UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Civil, Maritime and Environmental Engineering and Science

Thermal performance and occupant comfort in naturally ventilated UK junior schools outside the heating season

by

Despoina Teli

Thesis for the degree of Doctor of Philosophy

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ABSTRACT

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THERMAL PERFORMANCE AND OCCUPANT COMFORT IN NATURALLY VENTILATED UK JUNIOR SCHOOLS OUTSIDE THE HEATING SEASON

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Environmental conditions in school classrooms strongly affect pupils' health and productivity. Over recent years, there has been a growing concern in relation to pupil's thermal comfort as numerous UK schools have been experiencing summer overheating. Climate projections for the UK predict warmer summer temperatures for the years to come which may exacerbate overheating occurrence. Despite the high risk for thermal discomfort in schools, information on children's thermal response and preference is limited. Current standards and guides used for the design and refurbishment of buildings are based on research with adults, usually in office environments. These standards also provide thermal criteria for schools. The purpose of this work is to investigate the applicability of these criteria to school children and to extend the knowledge base of pupils' response towards their classroom's thermal environment.

Field studies were conducted in two typical UK schools, a light-weight post war school and a heavy-weight Victorian school. The studies included thermal comfort surveys and simultaneous measurements and long-term monitoring of indoor environmental variables. The analysis of the results addresses pupils' thermal sensation and preference trends, the potential impact of building characteristics and particularities of school environments, gender differences and adaptive behaviour in classrooms. It is shown that pupils' comfort temperatures were lower than those predicted by the commonly used thermal comfort models, highlighting the pupils' sensitivity to high temperatures. Overall, the pupils' thermal sensation trends, observed in this research, suggest that there may be temperature issues and risks which are not currently addressed in policy documents and standards related to school building design and operation, due to a lack of detailed understanding of children's thermal response.

Table of contents

List of figures

List of tables

Declaration of authorship

I, Despoina Teli, declare that the thesis entitled *Thermal performance and occupant comfort in naturally ventilated UK junior schools outside the heating season*, and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research.

I confirm that:

- this work was done wholly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- parts of this work have been published as: Teli et al. (2011), Teli et al. (2012) and Teli et al. (2013).

Signed: ………………………………………………………………………..

Date:…………………………………………………………………………..

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Finally, my biggest thanks go to my other half, Nikolaos Xafenias. We shared this long journey, which made it a lot easier and truly pleasant.

Glossary of terms

AC	Air Conditioned
ACH	Air changes per hour
APD	Actual People Dissatisfied
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BB	Building Bulletin
BSF	Building Schools for the Future
CIBSE	Chartered Institution of Building Services Engineers
Clo	Clothing insulation
DEC	Display Energy Certificate
DETR	Department of the Environment Transport and the Regions
DfE	Department of Education
DR	Draught rate
DTS	Dynamic Thermal Sensation
DUKES	Digest of United Kingdom energy statistics
EST	Energy Saving Trust
ET*	Effective Temperature
FR	Free Running
g-value	Solar heat gain coefficient
HVAC	Heating, ventilation, and air conditioning
Met	Metabolic rate
NASUWT	National Association of Schoolmasters Union of Women Teachers
NV	Naturally Ventilated
PD	Percentage of Dissatisfied due to local discomfort
PfS	Partnerships for Schools
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
RMR	Resting Metabolic Rate
SCATs	Smart Controls and Thermal Comfort
SET*	Standard Effective Temperature
T_a	Air temperature
$T_{a,out}$	Prevailing mean outdoor temperature
T_{comf}	Comfort temperature
T_n	Neutral temperature
T_{op}	Operative temperature
T_p	Preferred temperature
TPV	Thermal Preference Vote
T_r	Radiant temperature

T_{rm}	Exponentially weighted outdoor running mean temperature
TSV	Thermal Sensation Vote
UHI	Urban Heat Island
UKCP09	UK Climate Projections 2009
U-value	Thermal transmittance of materials

1. Introduction

1.1 Background

The quality of the indoor environment is known to affect occupants' health, well-being, productivity and comfort (Clements-Croome, 2006, Enander and Hygge, 1990, Wyon et al., 1979). Furthermore, thermal comfort determines to a great extent the energy consumption of buildings. In the UK, buildings account for approximately 40% of the total primary energy use (DUKES, 2011). As can be seen in Figure 1.1, in the service sector HVAC systems (heating, ventilation, and air conditioning) are responsible for about 50% of the energy consumption of buildings. The use of HVAC systems is mainly driven by the comfort conditions of the occupants. Therefore, in order to achieve both thermal comfort and a well-managed use of the HVAC systems, a good understanding of occupants' thermal perception is necessary.

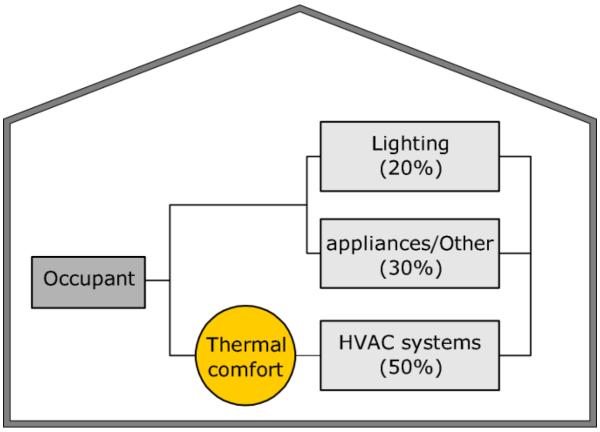

Figure 1.1. Energy use in a typical UK service sector building, data from: (DUKES, 2011).

Over several decades, a substantial amount of research has been undertaken on adult thermal comfort mainly in offices but little has been done in school environments, especially outside the heating season. The common approaches to thermal comfort, the thermo-physiological and the adaptive comfort approach, are based on studies with adult subjects and have constituted the basis for the existing international and regional thermal comfort standards [(ASHRAE, 2010), (ISO, 2005), (CEN, 2007), (ISSO, 2004)]. The same standards apply in schools but there is no guarantee that the thermal criteria for adults are also optimal for children.

Furthermore, comfort studies have focused on issues such as the comparison of different climates (Hwang et al., 2006), the difference between naturally ventilated and air-conditioned buildings (de Dear and Brager, 2002) or control strategies in naturally ventilated buildings (Raja et al., 2001). There is little information on the impact of different construction types or architectural characteristics on thermal comfort perception, especially with regards to school environments. For this reason, this study compares occupant thermal comfort conditions in two different school construction typologies, the light-weight post-war building and the traditional heavy-weight type.

In the UK, schools have been traditionally naturally ventilated. However, this is likely to change, as, over recent years, numerous UK schools have been experiencing summer overheating due to characteristics such as low thermal mass and highly glazed facades (CIBSE, 2005, Jenkins et al., 2009a). In 2008, a significant proportion of teachers (94% of respondents) reported that they had worked in excessively high temperatures during the summer term (NASUWT, 2008). Ambitious governmental school building initiatives, such as the PFI (Private Finance Initiative) and BSF programs (Building Schools for the Future), aimed to tackle this by building new schools and refurbishing existing ones (4ps and PfS, 2008). However, in 2010 the Government announced the cancellation of the new school building projects due to pressures on the public finances (Hansard Parliamentary Debates, 2010) which means that the life of the existing school building stock will have to be extended further. Therefore, this research investigates the thermal conditions in existing schools in relation to children's thermal sensation and the buildings' potential to provide comfort outside the heating season. It seeks to contribute to the understanding of pupils' thermal comfort conditions in schools outside the heating season, in terms of the classrooms' thermal performance and children's thermal perception.

Other aspects investigated in this research work include gender differences in relation to pupils' thermal sensation and preference, their feelings of overall comfort and tiredness and their adaptive behaviour in classrooms. Furthermore, the impact of building type and characteristics on pupils' perception of thermal comfort is examined. Finally, the study investigates the requirements for updating the existing thermal comfort models in order to address children's thermal perception.

1.2 Research aims and objectives

Aims

The study aims to investigate the thermal sensation of pupils in classrooms and compare it with existing thermal comfort models which are based on adult subjects. Furthermore, this research intends to identify factors which may influence the thermal comfort conditions in schools, additional to those given in commonly used comfort approaches. Finally, the thesis aims to identify the preferred thermal conditions in classrooms outside the heating season and discuss ways to achieve them.

Objectives

- To study the thermal sensation of school children and identify the temperatures found most comfortable by the pupils outside the heating season.
- To examine the influence of building characteristics, school schedule and occupant related factors, such as the controls and preferences of the teachers, on pupils' perception of thermal comfort.
- To investigate the applicability of existing international and regional comfort standards to school environments and to explore possible adjustments to the common thermal comfort approaches in order to account for the thermal perception of children.
- To compare the thermal comfort conditions outside the heating season in two case study schools representing the 'commonly found' UK school construction types (lightweight 1970s and heavy-weight Victorian).
- To assess the thermal performance of the school classrooms based on temperature thresholds from existing standards.
- To compare the classroom thermal performance with the comfort thresholds for children as determined in the previous steps, and to discuss the potential implication of the outcomes.
- To discuss the implications of the results for the design and refurbishment of school buildings.

