Relationship between children’s comfort temperature and outdoor climate: some methodological issues

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Abstract

Several recent studies have focused on children’s comfort criteria in schools, highlighting a need to develop an adaptive comfort model with application for children in naturally ventilated classrooms. This paper examines the influence of prior exposure to weather dynamics on children’s indoor thermal comfort. The field study was performed in naturally ventilated primary school classrooms during the warm season in Shiraz, Iran. Child-specific questionnaires were administered while concurrent indoor and outdoor climate measurements were conducted. This study has set out to obtain the adaptive comfort equation for children based on the methods used to develop comfort equations in ASHRAE 55 (2013) and EN 15251 (CEN, 2007). A sensitivity analysis was performed to test the relationship between children’s indoor comfort temperature and outdoor climate. Different measures of outdoor temperature were examined in order to identify a suitable metric for the outdoor climate, suggesting the strongest correlation coefficient with the comfort temperature. The result of the analysis shows that the running mean method with lower decay values (α=0.45) leads to higher correlation with children’s comfort temperature. However, the ‘true’ value of α remains debatable. The gradient of the comfort equation in relation to outdoor temperature for children is shown to be shallower than that of adults.

Keywords: Thermal comfort, adaptive model, outdoor air temperature, indoor comfort temperature, children, school classroom

1 Introduction

Despite the importance of maintaining thermal comfort in schools (Wargocki and Wyon, 2007), thermal comfort studies have largely concentrated on adults. While 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. 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. Further, some authors suggest that children feel comfortable at cooler temperatures than predicted by adaptive comfort standards (Mors et al., 2011; Teli et al., 2012; de Dear et al., 2015; Teli et al., 2015).

This paper aims to evaluate the adaptive thermal comfort model for children based on a field survey conducted in naturally ventilated primary schools in Iran during the warm period of the school year. To obtain the relation between thermal comfort indoors and the outdoor climate, survey data were examined to derive comfort temperature for children and define a suitable metric for the prevailing outdoor temperature. A sensitivity analysis was performed and various approaches were adopted to calculate the comfort temperature for the sampled children, mainly because the methods previously described in the literature
for deriving comfort temperature may not be applicable for children. To better understand the adaptive comfort relationships for children, this study tests different metrics of outdoor climate to identify a suitable metric that suggests the strongest correlation with children’s neutral temperature.

2 Calculating the comfort temperature

The ‘neutral or comfort temperature’ \( T_{\text{comf}} \) is the temperature defined as “the Operative Temperature at which either the average person will be thermally neutral or at which the largest proportion of a group of people will be comfortable” (Nicol and Humphreys, 2010). The analytic method of determining the neutral temperature differs between the two adaptive comfort approaches, the global adaptive comfort standard (ASHRAE 55, 2013) and its European counterpart (EN 15251, 2007), mainly because of different sample sizes used (de Dear, 2011; de Dear et al., 2013).

2.1 Linear regression analysis

In the ASHRAE RP-884 project (de Dear and Brager, 1998), the buildings’ indoor operative temperature \( T_{\text{op}} \) was binned into half-degree intervals, and the bins’ mean thermal sensation responses were analysed. The neutral temperature \( T_{\text{comf}} \) was calculated for each building by solving the weighted linear regression model between thermal sensation and operative temperature for a mean sensation vote of zero. The large sample sizes in the ASHRAE database, about 9000 of total 21000 questionnaires in NV buildings (de Dear et al., 1997), allowed for statistically significant regression models for estimation of the optimum comfort temperature at the individual building level (de Dear et al., 2013).

2.2 The Griffith method

The regression analysis method requires a substantial amount of data and a wide range of temperatures to estimate the neutral temperature accurately (Nicol and Humphreys, 2010). Therefore, another analysis technique, the so-called Griffiths method, was employed to determine neutrality in the EN 15251 adaptive model in order to address the smaller sample sizes in the SCATs (Smart Controls and Thermal Comfort) database (1449 of total 4655 samples in free-running buildings) (Nicol and Humphreys, 2010).

Compared to regression analysis which calculates mean value of comfort temperature over the several days or weeks of the survey period, the proposed Griffith method used in EN 15251 estimates a comfort temperature “of a particular person in a particular building in that particular month” (Humphreys et al., 2013). Humphreys et al. argue that day to day drift of the daily mean room temperatures during the survey period could introduce some bias in estimation of the regression coefficient and consequently in calculation of the comfort temperature when regression analysis is used.

