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Summertime Thermal Comfort in Australian School Classrooms

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Abstract

Considering school students spend up to one third of their day inside classrooms, it's surprising how few detailed empirical studies have been conducted into how the thermal environment of classrooms affects students' comfort and performance. Whereas PMV tends to exaggerate warm discomfort for adults, the literature suggests it ***unde***restimate children's actual thermal sensation, but there is no coherent explanation for this in terms of metabolic or other physiological differences to date. The aim of this study was to conduct a thermal comfort survey in actual classrooms with a view to empirically defining preferred temperatures, neutral temperatures, and acceptable temperature ranges for Australian school children, and to compare them with findings from adult populations. The study informs a thermal comfort (air conditioning) policy being developed for Australian schools.

The survey was conducted in a mixture of Air-Conditioned (AC), Evaporative-Cooled (EC), and Naturally-Ventilated (NV) classrooms in 10 schools during the Austral summer of 2013. Both Primary (grade) school and high schools were included in the sample. The survey was conducted twice a day (morning and afternoon), and the survey period varied between schools, from one week up to three weeks. After quality assurance processing a total of 3,129 questionnaires were retained from the sample of students and 138 samples were from the teachers.

An indoor operative temperature of about 22.5°C was found to be the students' neutral and preferred temperature, which is generally cooler than expected of adults under the same thermal environmental conditions, confirming earlier research findings in the thermal comfort literature. Working on the industry-accepted assumption that an acceptable range of indoor operative temperatures corresponds to mean thermal sensations of -0.5 through +0.5 (ASHRAE 2013; ISO 2005), the present analysis indicates an acceptable summertime range for primary and high school students from about 18.5 through to about 26.5°C operative temperature.

The paper concludes with hypotheses to explain differences between thermal comfort of children and adults.

Keywords

Thermal comfort, field study, school children, questionnaire, PMV, adaptive model

1 Introduction

It is commonly believed that warm indoor temperatures and the ensuing thermal discomfort result in decreased productivity/performance and mental acuity, and this generalizes to the educational arena, resulting in considerable public pressure being placed upon school administrations to provide indoor climates that optimise students' educational achievements (Mendell & Heath 2005; Wargocki & Wyon 2007; Bako-Biro et al. 2012). The flip-side of the coin is a collective responsibility to minimise the environmental impacts resulting from those classroom indoor climates. Their operational energy consumption and associated greenhouse gas emissions need to be minimised and justified, so here again there is clear requirement to identify exactly what indoor climatic conditions are actually required by school children. This paper describes a project in which classic thermal comfort field methods are applied to the question of thermal comfort of school children in Australia.

Table 1 Summary of previous thermal comfort field studies conducted in school classrooms

Study	Location	Climate	Season	Ventilation Type	Age Group	Sample Size	Neutral Temperature
Auliciems (1969)	England	Temperate	Winter	NV	11-16	624	16.5°C
Pepler (1972)	Oregon	Temperate	Spring and Autumn	NV and AC	7-17	NV: 100 AC: 66	NV: 21.5 to 25°C AC: 22 to 23°C
Auliciems (1973)	England	Temperate	Summer	NV	11-16	624	19.1°C
Auliciems (1975)	Australia	Sub-tropical	Winter	NV	8-12 and 12-17	Not given	Primary: 24.2°C Secondary: 24.5°C
Kwok (1998)	Hawaii	Tropical	Winter and Summer	NV and AC	13-19	NV: 2,181 AC: 1,363	NV: 26.8°C AC: 27.4°C
Kwok and Chun (2003)	Japan	Sub-tropical	Summer	NV and AC	13-17	74	Not calculated
Wong and Khoo (2003)	Singapore	Tropical	Summer	NV	13-17	493	28.8°C
Corgnati et al., (2007)	Italy	Mediterranean	Winter	NV	12-17	440	Not calculated
Hwang et al., (2009)	Taiwan	Sub-tropical	Autumn	NV	11-17	944	23 to 24°C
Zeiler and Boxem (2009)	Netherlands	Temperate	Winter	AC	Primary school	174	Not calculated
ter Mors et al., (2011)	Netherlands	Temperate	Winter, Spring and Summer	NV	3-11	79	Not calculated
De Giuli et al., (2012)	Italy	Mediterranean	Spring	NV	9-11	614	Not calculated
Liang et al., (2012)	Taiwan	Sub-tropical	Autumn	NV	12-17	1,614	22.4 to 29.2°C
Teli et al., (2012)	England	Temperate	Spring	NV	7-11	230	20.5°C

Note: Ventilation types include naturally-ventilated (NV) and air-conditioned (AC) classrooms.

Table 1 provides a summary of thermal comfort studies conducted over the past 40 years in school/classroom environments. Notwithstanding the geographic, climatic and demographic differences between the various studies in Table 1, several similarities can be identified. In almost all studies, the majority of school children surveyed (at least 50%) voted the immediate thermal environment within the three central categories of the common thermal sensation scale, i.e. ‘slightly cool’, ‘neutral’ and ‘slightly warm’ (Auliciems 1969; Pepler 1972; Auliciems 1973; Kwok 1997; Kwok 1998). Even when the outdoor climatic conditions were considerably warmer than average, such as those observed in Japan (Kwok & Chun 2003); Singapore (Wong & Khoo 2003); and Taiwan (Hwang et al. 2009; Liang et al. 2012); or cooler (Corgnati et al. 2007; De Giuli et al. 2012), the students’ mean thermal sensations were still within the ‘neutral’ category.

Table 1 also shows the neutral temperatures calculated for each study. Neutral temperature is defined as the temperature in which the greatest percentage of subjects can be expected to vote within the middle (‘neutral’) category of the ASHRAE 7-point thermal sensation scale. Thermal neutralities in Table 1 show considerable variation. Some ranged from as low as 16-20°C in the cooler climates of England (Auliciems 1969; Auliciems 1973; Teli et al. 2012); to 24°C and 26-27°C in sub-tropical Australia (Auliciems 1975) and Hawaii (Kwok 1998) respectively. Within the warmer climates of Taiwan and Singapore, school children were found to be neutral at temperatures around 28-29°C (Wong & Khoo 2003; Hwang et al. 2009). This broad relationship between indoor neutralities and outdoor climatic environment seems consistent with the adaptive comfort hypothesis (e.g. Humphreys, 1978; de Dear & Brager, 1998) and previous field studies involving adults in both AC and NV environments in similar climates (e.g. Humphreys 1978; de Dear et al. 1991; Busch 1992; Nicol et al. 1999).

