AUTHORS SUBMISSION VERSION

Please cite the RPG version of this paper using the following DOI:

10.1080/09613218.2015.998951

Journal: Building Research & Information

Routledge, Taylor & Francis Group

Investigating the principal adaptive comfort relationships for young children

Despoina Teli, Patrick A. B. James & Mark F. Jentsch

Published online: 15 Jan 2015

Investigating the principal adaptive comfort relationships for young children

Despoina Teli[1], Patrick A.B. James[1] , Mark F. Jentsch[2]

[1] *Sustainable Energy Research Group, Faculty of Engineering and the Environment, University of Southampton, Southampton SO17 1BJ, UK*
E-mails: D.Teli@soton.ac.uk, P.A.James@soton.ac.uk

[2] *Urban Energy Systems, Bauhaus-Universität Weimar, 99423 Weimar, Germany*
E-mail: mark.jentsch@uni-weimar.de

Abstract

Thermal comfort surveys in school classrooms suggest that children have different thermal preferences to adults. This implies a need to revisit the current adult-based thermal comfort models. This paper investigates the principal adaptive comfort relationships which form the basis of adaptive comfort theory, using 2,693 pupil thermal sensation responses and measured classroom temperatures from surveys in two naturally ventilated school buildings. The data were examined in two steps: firstly, each survey set; obtained over 1-day visits to the schools; was examined in order to derive the relationship between indoor temperature change and comfort vote with minimum impact of adaptation. Secondly, the dataset was investigated over the entire survey period, in relation to the weather experienced by the pupils in order to estimate their time for adaptation to outdoor temperature changes. The analysis shows that the basic adaptive comfort relationships are valid for children. However, a difference was found for the correlation coefficients of the comfort temperature to the outdoor running mean temperature between the schools, and a mismatch between their adaptive comfort equations. It is proposed that the difference in the consistency of the weather during the tests is the main reason for this discrepancy.

Keywords: adaptive comfort, children, Griffiths constant, natural ventilation, school buildings, school classrooms, thermal comfort

1. Introduction

The adaptive thermal comfort model is based on extensive fieldwork mainly in office environments, which led to the understanding of the adaptive relationship between climate and comfort (Nicol et al., 2012). Recent research investigated pupils' thermal sensation in UK school classrooms and found discrepancies between children's thermal responses and the predictions using adaptive comfort algorithms which were derived from surveys with adults (Teli et al., 2012, Teli et al., 2013). The differences found cover a range of parameters, such as thermal sensation, feeling of overall comfort and tiredness, long-term and immediate adaptive behaviour and interpersonal differences (Table 1).

Differences were also found between the observed thermal sensation of children and that predicted for adults under the same conditions in recent field studies in Australia (de Dear et al., 2014), Iran (Haddad et al., 2014) and in Chile (Trebilock and Figueroa, 2014). Furthermore, it has been shown that the existing overheating guidelines for schools in the UK: Building Bulletins 87 and 101 (DfES, 2003, DfES, 2006) and the new guidelines proposed by the Department for Education (Johnston and Partners, 2012) do not reflect teachers' views on pupils' comfort (Montazami and Nicol, 2013). This is important since uncomfortable classroom conditions have been found to influence the health and schoolwork performance of children (Mendell and Heath, 2005, Wargocki and Wyon, 2007). This suggests that a better understanding of children's thermal perception is required, necessitating a revisiting of current thermal comfort modelling approaches. This study focuses on adaptive comfort models, investigating pupils' thermal adaptation in naturally ventilated classrooms outside of the heating season.

1.1. Adaptive comfort models

There are two adaptive comfort models which have been developed to relate the occupant comfort temperature to the outdoor climate using data from thermal comfort field studies. These are the European adaptive model based on the SCATs database of field studies (McCartney and Nicol, 2002), used in the European standard EN 15251 (CEN, 2007) and expressed by equation (1), and the worldwide ASHRAE adaptive model (De Dear et al., 1997), used in ASHRAE standard 55 (ASHRAE, 2013), which is expressed by equation (2).

$$T_{comf} = 0.33T_{rm} + 18.8 \qquad (1)$$

$$T_{comf} = 0.31T_{\alpha,out} + 17.8 \qquad (2)$$

Where T_{comf} is the comfort temperature, T_{rm} the exponentially weighted running mean of the outdoor temperature and $T_{\alpha,out}$ the 'prevailing mean outdoor temperature', which has replaced in ASHRAE-55 the previously used "average of the mean monthly minimum and maximum daily air temperature for the month in question" (ASHRAE, 2013).

For the derivation of the adaptive equations (1) and (2), two constants have been used, corresponding to the main adaptive comfort relationships. The Griffiths constant expresses the linear relationship between comfort vote and indoor operative temperature (Humphreys et al., 2007), and the 'running mean constant' (α) reflects the time it takes for people to adapt to outdoor temperature changes (McCartney and Nicol, 2002). The values used for these constants were derived from the analysis of the two large databases of thermal comfort field data, the worldwide ASHRAE database (de Dear and Brager, 1998) and the European SCATs database (McCartney and Nicol, 2002), mainly obtained in offices with adult subjects.

The way the 'neutral' or 'comfort' temperature is estimated from field surveys differs between the two adaptive comfort approaches, mainly due to different sample sizes (de Dear et al., 2013). The ASHRAE database allowed for statistically significant regression analysis at the individual building level, whilst in the case of the SCATs database the so-called Griffiths method has been used, which can address cases of small samples of comfort votes. In this paper, the method used in the SCATs database has been applied as it was considered to be more appropriate for the school survey sample sizes and for consistency with the European EN 15251 model.

1.2. Griffiths constant

The Griffiths constant represents the relationship between thermal sensation and temperature, with the assumption that no adaptation has occurred (Nicol and Humphreys, 2010). It is the regression coefficient of comfort vote to operative temperature, when only the operative temperature is assumed to be changing and therefore reflects people's sensitivity to temperature changes. The estimation of this regression coefficient would require conditions which cannot be achieved in field studies as it is not possible to isolate the operative temperature as the only parameter influencing occupant thermal sensation. Therefore an optimum value for this coefficient has been estimated ('G'=0.5) (Humphreys et al., 2007), using data from the extensive SCATs (McCartney and Nicol, 2002) and ASHRAE (De Dear et al., 1997) databases of field studies. Further analysis was conducted in 2010, using a 'day-survey' methodology (Humphreys et al., 2010). This 'day-survey' methodology is also used in this paper.