In order to assess neutral temperature in case of a small number of subjects (or comfort votes) or small range of temperature, the Griffiths method (1990) introduced a constant value for the linear relationship between thermal sensation vote and operative temperature; i.e. the so called ‘Griffiths constant’, \( G (\degree/K) \) (Nicol et al., 2012, p.148). It is equivalent to the regression coefficient (Griffith slope) which relates the comfort temperature to the operative temperature and subjects’ thermal sensation votes; based on the assumption that no adaptation has happened (Nicol and Humphreys, 2010; Nicol et al., 2012, p.149). The neutral temperature can be calculated using the following relationship (Humphreys et al., 2007) from operative temperature \( T_{\text{op}} \), thermal sensation vote \( \text{TSV} \), and a standard value of regression coefficient taken as the Griffiths constant \( G \):
This equation can be applied to calculate comfort temperature from individual comfort votes, or estimate average neutral temperature from a group of votes using mean thermal sensation votes (TSV(mean)) and mean operative temperature (T_{op}(mean)) (Humphreys et al., 2007; Nicol and Humphreys, 2010; Nicol et al., 2012).

The estimation of the Griffiths constant is of importance in the precision of the estimated neutral temperature. However, it requires conditions which are not likely to be achieved in field studies where “...no adaptation to temperature changes takes place and measurement errors are excluded” (Nicol and Humphreys, 2010). Therefore, an optimum value for the Griffiths slope has been estimated (G=0.5) (Humphreys et al., 2007) using data from the SCATs and ASHRAE databases of comfort field studies (McCartney and Nicol, 2002; de Dear et al., 1997).

In EN 15251 (CEN, 2007), neutrality is calculated for each comfort vote assuming that a regression coefficient is equal to 0.5/K (Nicol and Humphreys, 2010), which corresponds to the rate of change in thermal sensation against operative temperature in situations where no adaptations take place. However, the validity of the presumed value of the Griffiths constant (0.50/K) in EN15251 (Nicol and Humphreys, 2010) is questioned (de Dear, 2011; de Dear et al., 2013). It is argued that Fanger’s PMV/PPD model (1970) provides a more reasonable method to estimate the Griffiths constant in the absence of adaptive actions, given that PMV/PPD poorly estimates thermal sensation of occupants in buildings where they have thermally adapted. In the absence of adaptation, taking summertime data found in the SCATs database (typical office wear of 0.6 clo, metabolic rate=70 W/m², air speed=0.13 m/s, RH=50%, T_{op}=28.1°C when PMV=+1), Fanger’s PMV/PPD model gives a value of 1/3.5=0.29/K which corresponds to a temperature decrease of 3.5 K to shift PMV from slightly warm to neutral (de Dear, 2011; de Dear et al., 2013). A recent study which examined the value of Griffiths constant in the comfort temperature calculation for school children shows that G=0.5/K could be applicable for children (Teli et al., 2015). However, more validation studies in different climates are required.

3 Expression of outdoor climate for use in the adaptive comfort model

The relationship of comfort temperature to the outdoor climate is expressed in terms of different measures of outdoor climate (Humphreys et al., 2013), predominantly as the monthly mean minima and maxima temperatures from meteorological records, the average of the minima and maxima daily air temperatures during the survey period, and a weighted running mean of the daily mean outdoor temperature prior to the survey day.

The monthly mean was commonly used as the expression for outdoor temperature (Humphreys, 1978; ASHRAE 55, 2004) primarily because it is readily available from meteorological data. According to de Dear (2011) the monthly mean outdoor temperature employed in ASHRAE’s adaptive model is highly correlated with neutrality derived over a time-period of several days to weeks. Therefore, it is given to be the most logical expression of prevailing outdoor temperature for data in the ASHRAE RP-884 database (de Dear, 2011).

ASHRAE 55 (2013) and EN 15251(CEN, 2007) recognised the linear relationship between comfort temperature indoors and the prevailing condition outdoors; however, the two Standards adopted different metrics of outdoor temperature. The outdoor climate index in ASHRAE 55 (2013) represents the prevailing mean outdoor air temperature for a time period
between 7 and 30 sequential days before the day in question (ASHRAE 55, 2013). It was previously expressed as the mean monthly outdoor air temperature (ASHRAE 55, 2010): i.e. average of the mean daily minimum and maximum outdoor temperature for the month in question. The recent version of the ASHRAE standard (ASHRAE 55, 2013) also permits a new metric for climate known as exponentially-weighted running mean of a sequence of mean daily outdoor temperatures prior to the day in question (T_{rm}).