From a comparison of their Singapore results with previous field studies involving school children, Wong and Khoo (2003) concluded that the differences in thermal neutralities were likely due to the students’ adaptation to, and tolerance of, higher temperatures in warmer climates. While the specific causal mechanisms behind this association are unclear, they suggested that the physiological (acclimatisation), psychological (expectation and habituation) and physical (clothing adjustment) adaptations observed in adult populations could also be relevant school children.

1.1 Issues related to the comfort standards

Current comfort standards, such as ISO 7730 (ISO 2005), EN 15251 (CEN 2007) and ASHRAE Standard 55 (ASHRAE 2013), determine design values for operative temperatures in indoors based on the heat-balance and adaptive thermal comfort models. Since no children were included in Fanger’s (1970) original heat-balance thermal comfort research behind PMV, there is no assurance that results obtained from field studies in offices or universities, or experiments conducted in climate chambers, will accurately reflect the thermal sensations and preferences of school children (ter Mors et al. 2011; Teli et al. 2012). Indeed, many studies have demonstrated that predictions by Fanger’s (1970) PMV-PPD model underestimate the actual thermal sensation of children i.e. children have been previously been noted to express warmer sensations than predicted by the PMV-PPD model (Kwok 1998; Kwok & Chun 2003; Wong & Khoo 2003; Zeiler & Boxem 2009; ter Mors et al. 2011). Furthermore, Teli et al., (2012) also revealed that children’s thermal preferences were cooler than those predicted by the adaptive standard in EN15251 (ter Mors et al. 2011; Haddad et al. 2013).

Many researchers have proposed reasons for the discrepancies between the thermal sensations of children and the PMV predictions. In comparison with adults, children are generally less sensitive to temperature changes (Humphreys 1977); have a faster rate of heat loss (McCullough et al. 2009); and have a greater sensitivity to changes in their core temperature (Anderson & Mekjavic 1996). Differences in metabolic rates of children and adults for typical indoor activities may possibly explain the differences in their thermal sensations when exposed to the same temperatures (Havenith 2007).

1.2 Effects of classroom temperature on school performance

A few studies conducted in the 1960s and 1970s suggest that moderate changes in room temperature affect children's ability to perform mental tasks requiring concentration, such as coding tests, multiplication problems, short-term memory retention, reading speed and comprehension (Pepler & Warner 1968; Wyon 1970; Wyon et al. 1979), and the impacts can be both positive and negative; for example speed of multiplication problems was reduced by higher temperatures in Pepler and Warners' study (1968) and yet their accuracy went up. From their extensive review of the research literature, Mendell and Heath (2005) found that warmer temperatures (above 24°C) tend to reduce performance, while colder temperatures (below 22°C) reduce manual dexterity and speed (Wyon et al. 1979; Kevan & Howes 1980; Levin 1995). However, these temperature ranges may be dependent on the climate zones in which the study is being conducted. For example, Auliciems (1972) found that British schoolchildren experienced optimal learning conditions at around 16°C.

The influence of moderately elevated temperatures on student performance was investigated in a recent series of field experiments conducted in Danish classrooms (Wargocki & Wyon 2006; Wargocki & Wyon 2007). The performance of various schoolwork performance tasks, from reading to mathematics, by 10-12 year old Danish children was measured during weeks in which moderately elevated classroom temperatures were avoided (by cooling from 25°C to 20°C). The students' speed and accuracy of task performance was assessed and the results indicated that reductions in the classroom temperature had a positive effect on Danish students' performance. As temperatures decreased from 25°C to 20°C, the average (normalised) speed of the performance tasks increased by approximately 2% per 1°C temperature decrease. However, changes in temperature did not have any measurable effect on the number of normalised errors (Wargocki & Wyon 2006; Fisk & Seppanen 2007; Wargocki & Wyon 2007), partially confirming the findings of Pepler and Warner discussed above (1968).

Despite the number of studies on the effects of temperature on children's schoolwork, there is relatively little information on whether students perform better (or worse) in air-conditioned (AC) or naturally ventilated (NV) environments and it is inconsistent. Studies conducted in the US during the 1950s and 1960s found that students performed better in thermally conditioned (AC) classrooms than in those without any form of heating or cooling (NV) (Pepler & Warner 1968; Pepler 1972). In one of the earliest recorded studies on the influence of temperature in AC classrooms on learning, Pepler and Warner (1968) studied six groups of six students in a climate-controlled chamber. Each group of students performed simulated schoolwork with chamber temperatures ranging from 17 to 33°C. It was found that as temperatures increased from 17 to 27°C, the students' speed of work decreased by 7%, whereas the rate of errors was highest at 17°C and lowest at 27°C which represents a 17% improvement (Pepler & Warner 1968).

In a similar study, Schoer and Shaffran (1973) reported three experiments in which 10 to 12 year old students in matched pairs were assigned to either a NV classroom (temperature was 26°C) or to an adjacent AC classroom (temperature of 22.5°C). Nineteen different tasks, ranging from simple and repetitive tasks (such as crossing out certain letters in a text) to school exercises (such as coding numbers onto machine-readable punch cards), were applied to each group every school day for 6-8 weeks. The students' performance was significantly better in the AC classroom by 5.7% (Schoer & Shaffran 1973). However, the differences reported in these case studies could have been influenced by external factors. For example, it is likely the subjects knew they were taking part in an experiment because they were driven to the experimental classrooms and instructed by experimenters and not their normal class teachers. Also, the students knew they were being tested as each test was timed with a stop-watch, and by talking to each other across the duration of the study they might have known there was a difference in temperature between the two classrooms. According to Wargocki and Wyon (2007), the observed differences in performance could have been due to a gradual process of discouragement and growing resentment between two groups of pupils.

Although Mendell and Heath (2005) provide a comprehensive review of the effects of temperature on student's classroom performance, several studies, such as those covered by Wyon (1970), were not included. In these experiments, three parallel classes of 9-10 year old children were exposed to each of the three classroom temperatures (20°C, 27°C and 20°C) for two hours. This corresponded with another study in which four classes of 11-12 year old children were exposed to 20°C and 30°C in the morning and afternoon (Holmberg & Wyon 1969). All temperatures were encountered in a balanced order. The children performed a number of numerical tasks (addition, multiplication, number-checking) and language-based tasks (reading and comprehension, supplying synonyms and antonyms) so that their rate of working and the number of errors could be quantified. Compared to 20°C, the children's performance was significantly lower for both tasks at 27°C and 30°C, especially during the afternoon as children started to fatigue (Holmberg & Wyon 1969). The findings suggest that rate of work in the numerical tasks, and reading comprehension and reading speed were reduced by raised temperatures, as the magnitude of the negative effect of temperature on performance was as great as 30% (Wyon 1970). These results were later supported by Wyon et al., (1979) in which the reading speed, comprehension and multiplication tasks performed by high school students (17 years of age) began to decline as temperatures reached 27°C.

