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Do the constants used in adaptive comfort algorithms reflect the observed responses of children in junior school classrooms?

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, United Kingdom
[2] Urban Energy Systems, Bauhaus-Universität Weimar, 99423 Weimar, Germany
*Corresponding author. Tel: +44 (0)2380592174, E-mail: D.Teli@soton.ac.uk

Abstract
This paper compares the values used for the Griffiths constant (G=0.5) and the running mean constant (α=0.8) in adaptive comfort algorithms with the values calculated from thermal comfort field surveys in two naturally ventilated junior schools in Southampton, UK. The surveys were conducted outside the heating season in 2011 and 2012 respectively, including both questionnaire surveys and environmental monitoring. A total of 2693 pupil responses were used for this analysis. The data was examined in two steps: first, each survey set; obtained over a 1-day visit to the school; was examined in order to derive the relationship between indoor temperature change and comfort vote with minimum impact of adaptation. Second, the dataset was investigated for the prolonged periods of the surveys, in relation to weather experienced by the pupils in order to estimate their time for adaptation to outdoor temperature changes. The paper gives an insight into the response of pupils to internal and external temperature changes, immediate and over prolonged periods, in comparison to adults.

Key words: School buildings, Griffiths constant, adaptive comfort, Field surveys, children.

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 by the authors investigated pupils' thermal sensation in school classrooms and found discrepancies between children's thermal responses and the predictions using adaptive comfort algorithms which were based on 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). Furthermore, research showed that the existing overheating guidelines found in the UK school 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). The above is important information since uncomfortable classroom conditions have been found to influence the health and schoolwork performance of children (Mendell and Heath, 2005, Wargocki and Wyon, 2007). It suggests that child-specific thermal comfort criteria are required, based on adaptive comfort modelling for children.

Table 1. Summary of results from authors' surveys with school children

Factor	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 in 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)]

For the derivation of the currently used adaptive equations for thermal comfort two constants are used, one expressing the linear relationship between comfort vote and operative temperature, called the 'Griffiths constant' (G) (Humphreys et al., 2007), and one reflecting the time it takes for people to adapt to outdoor temperature changes, the 'running mean constant' (α) (McCartney and Nicol, 2002). The values used for these constants were derived from the analysis of field data mainly in offices with adult subjects. This paper is revisiting these values for the case of children in naturally ventilated school classrooms. This analysis expands on the discrepancies found between the pupils' comfort temperatures and those calculated using the adaptive comfort model. In order to ensure more representative comfort predictions in school classrooms it is necessary to identify the source of these discrepancies and investigate their relation to adaptive comfort model components, such as the constants' G' and 'α'.

There are two adaptive comfort algorithms which have been developed to relate the occupant comfort temperature to the outdoor climate. These are the European adaptive algorithm based on the SCATs database (McCartney and Nicol, 2002), used in the European standard EN 15251 (CEN, 2007), and the worldwide ASHRAE adaptive algorithm (De Dear et al., 1997), used in ASHRAE standard 55 (ASHRAE, 2010). The way the 'neutral' or 'comfort' temperature is estimated differs between the two adaptive comfort projects, 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 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 algorithm.

The paper investigates whether G' and 'α' agree with pupils' responses from thermal comfort surveys in two naturally ventilated junior schools. This will help 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. Furthermore, the paper looks at pupils' thermal response rate to the outdoor climate, through exploration of the running mean constant 'α'.

1.1. 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. Further analysis was conducted in 2010, using a 'day-survey' methodology (Humphreys et al., 2010). The same method of estimation is used in this paper.

For setting up the adaptive comfort algorithm, the Griffiths constant 'G' is used in equation (1), which relates people's comfort temperature T_{comf} to the operative temperature T_{op} and their reported thermal sensation (Humphreys et al., 2007). The subjects' thermal sensation is expressed in the form of their 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.

