Revisiting thermal comfort models in Iranian classrooms during the warm season

Shamila Haddad, Paul Osmond and Steve King
Faculty of Built Environment, University of New South Wales, Sydney, NSW, Australia

ABSTRACT
The validity of existing thermal comfort models is examined for upper primary school children in classroom settings. This is of importance to enhance productivity in the learning environment and to improve the control of artificial heating and cooling, including the potential for energy savings. To examine the thermal perceptions of children aged 10–12 years in non-air-conditioned classrooms, three sets of field experiments were conducted in boys’ and girls’ primary schools in Shiraz, Iran. These were undertaken during regular class sessions covering cool and warm conditions of the school year, polling responses from 1605 students. This paper illustrates the overall methods and reports the results of the warm season field survey (N = 811). This investigation suggests that predicted mean vote-predicted percentage of dissatisfied (PMV/PPD) underestimates children’s actual thermal sensation and percentage dissatisfied in the investigated classrooms. The analysis shows that sampled children may be slightly less sensitive to indoor temperature change than adults. The upper acceptable temperature derived from children’s responses corresponding to mean thermal sensations of +0.85 is 26.5°C, which is about 1°C lower than the ASHRAE upper 80% acceptability limit. This implies that sampled children feel comfortable at lower temperatures than predicted by the ASHRAE Adaptive model during the warm season.

INTRODUCTION
School buildings are considered a significant building type in relation to the effects of indoor conditions on students’ health, learning and performance (Mendell & Heath, 2005). Indoor environmental conditions in schools are of particular importance as children are less resistant to adverse environmental conditions compared with adults, and thus the magnitude of environmental effects on their school work performance may be larger than that on office work performance by adults (Wargocki & Wyon, 2007; Wyon & Wargocki, 2006).

Field studies conducted in classrooms show that elevated temperatures may lead to reduced productivity (Wargocki & Wyon, 2007). The literature suggests that students’ achievement is affected, as discomfort decreases attention span when temperature and humidity exceed their comfort zone (King & Marans, 1979; Schneider, 2002). It is argued here that a re-examination of current approaches to thermal comfort could inform improved design of school buildings and thereby optimize conditions for students’ performance.

Fanger’s predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) approach (Fanger, 1970), and the adaptive model (de Dear & Brager, 1998; de Dear, Brager, & Cooper, 1997; Nicol & Humphreys, 1973, 2002) have been widely used in academic research to describe human thermal comfort. The PMV/PPD model is based on the steady-state heat balance derived from measurements in controlled environments. The adaptive comfort approach recognizes that people are in dynamic equilibrium with their environment (Humphreys, Rijal, & Nicol, 2013) and stay comfortable by taking a range of adaptations classified as physiological, behavioural and psychological (de Dear & Brager, 1998). This approach relates the occupant’s comfort temperature to the outdoor climate.

Research has predominantly focused on occupants of office buildings and residences (de Dear & Brager, 1998). Widely used comfort standards (ASHRAE 55, 2013; ISO, 7730, 2005) recommend comfort requirements for schools based on thermal comfort data developed primarily for adults’ work environments. Fanger (1973)
states that more research is required to explore the applicability of adults’ comfort conditions for children since no children were involved in his climate chamber study. Although children’s thermal comfort requirements are not significantly included in the existing thermal comfort data, ASHRAE 55 (2013) suggests that recommendations of that standard could be applicable for children in classroom situations.

Several studies have investigated the thermal perception of students in relation to the thermal conditions in classrooms over the past four decades (e.g., Al-Rashidi, Loveday, & Al-Mutawa, 2009; Auliciems, 1969, 1973, 1975; Corgnati, Filippi, & Viazzo, 2007; de Dear, Kim, Candido, & Deuble, 2015; Humphreys, 1977b; Hwang, Lin, Chen, & Kuo, 2009; Katafygiotou & Serghides, 2014; Kwok, 1998; Kwok & Chun, 2003; Liang, Lin, & Hwang, 2012; Wong & Khoo, 2003). A few were conducted in primary schools with young children (De Giuli, Da Pos, & De Carli, 2012; Humphreys, 1977b; Mors, Hensen, Loomans, & Boerstra, 2011; Teli, James, & Jentsch, 2015; Teli, Jentsch, & James, 2012; Trebilock & Figueroa, 2014), while other studies used combined data from primary and secondary schools (Auliciems, 1975; d’Ambrosio Alfano, Ianniello, & Palella, 2013; de Dear et al., 2015; Hwang et al., 2009). The literature also contains thermal comfort studies which target children in kindergarten classrooms (Fabbri, 2013; Yun et al., 2014).

A number of thermal comfort field studies conducted in classrooms have found that comfort predictions and requirements do not match those specified in adults’ thermal comfort standards. In recent studies, Mors et al. (2011) and Teli et al. (2012) demonstrate that PMV predictions underestimate the actual thermal sensation of children, whereas the results of most previous research on PMV predictions overestimate adults’ actual thermal sensation votes in naturally ventilated (NV) buildings. Some authors suggest that children’s comfort temperature is lower than is predicted by adaptive comfort models in classroom conditions. Unlike dwelling residents and most office occupants, students have limited opportunities for behavioural adaptation to stabilize the heat balance of their bodies, e.g., fewer degrees of freedom for clothing decisions based on indoor and outdoor weather conditions depending on culture, social custom and the presence of a school dress code. Also, the possibilities of modifying activity level or adjusting environmental variables are diminished for children during lessons; teachers are the active users who interact with the thermal conditions of classrooms. Further, children’s metabolic rates and typical outdoor and indoor activities during the school day affect how they perceive thermal comfort in the classroom.

**Research aims**

The above factors illustrate the challenge of establishing the most appropriate approach towards thermal comfort models in field studies with children, and thereby emphasize the importance of revisiting predictive models of thermal comfort for children, who are not just little adults.

This study reports the fieldwork method adopted in primary school classrooms and presents students’ subjective evaluation of thermal conditions. The specific aims of this research are as follows:

- To determine children’s actual thermal sensation and satisfaction in the classroom and investigate the applicability of PMV–PPD for children in naturally ventilated (NV) classrooms during sedentary activities.
- To identify acceptable indoor operative temperatures inside the classroom and understand how well predictions of ASHRAE 55 adaptive comfort model match with children’s responses.
Methods

The case study buildings and participants

Three fieldwork campaigns were conducted in four boys’ and girls’ primary schools in Shiraz (29°53’N, 52°58’E), in the south-west of Iran, during cool and warm conditions of the local school year (2012–13). The entire sample included in the analysis constitutes 1605 survey responses drawn from healthy upper primary children aged 10–12 years in 58 classrooms. Table 1 illustrates statistical summaries of sampled children and surveyed classrooms.

The participating school buildings were equipped with mechanical cooling systems (evaporative coolers) and water heating systems (radiator). All classrooms were NV using operable windows; there were no electric fans, and evaporative coolers were not running during the survey period. The sample school buildings all utilized medium-to-heavy weight construction systems with concrete/steel structure and brick walls. Windows were single glazed with aluminium frames. Table 2 presents the basic characteristics of the school buildings.

The field surveys and measurements were carried out over a minimum of seven and a maximum of 10 days in each ‘campaign’. This paper focuses only on data collected in the warmest period of the school year before the final examinations in May 2013. Since the results would be compared with the outcomes of studies with adults, this study followed conventional techniques and protocols for data gathering and statistical analysis commonly used in thermal comfort field surveys.

Indoor data collection and instrumentation

Four indoor environmental variables required for assessment of thermal comfort were collected parallel to questionnaire surveys in the selected classrooms: air temperature, globe temperature, air velocity and relative humidity. Instrumentation was three sets of Kimo AQ200 O units and related measuring probes; CO₂ concentration was measured at the time of survey in each classroom using a CO₂ probe operated independently with one AQ200 unit. All units and probes were factory calibrated prior to use in this study. Of the three classes of field studies in thermal comfort, Class I requires all environmental variables to be collected at three heights above the floor level based on the procedure and instrumentation set out in ASHRAE 55 and ISO 7730 (de Dear, 1998). Despite the difference in the average seated heights between children and adults, indoor environmental variables were collected in accordance with the recommendations of standards (ASHRAE 55, 2013; ISO 7726, 2001) from an array of instruments placed at 1.1, 0.6 and 0.1 m above the floor. This was primarily because children’s child-specific measuring heights are not included in the commonly used standards. However, during the unheated season in NV classrooms, apart from patches of direct sunlight, there was little variation of temperature caused by radiant temperature asymmetry and vertical thermal stratification. The specifications of the instruments are summarized in Table 3.