1.3 Aims of the current study

Considering school students spend up to one third of the day inside classrooms, the significance of providing comfortable environments for learning is obvious (Haddad et al. 2013). Unfortunately, how the thermal environment of classrooms affects students' comfort and performance has been understudied over the last 40 years, and the amount of Australian work in this topic is negligible. Whereas PMV tends to exaggerate warm discomfort for adults, it seems to underestimate children's actual thermal sensation, but there is no coherent explanation for this in terms of metabolic differences to date.

The literature on the impacts of thermal environment on children's school performance is, at best, inconsistent. Furthermore, the overwhelming majority of the research comes from colder climate zones than Australia, so the effects of acclimatization to the Australian climatic context is overlooked by these generalisations. Nonetheless, the literature demonstrate that increased classroom temperatures can have a negative effect on children's comfort and academic achievement; discomfort decreases the children's attention span when temperature and humidity exceed their comfort zone (Wyon 1970; Kwok 1997; Mendell & Heath 2005; Zeiler & Boxem 2009). But the actual span of temperatures comprising children's comfort zone is probably related to the thermal environment, both internal and out, to which they have become adapted – sliding up the temperature scale in warmer climates, and down the scale in cooler climates. By logical extension, therefore, air conditioning classrooms in Australia's summer potentially causes children to "acclimatise" to artificially cooler indoor conditions.

This study aims to:

- understand students' perception of classroom thermal environment, particularly in relation to current adaptive comfort guidelines

- understand students' attitudes towards different ways of adjusting their level of thermal comfort
- investigate thermal performance (overheating) of Australian school buildings
- apply ASHRAE adaptive comfort model as a rational basis for deciding whether or no classroom is overheating during summer.

2 Methods

2.1 Survey questionnaire and subjects

Questionnaire surveys and instrumental measurements of indoor thermal comfort parameters were carried out simultaneously in nine Australian schools during the late summer period of 2013. A total of 2,850 responses were obtained from nine schools, with the age of survey participants ranging from 10 to 18 years. The surveys were administered by the regular classroom teacher twice a day (morning and afternoon) in a mixture of classrooms with and without mechanical cooling systems (Air-Conditioned AC, Evaporative-Cooled EC and Naturally-Ventilated NV). And even though some classrooms were equipped with air conditioners, using operable windows and ceiling fans was regarded as the primary method of space cooling. The survey period varied between schools from one to three weeks. The participating schools are located generally in temperate, sub-tropical and semi-arid climate zones (Bureau of Meteorology 2013). Each school's ventilation type, climate zone and sample size (N) are summarised in Table 2.

Table 2 Summary of participating schools and students

Participating School		**Ventilation Type**	**Climate Zone**	**Respondent Sample**	
				N	**%**
Primary School	A	NV	Warm temperate	65	2.3
	B	AC	Warm humid summer, mild winter	428	15.0
	C	AC	Warm temperate	374	13.1
	D	EC	Hot dry summer, cool winter	300	10.5
	E	NV	Mild temperate	474	16.6
	F	EC	Hot dry summer, cool winter	450	15.8
High School	G	EC	Hot dry summer, cool winter	321	11.3
	H	NV	Warm temperate	214	7.5
	I	AC	Mild temperate	224	7.9
Total				2,850	100.0

Note: AC (Air-Conditioned), EC (Evaporative-Cooled), NV (Naturally-Ventilated)

The questionnaire recorded the information of the students' thermal sensation, thermal preference, activity level and clothing insulation (Table 3). Teachers checked questionnaire items prior to conducting the survey, examining whether the description was comprehensible to the students or not. ASHRAE's seven-point scale, with each response given a numerical value from -3 to +3 (i.e. *cold* = -3, *slightly cool* = -2, *neutral* = 0, *slightly warm* = +1, *warm* = +2, *hot* = +3), was used for the respondents to rate their thermal sensation by asking, "*Please circle how you feel right now?*" Students' thermal preference was rated with the McIntyre scale by asking, "*Would you like to be*?" on a three-point scale coded from -1 to +1 (i.e. *colder* = -1, *no change* = 0, *warmer* = +1).

Table 3 Summary of questionnaire items, scales and numerical coding used in the analysis

Questionnaire item	Measuring scale or answer coding
Thermal sensation	Hot (+3) Warm (+2) Slightly warm (+1) Neutral (0) Slightly cool (-1) Cool (-2) Cold (-3)
Thermal preference	Warmer (+1) No change (0) Colder (-1)
Activity level (MET)	Sitting (1.2) Active (3.0)
Clothing insulation (Clo)	Dress (0.54) Dress, Jumper (0.79) Dress, Jacket or Blazer (0.90) Skirt, Shirt (0.54) Skirt, Shirt, Jumper (0.79) Skirt, Shirt, Jacket or Blazer (0.90) Shorts, Shirt (0.36) Shorts, Shirt, Jumper (0.61) Shorts, Shirt, Jacket or Blazer (0.72) Long pants, Shirt (0.57) Long pants, Jumper (0.82) Long pants, Jacket or Blazer (0.93)

(from ASHRAE Standard 55-2013)

In relation to activity level, teachers instructed the students to check '*Sitting*' box if they had been sitting in the classroom for the 30 minutes prior to completing the survey. If the students had come from activities such as physical education, dance or outdoor playtime, they were guided to tick the '*Active*' box. The students' activity level recorded on the questionnaire as either 'Sitting' or 'Active' were equated to metabolic rates, MET = 1.2 and 3.0, which are corresponding to typical office sedentary activity and dancing/exercise respectively in ASHRAE 55 (2013). Assigning corresponding metabolic rates from the current comfort standards to the students' activity levels requires a special attention because the values appended in the comfort standards are based on an average adult. However, while the survey samples comes from a broad range of age groups (10~18 years), detailed information about the participants' demographic and physiological characteristics, including age, gender, body weight and body surface area were not collected. Therefore, adjustments to the compendium values of metabolic rates could not be made. One of the only field studies of children's metabolic rate in classroom settings by Havenith (2007) provide students' metabolic rate data for typical school activities. However the specific climatic setting (Northern European winter) of Havenith's study does not encourage extrapolation of his findings to places like Australia. School children in Northern European winter are possibly more sedentary than their counterparts in more benign climatic settings like Australia, where they are more likely to be actively running around outdoors during mid-morning recess, lunch-hours, of even during the brief class change-overs. Moreover, Havenith's data consisted of a very small number of subjects (N = 1 ~ 5 for each subject group). Considering the ethnic diversity of Australia, the sample number in Havenith's database seemed insufficient to warrant generalization.

Clothing insulation was estimated for each subject. Twelve typical clothing ensembles were created based on the combinations of school uniform garments. Insulation of the students' chairs, typically made of polypropylene, was estimated to have negligible incremental insulation. The clothing ensembles and corresponding clo values are also attached in Table 3.

