Developing an algorithm to illustrate the likelihood of the dissatisfaction rate with relation to the indoor temperature in naturally ventilated classrooms

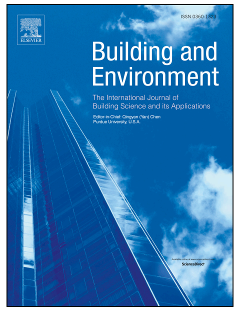
Montazami, A, Gaterell, M, Nichol, F, Lumley, M & Thoua, C

Original citation & hyperlink:
Montazami, A, Gaterell, M, Nichol, F, Lumley, M & Thoua, C 2016, 'Developing an algorithm to illustrate the likelihood of the dissatisfaction rate with relation to the indoor temperature in naturally ventilated classrooms' Building and Environment, vol 111, pp. 61-71. DOI: 10.1016/j.buildenv.2016.10.009
https://dx.doi.org/10.1016/j.buildenv.2016.10.009

DOI 10.1016/j.buildenv.2016.10.009
ISSN 0360-1323
ESSN 1873-684X

Publisher: Elsevier

Accepted Manuscript



Developing an algorithm to illustrate the likelihood of the dissatisfaction rate with relation to the indoor temperature in naturally ventilated classrooms

Azadeh Montazami, Mark Gaterell, Fergus Nicol, Mark Lumley, Chryssa Thoua

PII: S0360-1323(16)30401-2

DOI: 10.1016/j.buildenv.2016.10.009

Reference: BAE 4668

To appear in: *Building and Environment*

Received Date: 19 May 2016

Revised Date: 17 October 2016

Accepted Date: 18 October 2016

Regarding BAE 4668

Article title: Developing an algorithm to illustrate the likelihood of dissatisfaction rates in relation to the indoor temperature in naturally ventilated classrooms

Authors group with affiliations

Azadeh Montazami [a], Mark Gaterell[b], Fergus Nicol [c], Mark Lumley [d], Chryssa Thoua[d]

- [a] Coventry University, United Kingdom
- [b] University of Portsmouth, United Kingdom
- [c] London Metropolitan University, United Kingdom
- [d] Architype Ltd., United Kingdom

Developing an algorithm to illustrate the likelihood of the dissatisfaction rate with relation to the indoor temperature in naturally ventilated classrooms

Abstract:

There is a direct link between the attainment of children at school and the thermal conditions in classrooms and there are guidelines in place to help designers provide the most effective thermal conditions. However, results from thermal comfort surveys and the collection of the perception of 662 pupils, aged between 8 and 11 in 27 naturally ventilated classrooms from eight primary schools located in the West Midlands, UK during the cooling seasons of 2014 and 2015 suggest that simply designing to a threshold comfort temperature might not be enough to ensure the most effective learning environments are delivered. Indeed, these results confirm that children's threshold comfort temperatures are at least 3°C lower than adults during cooling seasons in a typical free running UK primary school classroom. Such a difference is important as it is teachers that almost invariably control internal comfort conditions and in adjusting to meet their own preferences might not deliver the most effective learning environments. Consequently, an algorithm has been developed that allows the likely satisfaction rate of children in relation to the indoor temperature in a primary school classroom to be mapped explicitly and provides the basis for comparing differences in satisfaction between adults and children in the same space. The use of this tool can further help designers and teachers deliver and control classroom environments in a way that maximises educational performance.

Keywords: Adaptive thermal comfort, overheating, children, perception, adult, primary schools

1. Introduction:

Providing thermal comfort in schools has a significant impact on children's performance and health particularly for those aged between 7-11 years old [1-2]. Current thermal comfort guidelines only help school designers to evaluate if a classroom is at risk of experiencing overheating without looking at the percentage of students who may be overheated [3-4]. In the UK a typical classroom accommodates 30 children [5]. As each child matters [6], it is essential to make sure that, wherever practicable, all children in a classroom are comfortable.

To achieve this, it is necessary to be able to assess the likely dissatisfaction rate in a typical UK classroom when the indoor operative temperature differs from the threshold comfort temperature. For this reason an understanding of the comfort temperature preferences and perceptions of children is essential, however it is important to note that the current thermal comfort guidelines (Standard EN 15251 [7] and TM 52 [8]) are based on preferences and perceptions of adults. In the last decade the few studies that focused on children concluded that there is a difference of up to 2°C between the thermal perceptions of children and adults [9]. This difference is due to the higher metabolic of children, different types of clothing and limited adaptive opportunity [10].

In addition, some studies suggest that the opportunity to control an environment affects the thermal perceptions of occupants, making them more tolerant to apparently uncomfortable conditions [11-13]. This relationship is complicated in primary schools as the teacher, who takes charge of controlling the internal environment, may have a different thermal perception from the children who are the main occupants of the classrooms.

This paper presents the results of a study that sought to: investigate the thermal comfort threshold of children; to design an algorithm that illustrates the likely dissatisfaction rate when the operative temperature differs from the threshold comfort temperature, as anticipated using the adaptive comfort theory; provide the basis for comparing differences in teacher's and children's thermal perception in the same space; and to study the impact of children's personal and environmental behaviour on their thermal perception.

1.1. Calculating comfort temperature using the adaptive model:

The 'neutral' or 'comfort' temperature (T_{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" [14]. There has been extensive research on thermal comfort over the last decades. As a result, there have been two main approaches in calculating thermal comfort which are the steady-state approach (i.e. thermo-physiological) [15-17] and the adaptive approach [18-19].

The steady-state model was developed using principles of heat balance and experimental data collected in a controlled climate chamber under steady state conditions [13]. The adaptive model, on the other hand, was developed based on hundreds of field studies with the idea that occupants dynamically interact with their environment [20]. Occupants control their thermal environment by means of clothing, operable windows, fans, personal heaters and sun shades [18-19, 22]. Literature shows that the adaptive approach better represents children's thermal perception compared to the static approach [4,9,23] and also children prefer lower temperatures based on the adaptive approach [9, 24].

Both American (ASHRAE 55) and European (EN 15251) thermal standards developed adaptive thermal models for buildings that were naturally ventilated [25, 26-7]. These standards have been developed from studies with adults as the focus rather than children. In these thermal models, the key element is the relationship between indoor comfort temperature and the prevailing outdoor conditions.

EN 15251 [7] adopted an exponentially weighted running mean temperature which "…captures and puts more emphasis on immediate perceptual and behavioural layers of human adaption compared to the longer term adaptive process operating at the physiological level" . An exponentially weighted running mean temperature (T_{rm}) is a more appropriate climate index compared to the daily mean or monthly mean temperature as adopted in the ASHRAE approach [27]. A weighted running mean temperature considers the significance of temperatures based on their distance in the past and suggests that recent thermal experiences are more important than those further in the past [14,20], T_{rm} for any given day is calculated from the equation (1):

$$T_{rm} = (T_{od-1}+\alpha\ T_{od-2}+\ \alpha^2\ T_{od-2}+\ldots) / (1+\alpha+\alpha+\alpha^2\ldots) \quad (1)$$

$$0<\alpha<1$$

According to BS EN 15251 [7], comfort temperature is calculated from the equation (2).

$$T_{comf} = 0.33\ T_{rm} + 18.8°C \qquad (2)$$

Nicol et al. [20] and The Chartered Institution of Building Services Engineers (CIBSE) [8] suggest that occupant discomfort is related to ΔT, the difference between the actual operative temperature (T_{op}) in the room and the comfort temperature (T_{comf}) in a free running building ($\Delta T=T_{op}-T_c$). BS EN 15251 [7] suggests that the likelihood of occupants feeling uncomfortable relates to the comfort temperature as well as the type of building and the nature of the occupants themselves.

To account for such factors, BS EN 15251 considers three building categories [7]. Building Category I is considered to include buildings where the occupants are particularly sensitive and vulnerable whereas Building Category II is considered for normal expectations in new or renovated buildings. Building Category III is considered for moderate levels of expectation and may be used for existing buildings. Equations 3, 4 and 5 show the calculation of thermal comfort in Building Categories I, II and III.

- Category I building - $T_{comf} = 0.33\ T_{rm} + 18.8 \pm \mathbf{2}$ (3)
- Category II building- $T_{comf} = 0.33\ T_{rm} + 18.8 \pm \mathbf{3}$ (4)
- Category III building - $T_{comf} = 0.33\ T_{rm} + 18.8 \pm \mathbf{4}$ (5)

1.2. Thermal comfort in a classroom

The above models have been developed using data from offices with adult subjects. However, factors such as metabolic rate, typical clothing and level of activity are likely to vary between adults and children and may result in differences in perceived comfort temperatures between these two groups. Consequently, such models may not be applicable for children. Indeed, recent studies on classroom conditions suggest they are likely reflect preferences of teachers rather than children [28] thereby raising the risk that children will not feel thermally comfortable with the concomitant impact on their performance or attainment. Consequently, there is a need to understand any differences between the thermal preferences of children and teachers in order to help teachers deliver thermal conditions that satisfy as many of their students as possible. Some studies have focused on children’s thermal perceptions and only a few of them calculated children’s comfort/neutral temperature. Table 1 illustrates the children’s comfort/neutral temperature according to studies carried out around the world.

Table 1. Review of children’s comfort/neutral temperature.