1.3 Thesis outline

This thesis consists of nine chapters which provide a holistic approach to the thermal performance of UK schools outside the heating season and pupils' thermal comfort perception in classrooms. Figure 1.2 shows a flowchart of the thesis structure.

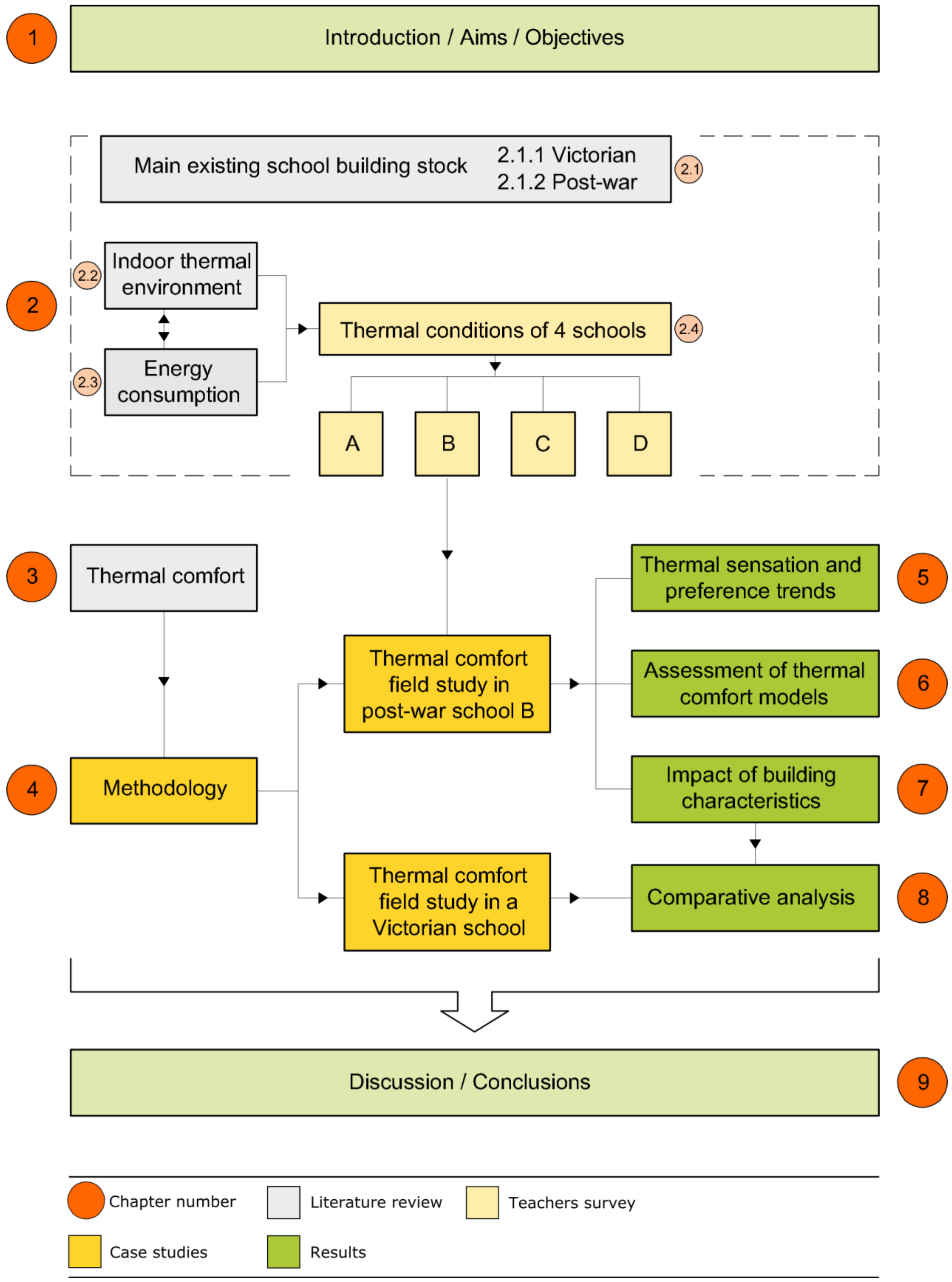

Figure 1.2. Flowchart showing the thesis structure.

2. UK school buildings

2.1 Main UK school building types

UK schools can be divided in two main categories, red-brick Victorian schools and post war light-weight structures. Most of the heavy-weight Victorian schools were constructed after the 1870 Elementary Education Act which made primary school education compulsory and therefore required quick construction of schools (Seabourne and Lowe, 1977). A large number of the existing buildings however belong to the second construction phase as one in five schools were destroyed in World War II and there was a huge demand for new buildings (Harwood, 2010). As an example, out of a total of 75 schools in Southampton, 25% were built between 1860-1940, 65% between 1950 and 1980 and 10% from 1991 onwards (information provided by Southampton City Council).

2.1.1 Victorian schools

Victorian schools are characterised by relatively compact layouts with floor to ceiling heights of typically 4.5m or even higher (DETR, 1997). They have large windows and usually a row of gables. The external walls are made of brick or stone with timber doors and timber pitched roofs covered with slate (DETR, 1997). In the early phases there was no standard design, therefore there is a variety of plan and elevation types from that period (Harwood, 2010). However, greater homogeneity was gradually developed. Figure 2.1 presents a diagrammatic plan and elevation of a typical Victorian board[1] school.

One of the main characteristics of board schools is the central hall, which was widely adopted by urban schools after 1880 (Harwood, 2010). The classrooms are usually located around the central hall for easier supervision by the head teacher. The idea of the central hall is based on the 18th century "schoolroom" which included a single classroom, initially followed by most board schools due to a lack of qualified teachers (Woolner et al., 2005).

Some designs were based on church architecture, including rose windows and a bell tower which provided storage space and also supported natural ventilation (Harwood, 2010). Due to small sites two to three storey schools were adopted in dense urban areas.

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[1] The 1870 Education Act allowed for schools to be controlled by locally elected school boards, hence the term: "board school"

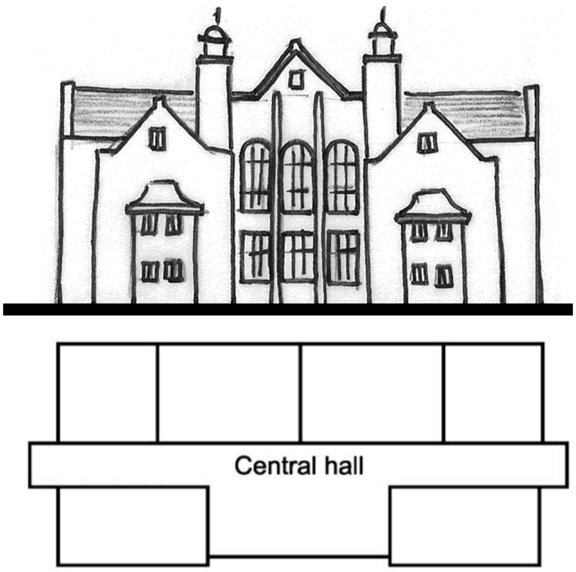


Figure 2.1. Example of a typical board school: elevation and diagrammatic plan.

2.1.2 Post-war schools

The destruction left by World War II initiated programs of social building reconstruction which had to be completed in a short timeframe (Tsoukala, 2000). Additionally, in 1944 the school leaving age was extended from 14 to 15 years which required additional space for more than 400,000 pupils (Maclure, 1984). The above affected the post-war school architecture and determined its characteristics, as explained below.

2.1.2.1 General plan and layout

The first post-war schools followed pre-1939 planning ideas and the 'Standards for School Premises Regulations 1945'[2], being single storey, long finger-plan buildings (Maclure, 1984). These schools are characterised by their large land use with only about 40 per cent of the total floor area being teaching spaces (CACfE, 1967). In Figure 2.2(a) the shaded area indicates that the corridor of such a school occupies a large space.

The finger-plan school provided improved physical conditions, i.e. better lighting and ventilation, compared to its predecessors, which were largely based on the Victorian board school concept (Figure 2.1). Better lighting conditions were achieved by orienting the teaching rooms to the south where possible (Ministry of Education, 1957). Cross ventila-

[2] The 'Standards for School Premises Regulations 1945' were published to fulfil the requirement of the 1944 Education Act for uniform standards between local authorities (Ministry of Education, 1957). They were commonly referred to as the 'Building Regulations'.

tion was obtained by using clerestory windows over the roof level of the corridor (Maclure, 1984) (Figure 2.3). Sound transmission between classrooms was minimized by keeping the rows of the finger-plan building apart and having storage spaces between the rooms (Ministry of Education, 1957). These ideas were followed up to about 1949.