2.2 Classroom indoor climate instrumentation and procedures

Physical indoor climatic data were collected at 15-minute intervals from each classroom. PT100 resistance temperature devices were calibrated and used to record air temperature and globe temperature. Air speed was registered with an Accusense F900 hot-wire anemometer with range of 0.15 – 5 m/s ± 10% and humidity was recorded by Vaisala INTERCAP Humidity and Temperature Probe HMP60. The sensor package was typically wall-mounted between 2 and 2.5m above floor-level within each classroom and connected to the internet through each school's internal wifi. This equipment configuration put the sensors outside the classroom's occupied zone, but was deemed necessary to protect from student tampering. In all of the classrooms surveyed our pilot investigations found no evidence that temperatures recorded by our wall-mounted instrument package differed significantly from those experienced by the students, as a result of vertical thermal stratification or radiant asymmetry. However it is possible that our air speed sensors were underestimating speeds in the free atmosphere within the occupied zone of some of our sample classrooms.

Individual survey responses were manually matched with corresponding time-stamped indoor thermal environmental data for subsequent analysis. The dataset received careful quality verification throughout this merge process. A range of comfort indices were then calculated, including operative temperature (T_o is an arithmetic average of both air and mean radiant temperatures), mean air velocity (V_{air}), relative humidity (RH), metabolic rate (MET), clo value (Clo), Actual Mean Vote (AMV is the mean value of the thermal sensation votes recorded by the subjects on the seven-point scale), Predicted Mean Vote (PMV was calculated with the ASHRAE ComfortTool) and Predicted Percentage Dissatisfied (also calculated with the ASHRAE ComfortTool).

2.3 Overheating/cooling analysis

As an index of classroom overheating or overcooling, the number of occupied hours in which indoor operative temperature exceeded the acceptable adaptive temperature limits, as prescribed in ASHRAE Standard 55-2013, was calculated. It is acknowledged that the adaptive model was developed from naturally ventilated spaces and so its scope of application should be limited to such spaces, but for the classrooms in this study having an air conditioning system, thermal conditioning of the space was primarily regulated through operable windows (the A/C systems in operation were invariably of the split-system type). Furthermore the actual usage of those split-system air conditioners was not monitored. Therefore data from every school, regardless of the presence or absence of an air conditioning system, have been retained in this overheating/cooling analysis. The ASHRAE

Standard 55's adaptive upper and lower 80% acceptability limit for each day of the monitoring period was defined based on the weighted, running 7-day mean outdoor temperature (ASHRAE 55-2013) referring to Bureau of Meteorology's closest weather station. Observed hourly indoor operative temperature of each classroom during school operating hours (from 8:30AM to 3:30PM) were then assessed as falling inside or outside the 80% acceptability band.

3 Results

3.1 Thermal comfort indices

Descriptive statistics including mean, range and standard deviation (S.D.) of each index are listed in Table 4. Indoor operative temperatures (T_o) recorded during this study fell within the range of 18.2 to 31.1°C, with a mean value of this summer season being 25.1°C. With a negligible mean speed of 0.07 m/s, air movement within the occupied zone exerted a marginal effect on subjects' thermal sensation. RH ranged from 26% to 78% with an average of 51%. Mean metabolic rate was 1.5 met indicating that most of the students were sitting in the classroom prior to the questionnaire being administered. Clothing insulation estimates were close to those typically assumed for adult office workers during the summer season (ASHRAE, 2010), with an average value of 0.45 Clo. The Actual Mean Vote on the thermal sensation scale (AMV = +0.45) for all student samples fell mid-way between *neutral* (0) and *slightly warm* (+1). The mean of the predicted PMV index across this sample was +0.34. The respondents' AMV (actual sensation vote) was marginally warmer than PMV (predicted sensation vote) by about 0.1 thermal sensation units. On the basis of the instrumental observations of the sample classrooms the PPD index predicted that 24% of the subjects, on average, would be dissatisfied with their thermal environment.

Table 4 Statistical summary of classroom indoor climate and thermal comfort indices

Index	Mean	Min.	Max.	S.D.
T_o (°C)	25.1	18.2	31.1	2.2
V_{air} (m/s)	0.07	0.00	0.62	0.08
RH (%)	51.4	25.97	78.23	9.5
MET	1.51	1.20	3.00	0.68
Clo	0.45	0.36	0.93	0.13
AMV	+0.45	-3.00	+3.00	1.38
PMV	+0.34	-2.50	+3.00	0.98
PPD (%)	24.2	5.00	99.4	25.6

Note: AMV, PMV and PPD were averaged results from individual calculations for each subject

3.2 Subjective assessment of the indoor thermal environment

Fig.1 illustrates the distribution of indoor operative temperature (T_o) recorded during the summer survey period. Each bar shows the number and percentage of survey samples falling within each operative temperature bin. Approximately 90% of observed operative temperature measurements fell within the range of 22 to 29°C.

Statistical distributions of the survey participants' perception of the thermal environment are summarised in Fig. 2. 42.2% of the students expressed their thermal sensation as *neutral*. More than twice as many votes fell in *warmer-than-neutral* region of the scale (i.e. including *slightly warm* 16.9%, *warm* 12.2%, and *hot* 10.4%) compared to the votes on *cooler-than-neutral* (i.e. including *slightly cool* 11.5%, *cool* 4.1%, and *cold* 2.6%). The PPD thermal comfort index is based on the assumption that people voting in the middle three categories (i.e. *slightly cool* -1, *neutral* 0, or *slightly warm* +1) of the 7-point thermal sensation scale are satisfied with their thermal environment. Extending this assumption to the Actual Mean Votes cast during this survey, 70.6% of the students were satisfied with their classroom thermal condition. By logical extension, votes on +2 (*warm*), +3 (*hot*), -2 (*cool*), or -3 (*cold*) can be regarded as expressions of thermal dissatisfaction, which in this survey amounted to 29.4%. This indicates that the classrooms in which the survey was conducted failed to meet the industry-accepted minimum standard of 80% acceptability, as recommended in regulatory documents such as ASHRAE's Standard 55 (ASHRAE, 2010). Thermal preference votes were consistent with the distribution of thermal sensation votes, and 41.8% of the survey participants wanted to be *cooler*, whereas only 11.3% wanted to be *warmer*.