For setting up the adaptive comfort equation (1), the Griffiths constant 'G' is used in equation (3), which relates people's comfort temperature T_{comf} to the operative temperature T_o and their reported thermal sensation (Humphreys et al., 2007). The subjects' thermal sensation is expressed in the form of their comfort vote (TSV: Thermal Sensation Vote) on a 7-point thermal sensation scale, such as the ASHRAE scale (hot, warm, slightly warm, neutral, slightly cool, cool, and cold). The calculated comfort temperatures are then used in the development of the adaptive relationship between the comfort temperature and the outdoor climate [equation (1)].

$$T_{comf}=T_o-TSV/G \qquad (3)$$

1.3. Running mean constant 'α'

The main principle of adaptive thermal comfort is to relate the comfort temperature to the outdoor climate. Initially, this relationship was expressed using the monthly mean of the outdoor temperature (Humphreys, 1978) but this approach did not take into account people's thermal experience, which suggests that recent weather conditions are more influential than earlier weather conditions experienced (CIBSE, 2006). Therefore, the running mean T_{rm} of the outdoor temperatures was chosen as a suitable outdoor climate index, weighted according to distance in the past. This is based on the adaptive comfort approach's assumption that comfort temperature is influenced more by recent experiences (Olesen, 2007). T_{rm} is calculated using equation (4) (Nicol et al., 2012).

$$T_{rm}=(1-\alpha)\cdot\{T_{ed-1}+\alpha\cdot T_{ed-2}+\alpha^2\cdot T_{ed-3}\ldots\} \qquad (4)$$

Where:

- T_{rm}= Exponentially weighted running mean of the outdoor temperature
- T_{ed-1}=Daily mean outdoor temperature for the previous day
- T_{ed-2},…= Daily mean outdoor temperature for the day before and so forth

The running mean constant α can take values between 0 and 1. It is essentially a time constant which "defines the quickening response of the running mean to changes in the outside temperature" (McCartney and Nicol, 2002). Its value, α=0.8, was estimated using survey data and corresponds to the strongest correlation between the respondents' calculated comfort temperature [equation (3)] and the outdoor running mean (Humphreys et al., 2007). Feeding into the equation which relates the comfort temperature to the outdoor temperature [equation (1)], 'α' is an indicator of the time it takes for people to adapt to outdoor climate variations.

The half-life λ of an exponentially weighted running mean temperature has been defined and can be calculated using equation (5) (Nicol and Humphreys, 2010). For α=0.8 the equation gives λ=3.5 days, which means that it takes about a week for the occupants to adapt to a step-change (increase or decrease by 1 ^{o}C) of the mean outdoor temperature.

$$\lambda=0.69/(1-\alpha) \qquad (5)$$

Humphreys et al (2013) argued that there is potentially a link between the value of α and the building's thermal inertia, suggesting that buildings with different thermal capacity may have different values of 'α'. This is investigated in the current paper, using two case study school buildings, which differ mainly in their thermal mass. The case study buildings represent two of the main school building types in the UK: (i) a 'medium/heavy' weight Victorian school and (ii) a Post World War II low thermal mass school (Harwood, 2010).

In summary, the values of both constants 'G' and 'α' were determined using adults' responses from the two key adaptive comfort databases of field studies (de Dear and Brager, 1998, McCartney and Nicol, 2002). Given the different thermal perception of children found from pupil surveys (Mors et al., 2011, Teli et al., 2012, Teli et al., 2013, de Dear et al., 2015, Haddad et al., 2014, Trebilock and Figueroa, 2014), these values need to be compared against children's responses. The analysis presented in this paper helps to understand the thermal response of pupils to indoor temperature changes through 'day-survey' analysis for the estimation of 'G', assuming that no or minimal adaptation has occurred. Pupils' thermal response rate to the outdoor climate is examined through exploration of the running mean constant 'α' and comparison of the adaptive comfort equations.

1.4. Adaptive comfort relationships in studies with young children

There are a number of studies that investigated children's thermal comfort conditions in school classrooms, covering a range of age groups. A rather small number of studies have focused on primary school children (Humphreys, 1977, Mors et al., 2011, Teli et al., 2012, De Giuli et al., 2012, Haddad et al., 2014, Trebilock and Figueroa, 2014) compared to secondary school children (Auliciems, 1969, Auliciems, 1973, Humphreys, 1973, Kwok and Chun, 2003, Wong and Khoo, 2003, Corgnati et al., 2007, Hwang et al., 2009, Al-Rashidi et al., 2009, Liang et al., 2012) or both primary and secondary combined (Auliciems, 1975, de Dear et al., 2015, d'Ambrosio Alfano et al., 2013). This analysis focuses on primary school children, as differences between primary and secondary could impact on children's thermal adaptation. Primary school children remain in a single classroom, whilst secondary school children move class with the topic, throughout the day. Furthermore, the activities and behaviour of secondary school children are closer to adulthood than those of young children aged 7-11 years old, and could therefore 'smoothen' potential differences found.

Table 2 lists thermal comfort studies which included primary school children and were conducted outside the heating season, for comparison in relation to the adaptive comfort relationships. It can be seen that from the few studies undertaken, only a small number included the calculation of the children' comfort (neutral) temperature and the regression coefficient of the thermal sensation vote to the operative temperature, whilst none of the surveys investigated the constants 'G' and 'α' and whether they reflected children's responses. Possible reasons for this may be a small sample size or a small range of indoor and outdoor temperatures. As can be seen in Table 2, most studies were conducted over a few days or weeks, which is not adequate for an investigation of the response to changes in the mean outdoor temperature and the value of 'α'. The period of three months of the surveys presented in this paper provides the opportunity for a preliminary evaluation of the applicability of the currently used values for young children.

2. Methods

The data used in this paper was collected during thermal comfort surveys in two naturally ventilated junior schools in Southampton on the South coast of England. The investigation included a 1970s light-weight and a Victorian medium thermal mass building, which were surveyed in 2011 and 2012 respectively. The surveys included questionnaires[1] tailored towards children and measurements of the key environmental parameters during the surveys.

2.1. Case study schools

The case study junior school buildings have rather different building typologies, as shown by the sketches in Figure 1. Building A is a typical example of a lightweight 1970s school in the UK, with steel frame construction and pre-fabricated concrete panels. The school has 8 classrooms and, in 2011, had around 240 enrolled pupils aged 7-11 in Years 3 to 6. The surveys were undertaken outside the heating season, from April to July 2011. School building B was surveyed one year later, from April to July 2012. This building was constructed in 1884, following typical Victorian school construction methods. It has 11 classrooms and had around 400 enrolled pupils aged 5-11 in 2012. The surveys took place in all classrooms of the two schools.