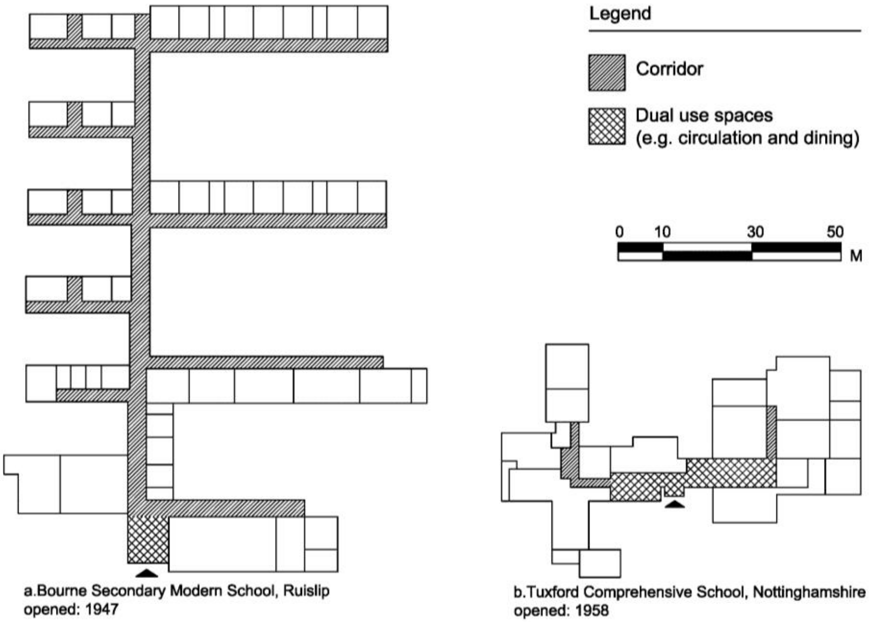


Figure 2.2. Diagrammatic plans: a. finger-plan and b. compact form (adapted from Maclure, 1984).

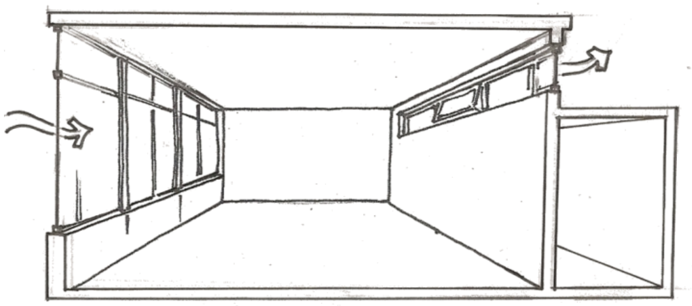


Figure 2.3. Clerestory lighting in classroom (early post-war schools).

During the first years of the 1950s more compact arrangements were built, for two main reasons, one educational and the other economic. The educational ideas were changing, requiring buildings with larger teaching areas and dual use of space by joining areas with the use of removable partitions (Ministry of Education, 1957). Furthermore, there was a need for cutting building costs after the extensive post-war reconstruction programme. Therefore, the buildings were gradually becoming more compact by a reduction in circulation areas and the addition of two storey sections (Ministry of Education, 1957) (Figure

2.2(b)). These changes also included the substitution of clerestory classroom lighting by louvred flat roof lights which reduced building volume, by reducing the classroom height, and increased planning flexibility (Figure 2.4).

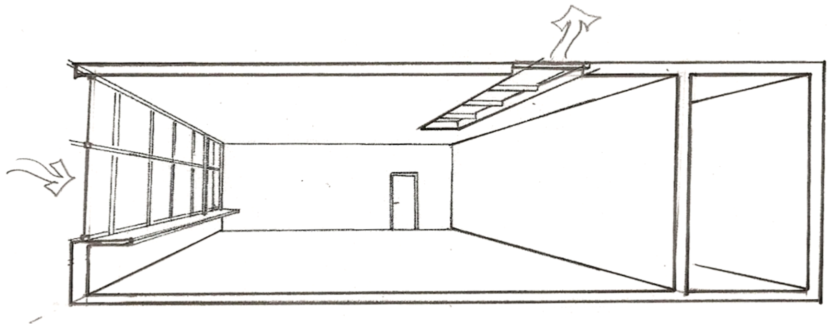


Figure 2.4. Flat roof light in replacement of clerestory lighting.

By the late 1950s and early 1960s another trend appeared which was derived from the American concept of the “school without walls” (Maclure, 1984). The open plan design aimed to provide more flexible arrangements of space compared to the series of separate identical classrooms. The open plan concept was mostly applied in primary schools but there were also some open-plan secondary schools built (Woolner et al., 2005). By the late 1970s about 10% of schools were of an open-plan design (Brogden, 2007). However, the design aroused discussions as it created a mechanically controlled indoor environment based on air-conditioning and artificial lighting (Maclure, 1984).

2.1.2.2 Structure

After the war, prefabrication and industrialisation were seen as necessary means of coping with the large demand for school places (Maclure, 1984). The aim was to apply one structural system in all schools (Saint, 1987). In 1944, the government recommended the development of a system which would allow construction of square classrooms of 24-foot (7,32m) sides. The system was proposed in 1947 and consisted of 8 feet 3 inches (2,50m) modules (Saint, 1987).

The standardised structural system was typically applied in the following four methods of school planning (Saint, 1987) (Figure 2.5):

A. The ‘bay’ plan, with spans of 8 feet 3 inches
B. The square grid, to a module of 8 feet 3 inches running in either direction
C. The square grid to a module of 3 feet 4 inches and
D. The ‘tartan grid’, to a module of 3 feet 4 inches with the columns not on the same grid lines as the walls and partitions.

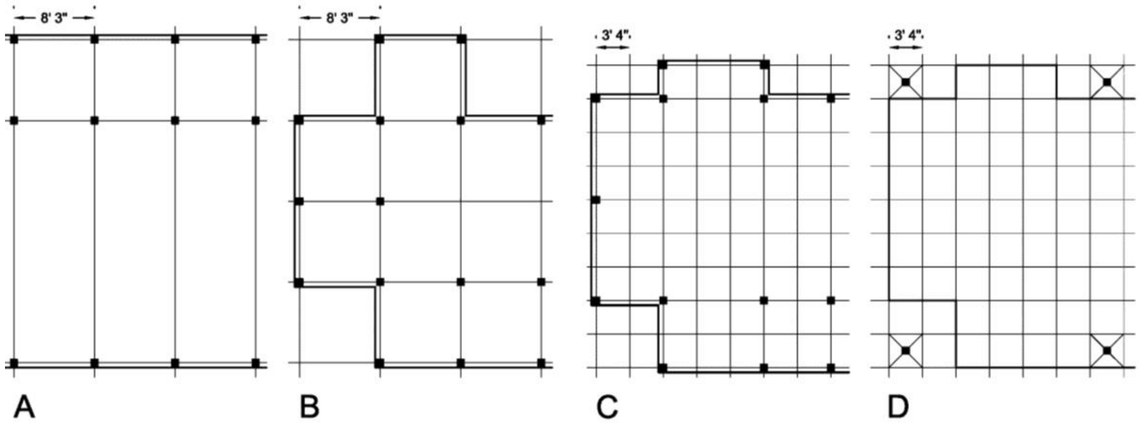


Figure 2.5. The four methods of school planning (based on Saint, 1987, p.68).

The 'bay' arrangement was widely used in schools of the 1940s and early 1950s. This produced plans with linear corridors and rows of rectangular classrooms (Saint, 1987). The grids permitted greater flexibility but they were more complex and cost more to develop. Both systems were adopted, but the grid started dominating by about 1950 (Saint, 1987).

2.1.2.3 Construction and materials

Two types of construction were used: light-weight construction and the traditional masonry construction. The new light-weight construction methods and materials were developed along with the structural system and by the 1960s they were largely adopted (Woolner et al., 2005). Nevertheless, in the 1950s three quarters of the schools were still built using traditional masonry construction methods (Maclure, 1984).

Traditional construction included the cavity wall system (Figure 2.6(a)). The outer leaf was built in facing bricks while the inner leaf was typically plastered brick. By the 1930s concrete blocks became popular for the inner leaf, but even as late as the 1950s bricks were still used.

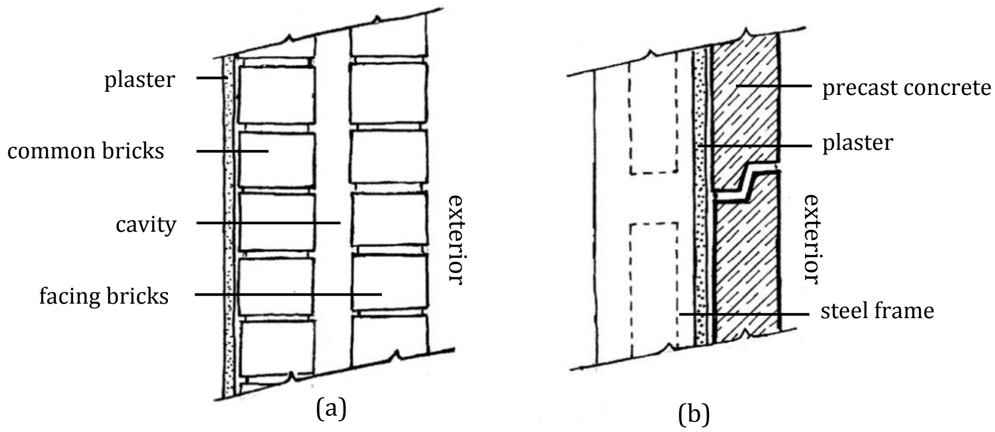


Figure 2.6. Detail of the traditional (a) and light-weight construction (b).