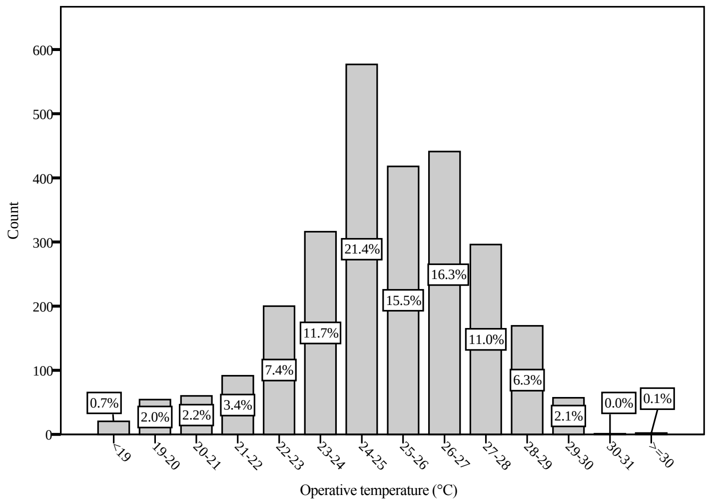

Fig. 1 Histogram of indoor operative temperature binned at 1°C intervals

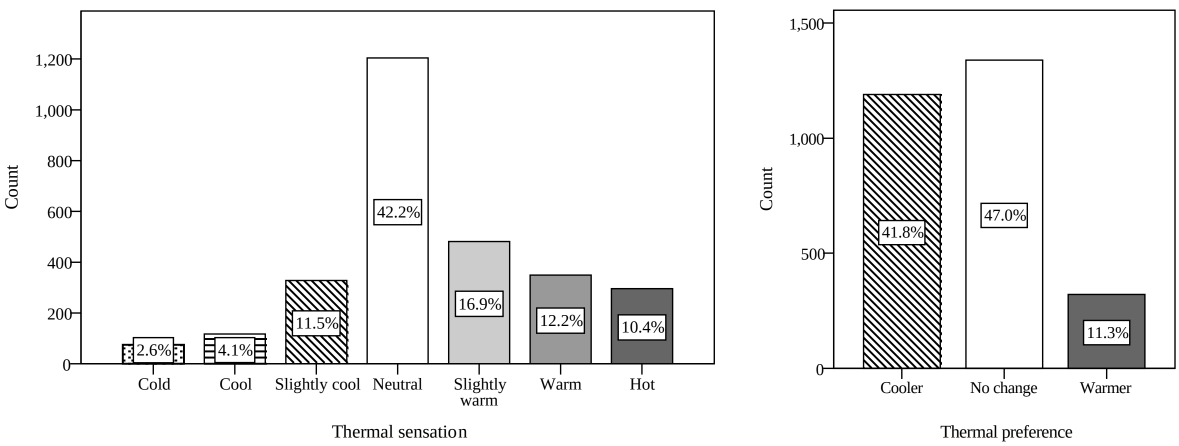

Fig. 2 Distribution of thermal sensation (left) and thermal preference (right) votes

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Fig. 3 shows the distribution of survey participants' thermal preference votes in relation to their thermal sensation votes. As thermal sensation increased (i.e. from cold to hot), the percentage of subjects voting for '*want cooler*' generally increased. As one might expect, the percentage of those preferring to be warmer (i.e. '*want warmer*' responses) tended to increase as thermal sensation decreased from warm to cool. However, this pattern is slightly asymmetrical with the percentage of subjects wanting to feel cooler under warmer-than-neutral conditions significantly higher (69-87%) than the percentage of subjects wanting to feel warmer under cooler-than-neutral conditions (36-61%). This probably reflects the season in which the survey was conducted, with preferences to return from warm to neutral being usually stronger than the opposite during the warm season (Brager *et al*. 2004). The apparent inconsistency between thermal preferences expressed by respondents who were feeling cooler-than-neutral is counterintuitive. For example 28% of respondents who felt cold (thermal sensation of -3) expressed a preference to feel even cooler. In order to test the hypothesis that the "right-here-right-now" preface to the questionnaire may not have been fully understood by the younger subjects in our sample, we cross-tabulated the thermal preference votes for all subjects voting -3 on the thermal sensation scale. A Chi Square test on this cross-tabulation indicated no significant differences between primary and high school students in our sample (Chi Squared = 1.55, df=2, p>0.05). Notwithstanding the statistical insignificance, most of the contradictory preference and sensation cases were primary school children.

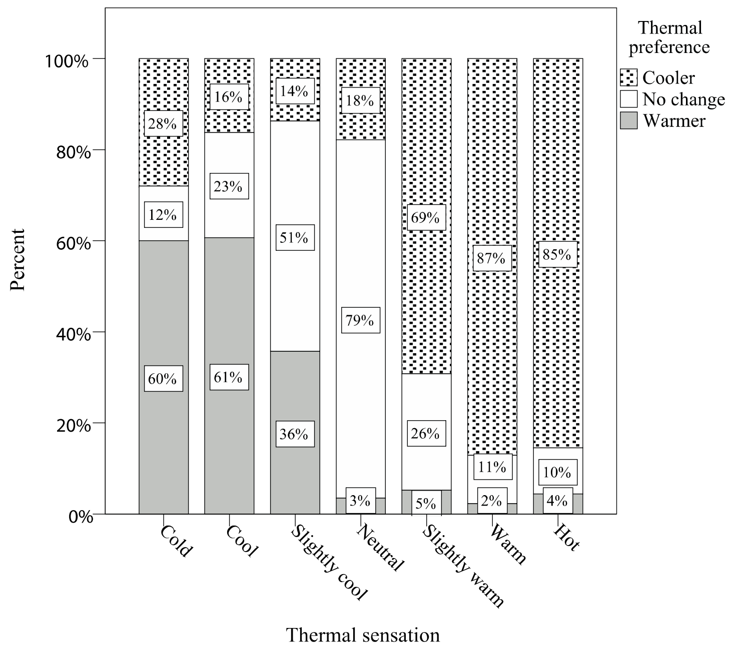


Fig. 3 Cross-tabulated thermal sensation and thermal preference

Fig. 4 illustrates the mean values and 95% confidence intervals for AMV and PMV categorized by indoor operative temperature binned by 1°C intervals. This figure shows how actual (AMV) and predicted (PMV) thermal sensations change depending on the indoor operative temperature. Below 23°C there seems to be no significant change in the subjects' thermal sensation, staying close to *neutral*. However, as indoor operative temperatures exceed 23°C there is a steady increase in mean thermal sensation. There were discrepancies and agreements between AMV and PMV index, depending on the temperature. From 22 up to 25°C the subjects' observed thermal sensations (AMV) were warmer than those predicted using the PMV-PPD model. AMV and PMV were well matched when operative temperature was within the range of 25-27°C. After operative temperature exceeded 27°C, PMV tended to overestimate the students' thermal sensation.