The two school buildings mainly differ in their thermal capacity. The external solid masonry wall of the Victorian school has a κ-value, i.e. thermal capacity per m^2 of wall of $\kappa = 169\ kJ/m^2K$, whilst the lightweight building's external walls have an average κ-value of $\kappa = 55\ kJ/m^2K$ (Teli et al., 2014). This means that the lightweight building has a quicker response to outdoor temperature changes compared to the Victorian building.

The surveys in both schools were scheduled to take place approximately every two weeks. Each classroom of school A was surveyed 6 times and, therefore, 48 surveys were carried out in total. In school B, 69 surveys were carried out. An average of 26 pupils responded to the questionnaire in each survey.

2.2. Thermal comfort surveys

For reasons of consistency, the same methods and equipment were used in both school studies. The survey procedure, questionnaire type and data processing details are summarised below:

- A questionnaire adapted for children was used, based on teachers' feedback (Teli et al., 2012). The questionnaire included questions about the respondent's thermal sensation vote (TSV) and thermal preference vote (TPV), the feelings of overall comfort and tiredness, whether the respondent was wearing a jumper (pullover) and the activity undertaken prior to the questionnaire. The surveys were taking place at least 15 minutes after the breaks, during class activities.
- The responses were checked for inconsistency. Responses with significantly conflicting votes (thermal sensation in clear contrast to thermal preference)

were excluded from the analysis (Teli et al., 2012, Teli et al., 2013). Previous investigations of the inconsistent cases showed no association of their occurrence to familiarity of pupils with the TSV and TPV questions or to their age group (Teli et al. 2013). In the entire sample, there were 39 missing TSV and 4 missing TPV votes respectively. It appears that between the two, the thermal sensation question was more difficult than the thermal preference question for some pupils to respond to.

- Environmental parameters (air speed, radiant temperature, air temperature, relative humidity) were measured during the surveys, following the standards of ISO 7726 "Ergonomics of the thermal environment- Instruments for measuring physical quantities" (CEN, 2001). CO_2 concentration was also measured, using an infrared absorption gas analyser.

Based on the small number of missing responses and inconsistent cases, the questionnaire can be considered as appropriate for junior school children (Teli et al., 2013). However, it should be highlighted that more research is required in order to develop a holistic methodology for surveying children. The methods currently used in thermal comfort research with young children presented in Table 2 are based on or adapted from those developed for adults. The extent to which children comprehend the thermal sensation scales and the role of their cognitive development in responding to thermal comfort surveys have not, however, been thoroughly investigated to date (Haddad et al., 2012).

3. Results

For the thermal comfort calculations presented in this paper, the pupils' thermal sensation votes (TSV) and the operative temperatures (T_o) measured during the surveys were used. This allows a comparison of the regression coefficients which were used for deriving the values of the Griffiths constant (G=0.5) and of the running mean constant (α=0.8) with the values calculated based on the thermal comfort school field survey data.

3.1. Relationship between comfort vote and operative temperature

The estimation of the regression coefficient (constant 'G') follows the 'day-survey' method of Humphreys et al (Humphreys et al., 2013). This includes the following:

- Calculation of the variables dTSV and dT_o for each response on a single day (day survey), where dTSV is the difference of the subjective thermal sensation vote (TSV) and the mean thermal sensation vote for the 'day-survey' ($TSV_{(day\ mean)}$) and dT_o is the difference of the operative temperature during the survey (T_o) and the mean operative temperature on that day ($T_{o(day\ mean)}$).
- Regression analysis of dTSV on dT_o of all the 'day-surveys'.

This process leads to a weighted average of the regression coefficient for all the 'day-surveys', which can provide a more reliable statistic than the analysis of small 'day-survey samples' (Humphreys et al., 2013). Following this method, for each day visit to the schools, the dTSV and dT_o for each thermal sensation response were calculated. Regression analysis was conducted in the SPSS statistical package, for both schools, combined and separately. A total of 26 day surveys were used. The calculated regression coefficients are statistically significant ($p<0.001$). The regression line of dTSV on dT_o for the entire dataset with the 95% confidence intervals can be seen in Figure 2. Each data point on the graph represents the dTSV for a single subjective response and the trend line resulted from the regression analysis of dTSV on dT_o for all 2,693 responses on all the days of the study. The narrow intervals suggest that the regression coefficient can be considered as reliable.

The regression coefficients are presented in Table 3, in comparison to the regression coefficients for the naturally ventilated buildings (NV) only of the SCATs and ASHRAE databases of thermal comfort field studies, as previously determined (Humphreys et al., 2010). The value of the regression coefficient for both schools is 0.313 with a standard error of 0.030, which is very similar to the values from the SCATs and ASHRAE databases. The variance of the operative temperature is also similarly low.

The common value of Griffiths constant G=0.5 was derived from the values of the SCATs and ASHRAE databases, following correction to account for errors in the predictor variable (operative temperature) due to its low variance (Humphreys et al., 2010). The correction of the regression coefficient can be assumed to also apply to the schools investigated here since the variance of the operative temperature is similarly low and, therefore, only the calculated regression coefficients of Table 3 are considered.

Looking at the results of each school separately, the light-weight school appears to have a lower variance of the operative temperature, which would not be expected based on the greater temperature fluctuation these buildings normally experience. The difference is probably related to the complex layout of the medium-weight school, with classrooms on several different orientations (NW, NE, SE, SW) and levels (ground and first floor classrooms). The surveys were conducted in different classrooms over a single day. In the light-weight school, the conditions were more uniform in this respect, as the classrooms face only two orientations, NE and SE. Furthermore, in the light-weight school the day-surveys were always conducted on one floor level (i.e. ground or first floor), minimising the impact of this parameter on temperature fluctuations.

As can be seen in Table 3, there is a difference of approximately 0.2 between the regression coefficients of the two schools based on the day-surveys. However, the regression coefficient of the thermal sensation vote to the operative temperature for the entire survey period was found to be identical in both schools, equal to 0.27. This suggests that the pupils' sensitivity to indoor temperature variation over the entire survey periods was similar, but over a day pupils in the light-weight school were more tolerant to temperature changes than pupils in the Victorian school. Where similar differences were found between naturally ventilated and air-conditioned buildings, it was suggested that people in naturally ventilated buildings were more tolerant because they are used to the temperature variations they experienced (de Dear and Brager, 1998, de Dear and Brager, 2002). A similar approach could be considered for buildings with different thermal mass, as occupants in low thermal mass buildings can be expected to experience higher diurnal temperature variations compared to occupants in medium to high thermal mass buildings. This assumption needs to be further investigated as the number of the day-surveys examined here is small (total of 26) to allow for final conclusions. However, the results for the combined school dataset showed a good agreement of the calculated day-survey regression coefficient with those calculated from surveys with adults.