Study	Location	Climate	Season	Ventilation type	Age group	No of responses	Tcomf / Tn (°C)
Auliciems (1969) [29]	England,UK	Temperate	Winter	NV	11 to 16	624	16.5°C
Pepler (1972) [30]	Oregon,US	Temperate	Spring / autumn	NV, AC	7 to 17	NV: 100/ AC:66	NV: 21.5-25°C AC: 22-23 °C
Auliciems (1973) [31]	England,UK	Temperate	Summer	NV	11 to 16	624	19.1°C
Auliciems (1975) [32]	Australia	Subtropical	Winter	NV	8 to 12 12 to 17	Not given	Primary school 24:2 °C Secondary school: 24:5 °C
Kwok (1998) [33]	Hawaii,US	Tropical	Winter/ summer	NV, AC	13 to 19	NV: 2181 AC:1363	NV: 26.88 °C AC: 27.48 °C
Wong and Khoo (2003) [34]	Singapore	Tropical	Summer	NV	13 to 17	493	28.8 °C
Hwang, Lin, Chen, and Kuo (2009) [35]	Taiwan	Subtropical	Autumn	NV	11 to 17	944	23 °C-24 °C
Liang, Lin, and Hwang (2012) [36]	Taiwan	Subtropical	Autumn	NV	12 to 17	1614	22.4°C-29.28°C
Teli, Jentsch, and James (2012) [9]	England,UK	Temperate	Spring	NV	7 to 11	230	20.8°C
de Dear et al. (2014) [37]	Australia	Subtropical	Summer	NV, AC, EC	10 to18	2850	22.4°C
Trebilcock (2014) [38]	Chile	Low temperature winter, high temperature summer	Winter/ summer	NV	9 to 11	774	21.1°C
Haddad et al. (2014) [39]	Iran	Temperate	Spring	NV	10 to 12	1,605	22.8°C

NV = Natural Ventilation
AC = Air Conditioning
EC= Evaporative Cooling

Results in Table 1 suggest that there is a relationship between the range of neutral temperatures and the climate conditions at the location of the study. The range of neutral temperatures in the UK which can be considered as a temperate/cold climate varied from 16°C to 20.8°C; this increases to 26°C –27.8°C in subtropical regions and reaches 28 °C –29.8°C in tropical regions. Given projected changes in the global climate, these findings highlight the likelihood that neutral/comfort temperatures will vary over time; a consequence that needs to be considered in the long term delivery of effective learning spaces. In addition, according to the adaptive comfort theory, the neutral/comfort temperatures for children are generally 2°C lower than that for adults which means children are more sensitive to higher temperatures [9, 40-41].

2. Methodology

2.1. Collecting data

This paper is part of a large case study assessing the indoor environmental quality of primary schools located in the West Midlands, UK. In order to assess the satisfaction rate of children in relation to the indoor temperature and evaluate the thermal comfort threshold in primary school classrooms, indoor operative temperatures in 27 classrooms from eight primary schools were recorded with black globe thermometers (37mm diameter). Temperatures were recorded for two weeks during parts of the cooling seasons of 2014 and 2015 while all the classrooms were naturally ventilated. Perceptions and preferences of 662 pupils regarding the thermal condition of classrooms at the time of survey and also the general thermal conditions of classrooms were gathered through the questionnaire. These questionnaires were prepared by the authors and considered the principles of questionnaire design for use with children [42-43]. The responses were collected in parallel to the measurement of the indoor operative temperatures in the classrooms. Outside temperature data for the study period were also collected from the UK metrological office [44]. Weather stations were generally no more than 5km from the study site which represent ambient temperatures in the vicinity of the schools.

Details of the schools, classrooms, their ventilation type and the number of respondents that participated from each classroom together with the date and time of the survey are presented in Table 2. Schools 1 to 3 have Mixed-Mode ventilation and are equipped with an MVHR system. The MVHR system in these schools works on bypass mode during the summer and therefore the schools are operated in a free running mode with no heating or cooling supplied; effectively making them equivalent to the naturally ventilated mode of schools 4 to 8.

Table 2. Summary of the collected data

Region	School	Classroom	Date	Time of survey	Age	Number	Ventilation type
Wolverhampton	1	1	07-Jul-14	a.m	8_11	24	Mix Mode
		2		p.m	9_10	21	Mix Mode
		3		a.m	10_11	27	Mix Mode
Wolverhampton	2	4	08-Jul-14	a.m	8_9	30	Mix Mode
		5		a.m	9_10	29	Mix Mode
		6		p.m	10_11	23	Mix Mode
Wolverhampton	3	7	10-Jul-14	a.m	7_8	21	Mix Mode
		8		a.m	9_10	29	Mix Mode
		9		a.m	10_11	20	Mix Mode
Wolverhampton	4	10	09-Jul-14	p.m	7_8	20	Natural
		11		p.m	7_8	23	Natural
		12		a.m	10_11	26	Natural
		13		a.m	10_11	25	Natural
Wolverhampton	5	14	11-Jul-14	a.m	9_10	26	Natural
		15		a.m	10_11	28	Natural
Herefored	6	16	14-Jul-14	a.m	8_9	28	Natural
		17		a.m	10_11	24	Natural
		18		a.m	10_11	25	Natural
		19		a.m	10_11	24	Natural
Coventry	7	20	01-Jul-15	a.m	9_10	19	Natural
		21	01-Jul-15	a.m	10_11	19	Natural
		22	09-Jul-15	p.m	10_11	26	Natural
		23	09-Jul-15	p.m	10_11	33	Natural
Coventry	8	24	01-Jul-15	a.m	9_10	19	Natural
		25		p.m	9_10	29	Natural
		26		a.m	10_11	22	Natural
		27		p.m	10_11	22	Natural

The questionnaire is divided into four main parts 1: General background information (i.e. year of study and gender) 2: Clothing information in order to understand if the respondent was wearing a jumper (pullover) while completing the questionnaire 3: Instant thermal perception (i.e. thermal sensation and preference at the time of the survey) and general thermal perception about the classroom's environment 4: Behavioural approach when they feel hot.

Thermal sensation was measured using a 7 point Likert scale enhanced with colour and descriptions which follows the method used in previous studies in this field [9, 38-39].

Clarity of the questions was checked with several teachers and head teachers as well as being compared with previous studies [9] before finalising the questionnaire. For example, the 'neutral' temperature corresponding to the central category of the ASHRAE 7-point scale [20] of thermal sensation was changed to

'OK', the 'slightly warm' was changed to 'a bit warm' and 'slightly cold' was changed to 'a bit cold' in order to provide greater clarity for children. The 7-point thermal preference scale developed by ASHRAE was reduced to a 5-point scale to children following the teachers' and head teachers' feedback regarding the complicated nature of thermal preference in comparison with thermal sensation. Also, teachers requested that each question was read out in order to eliminate any ambiguity. The lead author and one of the co-authors were present at the time of each survey in order to answer any questions. Table 3 illustrates the scales which were used to assess the thermal evaluation.

Table 3: The scale used in the questionnaire survey

TSV Scale Thermal Sensation Vote **At present I feel:**			TPV Scale Thermal Prefrence Vote **I would like to be:**	
Hot (+3)	Hot	☐		
Warm (+2)	Warm	☐	Warmer (+2)	☐
A bit warm (+1)	A bit warm	☐	A bit warmer (+1)	☐
Ok (0)	Ok	☐	As it is now (0)	☐
A bit cool (-1)	A bit cool	☐	A bit cooler (-1)	☐
Cool (-2)	Cool	☐	Cooler (-2)	☐
Cold (-3)	Cold	☐		

Questionnaires were filled in half an hour after students had been sat still in order to eliminate the impact of metabolic rate on their thermal perception. According to the literature, 15 minutes of sedentary activity is sufficient to enable a body to reach a stable state such that it will respond the prevailing thermal conditions after doing non sedentary activities (e.g. running) [45]. Half an hour has been adopted in previous studies and is considered to provide an appropriate safety margin [9, 38-39]. In order to prevent any confusion between the general and instant thermal perception, each group of questions was placed on different sides of the questionnaire sheet.

2.2. Data quality assurance

The process of data quality assurance eliminates the responses of the children who have not demonstrated an ability to share their perceptions of thermal comfort through the questionnaire.

While the questionnaires were developed in line with current guidance, the collected data still need to be tested in order to eliminate any inconsistencies. For example, this could be where children wished it was warmer while indicating that they already feel hot. It is suggested that these cases can be identified by adding up thermal sensation (TSV) and thermal preference (TPV). The case where (TSV+TPV) <-2 or (TSV+TPV)>2 were considered as inconsistent based on the fact that TSVs within [-3,-2] and [+2, +3] are thought to express dissatisfaction and one would not normally wish to enhance that sensation [13]. This approach of refining data has been adopted from previous studies [9, 38-39]. Inconsistencies which were excluded from the data set represent around 5% to 8% which suggests that a majority of children are capable of understanding the questionnaire (Figure 1). These figures are in line with a similar study where 7% of data were excluded [9].

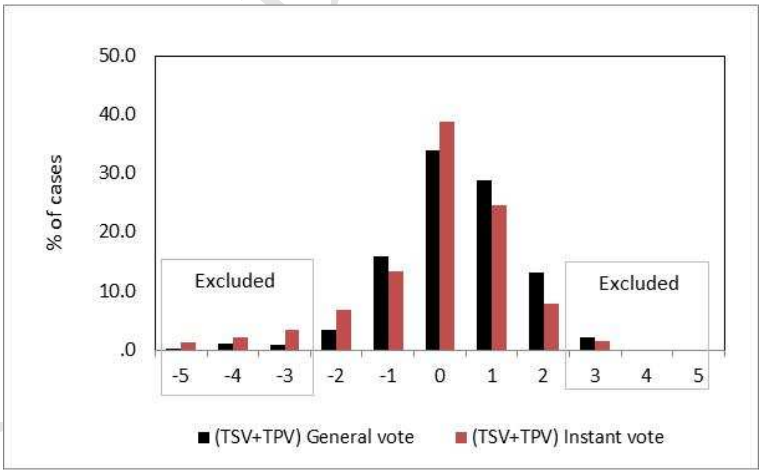


Fig 1. Excluded responses from the thermal comfort questionnaire considering both instant and general thermal perception

3. Analysis:

In order to understand the likely dissatisfaction rate in a typical UK classroom when the indoor operative temperature differs from the comfort temperature three stages of analysis are considered.

Stage one: the range of temperatures which will be comfortable for children are evaluated and the results compared with similar studies carried out in this field. The procedure of this evaluation will be validated by looking at the children's thermal preference.

Stage two: the likely dissatisfaction rate when there is a difference between the operative temperature and comfort temperature (T_{diff}) (derived from stage one) will be calculated and based on this calculation an algorithm will be developed that shows the likely satisfaction rate of children with relation to indoor temperature

Stage three: the impact of personal and environmental behaviour on an occupants' thermal sensation will be evaluated.