The adaptive model in EN 15251 (CEN, 2007) adopted an exponentially weighted running mean temperature, which “…captures and puts more emphasis on the immediate, perceptual and behavioural layers of human thermal adaptation compared to the longer-term adaptive processes operating at the physiological level” (de Dear, 2011). According to Humphreys et al. (2013) an exponentially weighted running mean temperature (T_{rm}) is a more appropriate climate index compared to the daily mean or the monthly mean temperature. This is based on the assumption underlying the adaptive approach in which neutral temperature is influenced by a person’s recent thermal experiences (Nicol and Humphreys, 2010). A running mean temperature gives weightings to temperatures based on their distance in the past and suggests that recent thermal experiences are more important than those further in the past (Nicol et al., 2012; Nicol and Humphreys, 2010). T_{rm} for any given day is calculated from the series:

\[ T_{rm} = \frac{(T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} + \ldots) / (1 + \alpha + \alpha^2 + \ldots)}{3.8} \]  

(Eq.2)

where constant \( \alpha \) is <1, \( T_{od-1} \) = the daily mean outdoor temperature for the previous day, \( T_{od-2} \) = the daily mean outdoor temperature for the day before that, and so on (Nicol et al., 2012, p.38). Because \( \alpha \) is <1, more weight is given to recent days’ temperature than the more remote past (de Dear, 2011). EN 15251 (CEN, 2007) provides an approximate equation using the mean temperature for the last seven days with recommended value of \( \alpha = 0.8 \) (Eq.3):

\[ T_{rm} = \frac{(T_{od-1} + 0.8T_{od-2} + 0.6T_{od-3} + 0.5T_{od-4} + 0.4T_{od-5} + 0.3T_{od-6} + 0.2T_{od-7})}{3.8} \]  

(Eq.3)

The exponential weighting method to derive running mean outdoor temperature gives decaying weights to the past mean daily outdoor temperature which suggests that recent days are more influential to the occupants’ comfort temperature than days in the more remote past (ASHRAE 55, 2013). The half-life (\( \lambda \)) of an exponentially weighted running mean is given in the following equation (Nicol and Humphreys, 2010; Humphreys et al., 2013):

\[ \lambda = 0.69 / (1 - \alpha) \]  

(Eq.4)

The running mean constant can vary between 0 and 1 and explains the speed of the running mean response to changes in the outdoor temperature (McCartney and Nicol, 2002). The constant \( \alpha \) is a time-constant that shows a time-period needed for people’s thermal adaptation to occur. This relation shows that larger values of \( \alpha \) result in longer half-life days.

The recommended value of \( \alpha \) in the ASHRAE standard (2013) varies within a range of 0.9 and 0.6 to calculate the exponentially-weighted running mean of outdoor temperature. These values depend on a slow and fast response running mean respectively. The \( \alpha = 0.9 \) is given to be more suitable for climates with minimal day to day temperature variation e.g. humid tropical climates, while lower values of \( \alpha \) seems more appropriate for climates where people are more familiar with day to day temperature dynamics (ASHRAE 55, 2013).

The optimum value of \( \alpha \) can established by deriving the strongest correlation between the indoor comfort temperature and the running mean outdoor temperature. To determine the
best value of the running mean constant, McCartney and Nicol (2002) examined the correlation between the calculated comfort and outdoor temperature using different measures of the outdoor temperature. The result of that investigation using data from the SCATs project suggests that the best value of the running mean constant is 0.8 (McCartney and Nicol, 2002). Using a value of α=0.8 in Eq.4, represents a half-life of 3.5 days (λ=3.5) which suggests a period of a week for thermal adaptation of occupants to a step-change in the mean outdoor temperature (Humphreys et al., 2013).

The study by de Dear (2011) questions the ‘true’ value of α and highlights the importance of the α coefficient in the adaptive comfort temperature standard. According to de Dear (2006) and de Dear (2011) a seven-day integration period is “short enough to incorporate recent weather dynamics, yet long enough to capture ‘weather memory and persistence’ effects in human clothing behaviour”.

4 Method
The field work was conducted in four boys’ and girls’ primary schools in Shiraz, in the south west of Iran, during the warm conditions of the local school year (May-2013). The entire sample included in the analysis constitutes 811 survey responses drawn from healthy children aged 10-12 years in 28 classrooms. All classrooms were in free running mode and naturally ventilated using operable windows. The participating school buildings all utilised medium-heavy weight construction systems. The four indoor environmental variables required for assessment of thermal comfort were collected in the selected classrooms, in accordance with the specifications relating to accuracy of measuring instruments and procedure set out in the standards (ASHRAE 55, 2013; ISO 7726, 2001) from an array of instruments placed at three levels, 1.1m, 0.6m and 0.1m, above the floor. Instrumentation was three sets of Kimo AQ200O units and related measuring probes. The instruments were placed at a mid-classroom location or near the centre, between the occupied rows of desks without impairing students’ visual access and routine activity. The outdoor temperatures were collected from the local weather station, Maxkon® WH 3081, to obtain concurrent data representing the school outdoor microclimate during each survey. The weather station shows the outdoor temperatures in 30-minute intervals with sufficient level of accuracy and resolution anticipating possible comparison with the bureau of meteorology data.