3.2. Relationship between comfort temperature and outdoor climate

The comfort temperature was calculated for each thermal sensation vote using equation (1) and a value of G=0.5, based on the analysis highlighted in the previous section. The running mean of the outdoor temperature was calculated using equation (4). The outdoor daily mean temperatures were derived from hourly data from the National Oceanographic Centre in Southampton (NOCS), which is located approximately 3km away from both schools. The running mean of the outdoor temperature was calculated for different values of 'α', ranging from 0.33 to 0.99, which correspond to different durations of adaptation, as can be seen in Table 4 (McCartney and Nicol, 2002). This is based on the values used in the analysis of the European SCATs database of field studies, as highlighted by Figure 3.

The calculated comfort temperatures from the pupils' thermal sensation votes were correlated with the exponentially weighted outdoor running mean for the different values of 'α'. Figure 4 shows the resulting correlation coefficients... As can be seen in Figure 4, using the data from both schools combined, the correlation coefficients generally agree with the UK trend from the SCATs field data, except for the big drop for α=0.99 (Figure 3), which does not appear in the school results (Figure 4). Based on the entire school dataset, the strongest correlation occurs for α=0.8 and starts to decline smoothly from a value of 0.9, but overall the weighting does not appear to be critical for the correlation. Overall, the highest correlation for a value of α=0.8 agrees with analyses of large datasets of thermal comfort surveys (Humphreys et al., 2013) and therefore it can be considered appropriate for use in schools, indicating a duration of approximately one week for adaptation to a change in outdoor temperature. However, it should be highlighted that the difference between the correlation coefficients is rather small.

Looking at the school types separately in Figure 4, there is a strong difference. The correlation of the comfort temperature with the outdoor running mean temperature is overall stronger in the light-weight school compared to the medium-weight school, which can be explained by the quick response of the building fabric of the light-weight school to outdoor temperature variations. The indoor environment that occupants experience is more strongly coupled to the outdoor temperature and therefore occupant comfort is strongly affected by the outdoor climate. By contrast, the medium thermal mass fabric of the Victorian school isolates the occupants from outdoor temperature variations by creating a more stable indoor thermal environment.

As can be seen in Figure 4, above a value of α=0.8 there is almost no change in the correlation coefficient in the case of the light-weight school, whilst in the case of the medium-weight school there is a clear gradual decrease, starting from a value of α=0.45. The flat trend of the correlation in the light-weight school indicates that the weighting of the mean outdoor temperature based on distance from the past is not that critical for the correlation between comfort temperature and outdoor temperature. This suggests that pupils' comfort temperature was similarly influenced by recent and past experiences. In the case of the heavy-weight building, the weighting appears to be important, with recent experiences having a stronger impact on pupils' comfort temperature than past events. This big difference between the schools is likely to be due to the influence of the weather conditions during the surveys which were undertaken in different years. This has resulted in different outdoor running mean temperature profiles, as can be seen in Figure 5. In 2012 the weather was rather unstable, with large drops in temperature during April and a very big spike at the end of May. This instability has completely disappeared in the outdoor running mean profile for α=0.99, whilst it is strongly apparent for α=0.45. Therefore, a stronger correlation with α=45 would be expected, as highlighted in Figure 4. In 2011, there was a gradual increase in the outdoor temperature and overall a more stable weather profile across the survey period. Therefore, the two running mean profiles in 2011 are still reflecting similar weather trends. This could explain the similar correlation coefficients of Figure 4 for the different values of α in the lightweight school surveyed in 2011, compared to the gradual drop highlighted in the Victorian school for higher values of α.

Overall, the analysis suggests that there may be differences in thermal adaptation due to the thermal mass of the buildings and the different weather profiles during the surveys. Comparison of survey data from different construction types across the same time period and hence weather would help to understand these issues better.

3.3. Adaptive comfort equations based on the survey data

Figure 6 shows the comfort temperatures (T_{comf}) of the Victorian and the post-war school survey as well as the EN 15251 comfort temperature line in relation to the outdoor running mean temperature. For 'α', the value of 0.8 was used, based on the fact that for the two schools combined, this was the value that reflected the strongest correlation between comfort temperature and outdoor running mean.

It can be seen in Figure 6 that children in general adapt to the outdoor climate in a different way to adults. The resulting regression lines from both school surveys are lower than the EN 15251 comfort line, confirming results from the field surveys listed in Table 2. Pupils would prefer lower temperatures than predicted using the adaptive comfort equation underlying the EN 15251 building category equations (CEN, 2007). The two school surveys agree in their general outcome that school children have lower comfort temperatures (approximately 2^{o}C lower) than adults in offices.

As can be seen in Figure 6, whilst the comfort temperature regression lines of the two school surveys lie below the EN 15251 line, they do not match well. The regression line of the Victorian school survey has a shallower slope indicating a weaker relationship between the pupils' comfort temperature and the outdoor temperature change, or, in other words, a weaker climatic adaptation, which further highlights the outcome from the comparison of the correlation coefficients between the two schools shown in Figure 4.

The difference between the two comfort equations once again highlights the strong impact of the variability of the weather conditions. The surveys were planned for every other week (whenever possible) in order to keep a well-distributed frequency of the surveys with the aim to capture a gradual climatic adaptation of the pupils. However, it can be seen in Figure 6 that, in the 2012 survey, there is a large gap in outdoor running means between 10.5 and 15.0 ^{o}C. This is due to a period of cool temperatures in 2012, followed by an almost immediate 'hot spell' in the end of May which marked the shift to warmer temperatures (Figure 7b). The sudden shift from rather cool temperatures to a warm period meant that in this year there was less of an opportunity for thermal adaptation as compared to 2011 (Figure 7a), as there was no gradual transition from cold to warm temperatures. This could have led to pupils being less tolerant to higher temperatures in 2012, which is reflected in the lower comfort temperatures for higher ambient temperatures in the Victorian school survey.