3.1. Comfortable temperature range for children

3.1.1. Thermal sensation vote and offset from adaptive comfort temperature

Adaptive comfort temperatures were calculated for each classroom on the days of monitoring using the adaptive thermal comfort formula suggested by European Standard EN 15251 [7] and TM 52 [8]. As outlined above, these formulae were developed using adult subjects. In each classroom and at each temperature the percentage of students who voted OK or Comfortable (i.e. a bit warm or a bit cool) are calculated. These responses were collected parallel to the measurement of indoor temperature in each classroom. According to previous research a 'neutral' thermal sensation is not always a preferred option and slightly warmer or cooler can be the favoured option based on the climate conditions [36, 42].

Figure 2 shows the proportion of children voting OK and Comfortable in relation to differences between indoor operative temperature and comfort temperature, calculated using the adaptive thermal comfort formula (Equation 2).

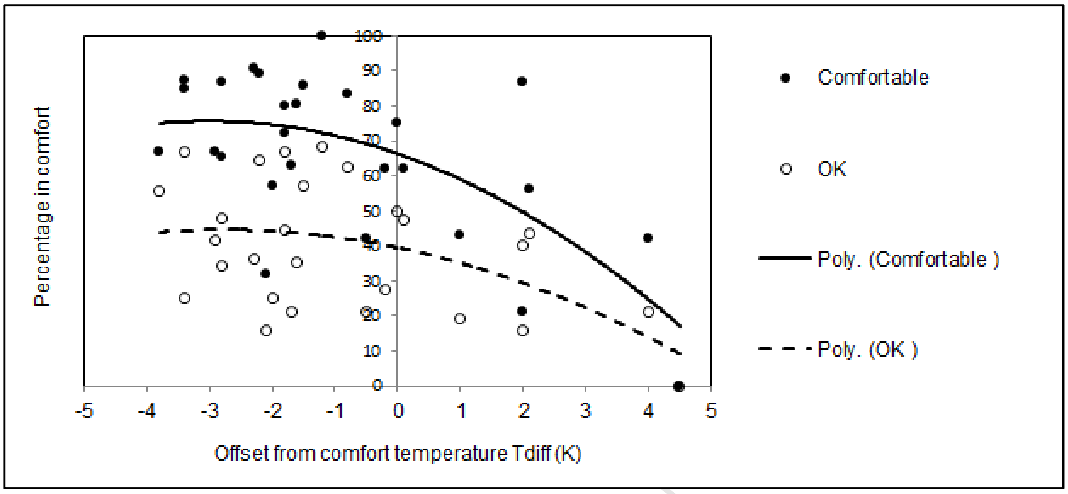


Fig. 2: The proportion of children voting OK and Comfortable in relation to the offset from the comfort temperature [Calculated based on $T_{comf} = 0.33\ T_{rm} + 18.8°C$]

Results suggest the percentage of children who feel Ok and Comfortable is higher when the difference between the comfort temperature and the indoor operative temperature reaches -3K. According to this study the percentage of children who feel comfortable is 65% when there is no difference between indoor operative temperature and adaptive comfort temperature while this figure reaches 75% (highest point) when the difference reaches -3K. The percentage of respondents who feel 'OK' is at the highest point (45%) when the offset from indoor and comfort temperature reaches -3K. This finding differs those from the Smart Controls and Thermal Comfort (SCAT) study [46] where the data relate to adult office workers (Figure 3). In the SCAT study, where T_{comf}±2K, over 80% of responders are comfortable and 55% feel Neutral (i.e., OK).

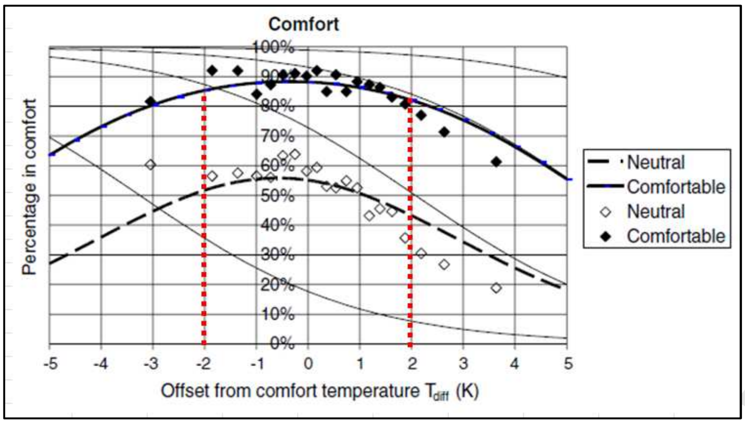


Fig. 3: The proportion of subjects voting OK and Comfortable in relation to the offset from comfort temperature

[Calculated based on $T_{comf} = 0.33\ T_{rm} + 18.8°C$][46]

The outcome of this study supports the findings of the previous studies [9, 24, and 37] that suggest children would feel most comfortable in a cooler indoor temperature.

Figure 4 shows the relationship between children voting Comfortable or OK and the indoor temperature. The level of children's thermal satisfaction (Comfortable vote) increases from 70% to nearly 80% when the classroom temperature decreases from 24°C to 20°C. These results suggest that such reductions in temperature are likely to improve the thermal satisfaction of a majority of the children.

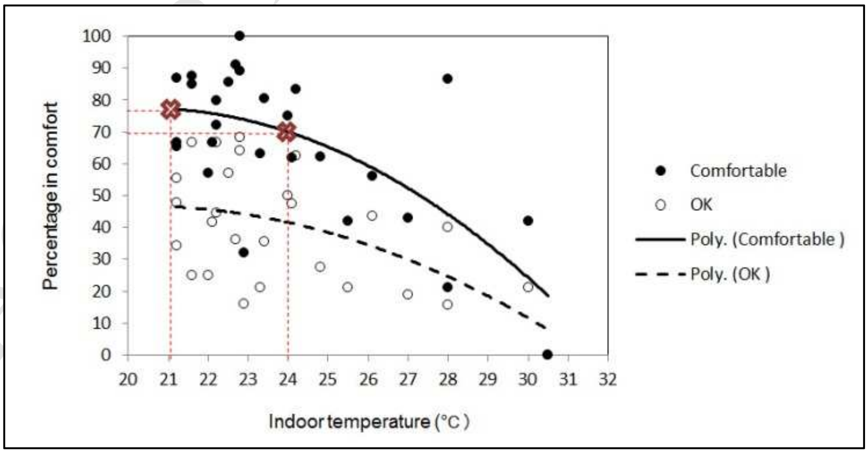


Fig. 4: The proportion of subjects voting OK and Comfortable in relation to classroom's indoor temperature

These results concur with those of previous research. According to two separate studies carried out among 10 to 12 year old children in Denmark and the USA, the results of language based tests [2] and mathematics scores [47] improved significantly when classroom temperatures were reduced from 25°C to 20°CFurther research considered the performance of two groups of children aged between 10 and 12 years old who were either in air-conditioned classrooms with a temperature of 22.5°C or without cooling with the temperature at 26°C. Result confirmed that their performance was significantly better in classrooms with a temperature of 22.5°C [48]. Another study in Sweden considered the effect on performance of exposing 9 to10 year old children to temperatures of 20°C, 27°C and 30°C , . Results suggested that their performance was significantly better when the children were exposed to 20°C [49].

Results in Figures 2 and 4 suggest the ranges of classroom temperatures are not evenly distributed. Out of twenty seven classrooms, seventeen have a temperature less than 24°C and ten have a temperature above 24°C. However, from Figures 2 and 4 there is likely to be a higher satisfaction when the indoor temperature is below 24°C (within the range of 21°C to 24°C) or the indoor temperature is between -2°C to -4°C from the comfort temperature.

3.1.2. Children's preference vote and offset from comfort temperature

Figure 5 shows the proportion of children who want 'No changes' and 'Changes' with relation to their thermal sensation in each classroom.

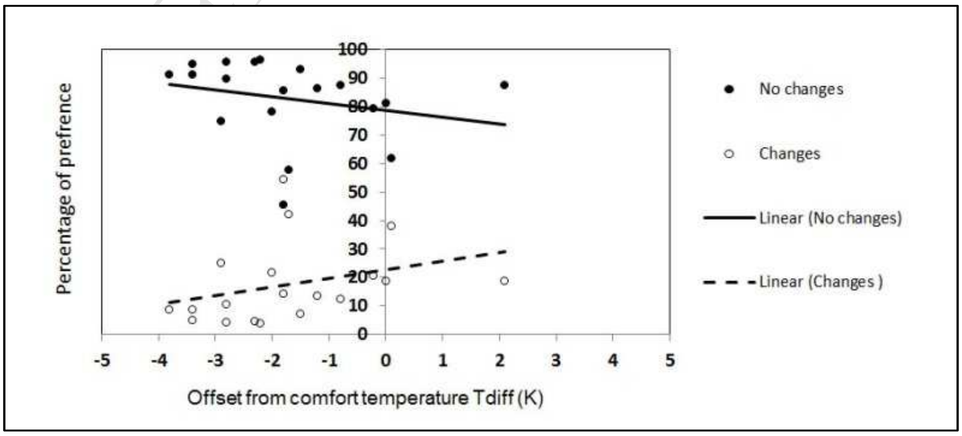


Fig 5: The proportion of children who voted No changes and Changes with relation to offset from comfort temperature [Calculated based on $T_{comf} = 0.33\ T_{rm} + 18.8°C$]

The ‘Changes’ vote is the sum of those votes to make the environment warmer or cooler and the ‘No changes’ vote is the sum of those votes to allow the surrounding environment to either stay ‘As it is now’, or make it ‘A bit warmer’ or ‘A bit cooler’. When there is a difference of approximately -3K between indoor operative temperature and comfort temperature, the percentage of children who do not want any changes is significantly higher while the percentage of children who want changes with relation to indoor temperature is significantly lower at this point. This result confirms the findings from the previous stages that suggest children’s comfort temperature is lower than for adult.