Globe temperature is commonly used to estimate the mean radiant temperature (ISO 7726, 2001) by applying the equation given in ASHRAE (2009). Humphreys (1977a) suggests that the optimum diameter of a globe thermometer for indoor spaces is approximately 40 mm when the air velocity is small. In this study, a globe thermometer was constructed using a table tennis
ball (38 mm diameter) with the Kimo SPS150 ambient temperature probe (Pt100 Class 1/3 DIN) placed in its centre. The globe was finished with matt black paint. The operative temperature was calculated as the average of dry bulb temperature and mean radiant temperature (ASHRAE 55, 2013), given that occupants were involved in sedentary activities and were not exposed to direct sunlight and air speed of more than 0.2 m s$^{-1}$ as specified in ASHRAE 55.

Omnidirectional sensors are required in class I field studies due to their capability to integrate turbulence intensity (de Dear, 1998). Therefore, three Kimo Omni-directional probes were utilized to measure air velocity at three heights above the floor corresponding to head, waist and ankle levels in sitting position. The sensor had a time constant of 0.6 s which is appropriate for small velocities typical of a classroom.

As physical variables were required to be monitored continuously in several schools and classrooms, portability of the instruments with quick set-up capacity and lightweight was of great importance. Therefore, the instruments were fitted compactly on a light transportable vertical pole (Figure 1). Three mounting plates held the units and probes at the three heights above the floor prescribed in ASHRAE 55 (2013) and ISO 7726 (2001). Another plate was located at 0.45 m to hold the AQ200 unit and CO2 probe. In the majority of classrooms, the instruments were placed in the centre, between the occupied rows of desks, without impairing students’ visual access and routine activity to characterize the thermal environment experienced by the students under normal class conditions. However, where it was not physically possible to place instrument at a mid-classroom location due to the seating arrangement, the equipment was located near the centre within the vicinity of the students’ desks to avoid any interference in the readings. Horizontally uniform indoor thermal environments were assumed in the occupied zone of the surveyed classrooms.

The instrumentation was set up in the selected classrooms during the class break. Measurement sampling frequency was programmed at a one-minute interval, and left running during the entire lesson time prior to the survey. This allowed the instruments enough time to acclimatize to the classroom’s thermal environment before readings were taken (Nicol, Humphreys, & Roaf, 2012, p. 121). The corresponding readings recorded during each survey were averaged for analysis. To ensure static thermal responses, Goto, Toftum, de Dear, and Fangter (2006) suggest that subjects need to maintain a stable

### Table 2. Basic information on selected school buildings.

| School code | Year built | Number of surveyed classrooms | Average classroom area (m$^2$) | Classroom orientation | Component structure | Window | Internal shading device | Cooling and ventilation type |
|-------------|------------|-------------------------------|--------------------------------|-----------------------|---------------------|--------|------------------------|-------------------------------|
| A           | 1997       | 8                             | 51.8                           | North-west–south-east | Reinforced concrete–brick wall | Single-glazed aluminium frame | Venetian/ fabric blinds | NV + EC (no operated EC) |
| B           | 2010       | 7                             | 42.0                           | North-east–south-west | Steel frame–brick wall | Single-glazed aluminium frame | Venetian blinds | NV + EC (no operated EC) |
| C           | 2006       | 7                             | 40.8                           | North-east–south-west | Steel frame–brick wall | Single-glazed aluminium frame | Fabric blinds | NV + EC (no operated EC) |
| D           | 2008       | 6                             | 32.0                           | North-east–south-west | Steel frame–brick wall | Single-glazed aluminium frame | Fabric blinds | NV + EC (no operated EC) |

Note: NV = naturally ventilated, EC = evaporative cooled.

### Table 3. Instrument specifications.

| Parameter                | Measuring range | Resolution | Accuracy                                                                 |
|-------------------------|-----------------|------------|--------------------------------------------------------------------------|
| Relative humidity (%)   | 5–95% RH        | 0.1% RH    | ±1.8% RH (15–25°C) ±0.4% × (T – 20) ±1.8% RH (15–25°C) or 0.04 × (T – 20) ±1.8% RH |
| Air temperature (°C)    | −20 to +80°C    | 0.1°C      | ±0.3% of reading ±0.25°C                                                 |
| Air speed (m s$^{-1}$)  | 0–5 m s$^{-1}$  | 0.01 m s$^{-1}$ | ±3% of reading ±0.05 m s$^{-1}$                                           |
| Globe temperature (°C)  | −50 to +250°C   | 0.1°C      | ±0.3% of reading ±0.25°C                                                 |
| CO2 (ppm)               | 0–5000 ppm      | 1 ppm      | ±3% of reading or ±50 ppm                                                |

Figure 2. Procedure of the field experiment.
level of activity for at least 15–20 minutes. Therefore, the survey was conducted during the last five minutes of the class session, before the next break. Such timing minimizes any influence on thermal sensation caused by students’ activities during the previous break. Figure 2 shows the fieldwork procedure in this study.

Outdoor data collection

Outdoor temperature is required as an input parameter in the adaptive comfort models. Since meteorological stations were far from the case study schools, a local weather station was located on the roof of a house close to the school buildings to obtain concurrent data representing the school outdoor microclimate during each survey. The outdoor conditions including temperature, humidity and wind speed were recorded for the duration of the study using a Maxkon WH 3081 weather station (Figure 3). The recording interval was half hourly, with sufficient level of accuracy and resolution anticipating possible comparison with the bureau of meteorology data.

Thermal comfort questionnaire survey

Fieldwork procedures combined simultaneous measurement of physical variables of the classrooms with survey of students’ subjective responses conducted on ‘right here, right now’ basis. Questionnaires were specifically designed for the target age group based on developmental psychology (Haddad, King, Osmond, & Heidari, 2012). Subjects were trained and given an explanation of the scales by the teacher before responding to the questionnaire. The questionnaire was presented in Persian, which is the most common written and spoken language in Iran. The children’s questionnaire consists of six questions, illustrated with pictorial images (see Appendix A in the supplemental data online). The aspects surveyed are as follows:

- **Students’ thermal sensation vote (TSV):** the ASHRAE seven-point scale (ASHRAE 55, 2013) was used. The pilot study suggested that children well understood the seven-point ASHRAE scale; however, for optimum accuracy and to keep children interested during the survey, a simple format of labelling response options followed by a pictorial presentation relevant to upper primary children was employed (Haddad et al., 2012). It should be noted that the meaning of ‘neutral’ corresponding to the central category of the ASHRAE scale may fail to describe children’s actual feeling of neutrality, mainly because ‘children may use different phrases or attach different shades of meaning to the same phrase’ (Humphreys, Nicol, & Roaf, 2015, p. 175). To enhance the accuracy of responses in the administered questionnaire, the term ‘neither cool nor warm’ was treated as synonymous to ‘neutral’ in the adult rating scale.
- **Students’ thermal preference vote (TPV):** using the three-point scale (McIntyre, 1982): want cooler, no change or warmer.
- **Thermal acceptability (TA):** children’s acceptability of current temperature was assessed with direct responses (yes/no).
- **Students’ clothing:** this was limited to whether the students wore jackets during the survey. Due to the schools’ restricted options for clothing items, a garment checklist was excluded from the questionnaire.
- **Students’ level of tiredness:** using a three-point scale that ranged from ‘Very sleepy and tired’ to ‘Not tired and sleepy’.
- **Students’ activities:** during school break prior to the class in which the survey was conducted.

Data analysis and results

Before analysis, the dataset was checked against outliers to ensure the reliability of children’s responses. Twenty-seven of the total number of responses (about 3.2% of 838
Table 4. Descriptive statistics of the classroom environmental parameters and thermal indices.

| Index                        | Minimum | Maximum | Mean | SD  |
|------------------------------|---------|---------|------|-----|
| Operative temperature (°C)   | 22.7    | 29.0    | 25.9 | 1.6 |
| Relative humidity (%)        | 24.8    | 53.4    | 38.3 | 8.0 |
| Air speed (m s⁻¹)            | 0.02    | 0.20    | 0.08 | 0.05|
| CO₂ (ppm)                   | 398     | 1819    | 949  | 410 |
| Outdoor temperature (°C)     | 19.6    | 31.2    | 26.8 | 2.9 |
| Clothing insulation (clo)    | 0.61    | 0.81    | 0.70 | 0.08|
| Metabolic rate (MET)         | 1.2     | 1.2     | 1.2  |    |
| TSV                         | −2.00   | +3.00   | +0.74| 0.98|
| PMV                         | −0.33   | +1.45   | +0.54| 0.39|
| PPD (%)                     | 5.0     | 48.0    | 14.4 | 10.1|

Note: TSV, PMV and PPD were calculated results for each subject.

questionnaires) were eliminated from the dataset, corresponding to questionnaires with incomplete, inconsistent and contradictory answers, as well as data from sick participants. The data were analysed with statistical analysis methods commonly applied in thermal comfort studies, mainly using the IBM SPSS version 22 and MATLAB.