For the new standardised structural system, suitable materials had to be selected. Structural prefabrication in concrete was not yet fully developed so light-weight steel frames were typically used (Figure 2.7). The traditional brick construction or the *in situ* concrete for the cladding required extensive site labour and was therefore substituted by light-weight pre-fabricated concrete panels (Saint, 1987) (Figure 2.6 (b)). The roof structure was usually concrete or metal decking covered with concrete (DETR, 1997).

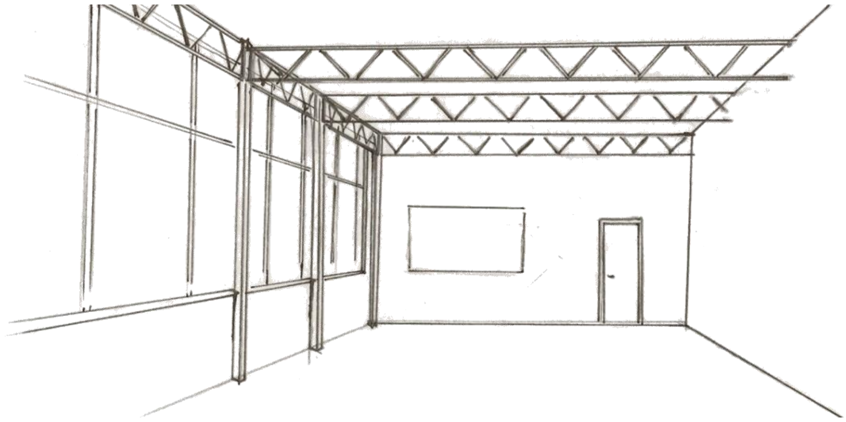


Figure 2.7. The light-steel frame which was one of the main characteristics of the new school type.

Post-war school buildings typically have metal casement windows or metal windows with timber sub-frames (DETR, 1997). They are also characterized by large glazed areas which served the need for daylight, in the general attempt to improve physical standards (Ministry of Education, 1957) (Figure 2.7). However, large glazed surfaces have an impact on the indoor thermal conditions: spaces are costly to heat (Ministry of Education, 1957) due to heat losses and summer overheating problems may occur due to large solar penetration. Such impacts on thermal environment are discussed in section 2.2.

2.2 Determinants of the indoor thermal environment and their impact on UK schools

A building's energy needs are strongly determined by the building's ability to provide comfort which is related to its indoor climate. Decisions on the ability of passive means, such as natural ventilation, to provide comfort or the need for mechanical air-conditioning as well as the evaluation of the level of heating required in a space, are based on the assessment of the indoor environment (Givoni, 1998). Therefore, the following sections discuss the parameters which influence the thermal environment inside the main UK school building types described in section 2.1.

The thermal conditions inside a building are determined by the interactions between the external climate and the building, the building shell and the internal space and between the internal space and the occupants (Oke, 1987). The parameters which determine the thermal environment in buildings are shown in Figure 2.8 and can be classified in 3 categories, as follows.

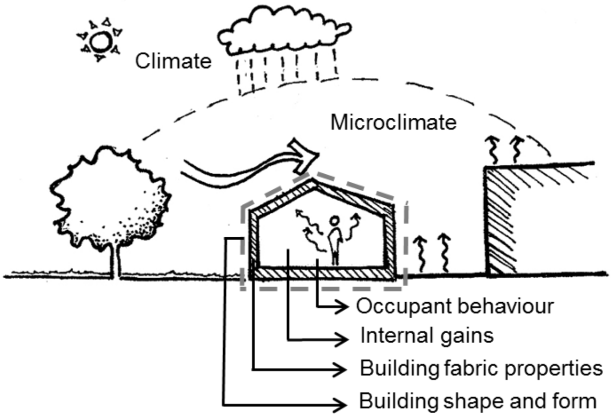


Figure 2.8. Parameters that determine indoor thermal conditions.

a. Environmental:

- External climatic conditions, i.e. the air temperature; relative humidity; etc.
- Microclimatic profile, i.e the local scale climate which is affected by the surrounding surfaces; the topography; vegetation; etc.

b. Related to the building:

- Building shape and form, i.e. the volume to surface ratio; the geometric relations; the building height.
- Building fabric properties, i.e. the properties of its construction materials.

c. Related to the occupants

- Internal gains, i.e. the thermal gains from humans and equipment.
- Occupant behaviour and preferences, e.g. closing blinds, opening windows, controlling cooling/heating systems

The above parameters are analysed below, with a special focus on their role in creating and influencing the thermal conditions in UK school buildings.

2.2.1 The impact of external climate on indoor thermal conditions

The first and most important parameter that affects the thermal conditions in buildings is the weather. The main climatic factors which affect human comfort are: air temperature, solar radiation, humidity and wind (Olgyay, 1992). Traditionally, man has been adapting his shelter to climate in order to ensure an acceptable indoor thermal environment. This is evident in vernacular architecture, from the selection of the appropriate location to the building form and materials. For example, the hemispherical Eskimo igloos addressed the survival problem in extreme cold with the insulating value of the snow and by deflecting the prevailing winds (Olgyay, 1992). In Mediterranean settlements, the high density with narrow streets and courtyards provided shading and allowed penetration of cool breezes in the summer (Rudofsky, 1977). Similar examples can be found in different climate zones around the world.

The technological achievements of the 20th century favoured the use of mechanical means for controlling the indoor environment, which led to some independence from the specific demands of regional climates. This has led to the loss of vernacular architecture principles in the design of many buildings. However, heating and cooling systems consume large amounts of energy and their extensive use conflicts with the goal to reduce greenhouse gas emissions (UK Parliament, 2008). A well-managed use of HVAC systems is essential and, therefore, climate-responsive strategies to control the indoor thermal environment are necessary.

The climate in the UK is temperate maritime, with warm summers and cool winters. It is characterised by wide variety due to the surrounding sea, the influences of mainland Europe and different topographies and land uses (Met Office, 2012). The variations from place to place can be seen in the maps of Figure 2.9, which show the annual averages for the 30-year period 1971-2000 of mean temperature, sunshine, mean wind speed and vapour pressure (Met Office, 2012). It can be seen that, in general, the south and east of the UK are characterised by warmer mean temperatures and tend to be sunnier, drier and less windy compared to places in the West and North. This means that buildings in the South and East of the UK experience warmer external climatic conditions than the rest of the UK. This is critical for UK schools as 40% of them (about 12,480 out of a total of 30,320) are located in this area (data from 2010, sources: England- DfE: Schools, Pupils and their Characteristics: January 2010, Northern Ireland: Northern Ireland Department of Education, Scotland- Summary statistics for schools in Scotland, 2010 edition, Wales- School Census, 2010).