The mismatch of the comfort lines shown in Figure 6 highlights that thermal adaptation is a dynamic process which depends on the way and timeframe in which weather changes occur. These parameters are not addressed in Figure 6, where only the relation of the comfort temperature to the outdoor running mean temperature change is illustrated. This outcome suggests that a regression line may not be the most appropriate way to represent the relationship between comfort temperature and outdoor climate, as it appears that the line is sensitive to annual variations as well as variations within the year itself, between for example warm and cold spells. Using a band instead of a line could be more appropriate, which has also been suggested by Humphreys et al (Humphreys et al., 2013), following their observation that the scatter of the data points on graphs relating comfort temperature to the prevailing mean outdoor temperature is not a random error but reflects real differences between comfort temperatures of surveyed subjects. Nevertheless, the above also indicates that such a band would not be identical for adults and children.

4. Conclusions

This paper investigated the basic adaptive comfort relationships for 2 case study naturally ventilated schools, a light-weight post-war and a medium-weight Victorian school. The typical values of the constants 'G' and 'α', used in adaptive comfort models, were compared with values which were derived from thermal comfort surveys conducted in the two junior schools. The European model of the EN 15251 standard was used for comparison, as it has been developed with field data from European countries and therefore was considered more appropriate for the investigated UK sample. The regression coefficients used for the estimation of G=0.5 in previous studies agree well with the combined results for the two school surveys, suggesting that this value can be used in the comfort temperature calculation for children, although this needs further validation. Overall, it appears that, assuming that no or minimal adaptation has taken place, children's response rate to indoor temperature changes can be considered similar to that of adults. However, a difference was identified between the regression coefficients of the two schools based on the day-survey analysis, which could be related to the different diurnal temperature variations experienced in the schools.

In terms of the time it takes for pupils to adapt to a step-change of the mean outdoor temperature, it seems that one week is the most likely duration, which corresponds to a value of 'α'=0.8. However, the difference between the correlation coefficients for different values of 'α' was very small to fully support this finding. Looking at the combined results for the two schools, there is no clear indication of the time it takes for pupils to adapt to changes of the outdoor conditions, making it difficult to establish a fixed appropriate value for 'α' for use with children. Furthermore, the comparison per school survey highlighted a difference in the correlation coefficients for high values of α, which suggests that weather instabilities might influence the correlation of the comfort temperature to the outdoor running mean temperature. Further research is needed to address this issue and investigate ways to integrate such variability in the adaptive comfort equation.

It should be noted that the use of only two schools in this analysis does not provide a complete assessment for the case of school buildings. Furthermore, each pupil only responded once to the questionnaire per 'day-survey'. More responses per 'day-survey' might give a more representative result in terms of thermal response over a day. Finally, for the comparisons in this study the methods and estimates in current literature were used, such as the half-life of the exponentially weighted running mean and the coefficients previously calculated from extensive worldwide field studies. The above limitations suggest that extensive fieldwork in schools is required in order to obtain more reliable data for the estimation and assessment of pupils' adaptive mechanisms.

Overall, the investigation of constants 'G' and 'α' for the case study schools suggests that a better understanding on the basic adaptive relationships for young children in different types of buildings is required. The overall need for further work to define the value of 'α' has also been recently highlighted by Humphreys et al. (2013). In this study, there were differences in the day-survey analysis between the light-weight and medium-weight school which suggest that buildings' thermal capacity is an important parameter potentially affecting occupants' thermal adaptation. The comparison between the comfort temperatures in the two schools and in EN 15251 in relation to the outdoor running mean temperature demonstrated an agreement in their general outcome that school children have lower comfort temperatures (approximately 2 ^{o}C lower) than adults in offices. Furthermore, the comparison between the schools showed a higher sensitivity of the pupils in the Victorian school at high ambient temperatures, compared to those in the post-war school. The sensitivity of the Victorian school pupils was most probably related to the weather conditions during summer 2012, with an extended relatively cool period and a subsequent rapid temperature rise. This means that, in the same climate, weather variability had a strong impact on pupils' thermal adaptation, influencing the time for adaptation and their tolerance to temperature thresholds. This could be critical for regions where weather anomalies are frequent and sharp changes could affect occupant comfort limits. This is particularly important for schools, as children typically spend their morning and lunchtime breaks outdoors, which means that they are highly exposed to weather changes. Furthermore, the findings show that the regression lines relating comfort temperatures to the outdoor climate are sensitive to these anomalies and therefore a temperature band instead of a line could be more appropriate for representing this relationship.

Acknowledgments

The authors would like to deeply thank the teachers and pupils who participated in the surveys. The research was conducted in the Faculty of Engineering and the Environment at the University of Southampton.

References

Al-Rashidi, K. E., Loveday, D. L. & Al-Mutawa, N. K. (2009). Investigating the Applicability of Different Thermal Comfort Models in Kuwait Classrooms Operated in Hybrid Air-Conditioning Mode. *In:* Howlett, R. J., Jain, L. C. & Lee, S. H. (eds.) *Sustainability in Energy and Buildings.* Springer Berlin Heidelberg.ASHRAE (2013). ANSI/ASHRAE Standard 55- Thermal Environmental Conditions for Human Occupancy. Atlanda: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Auliciems, A. (1969). Thermal requirements of secondary schoolchildren in winter. *Epidemiology & Infection,* 67**,** 59-65.

Auliciems, A. (1973). Thermal sensations of secondary schoolchildren in summer. *Epidemiology & Infection,* 71**,** 453-458.

Auliciems, A. (1975). Warmth and comfort in the subtropical winter: a study in Brisbane schools. *Epidemiology & Infection,* 74**,** 339-343.

CEN (2007). EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Brussels: CEN (European Committee for Standardization).

CEN (2001). EN ISO 7726:2001 Ergonomics of the thermal environment- Instruments for measuring physical quantities. Brussels: CEN (European Committee for Standardization).

CIBSE (2006). *Guide A-Environmental design,* London, Chartered Institution of Building Services Engineers.

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

d'Ambrosio Alfano, F. R., Ianniello, E. & Palella, B. I. (2013). PMV–PPD and acceptability in naturally ventilated schools. *Building and Environment,* 67**,** 129-137.

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

de Dear, R. J., Akimoto, T., Arens, E. A., Brager, G., Candido, C., Cheong, K. W. D., Li, B., Nishihara, N., Sekhar, S. C., Tanabe, S., Toftum, J., Zhang, H. & Zhu, Y. (2013). Progress in thermal comfort research over the last twenty years. *Indoor Air,* 23**,** 442-461.

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

de Dear, R. J. & Brager, G. S. (2002). Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. *Energy and Buildings,* 34**,** 549-561.

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. Sydney.

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.