**Thermal comfort indices**

Table 4 provides descriptive statistics of thermal environment and thermal indices including mean, range and standard deviation (SD) of each index. As shown, indoor operative temperature ($T_{op}$) fell within the range of 22.7–29.0°C, with an average of 25.9°C. Air speed ranged from 0.02 to 0.2 m s⁻¹ in the occupied zone of the classrooms, with 0.08 m s⁻¹ average. It only marginally affected subjects’ thermal sensation as it rarely exceeded 0.1 m s⁻¹. Relative humidity was within 25–53%, with an average of 38%. CO₂ concentration was mostly between 398 and 1400 ppm except in three cases where it exceeded 1600 ppm. The average outdoor temperature recorded at the time of survey was 26.8°C, with a maximum of 31.2°C and a minimum of 19.6°C.

Mean clothing insulation for sample children was 0.7 clo, which is close to the estimated value for adults’ office wear in the same cultural situation, reported as 0.75 and 0.7 clo for females and males respectively (Nasrollahi, Knight, & Jones, 2008). However, clothing insulation estimates for sample students during the warm season is about 0.2 clo units higher than what is assumed for typical office wear in summer based on the widely used standards (ASHRAE 55, 2013; ISO 7730, 2005). A metabolic rate (MET) of 1.2 was estimated as suggested in commonly used standards for sedentary activities (ASHRAE 55, 2013; ISO 7730, 2005).

The mean thermal sensation vote of all participating children was +0.74, which fell between +0.5 (slightly warm) to +1 (warm). The mean PMV was +0.54. Compared with PMV, mean TSV was slightly higher, which means that children feel slightly warmer than predicted by PMV, that is, 0.2 thermal sensation units. The PPD index predicted that 14% of children, on average, would be dissatisfied with their classroom thermal environment.

**PMV/PPD model predictions**

Fanger’s PMV model predicts the mean comfort vote of occupants and PPD with the indoor environment, based on four environmental variables together with two personal variables: metabolic rate and clothing insulation (Fanger, 1970).

The sample children were homogeneous in terms of social aspects as they were from the same cultural background. In each classroom students were in the same age group. Clothing patterns were very similar for each gender, firstly because of gender segregation in the Iranian educational system and dress code in schools, and secondly due to exposure to the same outdoor climate and cultural factors. Further, children were involved in sedentary activities during the 45-minute lesson period, after performing light- to high-intensity activities during each 15-minute school break.

**Estimation of clothing insulation**

In this study it was not practical to measure children’s actual clothing insulation due to the cost and lack of child-sized thermal manikins. Therefore, building on the findings of Al-Rashidi, Loveday, Al-Mutawa, and Havenith (2012) and Havenith (2007), children’s clothing level is estimated using tabulated values for individual garments given in the existing standards (ASHRAE 55, 2013; ISO 7730, 2005; ISO 9920, 2007). The thermal insulation value of clothing for combination of garments ($I_{cl}$) was calculated using the following equation (ISO 9920, 2007), which describes a summation of the effective thermal insulation of the individual garments ($I_{clu}$) making up the ensemble ($I_{cl}$):

$$ I_{cl} = \sum_{j=1}^{I_{clu}} I_{clu} $$

Since the main source of inaccuracy is in determining the appropriate values for individual garments, with overall accuracies in the order of ±25% (ASHRAE, 2009), care was taken to use the tables and to match the fabric material and style.

Children’s clothing level is estimated based on direct observation of the individual garments worn by the students during the study period. Females are required to
wear school uniform at all educational levels in the Iranian educational system according to religion and sociocultural aspects. Girls’ school uniform includes normal trousers, scarf and a dress with long sleeves. Boys wear trousers with long-sleeved shirts as their uniform during the school year. Figure 4 shows typical school uniforms worn by female and male students in this study.

Due to the school dress code, children had limited opportunity to modify their clothing ensembles in the surveyed classrooms. However, additional insulation was conferred by the jacket worn on top of the school uniform when it was required. Therefore, minor garments and underwear were excluded from the questionnaire. It only asks whether children wear a jacket in addition to their uniform at the time of the survey. The clo value of 0.25 (ISO 9920, 2007), corresponding to a light summer jacket, was added to the total clo value of the ensemble where students reported in the questionnaire that they wore a jacket/sweater.

It should be noted that several factors may affect clothing insulation (ISO 9920, 2007), e.g., the chair can provide additional insulation for seated subjects. Even though the clo value is a sensitive variable in the PMV equation, it was not practical to control all influencing factors in the field study. Therefore, thermal insulation provided by the wooden chair and bench used in the surveyed classrooms is estimated in line with the standards as equal to 0.01 clo (ASHRAE 55, 2013; ISO 7730, 2005).

To apply the clo value in the calculation of PMV–PPD, estimated values for each gender are used for the corresponding sample students since school uniforms were identical across all seasons and subjects were seated on similar chairs. Two values were estimated for individual students depending on whether they wore jackets over their uniforms: 0.86 or 0.61 for boys and 1.02 or 0.77 for girls during the warm season. For the calculation of PMV, the mean clothing insulation was estimated in each classroom using the following equation:

$$I_{cl} = \frac{1}{N} \sum_{i=1}^{N} I_{cl}$$  

where $N$ is the number of students; and $I_{cl}$ is individuals’ clothing insulation.

**Estimation of activity level**

Metabolic rates for sedentary activities are tabulated in the commonly used standards (ISO 7730, 2005; ISO 8996, 2004), which refer to an ‘average’ 30-year-old adult (male 70 kg, 1.8 m\(^2\) body surface area; female 60 kg, 1.6 m\(^2\) body surface area). The ISO standards estimate the metabolic rate of school sedentary activity as equal to office work: 1.2 MET, 70 W m\(^{-2}\). Similarly, in ASHRAE 55 (2013) the metabolic rate is nominated for an average adult, with a skin surface area of 1.8 m\(^2\) (Du Bois & Du Bois, 1916). ASHRAE 55 (2013) tabulates the metabolic rate for typical seated office activities from 55 to 70 W m\(^{-2}\) (1.0–1.2 MET) including reading seated, writing, typing and filing while seated. However, no school activity is included in the tabulated data.

The youth compendium of energy expenditure developed by Ridley, Ainsworth, and Olds (2008) provides a coding system on the energy cost of children and adolescents performing activities including school work based on the review of data undertaken by Ridley and Olds (2008). A review of the child physiology literature shows that children’s metabolic rate during class activity ranges from 1.2 to 1.4 MET corresponding to sedentary activities. A MET value of 1.4 is assigned for the energy cost of activities entitled ‘sitting quietly’ and ‘writing–sitting’, and 1.3 MET is assigned to ‘reading–sitting’ (Ridley et al., 2008).

In this study, students had more or less the same posture and were involved in activities with similar duration and intensity during class, predominantly restricted to reading, writing and listening to the teacher while seated for 45 minutes. Children engaged in different activities during the 15-minute school break in which the intensities varied from light to high, i.e., sitting and relaxing (1.1 MET) to playing in the school yard (6.3 MET) as suggested in the ‘Compendium of energy expenditures for youth’ (Ridley et al., 2008).

Notwithstanding that MET = 1.2 may underestimate the metabolic rate of school children due to a higher rate of outdoor activities compared with the adult office worker’s sedentary role, in this study a MET value of 1.2 is applied for analysis as typically used for seated office work (ASHRAE 55, 2013; ISO 7730, 2005). In addition to MET, resting metabolic rate (RMR) is shown to be...
an influential variable in Fanger’s PMV model (Haddad, Osmond, & King, 2013; Haddad, Osmond, King, & Heidari, 2014), which is set in the heat balance model based on adult physiology as 58.15 Wm\(^{-2}\). However, children have a higher basal metabolic rate, and that appears to decrease their comfort temperature (McIntyre, 1973).