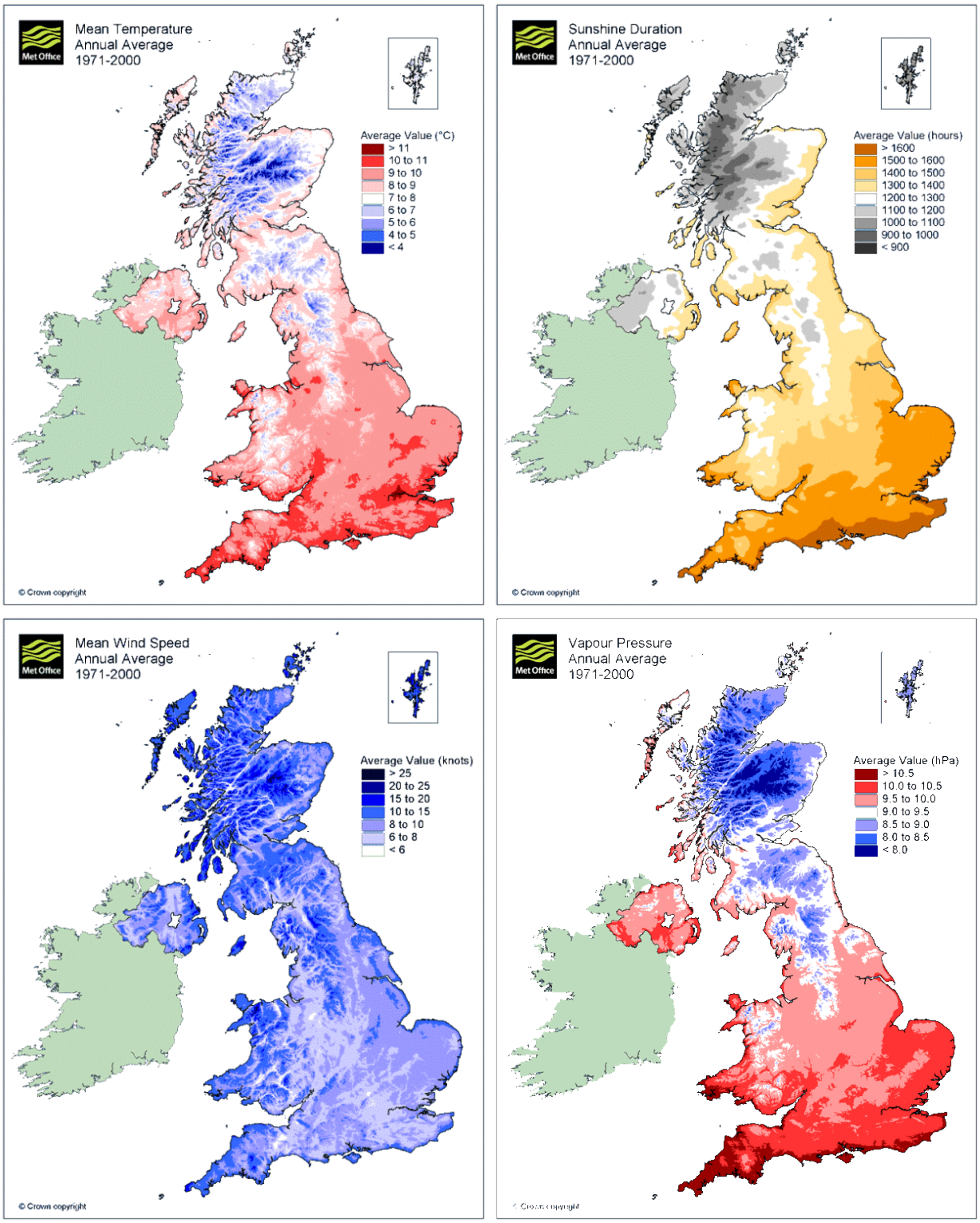


Figure 2.9. UK maps of annual averages of a) mean temperature b) sunshine c) mean wind speed (1 knot=0.514 m/s) and d) vapour pressure [image source: (Met Office, 2012): Contains public sector information licensed under the Open Government Licence v1.0].

Further to the seasonal and regional variations, during recent decades, there has been a trend for warmer temperatures (Jenkins et al., 2008). Figure 2.10 illustrates the annual time series of the UK annual mean temperature for the period 1910-2011 and the smoothed trend line (data from the UK Met Office). The grey-shaded area corresponds to the 30-yr baseline period which is used as a reference for climate analysis and for calculating future changes (Hulme et al., 2002). As can be seen, after the 30-yr baseline period there is a clear trend for higher temperatures. This change could be regarded as beneficial for the heating season but could have significant implications for the summer period leading to unacceptably warm conditions in buildings.

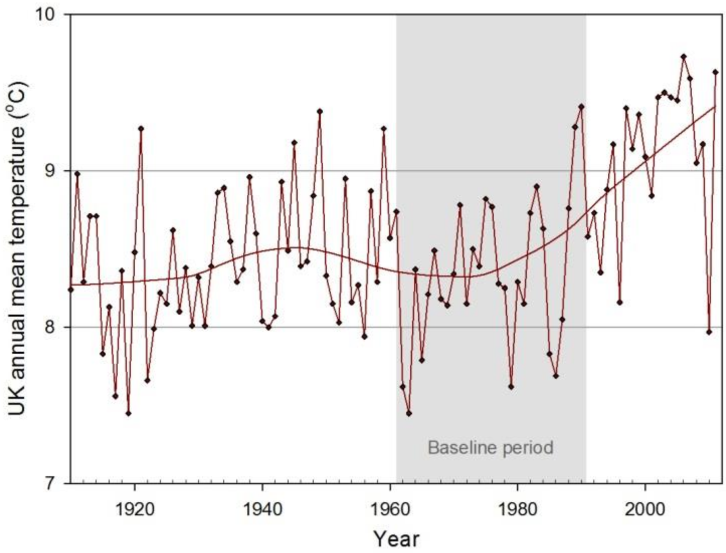


Figure 2.10. Mean annual temperature trend in the UK (Data from Met office: www.metoffice.gov.uk).

Figure 2.11 shows the annual time series of the mean summer temperature (June, July, August) for the period 1910-2011 and the smoothed trend line of England, Wales, N. Ireland and Scotland. It can be seen that there is a similar trend with an obvious rise since about 1960. However, the rising trend is more critical for England as it is the warmest of the regions with mean summer temperature of some years exceeding 16^{o}C (Figure 2.11). This means that existing naturally ventilated buildings, including most of the UK school building stock (Harwood, 2010), may not be suitable for such warmer temperatures. Furthermore, following the analysis on the different regional climates within the UK (Figure 2.9), the overheating risk of naturally ventilated schools located in the South and East of the UK could be even greater. This is highlighted in Figure 2.12, which shows the annual time series of the mean summer temperature of 3 UK cities, Edinburgh, London and Southampton, for the period 1914-2006 (data from the UK Met Office). It can be seen that there is a similar trend of rising summer temperatures between all 3 cities. However, in

London and Southampton, the mean summer temperature often exceeded 18°C while in Edinburgh it never exceeded 16°C. This highlights the importance of regional climates in assessing the external climatic conditions and trends that influence the indoor thermal environment, especially with regards to naturally ventilated buildings. Furthermore, the climate within cities is warmer than that of the surrounding rural areas due to urban heat island effects, as discussed in section 2.2.2 below. In London, for example, extreme Urban Heat Island (UHI) intensities of more than 7°C have been noted (Greater London Authority (GLA), 2006). As development increases, this UHI effect strengthens.

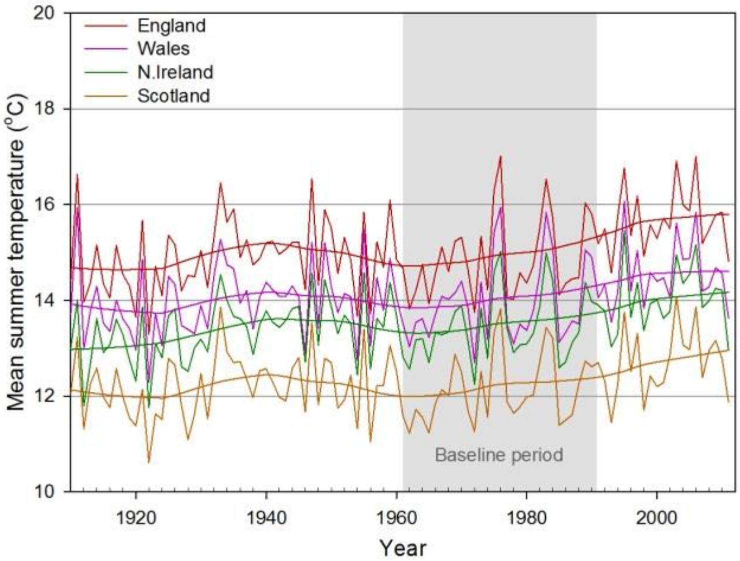


Figure 2.11. Mean summer temperatures and trend lines of: England, Wales, N. Ireland and Scotland (Data from Met office).

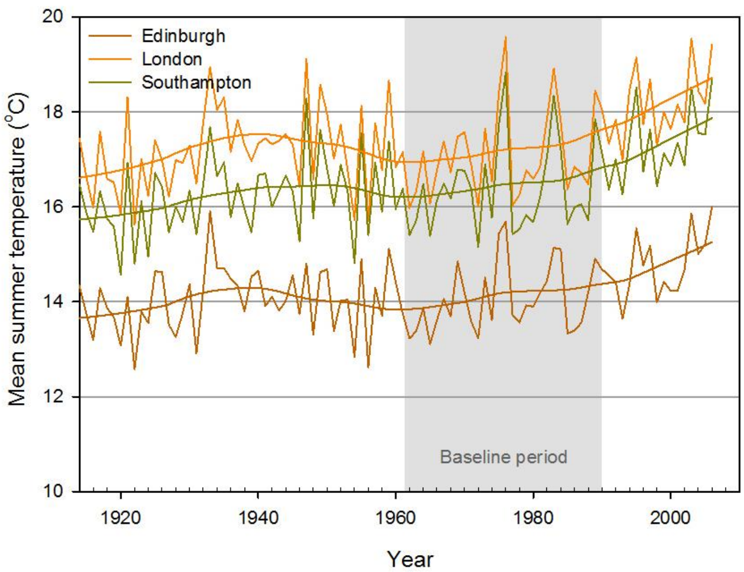


Figure 2.12. Mean summer temperatures and trend lines of: 3 UK cities, Edinburgh, London and Southampton (Data from Met office).

Further to the above, according to the 2009 UK Climate Projections (UKCP09) for the future climate in 2020s, under a medium emissions scenario for the UK, the summer mean temperature change is predicted to be about 1.5 ^{o}C while the summer mean daily maximum temperature change can be up to 3 ^{o}C, relative to a modelled 30-year baseline period of 1961–1990 (Jenkins et al., 2009b). This is likely to affect naturally ventilated schools in particular, as even higher summer temperatures will further increase the risk of overheating outside the heating season (Nicol et al., 2009).