3.2. Dissatisfaction rate when there is a differences between operative temperature and children comfort temperature

3.2.1. Comparing children’s and adult’s dissatisfaction rate

Figure 6 shows the relationship between the percentage of children (continuous line) who were in discomfort in relation to offset from comfort temperature (using the data collected in this study) compared with the percentage of adults (dotted line) who may be overheated with indoor temperature using Equation 7 [50].

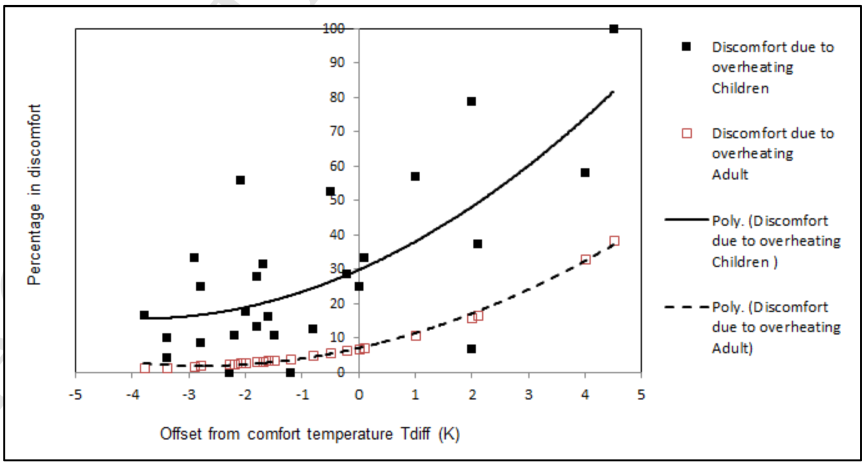


Fig 6: The proportion of subjects overheating in relation to the offset from comfort temperature

[Calculated based on $T_{comf} = 0.33\ T_{rm} + 18.8°C$]

$$P = \frac{e^{(0.4734 * \Delta T - 2.607)}}{\{1 + e^{(0.4734 * \Delta T - 2.607)}\}} \quad (7)$$

Figure 6 suggests the percentage of adults who are overheated is around 7% when the offset from comfort temperature is around 0K. This percentage increases to 30% when considering children's votes. This difference highlights the risk of children's thermal vulnerability compared to adults in the same space. However the comfortable benchmark which is used to plot Figure 6 is based on the adult comfortable threshold not children's. Figure 7 shows the likelihood of children overheating using the proposed children comfort temperature ($T_{comf\ children} = T_{comf\ adult}$ -3K) which has been discussed in this study, while Figure 8 shows the likelihood of adults overheating. According to Figure 7, the likely dissatisfaction rate for children can be calculated from the Equation 8.

$$P = 0.9\,(\Delta T)^2 - 0.2\,\Delta T + 15.5 \quad (8)$$

ΔT = Indoor operative temperature – ($T_{comf\ children} = T_{comf\ adult}$ -3K)

$$T_{comf/\ children} = T_{comf\ adult} - 3K$$

$$T_{comf\ /adult} = 0.33\ T_{rm} + 18.8°C$$

A comparison of these figures highlights the higher dissatisfaction rate when there is an offset from comfort temperature with children compared to adults considering suitable thermal comfort benchmark.

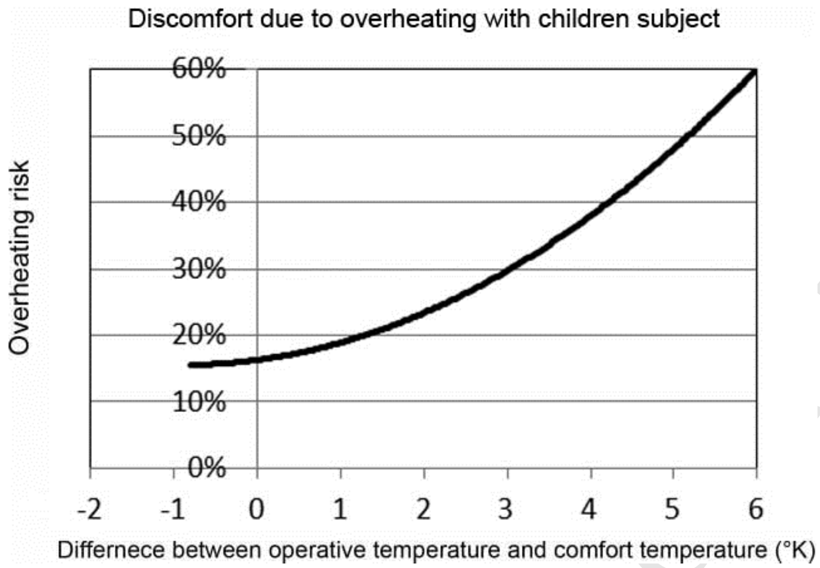


Fig 7: Discomfort due to overheating (children)
[Comfort temperature calculated based on $T_{comf/children}$= 0.33 T_{rm} +18.8°C – 3K]

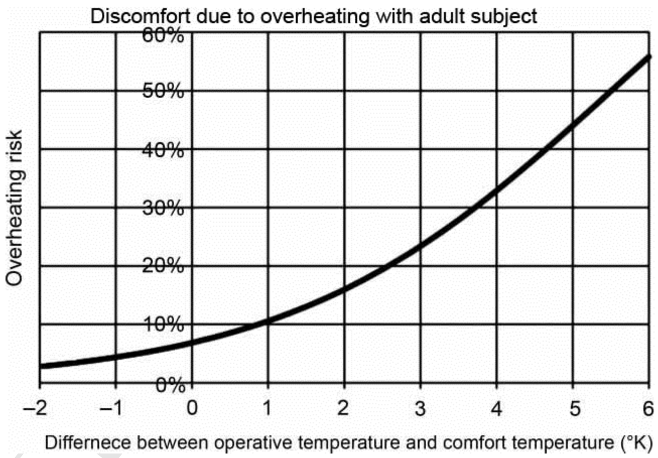


Fig 8: Discomfort due to overheating (adult) [4]
[Comfort temperature calculated based on $T_{comf/adult}$= 0.33 T_{rm} +18.8°C]

Table 4 shows the likely dissatisfaction rate when there is a difference between operative temperature and comfort temperature in a typical UK classroom with 30 children. The likely dissatisfaction rate is also calculated for an office with 30 workers. In a comfortable office space, while there is no difference between operative temperature and comfort temperature (T_{op}- $T_{comf /adult}$=0), using Figure 8, the likely dissatisfaction rate is 2 out of 30 workers while this amount using Figure 7 will reach 5 out of 30 children in a classroom with similar conditions (T_{op}- $T_{comf /children}$=0).

According to Figures 7 and 8, when there is no difference between indoor temperature and comfort temperature, the likelihood of overheating in a typical UK primary school classroom is around 16% while this figure is less than half (i.e.7%) in a similar office building. Therefore there are likely to be factors other than indoor temperature that influence an occupant's thermal sensation such as behaviour. Studies show that children can adopt personal behaviour such as adding or removing layers of clothing but their opportunity for adaptive behaviour is limited as they do not have a significant role in freely opening or closing windows or adjusting their activity level [51-52]. For this reason, there is a need to understand how children's and teacher's behaviour influences the thermal sensation of children which is discussed in the next section.

Table 4. The likely number who may overheat in a classroom and an office of 30 occupants

ΔT	Percentage of adult in Discomfort due to overheating Tcomf/adult=0.33 Trm+18.8°C	Percentage of adult in Discomfort due to overheating Tcomf/children=0.33 Trm+18.8°C - 3°C	Number of overheated in an office with 30 staff	Number of overheated in a classroom with 30 children
0	7	16	2	5
1	11	19	3	6
2	16	23	5	7
3	23	30	7	9
4	33	38	10	11
5	44	48	13	14
6	56	60	17	18
7	67	74	20	22
8	76	90	23	27

3.3. Occupant's behaviour and thermal sensation

Results outlined above suggest it is very challenging to satisfy all occupants, even in an environment where there is no difference between operative temperature and comfort temperature. Literature shows that the occupants' satisfaction is not only related to the thermal condition of a space but also to the behaviours that occupants adopt to achieve comfort [11-13]. This part of study illustrates how different behaviour influences an occupant's thermal sensation.

In this study children were asked to vote about their general thermal perception regarding their classroom's environment and also what would be their first behaviour when they feel overheated. Behaviour was grouped under personal changes and environmental changes. Personal changes refer to: taking off a jumper, drinking water and fanning themselves. Environmental changes refer to: asking teachers to open the classroom windows or door, let a classmate know their feelings of overheating and ask the classmate to do something or ask permission from a teacher to open windows or doors. In this study there are also some children that do not react and wrote 'do nothing' when they feel overheated.

Figure 9 shows the distribution of children's general thermal sensation of their classrooms in relation to their behaviours (i.e. personal change, environmental change and do nothing). A higher percentage voted to adopt personal changes compared to environmental changes.

Also, there are 9% of occupants that do nothing when they feel *Warm and Hot* and 13% of occupants that do nothing when they feel *Cold or Cool*.