In this investigation, RMR is also kept unchanged in the PMV model as it was originally developed in the heat balance model for adult subjects without any adjustment for physical and physiological differences between adults and children.

This uniformity of assumptions is applied to compare PMV predictions with actual thermal sensation votes of the students, and also allows comparison to be made between the results of studies conducted in primary schools. However, for a precise comparison, more insight into children’s metabolic rate is needed.

**Comparison of PMV–TSV and PPD–APD\(_{\text{actual}}\)**

To compare the relationship between PMV and TSV, weighted linear regressions were performed. Students’ mean thermal sensation votes within each 0.5°C indoor operative temperature bin were calculated and are plotted in Figure 5. Since the data were binned, the linear regression model was weighted according to the number of students making up each mean vote within each 0.5°C bin. The regression model (\(r^2 = 0.82, p < 0.0001\)) drawn from data across all sample students is statistically significant and has the equation:

\[
\text{TSV}_{\text{(mean)}} = -6.251 + 0.268 \times T_{\text{op}} \quad (3)
\]

PMV predictions were determined from the four indoor measured variables, the weighted average clo values, and MET as explained above. For the PMV–PPD calculations, the ISO 7730 (2005) equations were used and the Basic code given in ASHRAE 55 (2013) was implemented in MATLAB. This allows detailed calculation of PMV–PPD for indoor air speed below 0.1 m s\(^{-1}\) as well as adjustment of RMR (Haddad et al., 2014). The shaded area in Figure 5 shows the error band in the PMV prediction; error band limits are derived from the minimum and maximum clo values obtained within surveys. PMV in relation to classroom indoor operative temperature binned by 0.5°C interval is well fitted by the following equation:

\[
\text{PMV} = -5.339 + 0.225 \times T_{\text{op}} \quad (4)
\]

There is a strong positive relationship between PMV and indoor operative temperature (\(r^2 = 0.91\)) which is statistically significant (\(p < 0.0001\)). Figure 5 shows that the majority of actual thermal sensation points fall above those of PMV. The PMV regression line against indoor air temperature has a lower gradient than the observed thermal sensations. The comparison between the two fitted lines indicates PMV slightly underestimates the actual thermal sensation responses of children. However, the magnitude of underestimation is larger at higher temperatures, i.e., actual TSVs show a tendency to diverge toward more extreme responses at higher temperatures. Although the mean TSV is close to PMV around the neutral temperature, the neutral temperature derived based on survey responses is slightly lower than that predicted by Fanger’s PMV index.

The error bar in Figure 6 shows the mean value of the actual thermal sensation (TSV) and PMV of the students, and the 95% confidence intervals in the categories of indoor operative temperatures binned by 1°C intervals. This graph shows the discrepancies and agreements.
between TSV and PMV with reference to various operative temperatures.

As depicted in the error bar graph, children’s TSV remains close to neutral between 22 and 23°C with insignificant variation in their comfort votes. Subjects’ comfort vote level increases gradually with increase of temperature up to 27°C. As operative temperature exceeds 27°C, there is a significant increase in the mean thermal sensation of the students. A good agreement between mean TSV and PMV is shown within the range of 22–25°C, whereas between the ranges of 25–26 and 27–28°C PMV tend to underestimate children’s thermal sensation.

To compare PMVs derived from field study with those predicted by the ISO standard (ISO 7730, 2005) the cluster error bar plot also illustrates PMVs calculated with the same dataset but using clo value as prescribed in ISO 7730 for summer (clo = 0.5). Figure 6 shows that there is no overlap between PMVISO 7730 error bars and those of TSV, and that students constantly feel warmer than is predicted by PMV based on ISO 7730 (2005). This indicates that the prescribed clo value for summer leads to considerable error in prediction of the PMV model for the sample children.

One may speculate that the magnitude of discrepancy between PMV predictions and children’s TSV would be smaller if the sampled children wore clothing of lower clo level in the surveyed classrooms, as they would not have felt as warm as they did with relatively high clo value. However, this underestimation is in agreement with a number of studies with children where the reported mean clo values are lower than the prescribed value (Table 6). It is noteworthy that reduction of the clothing level is less likely to happen in this study due to the strict dress code in Iranian schools. It is further discussed in the ‘Behavioural adjustments in the classroom’ section.

The predicted percentage of dissatisfied (PPD) calculated based on the PMV–PPD model for each classroom and the actual percentage of dissatisfied (APD) derived from students’ questionnaire responses are compared in relation to PMV and T

| Thermal sensation votes | Unacceptable (0) | Acceptable (1) | Total |
|-------------------------|-----------------|---------------|-------|
|                         | (−3, −2)        | (−1, 0, 1)    | (+2, +3) | Total |
| Unacceptable (0)        | 1 (0.1%)        | 133 (16.4%)   | 156 (19.2%) | 290 (35.8%) |
| Acceptable (1)          | 0 (0.0%)        | 509 (62.8%)   | 12 (1.4%) | 521 (64.2%) |
| Total                   | 1 (0.1%)        | 642 (79.2%)   | 168 (20.7%) | 811 (100.0%) |

The obtained result indicates a poor agreement between PPD index and APD. A large number of the APD points fall above the PMV–PPD and PPD–T

Table 5. Cross-tabulation of thermal acceptability and ASHRAE sensation scales.

Thermal acceptability indicates that 35.8% of the students were not comfortable in the classroom at the time of survey (APDdirect), while based on the indirect method 20.8% appear to be dissatisfied with the classroom thermal condition (Table 5).

The higher level of APD compared with PPD on the warm side of neutral temperature may reflect that children are more sensitive to higher temperatures (Teli et al., 2012), thus they tend to express higher dissatisfaction than the assumptions (derived from adult studies) underlying PPD. The heightened level of warmth discomfort compared with PPD predictions may be explained by children’s high physical activity level during the school day, or the heavy level of clothing insulation and the restrictions placed on adjusting it, which leads to induce sweating with a small increase in activity level (Humphreys, 1973). The role of children’s thermal physiology in warm conditions needs to be explored.
Comparison of the results with previous studies

Table 6 presents recent literature on children’s thermal comfort in NV classrooms. Despite sensitivity of the PMV to assumptions of metabolic rate (Haddad et al., 2014), it shows methodological discrepancy between studies to estimate children’s metabolic rate mainly because of differing physical activities of subjects, and gaps in assumptions about children’s RMR, and MET in the PMV calculation. However, these studies reveal that PMV does not accurately predict children’s thermal sensation. As shown in Table 6, the summertime mean clo value used in previous studies is lower than that in this study. The error bars of PMV using prescribed summer clo value (0.5) completely fall below those of TSV (Figure 6). This indicates that the magnitude of underestimation in this study would be larger in case of lower clo values.

Comparison of the APD with average PPD shows that APD indirect (20.8%) is higher than the mean PPD (14%) calculated for sample classrooms. In the study by de Dear et al. (2015), the percentage dissatisfied, as derived from the ASHRAE scale, is 29.4% while the average PPD predicted that 24% of the subjects were dissatisfied with their thermal environment. Teli et al. (2012) shows that APD falls above the PPD line when PMV/PPD are calculated using the same metabolic rate values as in this study.

Acceptable range of operative temperature based on ASHRAE 55

Predictions of thermal satisfaction based on the PMV method

The mean thermal sensation of children in relation to the operative temperature of the classroom is used to derive comfort zone limits for 80% satisfaction. As defined in ASHRAE 55 (2013), comfort zone refers to conditions falling within and including PMV ranging from −0.5 to +0.5 in which PPD is expected to be 20%. The 20% rate of dissatisfaction corresponds to 10% dissatisfaction for general thermal discomfort, PPD = 10% when −0.5 < PMV < 0.5, and an additional 10% dissatisfaction due to local discomfort (ASHRAE 55, 2013), discomfort perceived in particular parts of the body caused by radiant temperature asymmetry, draft, vertical air temperature difference between the ankle and the head level, and floor surface temperature. The overall rate of dissatisfaction (PPD = 20%) is related to the limits of PMV = ±0.85, which assumes 80% of votes falling inside the central three categories of the ASHRAE scale.

To find the empirical limits of acceptable thermal environments for 80% satisfaction (ASHRAE 55, 2013) in line with this method, operative temperature was calculated for the mean TSV = ±0.85 using the linear regression model given in equation (3). Since children’s TSV points per classroom on average fall on the warm side of neutral during the warm season survey period (Figure 5), this study only focuses on upper limits of the comfort zone which corresponds to TSV = +0.85.