2.2.2 The role of the microclimatic profile

The microclimate describes the climate at a local scale. It is affected by the following parameters: "topography, soil structure, ground cover and urban forms" (Dimoudi, 1996), as illustrated in Figure 2.13.

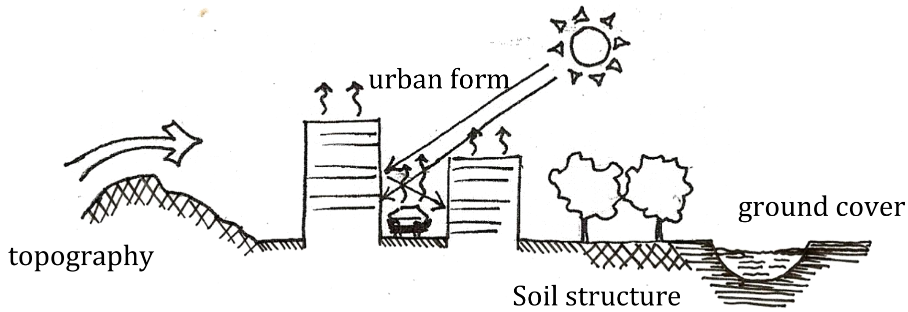


Figure 2.13. Parameters affecting the microclimate.

Air temperature in dense urban areas has been observed to be higher than in suburban and rural areas (de la Flor and Domínguez, 2004). This phenomenon, called Urban Heat Island (UHI), is driven by the following factors (Lamptey, 2009, Santamouris(ed), 2000):

- Anthropogenic heat through human activities.
- Urban canyon geometry which leads to decrease in long-wave radiation to the sky due to sky-view factor reduction and to greater absorption of incoming shortwave radiation. It also affects the wind velocity within the urban tissue.
- Thermal properties of building materials which increase daytime storage (and subsequently time-delayed nocturnal release) of solar energy.
- Air pollution which leads to a decrease in outgoing long-wave radiation.
- Increased convective heat flux due to the reduction of latent heat flux from evaporating surfaces.

The points given above influence the heat transfer within the urban environment and lead to increased air temperatures. Therefore, urbanisation leads to microclimatic modifications which may influence the indoor thermal conditions and, subsequently, the energy consumption of buildings for heating and cooling (Santamouris(ed), 2000).

Victorian schools were built over 100 years ago. Since their construction, their surrounding environment has most probably undergone transformation, especially due to urban growth. In general, schools were built in areas which could provide space for large school grounds, therefore mostly in suburban and rural areas. However, important changes have occurred to the surrounding environments of many school buildings. Urbanisation has resulted in denser built areas with more hard surfaces and less green spaces. A fundamental change occurred in the mode of transport with the widespread use of cars which had a great impact on the built environment. Some changes as a result of urbanisation can be identified by comparing aerial photographs of the schools in different time periods, as shown in the example below.

Figure 2.14 shows two schools in Southampton and their surrounding environments, in 1999 (left hand side) and 2007 (right hand side). In the first example, a large undeveloped area next to the school grounds was transformed to a parking space, so what used to be soft ground and vegetated areas has become a large tarmac area. This may have affected the microclimate around the school, given that a difference in relative air temperature above surface between asphalt and grass of 23°C has been reported (Doulos et al., 2004). In the second example, shown in Figure 2.14, a residential complex was built very close to the school building where an area of green space used to be. Further to the impact of the surface material change similar to the previous example, the additional building volumes might have affected the airflow around the school by deflecting the prevailing SW winds commonly experienced in Southampton (Met Office, 2012). If such changes occurred within only 8 years, it can be concluded that the surrounding environment of schools has most probably changed significantly since their construction. Such changes in the microclimatic conditions may have an impact on schools' indoor thermal conditions. For instance, in Mason Moor School in Southampton (Figure 2.14), the obstruction of the wind flow by the newly built residential complex has probably affected the ventilation potential of the SW side of the school. The above suggests that for the assessment of the thermal environment of schools it is essential to take into account changes in the microclimate that may have occurred and their impact on school areas.

Figure 2.14. Above: Swaythling Primary school, Southampton, constructed in 1907, Below: Mason Moor primary school, Southampton, constructed in 1952 (images adapted from: Google Earth).

2.2.3 The building shape and form

The main influence of building shape on the indoor thermal conditions is the surface area of the building envelope relative to the volume (Givoni, 1998). The surface to volume -or floor area- ratio of the building determines its exposure to solar radiation and the ambient air. Figure 2.15 shows two building configurations with the same volume but different envelope surface areas.

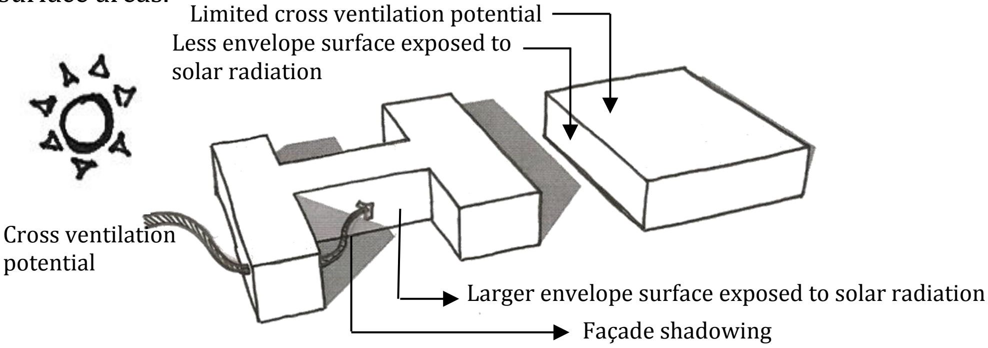


Figure 2.15. 'Finger-plan' and compact configuration.

Victorian school buildings typically have a high ventilation potential due to their high ceiling and therefore large volume (English Heritage, 2010). Compact building forms, such as most school buildings after 1952, result in smaller exposed surface areas, for a given volume or floor area of the building (Givoni, 1998) reducing heat loads but also, making cross ventilation difficult. In buildings with spread out plans, such as the early post-war finger-plan schools, large surfaces are exposed to solar radiation, which may lead to high indoor temperatures outside the heating season. However, in these buildings, the view of the sun is often obstructed due to overshadowing (see Figure 2.15), an effect which increases with latitude (Yannas, 2001). Furthermore, spread out buildings have better potential for cross ventilation (Givoni, 1998). Overall, the above school building configurations create different thermal environments and depending on their characteristics, e.g. their construction materials, may lead to overheating and/or ventilation issues outside the heating season.

Building form can influence the indoor temperatures by altering the microclimatic conditions (Shashua-Bar et al., 2004). For example, for courtyard forms studied by Shashua-Bar et al (Shashua-Bar et al., 2006), shallow built up units were measured to be warmer compared to the reference meteorological station, while deep units were found to be cooler. Similarly, the airflow pattern around buildings is significantly affected by different building shapes and orientations (Oke, 1987). For example, in Figure 2.16(b) the building is oriented diagonally to the flow resulting in two windward and two leeward sides whilst in (a) there are one windward and three leeward sides. This implies that the indoor thermal environment may be affected, depending on whether the building's configuration obstructs or deflects the airflow around it.

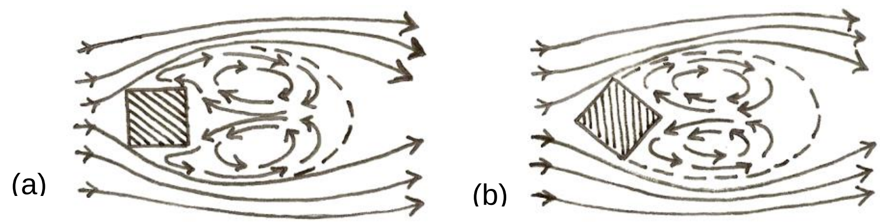


Figure 2.16. Different airflow pattern due to change in orientation (adapted from Oke, 1987).

The impact of changes to the airflow pattern can be identified in many existing school buildings, as many schools went through a number of alterations of their shape and form since they were built. This might have affected the thermal conditions inside the schools. Extensions for accommodating increasing numbers of pupils were common and can be seen in many school plans (Maclure, 1984). Figure 2.17 shows two schools in Southampton with different construction phases. In both examples, the extensions compromised the lighting and cross ventilation potential of the adjacent school spaces.