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 et al., 2012). The field survey and measurements were conducted during the last five minutes of the class session, before the next break to minimize any influence on thermal sensation caused by activities during the previous break. The survey participants were involved in sedentary activities (i.e. sitting quietly, writing-sitting, reading-sitting) during the 45 minute lesson period, after performing light to high intensity activities during each 15 minute school break. Since questioning students at the end of the class session may affect students’ perception about thermal comfort, the relation between the students’ tiredness and thermal sensation was examined. No statistically significant relationship was determined between the percentage of tiredness and sleepiness and the survey participants’ mean TSV ($r^2 \leq 0.1$, $p>0.05$).

5 Results and discussion
5.1 Calculation of comfort temperature in each school

Both linear regression and the Griffiths methods were used to derive children’s thermal neutrality in each school (Table 1). First, the neutral temperature in each school is calculated using simple linear regression analysis of the mean thermal sensation votes (TSV) as a function of classroom indoor operative temperatures aggregated into 0.5°C bins. Students’ mean TSV per survey are taken for analysis rather than all individual votes. Data are then weighted according to the number of students making up each mean vote within each 0.5°C indoor operative temperature bin.

Table 1. Calculation of the neutral temperature using different methods during the warm season

<table>
<thead>
<tr>
<th>School</th>
<th>Gender</th>
<th>N</th>
<th>Linear regression method</th>
<th>T\text{comf} °C - Griffiths method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>r²</td>
<td>p</td>
</tr>
<tr>
<td>A</td>
<td>Male</td>
<td>233</td>
<td>0.41</td>
<td>0.00</td>
</tr>
<tr>
<td>B</td>
<td>Male</td>
<td>219</td>
<td>0.87</td>
<td>0.00</td>
</tr>
<tr>
<td>C</td>
<td>Female</td>
<td>192</td>
<td>0.84</td>
<td>0.00</td>
</tr>
<tr>
<td>D</td>
<td>Female</td>
<td>167</td>
<td>0.87</td>
<td>0.00</td>
</tr>
</tbody>
</table>

\text{a}: Regression Coefficient  
\text{b}: Constant  
\text{c}: Neutral temperature based on linear regression of weighted binned mean TSV versus T\text{op}  
\text{d}: G=0.50/k based on the value used in EN15251 (Nicol and Humphreys, 2010)  
\text{e}: G=\delta\text{PMV}/\delta\text{T}_{\text{op}} based on data obtained in school surveys  
\text{f}: G=\delta\text{PMV}/\delta\text{T}_{\text{op}} taking data from SCATs database (de Dear et al., 2013)

Further, comfort temperature in each school is calculated based on the Griffiths method from Eq.1 using different constant values. First, the Griffiths method uses the value of the Griffiths constant (G=0.50/K) based on Humphreys et al. (2010), to predict neutrality of children. Secondly, the value of the Griffiths constant is obtained from the school survey data based on the rate of change of Fanger’s PMV to operative temperature, \delta\text{PMV}/\delta\text{T}_{\text{op}} (de Dear, 2011; de Dear et al., 2013). It is suggested that \delta\text{PMV}/\delta\text{T}_{\text{op}} for the sampled children is equal to 0.23 when children’s metabolic rate is taken as 1.2 during sedentary activities with average clothing level of 0.7 clo (Haddad et al., 2014). Notwithstanding that the Griffiths coefficient of 0.5/K is questioned in de Dear et al. (2013), the alternative value using the PMV/PPD model could not be determined with certainty for children, more likely because of the sensitivity of PMV/PPD model to variables like metabolic rate which are not validated for children (Haddad et al., 2014). The Griffiths constant is also taken as G=0.29/k based on de Dear (2011) and de Dear et al. (2013) for the comparative purposes.

Table 1 shows that the neutral temperature derived from Griffiths value of 0.50/K (Nicol and Humphreys, 2010) is higher than that calculated from the regression analysis of the mean TSV against T\text{op} or predicted by \delta\text{PMV}/\delta\text{T}_{\text{op}}. However, due to the relatively small number of school buildings participating in this study compared to the ASHRAE database, the method used in the SCATs database using the Griffiths constant (G=0.50/K) seems to be appropriate for the calculation of thermal neutrality; application of the regression method to derive neutrality may fail to produce statistically significant regression models with the outdoor climate. The sensitivity of the results to the selected value of the Griffiths constant is examined in order to derive adaptive comfort equation for sample children.
5.2 The prevailing mean outdoor air temperature