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

1.2. 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 climatic conditions are more influential than earlier experiences (CIBSE, 2006). Therefore, the running mean T_{rm} of outdoor temperatures was chosen as a suitable outdoor climate index, weighted according to distance in the past, 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 (2) (Nicol et al., 2012).

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

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 (1)] and the outdoor running mean (Humphreys et al., 2007). Feeding into the equation which relates the comfort temperature to the outdoor temperature, 'α' is an indicator of the time it takes for people to adapt to outdoor climate variations.

The half-life of an exponentially weighted running mean temperature has been defined and can be calculated using equation (3) (Nicol and Humphreys, 2010). For α=0.8 the equation gives λ=3.5, which means that it takes about a week for the occupants to adapt to a step-change of the mean outdoor temperature.

$$\lambda = 0.69/(1-\alpha) \quad (3)$$

Humphreys et al 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' (Humphreys et al., 2013). This will be investigated here, using the two case study school buildings, which differ mainly in their thermal mass.

In summary, the values of both constants 'G' and 'α' were determined using adults' responses from the two adaptive comfort databases. Given the different thermal perception of children found from pupil surveys (Teli et al., 2012, Teli et al., 2013), these values need to be compared against children's responses.

2. Methodology

The data used in this paper was collected during thermal comfort surveys in two naturally ventilated schools in Southampton, a light-weight and a Victorian high thermal mass building. The surveys included questionnaires tailored for children and measurements of the key environmental parameters during the surveys.

2.1. Case study schools

The case study junior school buildings are of different typologies, as shown in exemplar sketches in Figure 1. Building A is a typical example of a light-weight 1970s school in the UK, with steel frame construction and pre-fabricated concrete panels. It was constructed in 1978. The school has 8 classrooms. Around 240 pupils aged 7-11 were enrolled in Years 3 to 6 in the year of the survey. The surveys were undertaken in all 8 classrooms 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 around 400 enrolled pupils aged 5-11 (2012 data). The surveys took place in all 11 classrooms of the school.

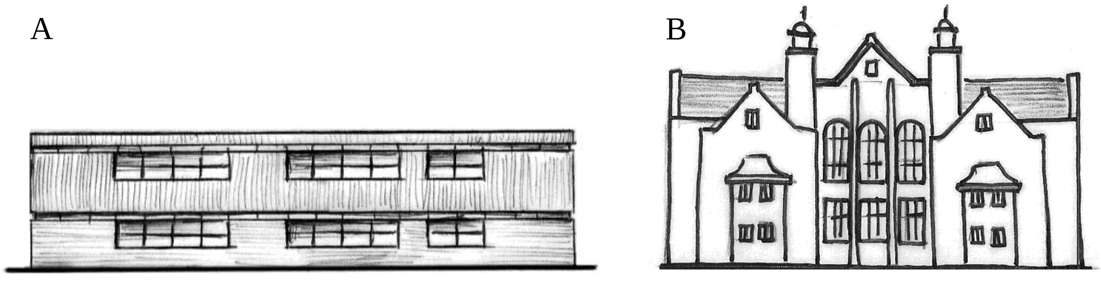

Figure 1. Sketch elevations of the types of school buildings surveyed, left: A. post-war light-weight building, right: B. Victorian heavy-weight building

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 (Teli, 2013).

2.2. Thermal comfort surveys

For reasons of consistency, the same methods and equipment were used in both school studies. The survey procedure, questionnaire and data processing details have been described in previous papers, based on the first school survey in 2011. Therefore, these are only summarised here:

- 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 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).
- 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.
- Environmental parameters (air speed, radiant temperature, air temperature, relative humidity and CO_2 concentration) were measured during the surveys, following the standards of ISO 7726 "Ergonomics of the thermal environment-Instruments for measuring physical quantities" (ISO, 2001).

3. Results

For the analysis presented in this paper, the pupils' thermal sensation votes (TSV) and the operative temperatures measured during the surveys (T_{op}) were used.