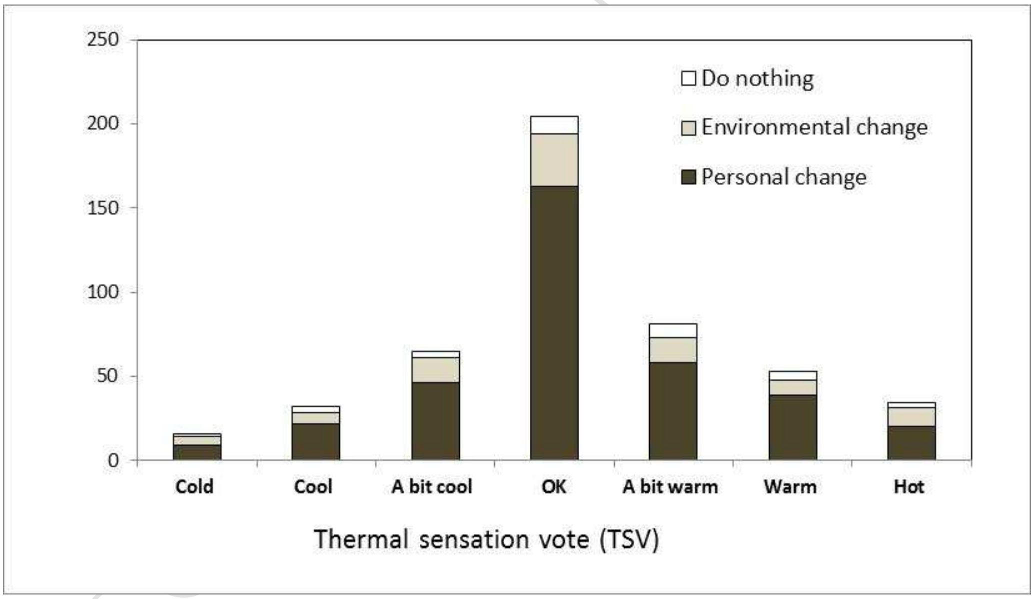


Fig 9: Distribution of thermal sensation vote from all the comfort surveys based on various behaviours

Figure 10 shows the relationship between the percentage of children who adopted '*environmental change*' and the percentage of children who are generally thermally satisfied with the classroom's environment. Figure 11 shows the percentage of children who adopted '*personal changes*' and the percentage of children who are generally thermally satisfied with the classroom's environment.

These results suggest that in a classroom with more children that adopt environmental behaviours, more are likely to be satisfied with the indoor temperature.

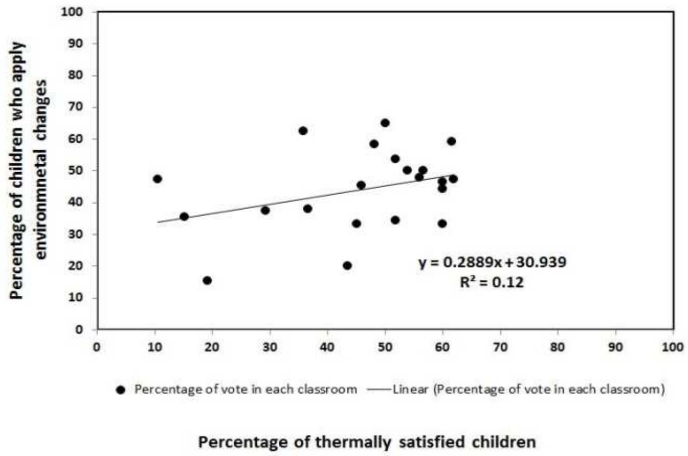


Fig 10: Relationship between children who apply environmental changes and satisfaction with indoor temperature

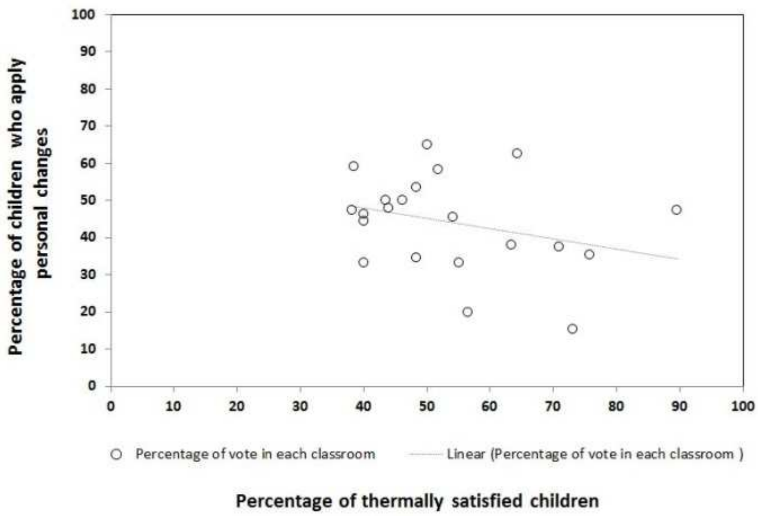


Fig 11: Relationship between children who apply personal changes with and satisfaction with indoor temperature

Figures 9 to 11 suggest that although around 74% of children adopt personal change while only 19% adopt environmental change, there is a higher level of thermal satisfaction in classrooms where they adopt the former rather than the latter.

4. Discussion:

The direct link between the attainment of children at school and the thermal conditions in classrooms means there is a need to ensure their thermal perceptions are considered in the design and refurbishment of such spaces [53]. For this reason, there is need to have a breadth of knowledge about thermal perceptions of both teachers and students as occupants of schools. This study collected the thermal perceptions of 662 children and the indoor operative temperatures of 27 classrooms in eight primary schools located in the West Midlands, UK, during the cooling seasons (i.e. June and July) of 2014 and 2015, The results of the analysis suggest that:

- The available guidelines only evaluate if a classroom as a single space is at risk of overheating without studying the likelihood of overheating among children and how the children's thermal perception can vary from their teacher. For this reason, this study developed an algorithm based on the suggested comfort temperature for children that can help building designers ensure comfort temperatures in classrooms reflect the perceptions of children. Using this algorithm, illustrated in Figure 7, will provide an opportunity to investigate the percentage of children who may be overheated in a typical UK classroom when there is a difference between indoor operative temperature and comfort temperature for children (i.e. T_{com}= 0.33 T_{rm} +18.8 – 3K). The likelihood of discomfort due to overheating for children can be calculated from Equation 8. This study also highlights that even when there is no difference between indoor temperature and comfort temperature the likelihood of different occupants (i.e. children and teacher/adult) being overheated will vary. For example, the likelihood of overheating in a typical UK primary school classroom is around 16%, (Figure 7) while this figure is less than half (i.e.7%) in a similar office building (Figure 8). This suggests that thermal perception is not only related to the indoor temperature but is influenced by other factors such as behaviour and opportunity to control the environment. The differences between dissatisfaction among children and office workers is likely to be related to the fact that adults in an office building have more freedom to control their environment while this will be limited in a primary school classroom which is mainly controlled by a teacher with different thermal sensations and preferences from children. This information helps the teacher as the main person in charge of controlling the classroom environment, firstly; to understand the thermal comfort of children in detail: secondly; to adopt an appropriate approach at the right time to establish a classroom environment which is suitable for the majority of children and consequently help maximise their academic performance.

- The results illustrate that a higher percentage of children are thermally satisfied when the classroom's indoor operative temperature is around 3K lower than the comfort temperature, estimated using existing approaches (i.e. T_{comf}= 0.33 T_{rm}+18.8° C), which is also likely to reflect the teachers' perceptions. [20]. This difference should be considered by building designers, building management systems and also teachers who mainly take control of the classroom environment. Children will be at risk of overheating and/or underperforming if classroom environments are controlled mainly according to the teachers' perceptions. In this study, the differences between indoor temperature and appropriate comfort temperature (i.e. T_{com}= 0.33 T_{rm} +18.8° C) only reached -4K. There is a need for further investigation to understand the impact on children's thermal perceptions when this difference goes beyond 4K . This study also illustrates that the percentage of children who are thermally satisfied is significantly higher when the indoor temperature is reduced from 24°C to 21°C. This result concurs with the findings of previous research which shows that such a change of temperature has a positive significant impact on students' performance [2, 48, 49, 54]. These results help teachers understand how to control classrooms more wisely in order to facilitate learning.

- This study confirms that there is a significant relationship between the percentage of children who are thermally satisfied in a classroom and the main behaviour that they adopt. Results suggest the percentage of children satisfied with the indoor temperature is significantly higher in the classrooms where children ask teachers to open the windows or doors rather than making personal changes (e.g. taking off a jumper or drinking water etc.). This result highlights the importance of a teacher's role in controlling classroom environments. In a classroom where children do not project their feelings to the teacher and only rely on personal behaviour, there is a lower level of satisfaction with indoor temperature. In contrast, in classrooms where children do not adopt any personal behaviour and only rely on their teacher to do something for them there might be a degree of distraction for teachers as well as other children. Consequently, it would be useful to explore ways by which teachers can help children express their thermal sensations as well as encourage them to adopt personal behaviour when they feel hot. Teachers should ensure as many children are satisfied with their environment as possible. Accordingly, more needs to be done to ensure children are encouraged to communicate their satisfaction with the indoor environment. Furthermore there are some students that do not adopt any reaction when they feel hot or cold. The result suggests perhaps more could be done to help children understand their options when they feel uncomfortable.

As a result, in order to help ensure future schools deliver effective learning environments:

1) Building designers need to deliver adaptable spaces in order to provide the freedom for teachers to control the classroom environment and respond to children's needs as well as their own without any difficulty. The developed algorithm illustrated in Figure 7 and Equation 8 enables the building designers

to predict the percentage of overheating in a classroom when there is a variation between indoor operative temperature and comfort temperature. This algorithm helps the teachers and school designers anticipate dissatisfaction rates under certain conditions for children and develop solutions that help to satisfy the maximum number of children. It also highlights that under completely comfortable environmental conditions the percentage of children who may overheat in a classroom is higher compared to a similar office space. This difference is likely to be due to the limitation of children in controlling the classroom environment and their metabolic rate.

2) School stakeholders (e.g. teachers, school designers, building management system, etc.) should be educated about the differences between teachers' and children's thermal perception and how poor classroom conditions could have a negative impact on children's learning process and their performance.

3) Teachers and parents need to encourage children to share their thermal perceptions with their teachers. Children's behaviour has a significant impact on their thermal perception. In particular, the percentage of children satisfied with an indoor temperature is significantly higher in the classrooms where children adopt environmental behaviour and ask teachers to open windows and doors rather than personal changes (e.g. taking off a jumper or drinking water etc.). Encouraging children to share this information will help ensure that classroom conditions are adjusted based on the children's thermal perception rather than those of adults.

5. Conclusion:

Results from this study suggest that there is a difference between the thermal perception of children and adults. Children prefer temperatures within their classroom to be up to 3K cooler than adults.. Higher thermal satisfaction has been recorded when the temperature in classrooms is reduced from 24°C to 21°C; which concurs with the range of effective temperatures thought to influence the academic performance of children.