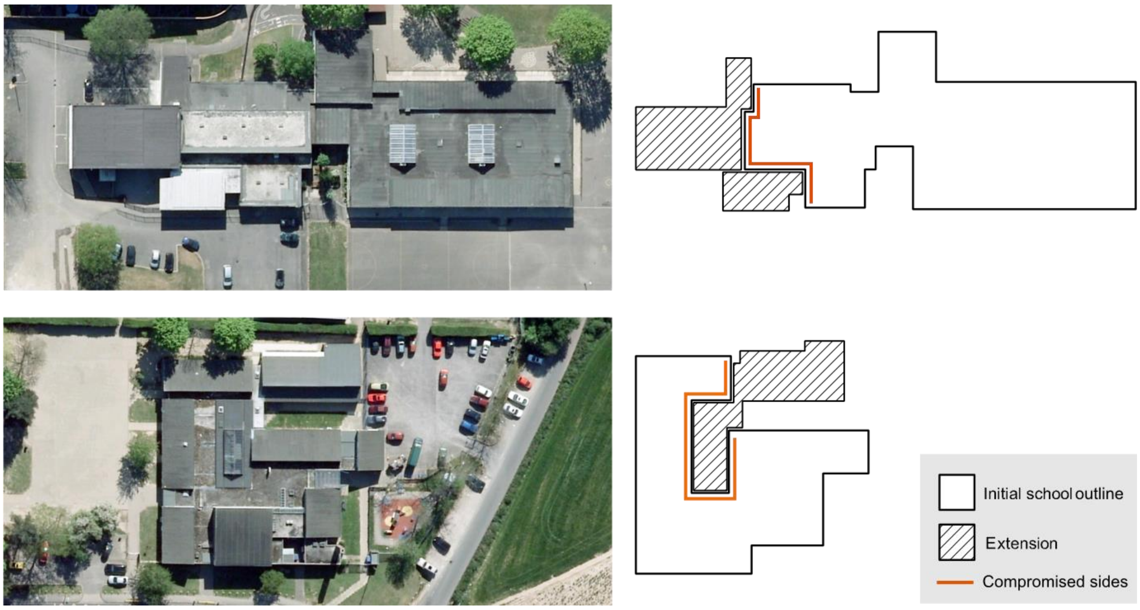


Figure 2.17. Above: Mason Moor school, Southampton, below: Holy Family Catholic Primary. Aerial photographs (Google Earth) and diagrammatic plans.

2.2.4 The building fabric properties

The building envelope is the main interface between the external and internal environments. The thermo-physical properties of its materials (façade materials, window openings, and roof cover) determine to a great extent the indoor thermal environment.

The material properties which influence the thermal performance of surfaces and subsequently the indoor thermal conditions (Figure 2.18) are:

- thermal transmittance
- reflectivity (albedo)
- emissivity
- thermal capacity

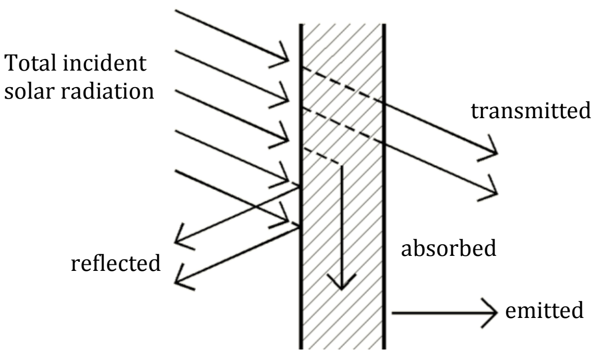


Figure 2.18. Heat exchange between the sun and the building envelope.

The **thermal transmittance** (U-value) of the building envelope is "the principal factor in the determination of the steady-state heat losses/gains" (CIBSE, 2006). It is the rate of transfer of heat (in watts) through one square meter of a structure divided by the difference in temperature across the structure (W/m^2K). The **thermal capacity** characterises the amount of heat that is required to change a body's temperature by a given amount (J/K). It expresses the ability of a material to store heat. High thermal capacity leads to time-delayed release of energy. Thermal transmittance and thermal capacity are the two main thermal properties of building elements which determine the heat flow and subsequently the thermal performance of buildings (Givoni, 1998).

Table 2.1 compares typical insulation values of Victorian and post-war school buildings. These building types were constructed in periods with either no or very low insulation requirements. However, they differ in their thermal capacity. The high thermal mass of Victorian school buildings has the ability to provide day-time cooling in summer by acting as a thermal store of heat, which is purged at night-time. On the contrary, the light-weight construction of the poorly insulated prefabricated post-war schools as described in section 2.1.2.3, made the spaces hard to heat in winter and often hot in the summer (Woolner et al., 2005) due to the quick response of their building elements. The post-war school building regulations were based on "outdated theories of infection" requiring no less than 6ACH (air changes per hour) in classrooms (Saint, 1987) (Table 2.2) while, in the current regulations for school buildings, a room with a value of 5ACH is considered as "well-ventilated" and is required for science labs to prevent the build-up of pollutants (DfES, 2006). The focus of the post-war period on fresh air exchange compromised to an extent the buildings' air tightness. Table 2.2 compares the recommended ventilation rates for school classrooms, based on past and current guides, in l/s/p and ACH. It can be seen that the current suggested rates are overall lower than those in the post-war regulations, except for the CIBSE Guide A, which recommends 10 l/s/p. However, the CIBSE Guide refers to the school Building Bulletin 101 for specific requirements for school buildings, where the minimum requirement is for 3l/s/p.

Table 2.1. Typical UK school building wall U-values (calculated based on properties of construction materials found in (CIBSE, 2006))

	U-value (W/m^2K)
Heavy-weight (Victorian) school (solid wall, no cavity)	~2.0
Light-weight (post-war) school	0.8-1.7
Recommended U-value for new buildings other than dwellings (The Building Regulations Part L, 2010)	0.28

Table 2.2. Suggested ventilation rates for school classrooms

	L/s/p	ACH[1]
Post-war school building regulations	-	6
CIBSE Guide A (recommended ventilation rate)	10	7.5
Building Bulletin 101 (minimum ventilation rate)	3	2.5
Building Bulletin 101 (achievable ventilation rate)	8	6

[1] The air changes per hour (ACH) were calculated for a typical UK classroom with an area of $60m^2$ and a height of 2.4m. The Post-war school building regulation was provided in ACH.

The **albedo** indicates a surface's or body's diffuse reflectivity. Higher albedo results in less solar radiation being absorbed by a building material. Emissivity is the relative ability of the material's surface to emit long-wave radiation. It is a measure of a material's ability to radiate absorbed energy. Common dark coloured cladding materials found in UK schools, such as brick, metal sheet or concrete panels, have low albedo (0.2 on average), compared to materials such as whitewashed stone or white marble (Table 2.3). This means that the school building materials absorb large amounts of solar radiation, which could contribute to classroom overheating during the summer period.

Table 2.3. Albedo of typical materials, adapted from: (Santamouris(ed), 2000). Highlighted are materials typical in UK school buildings.

Surface	Albedo	Surface	Albedo
Walls		*Roofs*	
Concrete	**0.10-0.35**	**Asphalt**	**0.10-0.15**
Brick/Stone	**0.20-0.40**	**Tar and gravel**	**0.08-0.18**
Whitewashed stone	0.80	Tile	0.10-0.35
White marble chips	0.55	Slate	0.10
Light-coloured brick	0.30-0.50	Corrugated iron	0.10-0.16
Red brick	**0.20-0.30**	Roof coatings	0.70-0.80
Dark brick and slate	**0.20**	*Paints*	
Limestone	0.30-0.45	White/Whitewash	0.50-0.90
		Red, brown, green	0.20-0.35
		Black	0.02-0.15

Two coefficients determine the heat gains from glazed surfaces, the U-value as described above and the **g-value** (Solar heat gain coefficient). The g-value is the fraction of incident solar radiation that actually gets through a glazed surface as heat gain, which includes both the directly transmitted radiation and the absorbed and re-radiated energy. The internal heat gains are affected by the windows' size, orientation and shading conditions. Large glazed surfaces, common characteristic of post-war schools, allow greater penetration of solar radiation which results in higher indoor temperatures (Kontoleon and Bikas, 2002). Many of the existing school buildings have single glazed clear glass windows (U= 4.8 and g=0.86). This means that a large amount of solar radiation is admitted through the windows inside the classrooms, unless there is some window shading provided.

2.2.5 Internal gains

One of the important determinants of the thermal environment inside buildings is the heat produced by humans and their activities. Especially when investigating overheating in buildings other than dwellings, it is important to understand the temporal variation in gains generated inside the buildings in order to identify times of peak temperatures due to internal gains which may coincide with large solar gains (Jenkins et al., 2009a).

Internal heat gain is the sensible and latent heat emitted within an internal space by the following sources (CIBSE, 2006):

- Human bodies
- Lighting
- Computing and office equipment
- Electric motors
- Cooking appliances and other equipment

In schools, activities alternate within the course of a day, with break-times for outdoor activities and lunch. During classes, the gains from occupants can be quite substantial due to the dense occupancy of the classrooms of up to 30 pupils. If the heat gains/person are taken as: 75 W for staff and 60 W for children (Jenkins et al., 2009a), then the total heat gains associated with occupants per classroom is 1875 W (30 children, 1 adult), which is quite significant. Furthermore, there has been an increase in the use of electrical equipment in schools (computers, photocopiers, interactive whiteboards and data projectors) (Godoy-Shimizu et al., 2011) which has also led to higher school internal gains.