De Giuli, Pontarollo, C.M., De Carli, M. & Di Bella, A. (2014). Overall Assessment of Indoor Conditions in a School Building: an Italian Case Study. *International Journal of Environmental Research,* 8 (1), 27-38.

DfES (2003). Building Bulletin 87. Guidelines for Environmental Design in Schools. UK Department for Education and Skills.

DfES (2006). Building Bulletin 101. Ventilation of School Buildings. UK Department for Education and Skills.

Haddad, S., King, S., Osmond, P. & Heidari, S. (2012). Questionnaire Design to Determine Children's Thermal Sensation, Preference and Acceptability in the Classroom. *PLEA2012 - 28th Conference, Opportunities, Limits & Needs Towards an environmentally responsible architecture, 7-9 November 2012*, Lima, Perú.

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. *Counting the Cost of Comfort in a changing world , 10-13 April 2014.* Cumberland Lodge, Windsor, UK.

Harwood, E. (2010). *England's Schools: History, architecture and adaptation*. Swindon, English Heritage.

Humphreys, M., Rijal, H. B. & Nicol, F. (2010). Examining and developing the adaptive relation between climate and thermal comfort indoors. *Adapting to Change: New Thinking on Comfort, 9-11 April 2010.* Cumberland Lodge, Windsor, UK.

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

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

Humphreys, M. A. (1978). Outdoor temperatures and comfort indoors. *Building Research & Information,* 6**,** 92 - 105.

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

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.

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

Johnston and Partners. (2012). EFA PSBP Natural Ventilation Strategy. Available: https://media.education.gov.uk/assets/files/pdf/b/ventilation%20strategy%20190912.pdf.

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

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

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

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

Montazami, A. & Nicol, F. (2013). Overheating in schools: comparing existing and new guidelines. *Building Research & Information,* 41**,** 317-329.

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

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

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

NOCS. *Meteorological station. National Oceanographic Centre, Southampton. A collaboration between NOCS & Met Office* [Online]. Available: http://www.noc.soton.ac.uk/noc_intranet/metstation/index.html [Accessed: 20/06/14].

Olesen, B. W. (2007). The philosophy behind EN15251: Indoor environmental criteria for design and calculation of energy performance of buildings. *Energy and Buildings,* 39**,** 740-749.

Teli, D., James, P. A. B. & Jentsch, M. F. (2013). Thermal comfort in naturally ventilated primary school classrooms. *Building Research & Information,* 41**,** 301-316.

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.

Teli, D., Jentsch, M. F. & James, P. A. B. (2014). The role of a building's thermal properties on pupils' thermal comfort in junior school classrooms as determined in field studies. *Building and Environment*, 82, 640-654.

Trebilock, M. & Figueroa, R. (2014). Thermal comfort in primary schools: a field study in Chile. *Counting the Cost of Comfort in a changing world , 10-13 April 2014.* Cumberland Lodge, Windsor, 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**,** 193-220.

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

Tables

Table 1. Summary of results from UK thermal comfort surveys with school children (Teli et al., 2012, Teli et al., 2013)

Parameter	**Survey results**
Comfort temperature	Children's comfort temperature was observed to be approximately 2 ^{o}C lower than predicted using the EN 15251 adaptive model
Feeling of overall comfort and tiredness	The pupils' perceived overall comfort was more associated with their feeling of tiredness rather than with their thermal sensation
Immediate adaptive behaviour	Weak response of children (based on clothing changes over the same day)
Long-term adaptation	Similar to adults', clothing level is decreasing when indoor temperatures increase
Interpersonal differences	Stronger in pupils than adults [mean pupil standard deviation S.D.=1.5, against adult mean S.D.=1.07 (Humphreys et al., 2007)]

Table 2. Thermal comfort surveys with primary school children in spring/summer seasons

Study	Location	Ventila-tion type	Age group	No of Responses	T_n (^oC)	Questionnaire survey period length	Regr. Coef.
Humphreys (1977)	England	NV	7-9	10,000	-	14 days	~0
Teli et al. (2012)	England	NV	7-11	1,314	20.8	12 days over 3months	0.27
Mors et al. (2011)	Nether-lands	NV	9-11	1,372	-	24 days over 3 seasons	-
De Giuli et al. (2012)	Italy	NV	9-11	614	-	1 day	-
de Dear et al. (2014)	Australi a	NV, AC, EC	10-18	2,850	22.4	1-3 weeks	0.12
Trebilock and Figueroa (2014)	Chile	FR	9-10	774	21.1	3-4 days	0.18
De Giuli et al. (2014)	Italy	NV	9-11	66	-	1 day	-
Haddad et al. (2014)[1]	Iran	NV	10-12	1,605	22.8	10 days/season	0.23

Notes:
NV: Natural Ventilation, AC: Air-Conditioning, EC: Evaporative cooling
T_n: Neutral temperature (operative temperature corresponding to TSV=0)
Regr.Coef.: Regression coefficient of the thermal sensation vote (TSV) upon the operative temperature in the classroom over the survey period.
[1] The neutral temperature in this study corresponds to the entire survey period, including winter.

Table 3. Regression coefficients for the naturally ventilated buildings in the SCATs and ASHRAE databases and the two schools, separately and combined (SPSS results)

Database	**No of observations**	**Variance of dT_o**	**Regression coefficient**	**Standard error of coefficient**
SCATs (NV) (Humphreys et al., 2010)	1440	0.744	0.361	0.030
ASHRAE (NV) (Humphreys et al., 2010)	2585	0.555	0.308	0.024
Both schools combined	2693	0.842	0.313	0.030
Light-weight school	1211	0.769	0.198	0.045
Heavy-weight school	1482	0.903	0.392	0.040

Table 4. Relationship between adaptation time and ‘α’ (McCartney and Nicol, 2002)

Value of ‘α’	**Approximate duration of adaptation to a step change of the mean outdoor temperature (in days)**
0.33	2
0.45	3
0.70	5
0.80	7
0.90	14
0.96	35
0.99	140

Figures

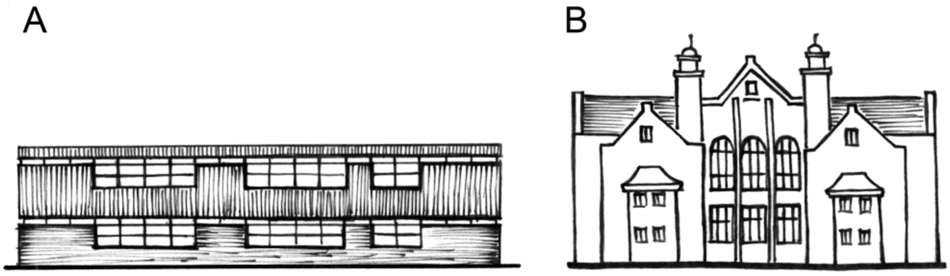

Figure 1. Sketch elevations of the types of school buildings surveyed, left: A. post-war light-weight building, right: B. Victorian medium-weight building