In order to maximise the delivery of effective learning environments there is a need to understand the thermal perception of each child within a classroom and anticipate the likely dissatisfaction rate when there is a variation between indoor temperature and corrected comfort temperature for children ($T_{comf/children}$ = $T_{comf/adult}$ -3K). This study presents an algorithm which is designed to help teachers and building designers predict the likely dissatisfaction rate within a classroom and thereby deliver effective learning spaces.

In addition to the difference between thermal perceptions of children and teachers there is also a significant relationship between a child's behavioural approach to modifying their personal comfort and their thermal satisfaction within classrooms. Such behaviours are likely to be guided by external influences of which teachers and building designers need to be cognisant.

Acknowledgements: The work was funded by Knowledge Exchange & Enterprise Network (KEEN) and Architype Ltd. We would like to extend our thanks to all students and teachers of the primary schools who are participated in this study.

References:

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

[2] Wargocki, P., & Wyon, D. P. (2007). The effects of moderately raised classroom temperatures and classroom ventilation rate on the performance of schoolwork by children (RP-1257). Hvac & R Research, 13(2), 193-220.

[3] Department for Education and Skills (DfES). (2016). Building Bulletin (BB) 101, 2016: Guidelines on ventilation, thermal comfort and indoor air quality in schools. London: DfES.

[4] Montazami, A., & Nicol, F. (2013). Overheating in schools: comparing existing and new guidelines. Building Research & Information, 41(3), 317-329

[5] Department for Education and Skills (DfES). (2007). Class size and education in England evidence report. London: DfES.

[6] Department for Education and Skills (DfES). (2003). Every child matters. London: DfES

[7] Cen, E. N. (2007). 15251, Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. European Committee for Standardization, Brussels, Belgium.

[8] CIBSE, TM52. (2013). The limits of thermal comfort: Avoiding overheating in European buildings. Chartered Institution of Building Services Engineers.

[9] Teli, D., Jentsch, M. F., & James, P. A. (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.

[10] Frumkin, H. (2006). Safe and healthy school environments. Oxford University Press, USA.

[11] 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(1), 55-88.

[12] Brager, G., Paliaga, G., & De Dear, R. (2004). Operable windows, personal control and occupant comfort. Centre for the Built Environment.

[13] Leaman, A., & Bordass, B. (1999). Productivity in buildings: the 'killer' variables. Building Research & Information, 27(1), 4-19.

[14] Nicol, F., & Humphreys, M. (2010). Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. Building and Environment, 45(1), 11-17.

[15] Fanger, P. O. (1970). Thermal comfort. Analysis and applications in environmental engineering. Thermal comfort. Analysis and applications in environmental engineering.

[16] Gagge, A. P., Fobelets, A. P., & Berglund, L. (1986). A standard predictive index of human response to the thermal environment. ASHRAE Trans.;(United States), 92(CONF-8606125-).

[17] Fiala, D. (1998). Dynamic simulation of human heat transfer and thermal comfort (Doctoral dissertation, HOCHSCHULE FÜR TECHNIK).

[18] Nicol, J. F., & Humphreys, M. A. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. Energy and buildings, 34(6), 563-572.

[19] De Dear, R. J., Brager, G. S., Reardon, J., & Nicol, F. (1998). Developing an adaptive model of thermal comfort and preference/Discussion. ASHRAE transactions, 104, 145.

[20] Nicol, F., Humphreys, M., & Roaf, S. (2012). Adaptive thermal comfort: principles and practice. Routledge.

[21] Humphreys, M., Nicol, F. and Roaf, S., 2015. Adaptive thermal comfort: Foundations and analysis. Routledge.

[22] Montazami, A. Gaterell, M., (2014), Occupants' behaviours in controlling blinds/curtains in the UK Primary Schools, , Proceedings of 8th Windsor Conference: Cutting the cost of comfort in a changing world, Windsor, UK, 10-13 April 2014. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

[23] Montazami, A. and Nicol, F., 2012, April. Using an inappropriate thermal benchmark leads to overheating in UK primary schools. In Proceedings of seventh Windsor conference: the changing context of comfort in an unpredictable world Cumberland Lodge, Windsor, UK. London: Network for Comfort and Energy Use in Buildings (pp. 12-15).

[24] Ter , S., Hensen, J.L., Loomans, M.G. and Boerstra, A.C., 2011. Adaptive thermal comfort in primary school classrooms: Creating and validating PMV-based comfort charts. Building and Environment, 46(12), pp.2454-2461.

[25] ASHRAE, A. S. (2013). Standard 55-2013. Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineering, Atlanta, GA.

[26] De Dear, R. (2011). Recent enhancements to the adaptive comfort standard in ASHRAE 55-2010. In 45th annual conference of the Australian and New Zealand

Architectural Science Association (ANZAScA 2011). Sydney: Faculty of Architecture Design and Planning, The University of Sydney.

[27] 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.

[28] 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.

[29] Auliciems, A. (1969). Thermal requirements of secondary schoolchildren in winter. Journal of Hygiene, 67(1), 59–65.

[30] Pepler, R. D. (1972). The thermal comfort of students in climate controlled and non-climate controlled schools. ASHRAE Transactions, 78(1), 97–109.

[31] Auliciems, A. (1973). Thermal sensations of secondary schoolchildren in summer. Journal of Hygiene, 71(3), 453–458.

[32] Auliciems, A. (1975). Warmth and comfort in the subtropical winter: A study in Brisbane schools. Journal of Hygiene, 74(3), 339–343.

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

[34] Wong, N. H., & Khoo, S. S. (2003). Thermal comfort in classrooms in the tropics. Energy and Buildings, 35(4), 337–351.

[35] Hwang, R. L., Lin, T. P., Chen, C. P.,&Kuo, N.-J. (2009). Investigating the adaptive model of thermal comfort for naturally ventilated school buildings in Taiwan. International Journal of Biometeorology, 53(2), 189–200.

[36] 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(6), 355–363.

[37] de Dear, R., Kim, J., Candido, C., & Deuble, M. (2015). Adaptive thermal comfort in Australian school classrooms. *Building Research & Information*, *43*(3), 383-398.

[38] Trebilock M, Figueroa R. Thermal comfort in primary schools: a field study in Chile. In: Nicol JF, Roaf, SC, Brotas, L and Humphreys, MA (eds) Proceedings of the 2014 Windsor Conference: Counting the cost of comfort in a changing world, (e-book) Network for Comfort and Energy Use in Buildings (NCEUB).

[39] Haddad, S., Osmond, P., King, S., & Heidari, S. (2014, April). Developing assumptions of metabolic rate estimation for primary school children in the calculation of the Fanger PMV model. In Proceedings of the 8th Windsor Conference: Counting the Cost of Comfort in a Changing World.

[40] De Dear, R., Akimoto, T., Arens, E., Brager, G., Candido, C., Cheong, K., Li, B., Nishihara, N., Sekhar, S. & Tanabe, S. 2013. Progress in thermal comfort research over the last twenty years. Indoor air, 23, 442-461.

[41] Nam, I., Yang, J., Lee, D., Park, E. and Sohn, J.R., 2015. A study on the thermal comfort and clothing insulation characteristics of preschool children in Korea. *Building and Environment*, *92*, pp.724-733.

[42] Haddad, S. H. A. M. I. L. A., King, S. T. E. V. E., Osmond, P. A. U. L., & Heidari, S. H. A. H. I. N. (2012, November). Questionnaire design to determine children's thermal sensation, preference and acceptability in the classroom. In PLEA2012–28th Conference, Opportunities, Limits & Needs Towards an environmentally responsible architecture, 7–9 November 2012.

[43] Holaday, B. and Turner-Henson, A. (1989) ' Reponses effects in surveys with cool-age children', Nursing Research, 38 (4), 248-250.

[44] Metrological office. (2014-2015), Data from Coventry, Wolverhampton and Hereford station retrieved from the UK Met office

[45] Goto, T., Toftum, J., Dear, R.D. and Fanger, P.O., 2000. Thermal sensation and comfort with transient metabolic rates. *Proceedings of indoor air*, pp.1038-1043.

[46] Nicol, F., & Humphreys, M. (2007). Maximum temperatures in European office buildings to avoid heat discomfort. *Solar Energy*, *81*(3), 295-304.

[47] Haverinen-Shaughnessy, U. and Shaughnessy, R.J., 2015. Effects of classroom ventilation rate and temperature on students' test scores. PloS one, 10(8), p.e0136165.

[48] Shoer L, Shaffran J. a, 1972. A combined evalution of three separate research projects on effect of thermal environment on learning and performance. ASHRAE Trans;79:97-108

[49] Holmberg, I. and Wyon, D.P., 1972. Systematic observation of classroom behaviour during moderate heat stress. Educational & Psychological Interactions.

[50] Nicol, J. F., Hacker, J., Spires, B., & Davies, H. (2009). Suggestion for new approach to overheating diagnostics. Building Research & Information, 37(4), 348-357.

[51] Hwang, R. L., Lin, T. P., Chen, C. P., & Kuo, N. J. (2009). Investigating the adaptive model of thermal comfort for naturally ventilated school buildings in Taiwan. International journal of biometeorology, 53(2), 189-200.

[52] Corgnati, S. P., Filippi, M., & Viazzo, S. (2007). Perception of the thermal environment in high school and university classrooms: Subjective preferences and thermal comfort. Building and environment, 42(2), 951-959.

[53] Wargocki, P. and Wyon, D.P., 2013. Providing better thermal and air quality conditions in school classrooms would be cost-effective. Building and Environment, 59, pp.581-589.

[54] Sarbu, I. and Pacurar, C., 2015. Experimental and numerical research to assess indoor environment quality and schoolwork performance in university classrooms. Building and Environment, 93, pp.141-154.