3.1. Relationship No 1: 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:

- Calculation of the variables dTSV and dT_{op} 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_{op} is the difference of the operative temperature during the survey (T_{op}) and the mean operative temperature on that day ($T_{op(day\ mean)}$).
- Regression analysis of dTSV on dT_{op} 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_{op} 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 for the entire dataset with the 95% confidence intervals can be seen in Figure 2. The narrow intervals suggest that the regression coefficient can be considered reliable.

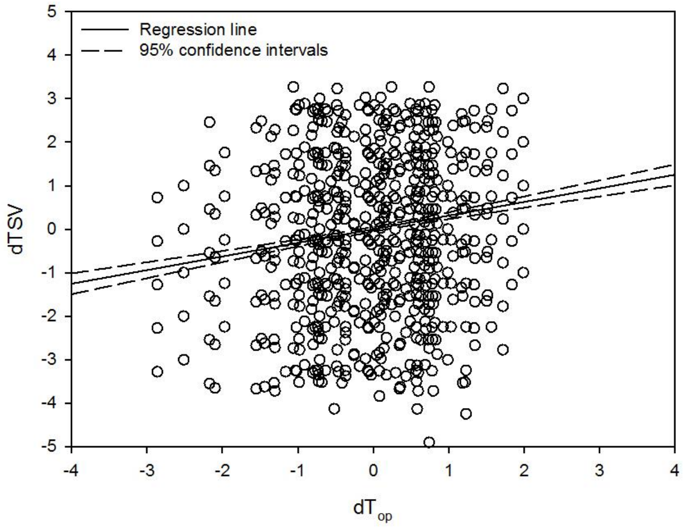

Figure 2. Difference of subjective thermal sensation vote and mean thermal sensation vote for the 'day-surveys' (dTSV) against the difference of the operative temperature during the surveys and the mean operative temperature on the 'day-surveys' (dT_{op})

The regression coefficients are presented in Table 2, in comparison to the SCATs and ASHRAE regression coefficients for the naturally ventilated buildings (NV) of the databases only, as previously estimated (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.

Table 2. 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_{op}**	**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

The 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 apply to the schools since the variance of the operative temperature is similarly low and, therefore, the comparison here regards the calculated regression coefficients of Table 2 only.

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 heavy-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 conducted on one level (ground or first floor), minimising the impact of that parameter on temperature fluctuations. It is evident that the distinction between building construction type and form is very important in such analyses.

3.2. Relationship No 2: Comfort temperature and outdoor climate

The comfort temperature was calculated for every thermal sensation vote using equation (1) and a value of G=0.5, based on the previous analysis. The running mean of the outdoor temperatures was calculated using equation (2). 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 3. This is based on the values used in the analysis of the SCATs database, as highlighted by Figure 3.

Table 3. Relationship between adaptation time and ‘α’

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

Figure 4 shows the correlation coefficients of the calculated comfort temperatures from the pupils’ thermal sensation votes with the exponentially weighted outdoor running mean. All values were significant ($p<0.001$). 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 database, except for the big drop for α=0.99, which does not appear in the school results (Figure 3). 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. It appears that a value of α=0.8 is appropriate for use in schools, indicating a duration of approximately one week for adaptation to a change in outdoor temperature.