This section examines different functions of the outdoor temperature calculated from the following methods for comparative purposes: the average daily air temperature, the arithmetic average considering the last 30 days prior to the day in question, and the exponentially weighted running mean temperature with various decay values ($\alpha$ set to 0.45, 0.65, and 0.8). Figure 1(a) shows the overlay of prevailing mean outdoor air temperatures during spring 2013; the grey shaded area refers to the survey period coinciding with the warm season of the school year. Outdoor mean daily air temperature shows the greatest variability, while arithmetic average of the last 30 days shows the smoothest oscillation. The running mean with $\alpha=0.45$ and $\alpha=0.65$ provide a faster response running mean to outdoor weather transients in more recent days than $\alpha=0.80$. Figure 1(b) illustrates the impact of the different decay values ($\alpha$) on the amplitude of the ASHRAE 55 upper 80% acceptable indoor temperature responses to outdoor weather transients during the survey period. It reveals that weather variability with $\alpha=0.45$ and $\alpha=0.65$ is greater compared to other functions. The curve corresponding to $\alpha=0.45$ in Figure 1(b) indicates a warming response in the acceptable indoor temperature limit by about 2.5 K from day 225 to 235, while the rise is reduced to about 1.5 K when $\alpha=0.8$ is used in the exponentially weighted running mean temperature.

5.3 Relationship between children’s comfort and outdoor climate

5.3.1 Sensitivity of regression equation to the values of $G$ and $\alpha$

A sensitivity analysis is performed to obtain the appropriate values of $G$ and the running mean constant ($\alpha$) for the sampled children and better understand the relationship between children’s indoor comfort temperature and outdoor climate. As Teli et al. (2015) noted, the optimum values of both constants $G$ and $\alpha$ need to be determined for children since these values were derived from adult based adaptive comfort databases (de Dear and Brager, 1998; McCartney and Nicol, 2002). Although the context of this field study differs from European countries involved in the SCATs project, the analysis methods used for the study of SCATs data (Humphreys et al., 2007; Nicol and Humphreys, 2010; Humphreys et al., 2013) are adopted here. This is mainly because of the small sample of children compared to the ASHRAE database, and limited indoor operative temperature changes during the survey period.
In this study, the comfort temperature for each individual TSV is calculated based on Eq.1 using various values of ‘G’. For the purpose of the sensitivity analysis, values of Griffith constant are taken as 0.5 and 0.4 (Nicol and Humphreys, 2010), 0.29 based on δPMV/δT_{op} (de Dear et al., 2013), and 0.23 based on δPMV/δT_{op} from data obtained in this study. A suitable measure of the outdoor temperature and the optimum value of α should be obtained using data from the children’s thermal comfort survey to correlate with the calculated value of neutral temperature. Different values of α were employed to calculate the running mean of outdoor temperature, using Eq.2, ranging between 0.33 and 0.90 similar to values used in the analysis of the SCATs database (McCartney and Nicol, 2002); each value suggests different durations of adaptation (Table 2). Prevailing mean 7-days, daily and monthly mean temperatures are included in the analysis for comparative purposes (Table 3).

Table 2 summarizes the sensitivity analysis of chosen values of G and α as described above. It includes the correlation coefficient (r) between the exponentially weighted running mean outdoor temperatures resulting from different values of α and the comfort temperatures calculated from children’s TSVs using the data from all sample schools combined. It should be noted that all reported values are statistically significant (P<0.001). Table 2 suggests that the correlation between the comfort temperature and the outdoor running mean temperature for all values of G is strongest when α=0.45. However, for each value of G, the values of correlation coefficients are not very sensitive to the values of α. As depicted from the table, G=0.5 appears to be the optimal value of G for the sample children; the higher values of the Griffiths constant provide the larger correlation coefficients. This is likely explained by the fact that occupants’ comfort temperature derived from this value of G is related to the operative temperature, and that operative temperature correlates to the outdoor temperature in naturally ventilated buildings (Nicol and Humphreys, 2010).

<table>
<thead>
<tr>
<th>G</th>
<th>α=0.33</th>
<th>α=0.45</th>
<th>α=0.65</th>
<th>α=0.7</th>
<th>α=0.8</th>
<th>α=0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>λ=1</td>
<td>λ=1.3</td>
<td>λ=2</td>
<td>λ=2.3</td>
<td>λ=3.5</td>
<td>λ=6.9</td>
</tr>
<tr>
<td>0.50</td>
<td>0.355</td>
<td>0.363</td>
<td>0.361</td>
<td>0.360</td>
<td>0.354</td>
<td>0.347</td>
</tr>
<tr>
<td>0.40</td>
<td>0.225</td>
<td>0.231</td>
<td>0.230</td>
<td>0.231</td>
<td>0.227</td>
<td>0.223</td>
</tr>
<tr>
<td>0.29</td>
<td>0.061</td>
<td>0.070</td>
<td>0.067</td>
<td>0.070</td>
<td>0.068</td>
<td>0.067</td>
</tr>
<tr>
<td>0.23</td>
<td>n.s</td>
<td>n.s</td>
<td>n.s</td>
<td>n.s</td>
<td>n.s</td>
<td>n.s</td>
</tr>
</tbody>
</table>

a: G = Griffiths constant  
b: T_{rm} = Exponentially weighted outdoor running mean temperature  
c: Values of Griffith constant are taken based on Nicol and Humphreys (2010)  
d: Based on δPMV/δT_{op} taking data from SCATs database (de Dear, 2011; de Dear et al., 2013).  
e: Based on δPMV/δT_{op} taking data from the sample schools