Study	Location	Climate	Season	Ventilation type	Age group	No of responses	Tcomf / Tn (°C)
Auliciems (1969) [29]	England,UK	Temperate	Winter	NV	11 to 16	624	16.5°C
Pepler (1972) [30]	Oregon,US	Temperate	Spring / autumn	NV, AC	7 to 17	NV: 100/ AC:66	NV: 21.5-25°C AC: 22-23 °C
Auliciems (1973) [31]	England,UK	Temperate	Summer	NV	11 to 16	624	19.1°C
Auliciems (1975) [32]	Australia	Subtropical	Winter	NV	8 to 12 12 to 17	Not given	Primary school 24:2 °C Secondary school: 24:5 °C
Kwok (1998) [33]	Hawaii,US	Tropical	Winter/ summer	NV, AC	13 to 19	NV: 2181 AC:1363	NV: 26.88 °C AC: 27.48 °C
Wong and Khoo (2003) [34]	Singapore	Tropical	Summer	NV	13 to 17	493	28.8 °C
Hwang, Lin, Chen, and Kuo (2009) [35]	Taiwan	Subtropical	Autumn	NV	11 to 17	944	23 °C-24 °C
Liang, Lin, and Hwang (2012) [36]	Taiwan	Subtropical	Autumn	NV	12 to 17	1614	22.4°C-29.28°C
Teli, Jentsch, and James (2012) [9]	England,UK	Temperate	Spring	NV	7 to 11	230	20.8°C
de Dear et al. (2014) [37]	Australia	Subtropical	Summer	NV, AC, EC	10 to18	2850	22.4°C
Trebilcock (2014) [38]	Chile	Low temperature winter, high temperature summer	Winter/ summer	NV	9 to 11	774	21.1°C
Haddad et al. (2014) [39]	Iran	Temperate	Spring	NV	10 to 12	1,605	22.8°C

NV = Natural Ventilation
AC = Air Conditioning
EC= Evaporative Cooling

Region	School	Classroom	Date	Time of survey	Age	Number	Ventilation type
Wolverhampton	1	1	07-Jul-14	a.m	8_11	24	Mix Mode
		2		p.m	9_10	21	Mix Mode
		3		a.m	10_11	27	Mix Mode
Wolverhampton	2	4	08-Jul-14	a.m	8_9	30	Mix Mode
		5		a.m	9_10	29	Mix Mode
		6		p.m	10_11	23	Mix Mode
Wolverhampton	3	7	10-Jul-14	a.m	7_8	21	Mix Mode
		8		a.m	9_10	29	Mix Mode
		9		a.m	10_11	20	Mix Mode
Wolverhampton	4	10	09-Jul-14	p.m	7_8	20	Natural
		11		p.m	7_8	23	Natural
		12		a.m	10_11	26	Natural
		13		a.m	10_11	25	Natural
Wolverhampton	5	14	11-Jul-14	a.m	9_10	26	Natural
		15		a.m	10_11	28	Natural
Herefored	6	16	14-Jul-14	a.m	8_9	28	Natural
		17		a.m	10_11	24	Natural
		18		a.m	10_11	25	Natural
		19		a.m	10_11	24	Natural
Coventry	7	20	01-Jul-15	a.m	9_10	19	Natural
		21	01-Jul-15	a.m	10_11	19	Natural
		22	09-Jul-15	p.m	10_11	26	Natural
		23	09-Jul-15	p.m	10_11	33	Natural
Coventry	8	24	01-Jul-15	a.m	9_10	19	Natural
		25		p.m	9_10	29	Natural
		26		a.m	10_11	22	Natural
		27		p.m	10_11	22	Natural

TSV Scale Thermal Sensation Vote **At present I feel:**		
Hot (+3)	Hot	
Warm (+2)	Warm	
A bit warm (+1)	A bit warm	
Ok (0)	Ok	
A bit cool (-1)	A bit cool	
Cool (-2)	Cool	
Cold (-3)	Cold	

TPV Scale Thermal Prefrence Vote **I would like to be:**	
Warmer (+2)	☐
A bit warmer (+1)	☐
As it is now (0)	☐
A bit cooler (-1)	☐
Cooler (-2)	☐

	(TSV+TPV) General vote	(TSV+TPV) Instant vote
-5	.3	1.2
-4	1.0	2.1
-3	.9	3.4
-2	3.4	6.7
-1	15.9	13.5
0	34.0	39.0
1	28.9	24.7
2	13.2	7.8
3	2.2	1.5
4	0.0	0.0
5	0.0	0.0

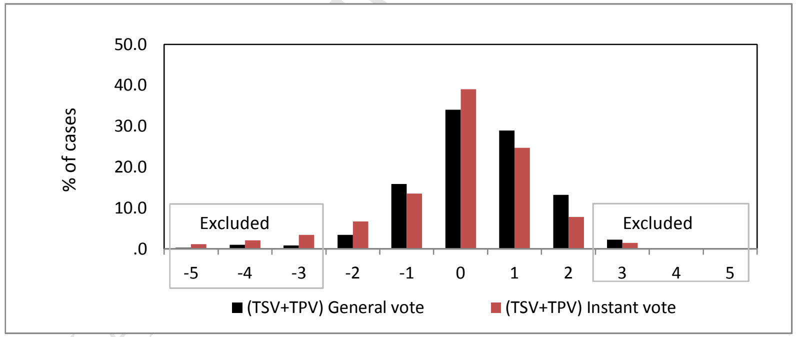


Figure.1

ΔT	Comfortable	OK
0.1	62	48
2.1	56	44
0.0	75	50
-1.7	63	21
-0.2	62	28
-3.8	67	56
-2.8	66	34
-1.5	86	57
-2.0	57	25
-1.8	72	44
-1.8	80	67
-1.2	100	68
-2.8	87	48
-0.8	83	63
-2.2	89	64
-3.4	88	67
-2.9	67	42
-2.3	91	36
-3.4	85	25
4.0	42	21
2.0	87	40
-0.5	42	21
2.0	21	16
1.0	43	19
4.5	0	0
-1.6	81	35
-2.1	32	16

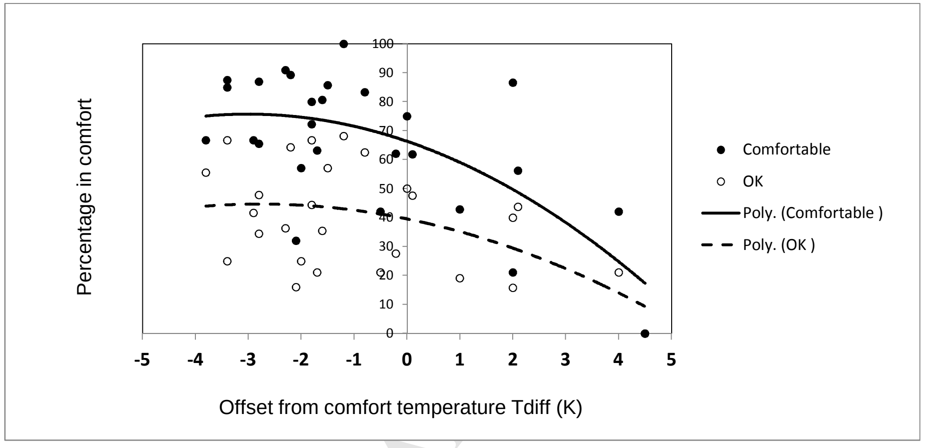


Figure 2

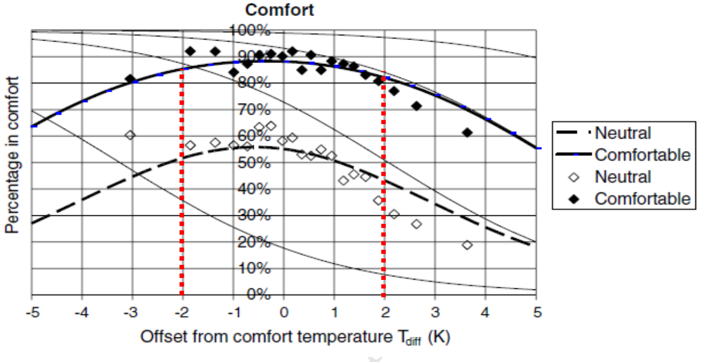


Figure 3

ΔT	Comfortable	OK
24.1	**62**	48
26.1	**56**	44
24	**75**	50
23.3	**63**	21
24.8	**62**	28
21.2	**67**	56
21.2	**66**	34
22.5	**86**	57
22	**57**	25
22.2	**72**	44
22.2	**80**	67
22.8	**100**	68
21.2	**87**	48
24.2	**83**	63
22.8	**89**	64
21.6	**88**	67
22.1	**67**	42
22.7	**91**	36
21.6	**85**	25
30	**42**	21
28	**87**	40
25.5	**42**	21
28	**21**	16
27	**43**	19
30.5	**0**	0
23.4	**81**	35
22.9	**32**	16

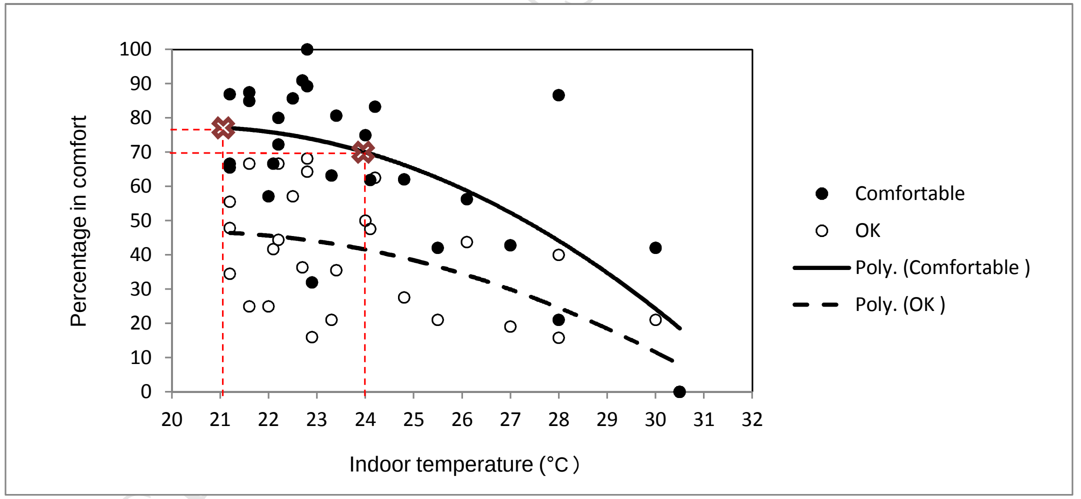


Figure.4

	No changes	Changes
0.1	62	38
2.1	88	19
0.0	81	19
-1.7	58	42
-0.2	79	21
-3.8	91	9
-2.8	90	10
-1.5	93	7
-2.0	78	22
-1.8	45	55
-1.8	86	14
-1.2	86	14
-2.8	96	4
-0.8	88	13
-2.2	96	4
-3.4	91	9
-2.9	75	25
-2.3	95	5
-3.4	95	5