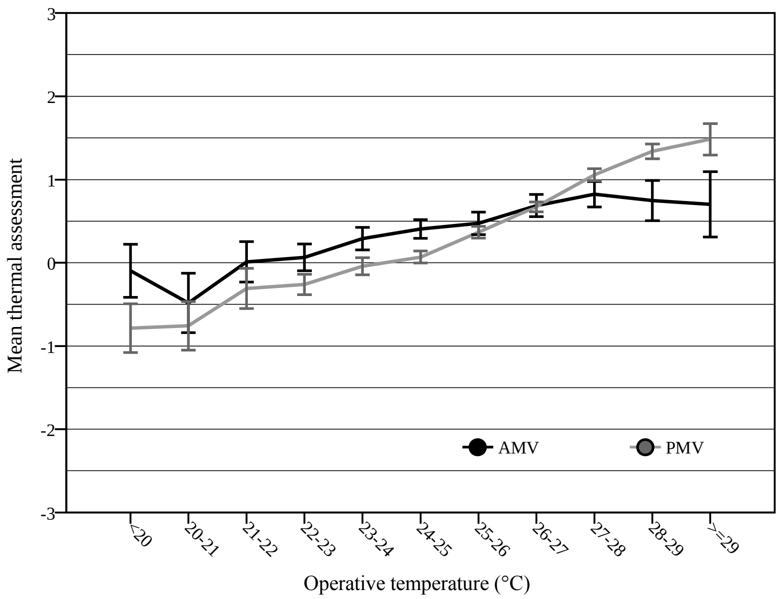


Fig. 4 Actual (AMV) and predicted (PMV) mean thermal sensation in relation to indoor

operative temperature. Error bars represent 95% confidence intervals

In order to investigate preferred temperature and neutral temperature, students' thermal preference votes and thermal sensation votes were binned into 0.5°C intervals of indoor operative temperature. Note that the subjects who were engaged in activities other than '*Sitting*' were excluded from the estimation of both preferred and neutral temperature (i.e. non-sedentary subjects were excluded in the analysis). Thermal preference votes within each half-degree of operative temperature bin became the basis of the probit regression models (depicted in Fig. 5). The *z*-statistic, with associated *p*-values for the regression coefficients, and the chi-square test indicate that the fitted model was statistically significant ($p<0.001$). The point of intersection between '*want cooler*' and '*want warmer*' probit models is taken to represent the group's preferred temperature - in this analysis, 22.2°C.

Fig. 6 shows the mean thermal sensation votes plotted against operative temperature. The linear regression model was weighted by number of responses within each half-degree operative temperature bin. The regression model (r^2 = 0.76, $p<0.001$ for regression coefficient and constant) fitted to bin-mean vote is:

$$\textit{mean thermal sensation vote} = 0.124 \times T_o - 2.777 \qquad (1)$$

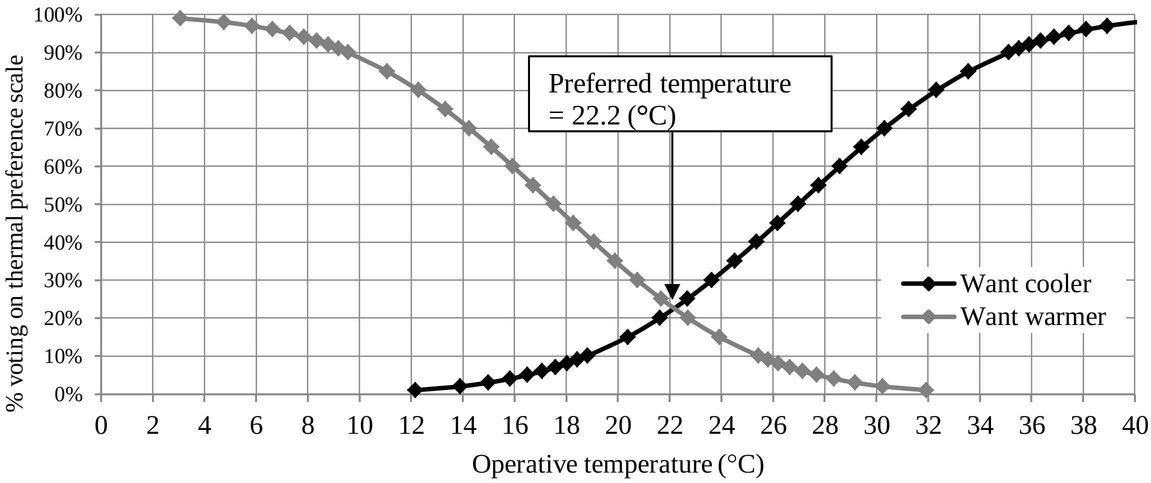


Fig. 5 Probit regression models fitted to thermal preference percentages

The neutral temperature estimated by this new equation (above) is 22.4°C, approximately the same as the preferred temperature of 22.2°C. According to the equation, on average, eight degrees of operative temperature change shifts the group's mean thermal sensation one point on the seven-point scale (one divided by the regression coefficient of 0.124 in Equation 1). In adaptive thermal comfort theory we regard the gradient of this regression equation as being inversely proportional to the adaptability of the building occupants under analysis; a very shallow gradient indicates the subjects were able to adapt very effectively to changes in temperature (instead of feeling over- or under-heated and shifting their thermal sensation accordingly), whereas a steep regression line suggests the subjects were not successful in adapting because they quickly felt warm (or cool) as the room temperature shifted away from their neutrality. At more than eight degrees per thermal sensation unit, the regression equation shows this sample to be *remarkably successful at adapting* to changes in indoor temperature.

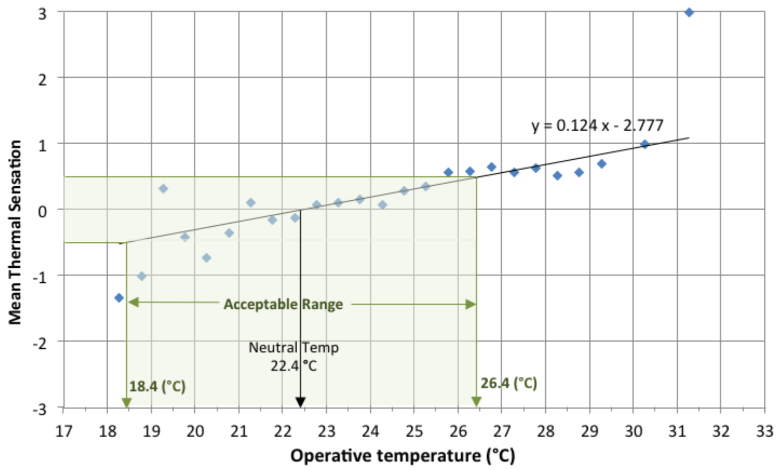


Fig. 6 Mean thermal sensation votes (-3 = *cold*, through 0 = *neutral* to +3 = *hot*) related to indoor operative temperature. The regression equation is weighted by number of responses.