The regression slope is a measure of sensitivity to temperature change and demonstrates how much the thermal comfort vote increases per 1 K rise in operative temperature (Humphreys, Nicol, & Rijal, 2007). It is ‘inversely proportional to the adaptability of the building occupants under analysis’ (de Dear et al., 2015, p. 391). Hence, a shallow regression slope shows an effective adaptability of subjects, while a steep gradient indicates that children are not very adaptable to change in the classroom thermal environment.

The regression gradient is 0.27 units/°C for the sample children. This is consistent with the regression coefficient reported by Teli, James, and Jentsch (2013) and Yun...
Table 6. Summary of thermal comfort field surveys in naturally ventilated primary school classrooms in spring/summer seasons.

| Reference            | Location | Age group (years) | Physical measurement | MET, RMR       | Mean clo | Climatic condition | N  | Survey period | \( T_n \) (°C) | \( B \) |
|----------------------|----------|-------------------|----------------------|----------------|----------|-------------------|----|---------------|----------------|-------|
| de Dear et al. (2015) | Australia| 10–15             | Wall-mounted: between 2.0 and 2.5 m above floor level | Mean MET\(^a\): 1.51 RMR: n.a. | 0.45\(^b\) | A Warm temperate   | 65 | 2 weeks       | 21.9          | 0.33  |
|                      |          |                   |                      |                 |          | B Warm humid summer, mild winter | 428 | 4 weeks       | 24.5          | 0.35  |
|                      |          |                   |                      |                 |          | C Warm temperate   | 374 | 3 weeks       | 20.9          | 0.18  |
|                      |          |                   |                      |                 |          | E Mild temperate   | 474 | 3 weeks       | 23.9          | 0.46  |
| Teli et al. (2012)   | England  | 7–11              | Centre: at a height of 1.1 m | MET and RMR: adjusted | Boys: 0.4 Girls: 0.35 | Temperate | 230 | 12 days over three months | 20.8          | 0.27  |
| Mors et al. (2011)   | Netherlands| 9–11            | Centre: at heights between 0.5 and 1 m | Mean MET: 1.26 adjusted | RMR: n.a. | Summer: 0.3 Winter: 0.9 | Temperate | 79 | 24 days over 3 seasons | –            | –     |
| Yun et al. (2014)    | Korea    | 4–6               | Close to centre: at a height of 1.1 m | Mean MET: 1.37 adjusted | RMR: n.a. | 0.35 | Temperate with four distinct seasons | 119 | Over 3 months | 22.1          | 0.29  |
| This study           | Iran     | 10–12             | Centre: at heights of 0.1, 0.6 and 1.1 m | MET: 1.2 RMR: n.a. | 0.7 | Warm dry summer, cool winter | 811 | 10 days | 23.3          | 0.27  |

Notes: RMR = resting metabolic rate; \( N \) = number of sample respondents; \( T_n \) (°C) = neutral temperature; \( B \) = regression coefficient.
\(^a\)Of the entire sample schools, only primary schools are included; schools A and E were naturally ventilated, and schools B and C were air-conditioned. AC schools are included here for comparative purposes since thermal conditioning of these schools was primarily regulated through operable windows.
\(^b\)Mean clo and MET values in this study corresponds to the entire sample, including all primary and secondary schools.
\(^c\)The survey period in this study covers winter, spring and summer.
\(^d\)This study was conducted in a kindergarten classroom; it is included for comparison.

et al. (2014), but higher than coefficient values derived by Trebilock and Figueroa (2014) and de Dear et al. (2015) when data from the entire sample of students are analysed. However, de Dear et al. (2015) introduced two distinct groups of 'highly adaptable' and 'not very adaptable' schools when thermal sensitivity was analysed for each school separately; with the average slope being 0.18 and 0.38 respectively (Table 6). The regression equation derived for all sample schools suggests that the mean thermal sensation unit increases 1 point per 3.7 K increase in the classroom indoor operative temperature.

Analysis of field data from de Dear (1998) and the Smart Controls and Thermal Comfort (SCATs) (McCartney & Nicol, 2002) databases indicates a greater mean value of the regression coefficient (0.37 ± 0.02 units/°C) for adults (Humphreys et al., 2007) compared with the coefficient derived in this study for children. The weighted linear regression of bin-mean thermal sensation on operative temperature given by de Dear et al. (1997) shows that the mean (±SD) model gradient is \( 0.27 ± 0.134 \) for NV buildings. This implies that the sample children are similar or slightly less sensitive to temperature change compared with adults.

The upper acceptability limits for each of the four school buildings are given in Table 7 for further comparison between acceptable values of operative temperature calculated for each building. To better understand thermal sensitivity of children in response to changes in thermal environment, Table 7 also summarizes the equations derived from the weighted linear regression of the mean thermal sensation votes against operative temperature binned by 0.5°C intervals for each corresponding school building.

Table 7. Linear regression analysis of TSV on \( T_{op} \) and acceptability limits for schools.

| School | Gender | \( N \) | \( R^2 \) | \( P \) | \( B^a \) | \( C^b \) | \( T_n \) (°C)\(^c\) | UL20 (°C)\(^d\) | \( \delta T_{op} \) SD | Mean \( T_{op} \) (°C) | \( T_{max-min} \) (K)\(^e\) |
|--------|--------|-------|--------|------|--------|--------|----------------|----------------|----------------|----------------|----------------|
| A      | Male   | 233   | 0.41   | 0.000| 0.165  | -3.666 | 22.2          | 27.4           | 0.79            | 26.0           | 15.1           |
| B      | Male   | 219   | 0.87   | 0.000| 0.277  | -6.586 | 23.8          | 26.8           | 0.16            | 25.7           | 15.6           |
| C      | Female | 192   | 0.84   | 0.000| 0.287  | -6.724 | 23.8          | 26.4           | 0.54            | 26.2           | 15.0           |
| D      | Female | 167   | 0.87   | 0.000| 0.282  | -6.326 | 22.4          | 25.4           | 0.50            | 25.8           | 15.3           |

Notes: \(^a\)\( B \) = regression coefficient.
\(^b\)\( C \) = constant.
\(^c\)\( T_n \) (°C) = neutral temperature.
\(^d\)UL20 = upper limit for PPD = 20% (°C), when TSV = 0.85.
\(^e\)\( T_{max-min} \) (K) = daily outdoor temperature range (maximum – minimum).
As inferred from Table 7, the regression gradient in schools B–D is steeper than that for school A. Accordingly, children in these schools seem to be less adaptable to indoor temperature change than sample children from school A. The upper acceptability limits confirm this finding, indicating that students in these schools have stricter upper temperature limits compared with children in school A.

While the three forms of thermal adaptation, namely physiological, behavioural and psychological (de Dear & Brager, 1998), could be relevant to children, the specific reason behind the observed differences in the acceptability level of children in school A over the entire survey period is not very obvious. It can be explained by several factors including indoor and outdoor temperature variation, building-related factors, survey conditions and behavioural constraints.

The impact of building characteristics on thermal comfort in classrooms is investigated by Teli et al. (2012) who introduce orientation as the main building-related factor that leads to differences between children’s thermal perception. As shown in Table 2, orientation of classrooms seems to be the most obvious building-related difference between schools that could contribute to different thermal sensitivity of children in school A. Further research is required to verify this observation.

De Dear et al. (2015, p. 397) highlight that the ‘diversity of indoor and outdoor thermal exposures both influence thermal sensitivity and adaptability of school children in the classroom setting’. To understand the influence of indoor thermal exposure, classroom temperatures that children encounter during a single school day are applied to derive an index of thermal variety. That is because during the prolonged survey period, no significant difference between the standard deviation of indoor temperature is observed. \(\delta T_{op}\) is calculated by subtracting the mean operative temperature on that day \(T_{op} \text{ day mean}\) from the operative temperature during the survey \(T_{op}\) (Humphreys et al., 2013). Results indicate that the standard deviation of \(\delta T_{op}\) over a survey day in school A is higher than that in other schools. Since this study was conducted over several days, the effects of outdoor temperature dynamic are not apparent; all sample schools had similar monthly mean temperature and daily temperature range (maximum – minimum). A more protracted survey period is proposed to examine the influence of day-to-day changes of outdoor temperature on the adaptability of children.