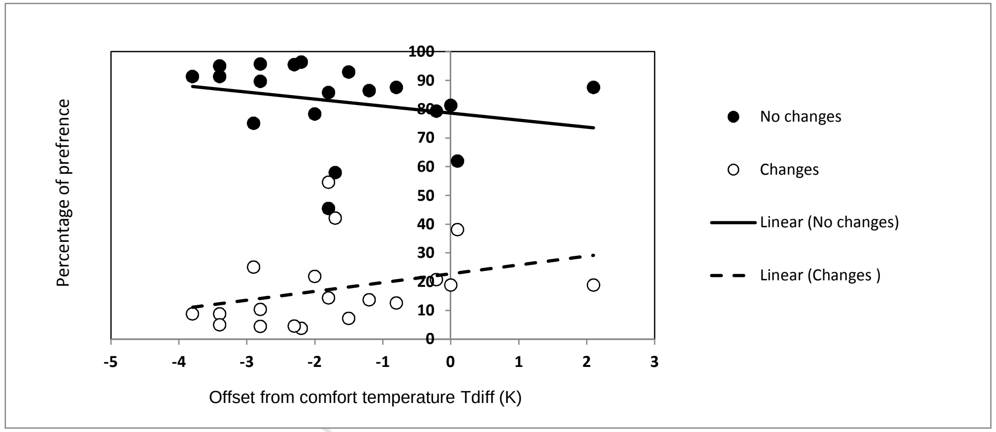


Figure 5

ΔT	Discomfort due to overheating Children	Discomfort due to overheating Adult
0	33	7
2	38	17
0	25	7
-2	32	3
0	29	6
-4	17	1
-3	25	2
-2	11	3
-2	18	3
-2	28	3
-2	13	3
-1	0	4
-3	9	2
-1	13	5
-2	11	3
-3	4	1
-3	33	2
-2	0	2
-3	10	1
4	**58**	33
2	7	16
-1	53	6
2	79	16
1	57	11
5	100	38
-2	16	3
-2	56	3

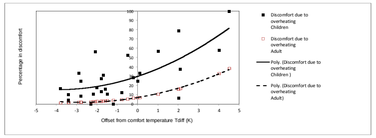


Figure 6

3K

		ΔT	Discomfort due to overheating Children
0%	0	3	33.00%
0%	2	5	38%
0%	0	3	25%
0%	-2	1	32%
0%	0	3	29%
0%	-4	-1	17%
0%	-3	0	25%
0%	-2	2	11%
0%	-2	1	18%
0%	-2	1	28%
0%	-2	1	13%
0%	-1	2	0%
1%	-3	0	9%
0%	-1	2	13%
0%	-2	1	11%
0%	-3	0	4%
0%	-3	0	33%
0%	-2	1	0%
0%	-3	0	10%
1%	**4**	7	**58%**
1%	2	5	7%
1%	-1	3	53%
1%	2	5	79%
1%	1	4	57%
0%	5	8	100%
0%	-2	1	16%
1%	-2	1	56%

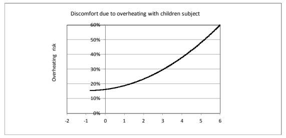
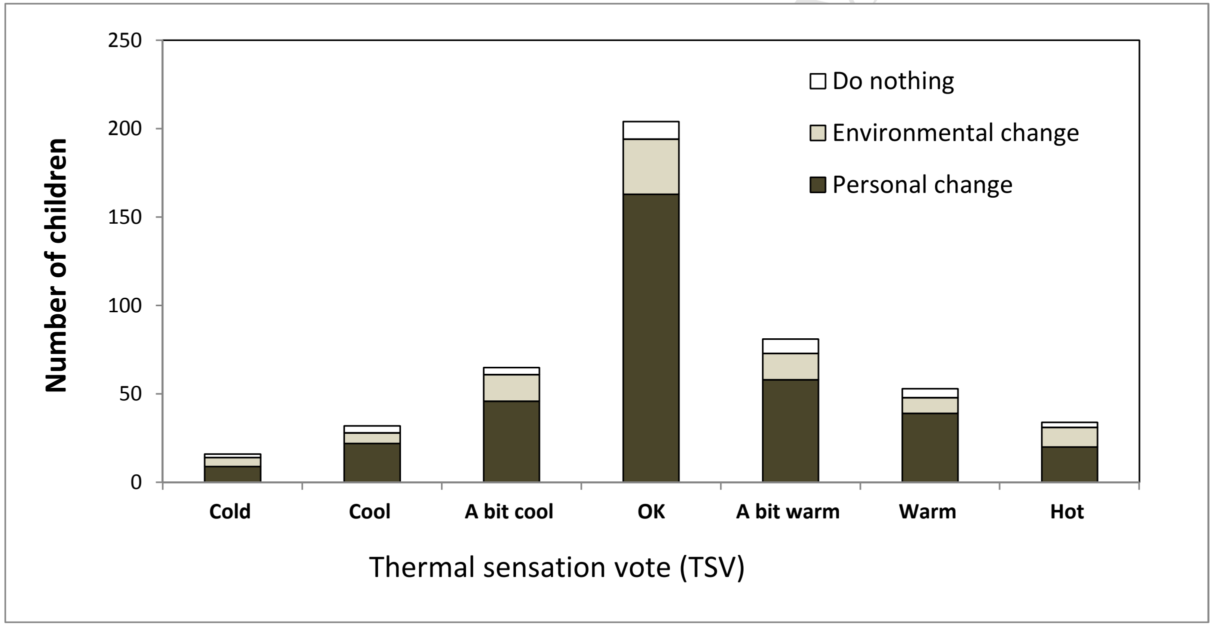


Figure 7

ΔT	Percentage of adults in discomfort due to overheating $T_{comf/adult} = 0.33\ T_{rm} + 18.8°C$	Percentage of children in discomfort due to overheating $T_{comf/children} = T_{comf/adult} - 3K$	Number of overheated in an office with 30 saff	Number of overheated in a classroom with 30 children
0	**7**	**16**	2	5
1	**11**	**19**	3	6
2	**16**	**23**	5	7
3	**23**	**30**	7	9
4	**33**	**38**	10	11
5	**44**	**48**	13	14
6	**56**	**60**	17	18
7	**67**	**74**	20	22
8	**76**	**90**	23	27

Table 4

	Personal change	Environmental change	Do nothing
Cold	9	5	2
Cool	22	6	4
A bit cool	46	15	4
OK	163	31	10
A bit warm	58	15	8
Warm	39	9	5
Hot	20	11	3



	Percentage of vote in each classroom
62	47
62	59
60	33
60	44
60	46
57	50
56	48
54	50
52	34
52	54
	65
	58
	45
	33
	20
	38
	63
	38
	15
	35
	47

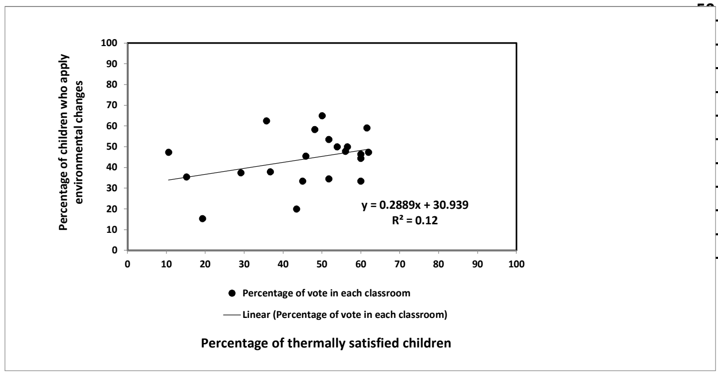


Figure.10

	Percentage of vote in each classroom
	47
	59
	33
	44
	46
	50
	48
	50
	34
	54
	65
	58
	45
	33
	20
	38
64	63
71	38
73	15
76	35
89	47

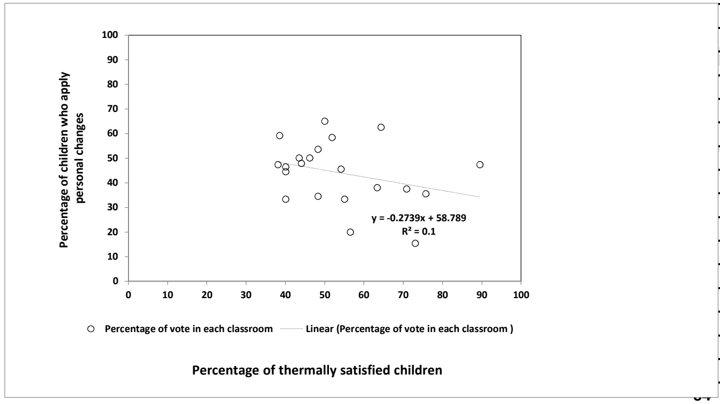


Figure.11

Highlights:

Thermal conditions of naturally ventilated schools assessed during cooling seasons.

Results show that children's thermal perception is up to 3K different from adults.

An algorithm developed to predict children's thermal dissatisfaction rate.

Children's thermal perception affected by their behaviour; environmental and personal

Teachers should be trained to control classroom considering children's perceptions