In addition to occupants’ adaptive behaviour, outdoor running mean temperature could reflect the effects of the building fabric on the operative temperature (Nicol and Humphreys, 2010). According to Humphreys et al. (2015, p.306) the value of α is an indicator of “the thermal inertia of the building together with the delayed behavioural responses of the occupants to temperature changes within the building”. Thermal inertia decreases the temperature swings and leads to some time-lag between the indoor and outdoor environment (Nicol and Humphreys, 2010). Due to the effect of building thermal inertia on the optimal value of α, more study in both medium and light-weight schools and
within an expanded range of indoor and outdoor temperature is desirable to draw a conclusion on the appropriate value of $\alpha$ for children.

Table 3 compares different metrics of the outdoor temperature. The optimum value of $G=0.5/K$ is selected to calculate thermal neutrality for each individual student as explained above. Children’s comfort temperatures are regressed against various measures of the outdoor temperature including monthly mean, daily mean, prevailing mean 7-days, and running mean outdoor temperature where values of $\alpha$ vary between half-life ($\lambda$) of about one day (0.33) and seven days (0.90). Coefficients of determination ($r^2$) and regression coefficients are presented in Table 3.

As inferred from this table the maximum variance of comfort temperature explained by the outdoor climate occurs when running mean outdoor temperature with $\alpha=0.45$ is used. It indicates a period of about three days for children’s adaptation to outdoor temperature variation. However, it should be noted that the coefficient of determination ($r^2$) is not very sensitive to the values of $\alpha$. The coefficient of determination using $\alpha=0.45$ is just 0.007 higher than that when the recommended value of $\alpha$ for adults ($\alpha=0.80$) is used. Similarly, the increment in $r^2$ over that obtained when $\alpha=0.65$ or $\alpha=0.70$ is negligible. As de Dear (2011) noted, this increment may not be statically significant.

Table 3. Comparison of different metrics of the outdoor temperature using G constant=0.5/K

<table>
<thead>
<tr>
<th>Metric of outdoor temperature</th>
<th>$b^*$</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly mean</td>
<td>1.426</td>
<td>0.130</td>
</tr>
<tr>
<td>Daily mean on which the survey took place</td>
<td>0.291</td>
<td>0.119</td>
</tr>
<tr>
<td>Prevailing mean 7-days</td>
<td>0.394</td>
<td>0.115</td>
</tr>
<tr>
<td>$T_{rm}$: $\alpha = 0.90$ (2$\lambda \sim$ 14days)</td>
<td>0.552</td>
<td>0.121</td>
</tr>
<tr>
<td>$T_{rm}$: $\alpha = 0.80$ (2$\lambda \sim$ 7days)</td>
<td>0.328</td>
<td>0.125</td>
</tr>
<tr>
<td>$T_{rm}$: $\alpha = 0.70$ (2$\lambda \sim$ 5days)</td>
<td>0.276</td>
<td>0.130</td>
</tr>
<tr>
<td>$T_{rm}$: $\alpha = 0.65$ (2$\lambda \sim$ 4day)</td>
<td>0.258</td>
<td>0.130</td>
</tr>
<tr>
<td>$T_{rm}$: $\alpha = 0.45$ (2$\lambda \sim$ 3day)</td>
<td>0.246</td>
<td>0.132</td>
</tr>
<tr>
<td>$T_{rm}$: $\alpha = 0.33$ (2$\lambda \sim$ 2day)</td>
<td>0.234</td>
<td>0.126</td>
</tr>
</tbody>
</table>

*: Regression coefficient of individual student’s comfort temperature (G=0.5) on outdoor temperature

5.3.2 Regression equation between children’s indoor comfort and outdoor climate

Two methods are employed to establish adaptive comfort equations for the sampled children as summarized in Table 4: regressing children’s mean comfort temperature per survey on the running mean of outdoor temperature with the optimum value of the Griffiths constant and $\alpha$ (G=0.5, $\alpha=0.45$), and with the same value of G and the recommended value for $\alpha$ of 0.80 (Humphreys et al., 2015; Humphreys et al., 2013).