Regression equations describing the dependence of sample mean thermal sensation on mean indoor operative temperature are often used to define acceptable temperature limits for a particular sample. In the case of ASHRAE 55-2013, the so-called "comfort zone," as expressed on a temperature-humidity graph (psychrometric chart), has its boundaries defined as -0.5 PMV on the cool side and +0.5 PMV on the warm side. The logic behind this definition is encapsulated in the Predicted Percentage Dissatisfied (PPD) index. In classic thermal comfort theory PPD reaches its minimum value when PMV equals zero (i.e. neutrality). That is, when the average person feels thermally neutral, we can expect a minimum of complaints form the entire group in that environment. Minimum PPD is set to 5%, reflecting the fact that we can never satisfy all of the occupants within a space with a single thermal environment. As PMV deviates from "neutral" in both the warm or cool direction, the PPD starts to increase. When the group's mean thermal sensation (PMV) equals plus or minus 0.5, PPD climbs to 10% (i.e. one in ten people in the group will have a thermal sensation falling outside the satisfactory or acceptable central three categories of -1, 0, +1 on the 7-point sensation scale). To this PPD of 10% dissatisfied ASHRAE 55-2013 adds another 10% dissatisfied resulting of *local* discomforts like draft, vertical temperature stratification and plane radiant asymmetry, bringing the total percentage dissatisfied from global and local discomforts combined to 20% Eighty percent acceptability (i.e. 20% dissatisfied) is the internationally agreed design target and the same definition of acceptable mean thermal sensations is adopted in the International Standards Organization's thermal comfort standard, ISO 7730 (2005); -0.5 < PMV < +0.5, corresponding to PPD=10% + another 10% dissatisfaction from local discomforts, bringing the total dissatisfied to 20%

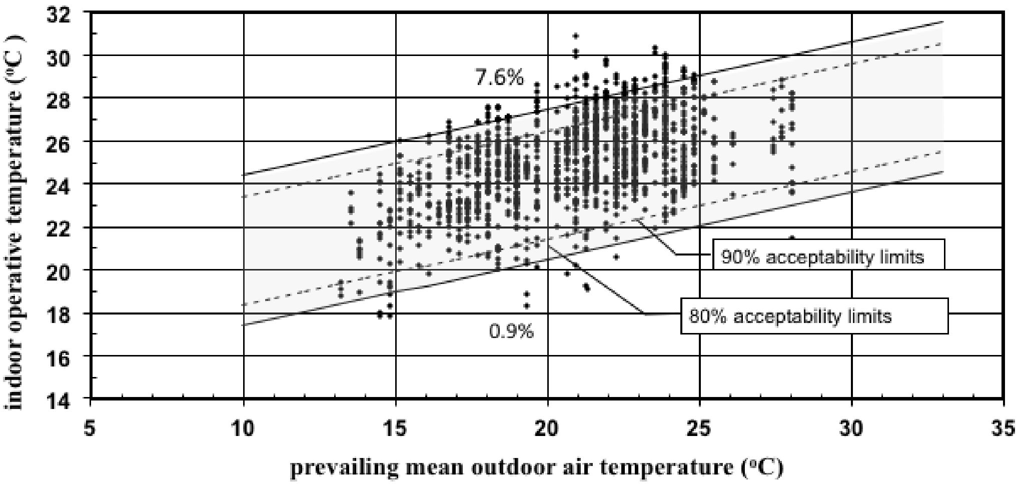
This same fundamental logic, as adopted in ASHRAE (55-2013) and also ISO (7730-2005) to define their comfort zones, can be applied to the results obtained in this thermal comfort survey of school children in the present study, but with key difference - rather than use ***predicted*** mean thermal sensations (PMV), we have the advantage of ***actual*** mean thermal sensations, as depicted in Fig. 6. The mean indoor operative temperatures corresponding to group mean thermal sensations of +0.5 and -0.5 stretch from 18.4°C up to 26.4°C (see shaded region on Fig. 6), and this acceptable comfort zone can be compared to that of ASHRAE 55. Based on the mean outdoor air temperature of the survey month (Bureau of Meteorology), 80% acceptable operative temperature limits were calculated (Table 5). In general, the adaptive model estimated 21.0~28.0 °C as 80% acceptable operative temperature range for the 9 schools. These Australian school children felt comfortable in a lower range of operative temperature (18.4~26.4°C) than that predicted by the adaptive model (21.0~28.0°C).

Table 5 ASHRAE 55's 80% acceptable operative temperature range for 9 schools

School	Mean monthly outdoor air temperature (°C)	Lower 80% acceptability limit (°C)	Upper 80% acceptability limit (°C)
A	22.7	21.3	28.3
B	22.7	21.3	28.3
C	22.1	21.2	28.2
D	16.5	19.4	26.4
E	22.0	21.1	28.1
F	21.2	20.9	27.9
G	22.5	21.3	28.3
H	23.0	21.4	28.4
I	22.3	21.2	28.2
Average of 9 schools		21.0	28.0

3.3. Over-heating/cooling analysis

Fig. 7 illustrates the number of hours falling beyond ASHRAE 55's 80% acceptable operative temperature range. Out of total 1,341 school operating hours during the monitoring period, the percentage of hours exceeding the adaptive 80% upper acceptability limit was 7.6% (102 hours). The number of occupied hours that indoor operative temperatures dropped below the lower 80% limit was negligible (0.9%). Differences in the total number of occupied hours between each school are due to the different periods in which temperature was measured at the various schools. The highest percentage of overheated hours during the measurement period was reported in School F (23.1%), followed by School I (11.6%), in which classroom were equipped with either air-conditioning or evaporative-cooling system. It should be noted that the temperature data in this analysis could include hours in which the classroom was unoccupied. Therefore the overheating hours of AC or EC spaces could simply be the result of the air conditioning system not being used on hot days if the classroom happened to be unoccupied.