**Predictions of thermal satisfaction based on the adaptive method**

According to the international adaptive comfort standard used for NV spaces (ASHRAE 55, 2013, p. 39): environmental measurements are linked to satisfaction through an empirical model in which the prevailing mean outdoor temperature determines the position of percent satisfied contours bordering the comfort zone.

The ASHRAE adaptive model (de Dear et al., 1997) used in ASHRAE 55 (2013) defines the acceptable zone for naturally conditioned buildings within which 80% or 90% of building occupants find the thermal conditions acceptable and is delineated using the relationship between the indoor comfort temperature and the outdoor climate.

The comfort equation for NV buildings derived from the RP-884 ASHRAE worldwide database (de Dear et al., 1997) conducted primarily in office buildings is expressed as:

\[
T_{\text{conf}} = 0.31 \times T_{\text{ref}} + 17.8
\]

where \(T_{\text{conf}}\) is the optimal operative temperature for thermal comfort; and \(T_{\text{ref}}\) represents the prevailing mean outdoor air temperature for a time period between seven and 30 sequential days before the day in question (ASHRAE 55, 2013). The climate metric was previously expressed as the mean monthly outdoor air temperature (ASHRAE 55, 2010), i.e., the average of the mean daily minimum and maximum outdoor temperature for the month in question.

The recent version of the ASHRAE standard permits a new metric for climate known as the exponentially weighted running mean of a sequence of mean daily outdoor temperatures prior to the day in question \(T_{\text{rm}}\). According to Humphreys et al. (2013), this is a preferred outdoor temperature index. It gives weight to temperatures according to their distance in the past, which is calculated from the series:

\[
T_{\text{rm}} = \frac{T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} \ldots}{1 + \alpha + \alpha^2 \ldots}
\]

where constant \(\alpha\) is < 1; \(T_{od-1}\) is the daily mean outdoor temperature for the previous day; \(T_{od-2}\) is the daily mean outdoor temperature for the day before that, and so on (Nicol et al., 2012, p. 38). The running mean constant \(\alpha\) explains the speed of the running mean response to changes in the outdoor temperature (McCartney & Nicol, 2002). Because \(\alpha\) is < 1, more weight is given to recent days’ temperature than the more remote past (de Dear, 2011). The recommended value of \(\alpha\) in ASHRAE 55 (2013) varies within a range of 0.9 and 0.6. The calculation of running mean outdoor temperature and the appropriate value of \(\alpha\) are explained in detail by de Dear (2011), Nicol and Humphreys (2010), and...
Humphreys et al. (2013); however, to date the optimum value of $\alpha$ has not been validated for children.

ASHRAE Standard 55 determines the upper and lower limits of thermal acceptability based on the $T_{\text{comf}}$ criterion. Therefore, the acceptable limits are derived from acceptable operative temperatures within which 80% or 90% of the occupants are satisfied; $T_{\text{lim}}(80) = 3.5$ K for typical applications and $T_{\text{lim}}(90) = 2.5$ K when a higher standard of thermal comfort is desired.

In this study, the 80% acceptability limits of children were predicted using the ASHRAE 55 adaptive comfort standard from the measured outdoor temperature. Two different metrics for the climate axis are used: the mean outdoor air temperature of a month prior to the day the survey was conducted ($T_{\text{out}}$), and weighted running seven-day mean outdoor temperature ($T_{\text{rm}}$) for the day in question; the constant value of $\alpha$ is taken to be 0.8 as recommended by Humphreys et al. (2013). The upper 80% acceptability limits for each survey day are calculated and acceptable indoor operative temperatures are tabulated for each building (Table 8).

As can be seen from Table 8, the upper 80% acceptability limits obtained from monthly mean outdoor air temperature and exponentially weighted running mean outdoor temperature ($\alpha = 0.8$) for all surveyed schools are 27.3 and 27.5°C respectively. This result suggests that values predicted by ASHRAE’s adaptive comfort model (irrespective of outdoor temperature index) are higher than the upper temperature limit derived from sampled children’s responses, i.e., 26.5°C, which implies that children require cooler operative temperatures to achieve thermal comfort. Such difference is more apparent in girls’ schools (schools C and D).

Comparison of the upper 80% acceptability limit for each school building reveals that acceptable operative temperature limits are similar across all schools; this is in accord with the similar prevailing mean outdoor temperatures during the survey period. By changing the measure of prevailing mean monthly outdoor temperature to the weighted running seven-day mean outdoor temperature, comfort limits slightly shift to warmer temperatures which reflects the effect of warmer outdoor temperature in more recent days prior to each survey day.

Students’ thermal perception is further compared with the adaptive thermal comfort model established in ASHRAE 55 (2013). Figure 8 shows the 80% and 90% acceptable ranges (solid lines) as given in the adaptive standard. The dashed line represents the reference line corresponding to the comfort equation which is the base line for deriving the upper and lower limits of the comfort zone (equation 5). This graph compares the recommended temperature limits based on ASHRAE 55 (2013) with the operative temperatures determined during the surveys in relation to the prevailing mean outdoor temperature; using averages for the past 30 days, and the running mean of the last seven days prior to

| School | Acceptable limits based on $T_{\text{out}}$ | Acceptable limits based on $T_{\text{rm}}$ |
|--------|---------------------------------|---------------------------------|
| A      | 19.3 27.3                       | 19.9 27.5                       |
| B      | 19.5 27.3                       | 20.6 27.7                       |
| C      | 19.3 27.3                       | 19.8 27.4                       |
| D      | 19.3 27.3                       | 20.0 27.5                       |
| Average| 19.3 27.3                       | 20.1 27.5                       |

Notes: $a$ $T_{\text{out}}$ = prevailing mean monthly outdoor air temperature (°C).

$\alpha$ $T_{\text{rm}}$ = exponentially weighted running mean of the daily mean outdoor air temperature (°C); $\alpha = 0.8$.

$\alpha$ $T_{\text{out}}$ = upper 80% acceptability limits (°C).

Figure 8. Acceptable operative temperatures in relation to monthly mean outdoor air temperature (a) and weighted running mean outdoor temperature (b) plotted on the ASHRAE diagram.
the day in question. Data bins are grouped into 0.5°C indoor operative temperature intervals for clarity. In order to compare the thermal acceptability zones as outlined in the ASHRAE adaptive comfort model (ASHRAE 55, 2013) with the actual thermal satisfaction of students, the per cent of thermal sensation votes on the central categories of the ASHRAE scale (−1, 0, +1) corresponding to each pair of observed $T_{op}$ and $T_{out}/T_{rm}$ are grouped in three acceptability levels and plotted on the adaptive thermal comfort chart. To facilitate this comparison better, the graph also contains a figure that shows the mean TSV in each group of acceptability levels.

Figure 8 illustrates that a large number of measured operative temperatures in the classrooms fall within the ASHRAE adaptive limits and students’ comfort relatively follows the predictions of ASHRAE 55. However, observed situations in some classrooms exceed the upper limit where children tend to feel uncomfortably warm (TSV_{mean} > +1). For the operative temperature around 27°C, the acceptability level observed for sample children was lower than the predicted level based on the ASHRAE 55 limits. In addition, notwithstanding that the observed operative temperature is assessed as comfortable by the ASHRAE adaptive comfort model, the acceptability level does not comply with the actual satisfaction level of all sample students. As depicted in the graph, a large number of children experienced unacceptable thermal conditions even when the operative temperature fell within the notionally acceptable range. The result suggests that the acceptability level of the sample children is lower than that predicted by the ASHRAE adaptive limits, which is consistent with the outcome of other recent studies (Chen, Hwang, & Shih, 2014; Mors et al., 2011). The underrepresentation of children’s acceptability level by the ASHRAE standard may be explained by students’ reduced tolerance to high temperature (Chen et al., 2014). Moreover, as shown by Brager, Paliaga, and de Dear (2004), the availability of environmental controls affects occupant satisfaction with the indoor thermal environment. Therefore, further investigation in relation to children’s adaptive behaviours in the classroom is proposed.

**Behavioural adjustments in the classrooms**

Behavioural thermoregulation involves several adaptive actions that affect the heat balance between the human body and the surrounding thermal environment (de Dear et al., 1997), including changes of clothing insulation, metabolic rate and posture, moving to a different thermal environment, and using devices to control thermal conditions (Nicol et al., 2012, p. 19).