The adaptive comfort equation was also derived based on the methods used in ASHRAE RP-884 where neutral temperature in each building is derived from regression analysis of the thermal sensation in relation to the operative temperature. However, regressing neutral temperatures obtained for each investigated school, from the linear regression model of the mean TSV against $T_{op}$, on the prevailing outdoor temperature failed to reach statistical significance ($p$-value>0.05). This is more likely because neutrality was derived from a small sample of schools. In other words, the sample size was not large enough to yield a robust and accurate relationship between school’s indoor comfort temperature and the outdoor climate. More observations from several schools would be desirable to better understand the relationship between neutral temperature and the outdoor climate when school’s comfort temperature is derived from the regression model.
For comparative purposes, Table 4 includes adaptive comfort equations outlined in Humphreys et al. (2015), ASHRAE 55 (2013) and EN15251 (2007) adaptive comfort standards, and regression equation proposed for adults from the same cultural background (Heidari, 2014). According to Heidari (2014, p.114) $\alpha=0.80$ is a reasonable value for adult subjects in Iran. Children’s comfort equation based on children’s individual responses in a medium-weight school in the UK is also included in Table 4, where $T_{rm}$ is calculated from a value of $\alpha=0.80$ (Teli et al., 2015).

Comparison of the methods used to obtain adaptive comfort equation from children’s mean comfort temperature per survey indicates that regression equation using Griffiths method with value of $G=0.5$, and $\alpha=0.45$ provides a shallower regression slope and a higher coefficient of determination ($P<0.0001, r^2=0.583$) than the same method using $\alpha=0.80$ ($P<0.0001, r^2=0.556$). As noted previously, despite a small difference between the $r^2$ statistics, $\alpha=0.45$ seems to be suitable for use in the investigated schools. A similar result has been found when children’s comfort temperature was calculated from each individual comfort vote and regressed against the outdoor running mean temperature.

Table 4. Adaptive comfort equation for different characterization of the outdoor temperature

<table>
<thead>
<tr>
<th>Database</th>
<th>Adapative comfort equation</th>
<th>Metrics of climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humphreys et al. (2015)</td>
<td>$T_{comf} = 0.53T_{rm} + 13.8$</td>
<td>$T_o$</td>
</tr>
<tr>
<td>ASHRAE55 (2013)</td>
<td>$T_{comf} = 0.31T_{pma(out)} + 17.8$</td>
<td>$T_{pma(out)}$</td>
</tr>
<tr>
<td>EN15251 (2007)</td>
<td>$T_{comf} = 0.33T_{rm} + 18.8$</td>
<td>$T_{rm}$ $\alpha=0.80$</td>
</tr>
<tr>
<td>Heidari (2014)</td>
<td>$T_{comf} = 0.36T_{rm} + 17.6$</td>
<td>$T_{rm}$ $\alpha=0.80$</td>
</tr>
<tr>
<td>Teli et al. (2015)</td>
<td>$T_{comf} = 0.19T_{rm} + 19.1$</td>
<td>$T_{rm}$ $\alpha=0.80$</td>
</tr>
<tr>
<td>This study-warm season</td>
<td>$T_{comf} = 0.34T_{rm} + 17.6$</td>
<td>$T_{rm}$ $\alpha=0.80$</td>
</tr>
<tr>
<td>This study-warm season</td>
<td>$T_{comf} = 0.25T_{rm} + 19.1$</td>
<td>$T_{rm}$ $\alpha=0.45$</td>
</tr>
</tbody>
</table>

- $T_o$: Prevailing mean outdoor temperature. In case of running mean temperature $\alpha=0.80$.
- $T_{pma(out)}$: Prevailing mean outdoor temperature. In case of running mean temperature: $0.6<\alpha<0.9$
- $T_{rm}$ :Weighted running mean of outdoor temperature
- $T_{comf}$: calculated $T_{comf}$ from all individual responses ($r^2=0.029$)
- $T_{comf}$: calculated $T_{comf}$ per survey based on Griffiths method ($\alpha=0.80$ - $r^2=0.556$)
- $T_{comf}$: calculated $T_{comf}$ per survey based on Griffiths method ($\alpha=0.45$ - $r^2=0.583$)

The resulting regression equation with the value of $\alpha=0.45$ in Table 4, was solved to find the operative temperature range that would be thermally neutral for the sampled children. It is revealed that the mean indoor comfort temperature per survey varies between 23.2°C and 25.2°C when the outdoor $T_{rm}$ ranges between 16.5°C to 24.2°C during the survey period. The neutral temperature of 23.2°C at the outdoor running mean temperature of 16.5°C is the same as the comfort temperature calculated from the weighted regression model of the mean TSV as a function of the classroom operative temperature binned into 0.5°C intervals ($TSV_{(mean)} = -6.251 + 0.268 \times T_{op}$, $r^2=0.82$, $P<0.001$). The adaptive comfort equation suggests that the sampled children were capable of tolerating indoor temperatures up to 25.2°C when the outdoor running mean temperature was high ($T_{rm}=24.2^\circ C$); this is 2 °C higher than predicted neutral temperature from the above equation.