School	Ventilation type	Total occupied hours	Above upper 80% limit		Below lower 80% limit	
			Total hours	Percent	Total hours	Percent
A	*NV*	*49*	*0*	*0.0*	*2*	*4.1*
B	*AC*	*133*	*0*	*0.0*	*0*	*0.0*
C	*AC*	*98*	*0*	*0.0*	*3*	*3.1*
D	*EC*	*300*	*19*	*6.3*	*3*	*1.0*
E	*NV*	*77*	*0*	*0.0*	*1*	*1.3*
F	*EC*	*182*	*42*	*23.1*	*0*	*0.0*
G	*EC*	*105*	*2*	*1.9*	*3*	*2.9*
H	*NV*	*173*	*13*	*7.5*	*0*	*0.0*
I	*AC*	*224*	*26*	*11.6*	*0*	*0.0*
Total		*1,341*	*102*	*7.6*	*12*	*0.9*

Fig. 7 Scatter plot of hourly indoor operative temperature compared to ASHRAE Standard 55's 80% and 90% thermal acceptability limits

4 Discussion

This paper presents results from a thermal comfort study of nine Australian schools, conducted in the summer months of early 2013. The survey participants' subjective assessments of thermal environment using thermal sensation and preference rating scales presented in a "right-here-right-now" questionnaire were statistically analysed and compared with the corresponding time-stamped climatic data measured on the site. While this survey was admittedly based on a small sample of schools, there is a sufficient empirical basis for proposing an acceptable range of indoor environmental temperatures for school classrooms during summer months.

Both linear and probit regression analyses estimated that an indoor operative temperature of about 22.5°C was the students' neutral and preferred temperature. This is generally cooler than we expect of adults under the same thermal environmental conditions. Working on the industry-accepted assumption that an acceptable range of indoor operative temperatures corresponds to mean thermal sensations of -0.5 through +0.5 (ASHRAE 2013; ISO 2005), the present analysis indicates an acceptable summertime range for primary and high school students from about 18.5 through to about 26.5°C operative temperature.

Notwithstanding the physiological differences between adults and children, it is important to understand the unique characteristics of school environments compared to those typical of climate chambers, offices and universities (i.e. environments in which the thermal comfort of adults has been investigated). School children are often engaged in a wider range of activities (outdoor playtime occurs twice a day) in more densely occupied rooms (between 20 to 40 students per class) with limited adaptive opportunities (students typically wear compulsory uniforms and any environmental controls are operated by the teachers) (Teli et al. 2012). These differences can be expected to affect the students' perceptions of comfort, the thermal conditions within school and classroom environments must be considered carefully when analysing field study findings (Zhang et al. 2007).

Speculating on the possible cause of this anomaly, perhaps the current generation of Australian school children are adapting to (Brager & de Dear 1998; de Dear & Brager 1998), or even becoming *addicted* to a narrower band of indoor temperatures as a result of their long exposures to air-conditioning (Cândido *et al.* 2010). The adaptive theory of thermal comfort suggests that our comfort expectations and tolerance are defined from own thermal experience – we adapt to the range of temperatures to which we are exposed, and the exposures that count most are those occurring most recently. Most of the school children comprising this current sample were born since there was a dramatic increase in AC penetration rates in the residential sector in this country. There was a doubling from 25% to over 50% between 1999 and 2004 (Wilkenfeld 2004) and the trend seems certain to continue in the foreseeable future. Numerous explanations have been offered for this sudden change in the way Australians live, but probably the most compelling is simply the fact that the Australian market experienced a sudden decrease in retail price of air conditioning equipment when our market was opened up to cheap product sourced mainly from China. Air conditioning equipment, most typically simple split systems, became significantly more affordable in the late 1990s and Australian residential consumers responded positively.

The "air-conditioning addiction" hypothesis was reinforced by responses to the behavioural questions included in the questionnaire for this project. There was an item specifically asking students to identify their ***preferred thermal adaptive behaviours*** from a list of common options. '*Use air-conditioner'* emerged as the most common selection, followed by '*do nothing*' and '*use fans*.' In the survey's naturally ventilated classrooms, the percentage voting for '*use AC*' proportionally increased as indoor temperature rose. When indoor operative temperature was greater than 28°C, using an air-conditioner became the overwhelmingly dominant thermal behavioural response suggested by the students.

The major policy question arising from these observations and conjectures is whether or not the State Government (in charge of the education portfolio in the Australian context) should design, build and operate its school building stock in a way that reflects, or even anticipates these comfort pressures to air condition every classroom and buffer their occupants entirely from the natural rhythms of daily weather, season and climate? Putting aside the question of environmental sustainability of such a policy choice, there are strong counter-arguments, including the negative impacts of air conditioning on indoor air quality (especially through vastly reduced ventilation rates), which would adversely affect children's health and their educational attainment. A majority of the air conditioning equipment being installed across the State's classroom stock is of the split-system type, and this type of equipment recirculates 100% of the air it conditions; outdoor ventilation air is not a function performed by split systems, so unless the teacher has specifically made an effort to provide supplementary ventilation by opening a classroom window or door to the outside, it is highly likely that the indoor air quality in classrooms with split systems in operation would fall below levels recommended in the relevant standards and guidelines. A critical literature review conducted on indoor air quality impacts on student performance found "suggestive evidence" linking low ventilation rates to decreases in performance (Mendell & Heath, 2005). However that review found the causal linkage of ventilation rate to a variety of adverse health effects such as "sick building syndrome" symptoms was even more compelling than the performance impacts. Clearly these complex and intertwined issues of indoor air quality, ventilation, student performance and health need to be taken into consideration alongside the present study's findings on thermal comfort before setting any major policy decisions on the question of air conditioning versus natural ventilation in the classrooms of NSW.

On the basis of the research evidence revealed in this project we recommend State education authorities refrain from rolling out air conditioning to ***every*** classroom in the State, but rather to restrict its installation to classrooms where there is ***demonstrable overheating*** occurring, and once it is installed in a space, to operate the equipment as the ***comfort strategy of last resort***, not as the default. Decisions about where to install air conditioning should rationally be made where there is evidence of systematic overheating; where acceptable classroom temperatures are defined in relation to the adaptive comfort 80% acceptability. Furthermore, in classrooms where air conditioning is already installed, we recommend a policy of operating it if and only if there is an upper acceptable temperature exceedance in progress. We recognise this will involve removal of individual teachers from decisions about when to turn on air conditioning equipment.

Conclusions

- A large field survey of thermal comfort in Australian grade- and high-schools has been conducted during the second half of the summer season.
- Neutral and preferred operative temperatures were about 22.5^{o}C, which falls below predictions of both PMV and adaptive models of thermal comfort.
- This finding reiterates the findings of other researchers, but a coherent explanation of why children's thermal sensations fall below that of adults in the same temperatures has to be developed.
- Despite the lower-than-expected neutrality, the school children in this survey demonstrated considerable adaptability to indoor temperature variations, with one thermal sensation unit equating to approximately eight degrees operative temperature.
- By applying the rule-of-thumb that group mean thermal sensations between -0.5 and +0.5 correspond to the range of acceptable operative temperature, the current survey found an acceptable range of 18.4 to 26.4^{o}C (presumed to be the 80% acceptable range).
- The upper acceptable operative temperature limit of 26.4 falls about one-and-a-half degrees cooler than the conventional adaptive comfort standard (ASHRAE 55-2013) predicts when applied to the outdoor temperatures observed in this survey.

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