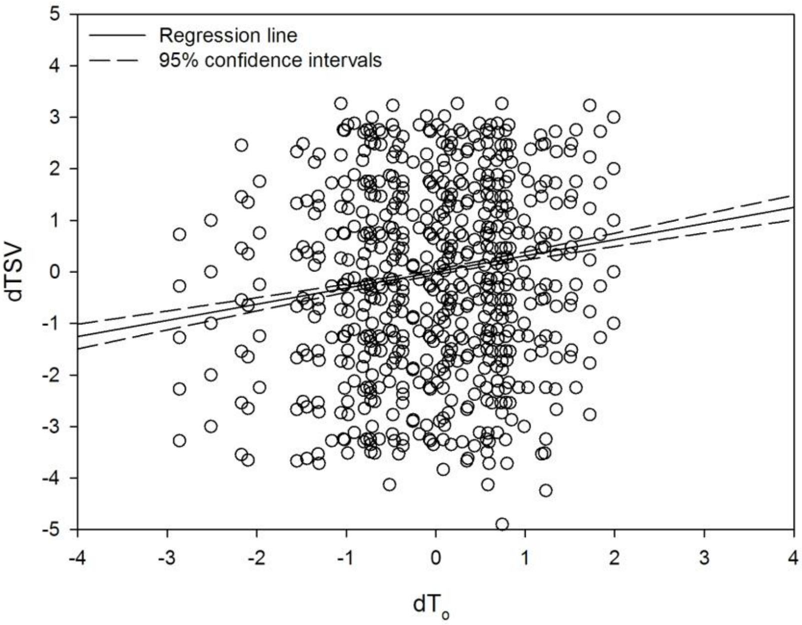

Figure 2. Difference of subjective thermal sensation vote and mean thermal sensation vote for the ‘day-surveys’ (dTSV) against the difference of the operative temperature during the surveys and the mean operative temperature on the ‘day-surveys’ (dT_o) for both schools combined

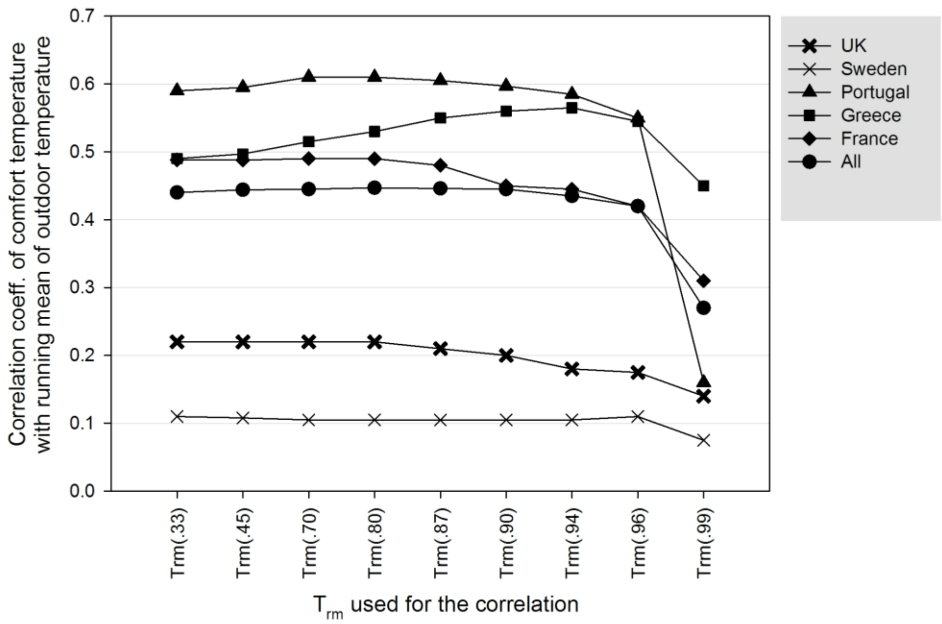

Figure 3. Correlations between comfort temperature and the running mean outdoor temperature, total and per country, as calculated from the SCATs database [adapted from McCartney and Nicol (2002)]

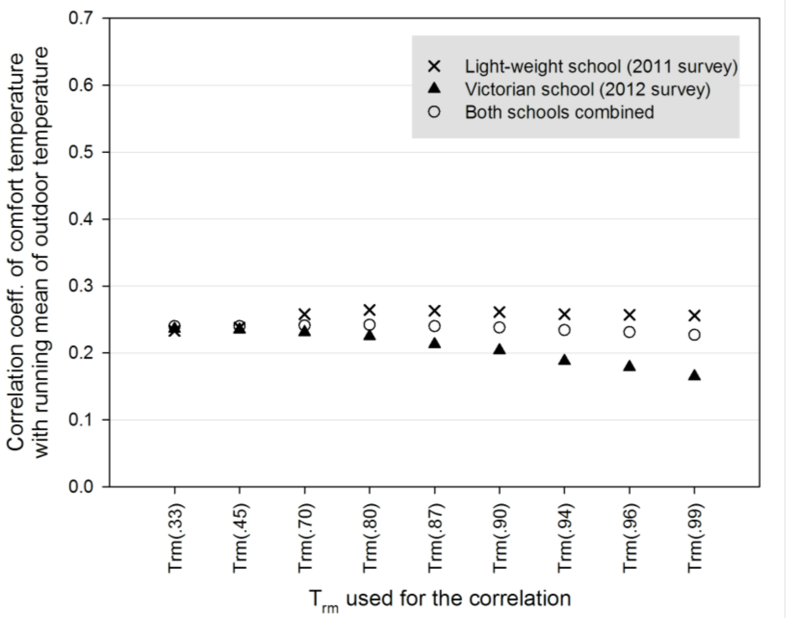

Figure 4. Correlations between comfort temperature and the running mean outdoor temperature for different values of ‘α’, as calculated from the two case study schools, separately and combined