In this study, children have very limited opportunities for behavioural adaptations during lesson time. The most apparent behavioural response of the sample children is limited to adjustment of their clothing level, and more specifically adding/removing light jackets worn over the school uniform. Similar to Corgnati, Ansaldi, and Filippi (2009), the sample children neither have freedom to change their activity level to adapt to the classroom thermal condition nor have individual access to operable windows/doors. However, they are free to take these actions during the school break. Teachers have the main behavioural control over the environmental conditions, predominantly by opening/closing windows which allows natural ventilation and increases air speed within the occupied zone.

Children’s mean clothing insulation level was relatively static during the warm survey period; the dress code leads to small differences between individuals’ mean clothing levels within each gender. It is worth noting that dress code policy in the sample schools is designated in accordance with socio-cultural factors. Consequently, the possibility of clothing adjustment with respect to the classroom operative temperature variation is less likely to happen.

The stringent school dress code and probably parents’ instructions limit the ability of children to adapt their clothing insulation to temperature change completely. These pressures acting on children prevent them from achieving comfort. The high clo values in this study due to existing rules and conventions together with the children’s high thermal sensations tend to suggest that children were overdressed for the weather experienced. It is inferred that a certain amount of thermal comfort would not be sacrificed if children were able to adapt themselves successfully to the classroom thermal environment by adjusting by their clothing level. Therefore, lack of opportunities for personal and environmental controls in the classroom can contribute to the students’ heightened level of dissatisfaction, especially at higher indoor operative temperatures.

**Conclusions**

This study investigated a thermal comfort evaluation in NV school classrooms during the warm season of the school year in Iran. Predictions of Fanger’s PMV/PPD and the ASHRAE adaptive comfort model were compared with children’s TSV/APD derived from an actual thermal comfort field study. The results suggest that thermal comfort models given in the standards do not accurately predict children’s thermal sensation in the classroom. It appears that children have a warmer thermal sensation than would be expected based on adult-
based models and require cooler indoor operative temperatures to achieve thermal comfort in the classroom. This highlights the need for adjustments to current comfort models to incorporate thermal perception of children. This is of particular importance in school building design, mainly because of the adverse effect of elevated temperature on children’s schoolwork performance. However, more research over a wider range of conditions and age groups is required with specific reference to child-based methods and measurement protocols.

This study shows that PMV developed for adult subjects slightly underestimates the mean TSV of children and PPD appears to predict a lower value than children’s APD. Comfort temperature during the survey period derived from regression analysis of children’s comfort responses against operative temperature (23.3°C) is slightly lower than that predicted by the PMV model.

The upper 80% acceptability limits predicted by ASHRAE’s adaptive comfort model from outdoor climate during field surveys are higher than the upper acceptable temperature limits derived from sampled children’s responses. This implies that children generally feel comfortable at cooler temperatures than defined by the adaptive comfort standard. In addition, children’s acceptability level is lower than that predicted by ASHRAE adaptive limits. Limitations on behavioural adjustments could explain children’s thermal discomfort and reduced tolerance to high temperatures in the sample classrooms. It is therefore suggested that children might need different comfort criteria than those of adults with stricter upper temperature limits during warm seasons. The implications of additional comfort cooling could be significant for schools’ energy demand.

Apart from the different comfort requirements for children, this study reveals that the issue of facilitating adaptive actions at school seems critical. That is mainly because the most common and important adaptive mechanism, behavioural adjustments, is not sufficiently used in the investigated Iranian classrooms. The relatively high clo value in this study when considering the outdoor temperature range during the survey period indicates a more stringent limitation on behavioural adjustments than is generally applied in schools. Therefore, suitable fabric and redesign of garments which could incorporate adequate weather flexibility and facilitating clothing adjustments up to the socially permitted level could be part of a strategy to reduce thermal discomfort in schools. The adaptive mechanisms in school classrooms and how these affect children’s comfort need to be further explored.

The regression gradient as a measure of thermal sensitivity identifies two distinct groups of schools with shallow and relatively steeper gradients indicating different adaptability levels of students. This indicates that thermal comfort criteria of each school building need to be assessed on a case-by-case basis. Future research is required to verify the influence of building-related factors and to explore the impact of outdoor thermal variations on children’s thermal perception in classrooms.

Disclosure statement
No potential conflict of interest was reported by the authors.

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 R. J. Howlett, L. C. Jain, & S. H. Lee (Eds.), Sustainability in energy and buildings (pp. 347–355). Berlin: Springer.
Al-Rashidi, K. E., Loveday, D. L., Al-Mutawa, N. K., & Havenith, G. (2012). A comparison of methods for assessing the thermal insulation value of children’s schoolwear in Kuwait. Applied Ergonomics, 43(1), 203–210. doi:10.1016/j.apergo.2011.05.010
Anderson, G. S., & Mekjavic, I. B. (1996). Thermoregulatory responses of circum-pubertal children. European Journal of Applied Physiology and Occupational Physiology, 74(5), 404–410. doi:10.1007/BF02337720
ASHRAE. (2009). ASHRAE handbook – Fundamentals American society of heating, refrigeration and air conditioning engineers, Inc.
ASHRAE 55. (2010). ANSI/ASHRAE standard 55-2010, thermal environmental conditions for human occupancy: American society of heating, refrigeration and air conditioning engineers, Inc.
ASHRAE 55. (2013). ANSI/ASHRAE standard 55-2013, thermal environmental conditions for human occupancy. Atlanta, GA: American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.
Auliciems, A. (1969). Thermal requirements of secondary schoolchildren in winter. Journal of Hygiene, 67(01), 59–65. doi:10.1017/S0022172400041425
Auliciems, A. (1973). Thermal sensations of secondary schoolchildren in summer. Journal of Hygiene, 71(03), 453–458. doi:10.1017/S002217240004643X
Auliciems, A. (1975). Warmth and comfort in the subtropical winter: A study in Brisbane schools. Journal of Hygiene, 74(03), 339–343. doi:10.1017/S0022172400046854
Bar-Or, O. (1989). Temperature regulation during exercise in children and adolescents: Perspectives in exercise science and sports medicine, II. Youth, exercise and sport. Indianapolis, IN: Benchmark Press.
Bragar, G. S., Paliaga, G., & de Dear, R. (2004). Operable windows, personal control and occupant comfort. ASHRAE Transactions, 110(2), 17–35.
Chen, C.-P., Hwang, R.-L., & Shih, W.-M. (2014). Effect of fee-for-service air-conditioning management in balancing thermal comfort and energy usage. International Journal of...
Biometeorology, 58(9), 1941–1950. doi:10.1007/s00484-014-0796-6

Corgnati, S. P., Ansaldi, R., & Filippi, M. (2009). Thermal comfort in Italian classrooms under free running conditions during mid seasons: Assessment through objective and subjective approaches. Building and Environment, 44(4), 785–792. doi:10.1016/j.buildenv.2008.05.023

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(2), 951–959. doi:10.1016/j.buildenv.2005.10.027
d’Ambrosio Alfano, F. R., Ianniello, E., & Palella, B. I. (2013). PMV–PPD and acceptability in naturally ventilated schools. Building and Environment, 67(0), 129–137. doi:10.1016/j.buildenv.2013.05.013

de Dear, R. (2011). Recent enhancements to the adaptive comfort standard in ASHRAE 55–2010. 45th annual conference of the Architectural Science Association (ANZAScA 2011), Sydney, Faculty of Architecture Design and Planning, The University of Sydney, Australia.

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

de Dear, R. J., & Brager, G. S. (1998). Developing an adaptive model of thermal comfort and preference. ASHRAE Transaction, 104(1), 145–167.

de Dear, R. J., Brager, G. S., & Cooper, D. J. (1997). Developing an Adaptive Model of Thermal Comfort and Preference. Final Report [on] ASHRAE RP-884, Macquarie University, Sydney.

de Dear, R. J., Kim, J., Candido, C., & Deuble, M. (2015). Adaptive thermal comfort in Australian school classrooms. Building Research & Information, 43(3), 383–398. doi:10.1080/09613218.2015.991627

De Giuli, V., Da Pos, O., & De Carli, M. (2012). Indoor environmental quality and pupil perception in Italian primary schools. Building and Environment, 56, 335–345. doi:10.1016/j.buildenv.2012.03.024

Du Bois, D., & Du Bois, E. F. (1916). Clinical calorimetry: Tenth paper a formula to estimate the approximate surface area if height and weight be known. Archives of Internal Medicine, XVII(6_2), 863–871. doi:10.1001/archinte.1916.00081300100002

Fabbri, K. (2013). Thermal comfort evaluation in kindergartens: PMV and PPD measurement through datalogger and questionnaire. Building and Environment, 68, 202–214. doi:10.1016/j.buildenv.2013.07.002

Falk, B. (1998). Effects of thermal stress during rest and exercise in the paediatric population. Sports Medicine, 25(4), 221–240. doi:10.2165/00007256-199825040-00002

Falk, B., & Dotan, R. (2008). Children’s thermoregulation during exercise in the heat – A revisit. Applied Physiology, Nutrition, and Metabolism, 33(2), 420–427. doi:10.1139/H07-185

Fanger, P. O. (1970). Thermal comfort. Copenhagen: Danish Technical Press.