Table 4 implies that children’s adaptive comfort equation using Griffiths method and $\alpha=0.80$ is remarkably similar to that of adults from the same cultural background over hot conditions (Heidari, 2014, p. 109), although statistically a less reliable correlation compared to the former method when a value for $\alpha$ of 0.45 is used. Despite different indices used to represent outdoor climate, the comparison between the neutral temperatures derived for the sampled children and those predicted by the ASHRAE 55 adaptive equation as a function
of the outdoor running mean temperature provides similar results. As can be seen from Table 4, the gradient of children’s regression equation when \( \alpha=0.45 \) is considerably shallower than those of adults in the EN 15251(CEN, 2007), and other adult-based studies (Heidari, 2014; Humphreys et al., 2015). This could be an artefact of the different measures of outdoor climate used in this study, \( \alpha=0.45 \). The shallower regression gradient may indicate a weaker relationship between the children’s neutral temperature and the outdoor temperature change. It can be noticed that in the same climate the sampled children feel comfortable at cooler temperatures than adult subjects. At higher outdoor temperatures, sampled children in the investigated schools showed up to 2°C lower neutral temperatures than adults in office buildings. Similar to the results of this study, Teli et al. (2015) found a shallower regression slope and a weaker climatic adaptation in the medium-weight schools compared to adults; however, a different measure of outdoor climate was used (\( \alpha=0.80 \)).

In Humphreys et al. (2015, p.309) the scatter of the points around the regression line relating comfort temperature to the prevailing mean outdoor temperature is not a random error but rather indicates real differences between the neutral temperatures of subjects at any prevailing mean outdoor temperature. According to the same study a temperature band is preferable to a line for representing the relationship between comfort temperature and prevailing mean outdoor temperature. However, this band may not be identical for children and adults based on Teli et al. (2015). Figure 2 shows the scatter plot of the comfort temperature per survey against the exponentially weighted running mean outdoor temperature when \( \alpha=0.45 \) \((r^2=0.58, P<0.0001)\). The band consists of 95% of the neutral temperatures per survey. The comfort temperature band seem to be narrower in case of sample children than that of adults as obtained in Humphreys et al. (2015, p.308). It can be inferred from Figure 2 that the upper limit of comfort temperature is lower for children, which is critical for classroom’s thermal performance during warm days of the school year.

![Figure 2. The classrooms’ neutral temperatures (°C) per survey against the running mean outdoor temperature (°C)](image)

### 6 Conclusion

This paper investigates the methods used to develop the adaptive thermal comfort equation relating children’s neutral temperature to the outdoor climate. It draws on a total of 811 thermal comfort study responses gathered from naturally ventilated classrooms in 4 school buildings during the warm season in Iran. The differences between the methods used to
develop adaptive comfort equations in ASHRAE55 (2013) and EN15251 (2007) standards are explained. The principal stages in the construction of the adaptive comfort equation based on children’s responses from thermal comfort field survey are justified. Correlation analysis is performed to show the sensitivity of the derived equation to the choices made at each stage of analysis. The neutral temperature is obtained using various methods and a suitable metric for climate axis is defined from the survey data. The sensitivity of the results to the values chosen for the Griffiths constant and ‘α’ are examined. From the analysis result it seemed appropriate to choose 0.5 as the Griffiths constant for the sampled children; however, the need for a validation study is proposed. The analysis of data presented in this paper shows that the preferred metric for the prevailing outdoor temperature is the exponentially weighted running mean outdoor temperature, with a value of α in the region of 0.45. A running mean with an α of 0.45 seems to better correlate with children’s comfort temperature which means that the range of running mean temperature is greater for children than for adults. This finding suggests that the children or their parents are responding to changes in the weather more quickly than adults (Nicol and Humphreys, personal communication, June 2015).

The adaptive comfort model derived for the sampled children has a shallower regression slope compared to adults’ adaptive equations. The smaller regression coefficient may be explained by different explanatory variable, running mean temperature, in the two cases. Moreover, it may suggest that the children are adapting to the outdoor changes more quickly, but less completely than adults would. In this investigation, children’s neutral temperatures ride lower than the ASHRAE 55 and EN 15251 models for NV buildings. At higher outdoor temperatures, the upper limit of indoor comfort temperature for children is up to 2°C lower than that for adults. 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. The results presented in this study contribute to a growing understanding of adaptive thermal comfort for children in school buildings. Further work in a larger sample of school buildings with different construction types, and reflecting different cultures and climates may improve the expression of outdoor temperature and comfort indoors for children which is important to understand the most logical explanation for different pattern of children’s adaption to outdoor climate.

References


