way, it suggests a potential trend towards lower clothing levels which leads to higher indoor temperatures and, consequently, higher heating demand.

Based on the small sample analyzed here, no relationship was found between the CO_2 concentration in the classroom and children's own assessment of air quality. However, the role of CO_2 needs to be further investigated as research has suggested that there may be a link between CO_2 levels and thermal sensation (Gauthier et. al. , 2015), exceeding the mere association with air quality. Such relationship will be explored with the data to be collected in January/February 2016. The larger number of surveys will enable the investigation of relationships such as between the air quality assessment and operative temperature.

5 CONCLUSIONS

This pilot study focused on children’s thermal comfort in winter and is part of a project which investigates the year-round thermal preferences of children in Sweden and UK. The analysis of current thermal criteria for schools shows that there is a large variation in the recommended operative temperature ranges whilst recommended winter temperatures in specific Swedish and UK guidelines for schools are lower than those for other building types. Furthermore, there is variation in observed or calculated neutral temperatures in the fairly limited published research on children’s thermal comfort in winter. This variation could be related to the timespan of up to 40 years between some of these studies, which further highlights the need for field data that include children’s own assessment of their environment. A small difference was found between children’s TSV and PMV, in agreement with previous studies in summer season. The average comfort temperature in this study was 22.1±2.4 ^{o}C, lower than the neutral temperature calculated using the PMVs, but higher than the guidelines for children in Sweden and UK. Comparison between the CO_2 concentration and children’s assessment of the classroom’s air quality highlighted the difficulty in perceiving its effect, as no relationship was identified. However, this needs further investigation with the extended dataset, as the limited number of surveys used in this analysis cannot lead to conclusive results.

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