Fanger, P. O. (1973). Assessment of man’s thermal comfort in practice. British Journal of Industrial Medicine, 30(4), 313–324. doi:10.1136/oem.30.4.313

Goto, T., Tofum, J., de Dear, R., & Fanger, P. (2006). Thermal sensation and thermophysiological responses to metabolic step-changes. International Journal of Biometeorology, 50(5), 323–332. doi:10.1007/s00484-005-0016-5

Haddad, S., King, S., Osmond, P., & Heidari, S. (2012). Questionnaire design to determine children’s thermal sensation, preference and acceptability in the classroom. Lima, Peru: PLEA.

Haddad, S., Osmond, P., & King, S. (2013). Metabolic rate estimation in the calculation of the PMV for children. Cutting Edge: 47th International Conference of the Architectural Science Association, Hong Kong.

Haddad, S., Osmond, P., King, S., & Heidari, S. (2014). Developing assumptions of metabolic rate estimation for primary school children in the calculation of the Fanger PMV model. The 8th Windsor conference: Counting the Cost of Comfort in a Changing World, Cumberland Lodge, Windsor Great Park, UK.

Havenith, G. (2007). Metabolic rate and clothing insulation data of children and adolescents during various school activities. Ergonomics, 50(10), 1689–1701. doi:1080/00140130701587574

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

Humphreys, M. A. (1977a). The optimum diameter for a globe thermometer for use indoors. Annals of Occupational Hygiene, 20(2), 135–140. doi:10.1093/annhyg/20.2.135

Humphreys, M. A. (1977b). A study of the thermal comfort of primary school children in summer. Building and Environment, 12(4), 231–239. doi:10.1016/0360-1323(77)90025-7

Humphreys, M. A., Nicol, J. F., & Rijal, H. B. (2007). Field studies of indoor thermal comfort and the progress of the adaptive approach. Advances in Building Energy Research, 1(1), 55–88. doi:10.1080/17512549.2007.9687269

Humphreys, M. A., Nicol, J. F., & Roaf, S. (2015). Adaptive thermal comfort: Foundations and analysis. London: Routledge.

Humphreys, M. A., Rijal, H. B., & Nicol, J. F. (2013). Updating the adaptive relation between climate and comfort indoors; new insights and an extended database. Building and Environment, 63, 40–55. doi:10.1016/j.buildenv.2013.01.024

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(2), 189–200. doi:10.1007/s00484-008-0203-2

ISO 7726. (2001). Ergonomics of the thermal environment. Instruments for measuring physical quantities. Brussels: International Standards Organization.

ISO 7730. (2005). Ergonomics of thermal environment analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. London: International Standards Organization.

ISO 8996. (2004). Ergonomics of the thermal environment – Determination of metabolic rate. Geneva, Switzerland: International Organization for Standardization.

ISO 9920. (2007). Ergonomics of the thermal environment – Estimation of thermal insulation and water resistance of a clothing ensemble. Geneva, Switzerland: International Organisation for Standardisation.
Katafygiotou, M. C., & Serghides, D. K. (2014). Thermal comfort of a typical secondary school building in Cyprus. *Sustainable Cities and Society*, 13, 303–312. doi:10.1016/j.scs.2014.03.004

King, J., & Marans, R. W. (1979). The physical environment and the learning process.

Kwok, A. G. (1998). Thermal comfort in tropical classrooms. *ASHRAE Transactions*, 104(1B), 1031–1047.

Kwok, A. G., & Chun, C. (2003). Thermal comfort in Japanese schools. *Solar Energy*, 74, 245–252. doi:10.1016/S0038-092X(03)00417-6

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. doi:10.1016/j.apenergy.2012.02.004

McCullough, E. A., Eckels, S., & Harms, C. (2009). Determining temperature ratings for children’s cold weather clothing. *Applied Ergonomics*, 40(5), 870–877. doi:10.1016/j.apergo.2008.12.004

Mccullough, E. A., Eckels, S., & Harms, C. (2009). Determining temperature ratings for children’s cold weather clothing. *Applied Ergonomics*, 40(5), 870–877. doi:10.1016/j.apergo.2008.12.004

McIntyre, D. A. (1973). A guide to thermal comfort. *Applied Ergonomics*, 4(2), 66–72. doi:10.1016/0003-6870(73)90079-3

McIntyre, D. A. (1982). Chamber studies – Reductio ad absurdum? *Energy and Buildings*, 5(2), 89–96. doi:10.1016/0378-7788(82)90003-2

Mendell, M. J., & Heath, G. A. (2005). Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. *Indoor Air*, 15(1), 27–52.

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(12), 2454–2461. doi:10.1016/j.buildenv.2011.05.025

Nasrollahi, N., Knight, I., & Jones, P. (2008). Workplace satisfaction and thermal comfort in air conditioned office buildings: Findings from a summer survey and field experiments in Iran. *Indoor and Built Environment*, 17(1), 69. doi:10.1177/1420326X07086945

Nicol, J. F., & Humphreys, M. A. (1973). Thermal comfort as part of a self-regulating system. *Building Research and Practice*, 1(3), 174–179. doi:10.1080/09613217308550237

Nicol, J. F., & Humphreys, M. A. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings*, 34(6), 563–572. doi:10.1016/S0378-7788(02)00006-3

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(1), 11–17. doi:10.1016/j.buildenv.2008.12.013

Nicol, J. F., Humphreys, M. A., & Roaf, S. (2012). *Adaptive thermal comfort: Principles and practice*. London: Routledge.

Ridley, K., Ainsworth, B. E., & Olds, T. S. (2008). Development of a compendium of energy expenditures for youth. *International Journal of Behavioral Nutrition and Physical Activity*, 5(1), 45. doi:10.1186/1479-5868-5-45

Ridley, K., & Olds, T. S. (2008). Assigning energy costs to activities in children: a review and synthesis. *Medicine & Science in Sports & Exercise*, 40(8), 1439–1446. doi:10.1249/0b013e31817279ef

Schneider, M. (2002). Do school facilities affect academic outcomes? Retrieved 25 August 2011, from http://www.ncef.org/pubs/outcomes.pdf

Teli, D., James, P. A. B., & Jentsch, M. F. (2013). Thermal comfort in naturally ventilated primary school classrooms. *Building Research & Information*, 41(3), 301–316. doi:10.1080/09613218.2013.773493

Teli, D., James, P. A. B., & Jentsch, M. F. (2015). Investigating the principal adaptive comfort relationships for young children. *Building Research & Information*, 43(3), 371–382. doi:10.1080/09613218.2015.998951

Teli, D., Jentsch, M. F., & James, P. A. B. (2012). Naturally ventilated classrooms: An assessment of existing comfort models for predicting the thermal sensation and preference of primary school children. *Energy and Buildings*, 53, 166–182. doi:10.1016/j.enbuild.2012.06.022

Treiblock, M., & Figueroa, R. (2014). *Thermal comfort in primary schools: a field study in Chile*. The 8th Windsor conference: Counting the Cost of Comfort in a Changing World, Cumberland Lodge, Windsor Great Park, UK.

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(2), 193–220. doi:10.1080/10789669.2007.10390951

Wong, N. H., & Khoo, S. S. (2003). Thermal comfort in classrooms in the tropics. *Energy and Buildings*, 35(4), 337–351. doi:10.1016/S0378-7788(02)00109-3

Wyon, D. P., & Wargocki, P. (2006). Room temperature effects on office work. In D. Croome (Ed.), *Creating the productive workplace* (2nd ed., pp. 181–192). London: Taylor & Francis.

Yun, H., Nam, I., Kim, J., Yang, J., Lee, K., & Sohn, J. (2014). A field study of thermal comfort for kindergarten children in Korea: An assessment of existing models and preferences of children. *Building and Environment*, 75, 182–189. doi:10.1016/j.buildenv.2014.02.003