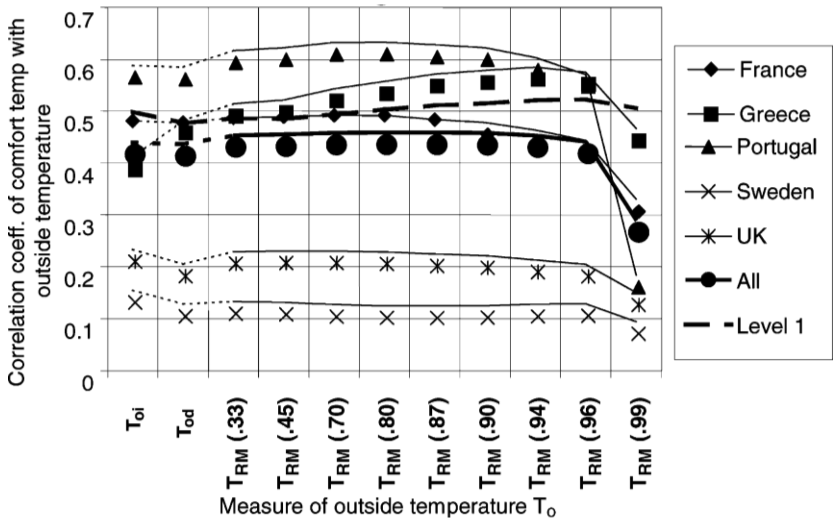

Figure 3. Correlations between comfort temperature and measures of the outdoor temperatures, total and per country, as calculated from the SCATs database (McCartney and Nicol, 2002).

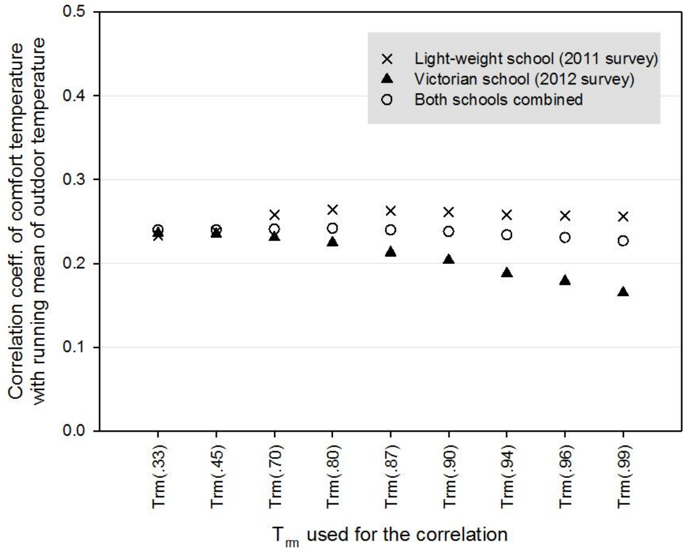

Figure 4. Correlations between comfort temperature and the running mean outdoor temperature for different values of 'α', as calculated from the two case study schools, separately and combined.

Looking at the school types separately, 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 heavy-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 coupled to the outdoor temperature and therefore occupant comfort is strongly affected by the outdoor climate. In contrast, the high 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 heavy-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, probably because the indoor environment is not significantly affected by these events, allowing for past experiences to fade. Overall, the analysis suggests that there may be differences in thermal adaptation due to the thermal properties of the buildings. Comparison of survey data from different construction types would help to understand these issues better.

4. Conclusions

This paper compared the typical values of the constants 'G' and 'α', used in adaptive comfort algorithms, with values which were derived from thermal comfort surveys in two naturally ventilated junior schools. The regression coefficients used for the estimation of G=0.5 in previous studies agree well with the survey results suggesting that this value can be used in the comfort temperature calculation for children, although this needs further validation. Overall, it appears that, assuming no or minimal adaptation has taken place, children's response rate to indoor temperature changes can be considered similar to that of adults.

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. The comparison per school construction type highlighted a difference which suggests that the building's thermal properties influence the time it takes for occupants to adapt to outdoor temperature changes.

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 in general. 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. These limitations suggest that extensive fieldwork in schools is required in order to obtain more reliable data for the estimation and assessment of pupils' comfort in classrooms.

Overall, the constants 'G' and 'α' appear to be as appropriate for use in school environments as they are for environments with adults [However, the overall need for further work to define the value of 'α' has been recently highlighted (Humphreys et al., 2013)]. There were differences between the light-weight and heavy-weight school which suggest that buildings' thermal capacity is an important parameter affecting occupants' thermal adaptation.

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