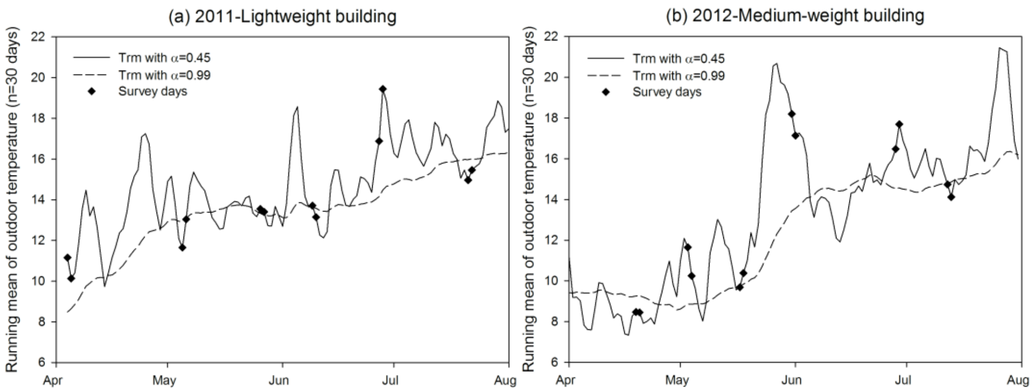

Figure 5. Running mean of the outdoor temperature for the survey period, calculated with α=0.45 and α=0.99 (a) in 2011 and (b) 2012

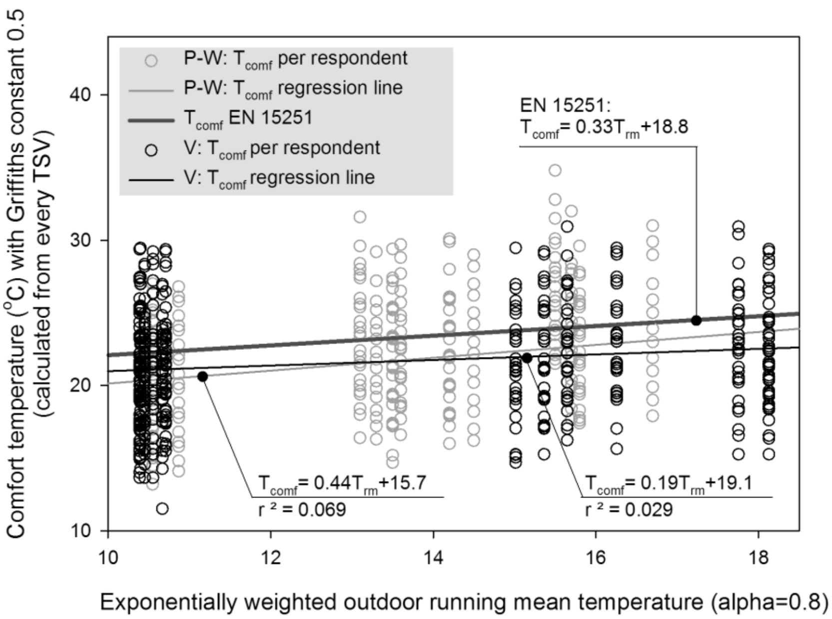

Figure 6. Calculated individual comfort temperature of all subjects against the exponentially weighted outdoor running mean temperature of the 2012 and 2011 surveys (light grey) in relation to the EN 15251 comfort temperature line. (P-W: post war school, V: Victorian school)

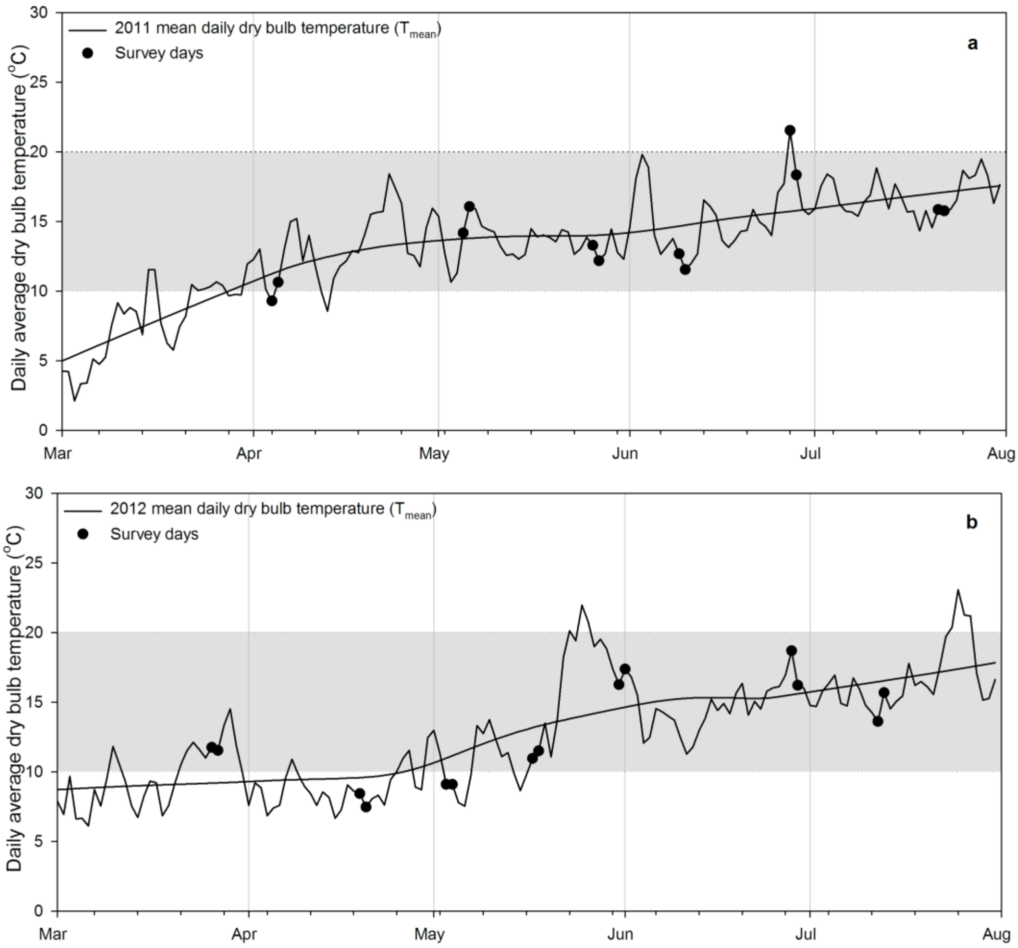

Figure 7. Southampton mean daily dry bulb temperature during the survey period months in (a) 2011 and (b) 2012, with the survey days highlighted for both years

Endnote

[1] A sample questionnaire can be found in Teli et al. (2013).