2.2.6 Occupant behaviour

The indoor thermal environment also depends on the available controls to building occupants which can modify the effects of the outdoor climate (Raja et al., 2001). These controls may include:

- HVAC systems
- Electric fans

- Openable windows, doors, blinds, curtains or solar shading control
- Lighting control

In schools, typical controls of the indoor environment may include all of the above. The majority of the UK schools are naturally ventilated and, therefore, the indoor thermal environment outside the heating season is mainly controlled by the occupants. However, the availability and usability of controls in schools are rather complex issues, as safety and security considerations to an extent limit their use, e.g. window opening size, night-time purge ventilation possibility. In addition, controls, such as window opening, may not be accessible while their use is restricted to the teachers, who are responsible for the environment that the pupils experience. This research aims to investigate the way environmental controls are used in school classrooms and how their use affects pupils' comfort.

2.3 Energy consumption in UK schools

Schools have been estimated to produce 1.32% of the UK's total CO_2 emissions (Global Action Plan et al., 2006). With the UK Government's target to reduce greenhouse gas emissions by 80% from 1990 levels by 2050 (UK Parliament, 2008) the non-domestic sector, including schools, should contribute to emissions savings (Godoy-Shimizu et al., 2011), despite the small overall share in emissions of schools.

As can be seen in Figure 2.19, the main source of the schools' carbon footprint is building energy use, followed by procurement and travel (DCSF, 2010). Space heating is the largest consumer of energy, constituting 60% of a typical school's energy consumption (Figure 2.19). As can be seen in Figure 2.20, mechanical ventilation and cooling have a very small share to the education-sector energy consumption, highlighting the fact that UK educational buildings (schools and universities) have traditionally been naturally ventilated.

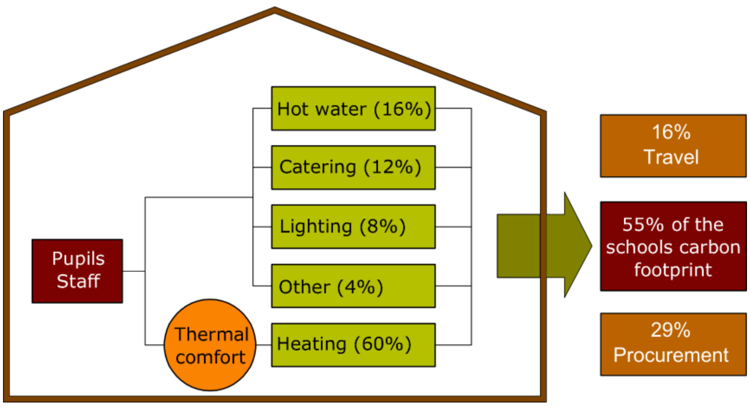


Figure 2.19. Energy consumption of a typical school, data from: (Carbon Trust, 2010, DCSF, 2010).

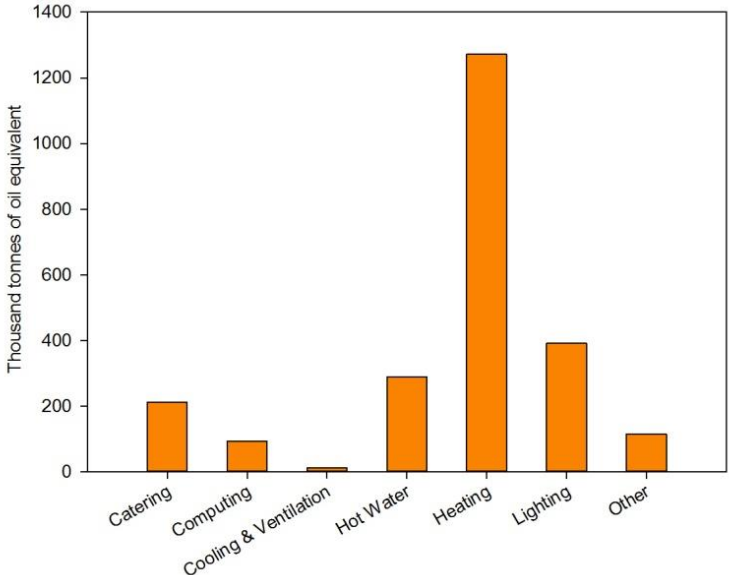


Figure 2.20. Energy consumption in the education sub-sector (schools and Universities) by end use 2009 (Source: Department of Energy and Climate Change- secondary analysis of data from the Digest of UK Energy Statistics and Building Research Establishment).

CIBSE has defined energy benchmarks for 29 building categories, for use as a reference for the assessment of buildings' energy efficiency (CIBSE, 2008). These benchmarks are needed for issuing the Display Energy Certificate (DEC), which is mandatory in England and Wales since October 2008 for schools (UK Parliament, 2007) and presents the actual metered energy use of buildings on an annual basis. For schools, the energy benchmarks are: fossil-thermal (heating)=150kWh/m^2 and electricity=40kWh/m^2, both of which represent the median for the existing school building stock. However, it has been found that these benchmarks overestimate fossil-thermal energy consumption and underestimate electricity consumption (Godoy-Shimizu et al., 2011).

It should be noted that the fossil-thermal energy consumption includes heating associated with natural ventilation, which can be calculated using equation (2.1) (MacKay, 2009)

$$Q = 1/3 * N * V * \Delta\theta \qquad (2.1)$$

Where Q= ventilation heat load (Wdays), N= Number of air changes per hour (AC/h), V=volume and Δθ=heating degree-days[3].

[3] 'Heating degree-days' (HDD) are the accumulated temperature difference between the prevailing ambient temperature and a 'base temperature', above which no heating is required (in the UK, base temperature: 15.5^{o}C) (CIBSE, 2006). HDD is a measure of heating energy demand in buildings.

As an example, the typical heat load associated with ventilation of a standard classroom in the South of the UK with V=144m^3 (60m^2*2.4m), N≃5 AC/h (DfES, 2006) and Δθ≃2000 (approximate mean total degree-days for Southern UK (CIBSE, 2006)) is: Q= 1/3*5*144*2000 Wdays = 480 kWdays = 11520 kWh. Per m^2 floor-plan: 11520/60=192 kWh/m^2. Taking into account the occupancy hours (school hours=8=1/3day) when heating is on: Q=192/3=64kWh/m^2. This is more than one third of the fossil-thermal energy benchmark for schools (150kWh/m^2), which means that a substantial amount of the heat load in schools is associated with ventilation.

Figure 2.21 shows the annual electrical and fossil energy use variation in kWh/m^2 according to UK school type and percentile for the period 1995-2008. The 25th percentile corresponds to 'good practice' schools and the 50th percentile (median) to the typical schools (BRE, 1998). As can be seen, there has been a reduction in fossil-thermal energy use which, however, was offset by rises in electrical energy use. This trend is reflected in the variation of CO_2 emissions, as demonstrated in Figure 2.22 for the period 1999-2008. As can be seen, both the median and 'good-practice' emissions have increased over these 9 years. This suggests that the CO_2 savings achieved through stricter insulation and heating plant requirements over recent years have been offset by the increase in electrical equipment use, coupled with the high carbon intensity of the grid (Godoy-Shimizu et al., 2011). This highlights the complexity in deciding and applying carbon emissions reduction measures and the need for a holistic investigation of schools' energy performance for a better understanding of the parameters that determine their energy use.

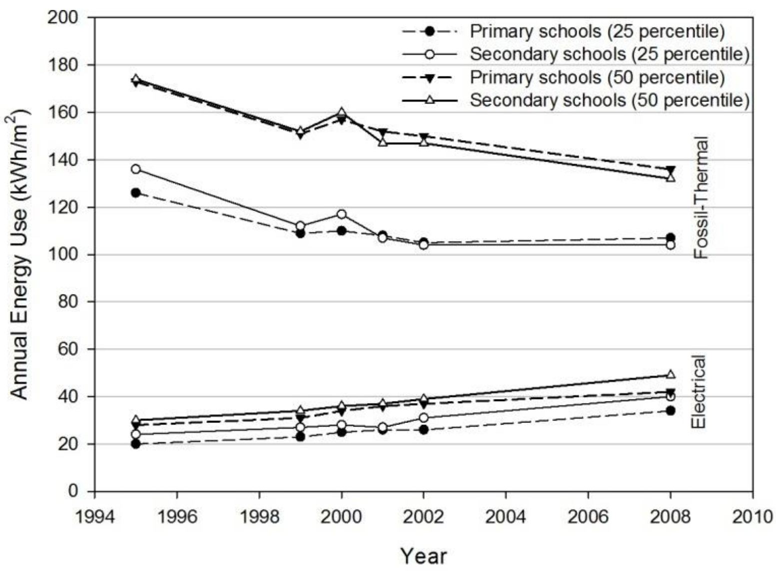


Figure 2.21. Energy use in UK schools for the years 1995, 1999-2002, 2008. Adapted from: (Godoy-Shimizu et al., 2011). Data sources: (BRE, 1998), (DfES, 2003b) and DEC database 2008-2009.

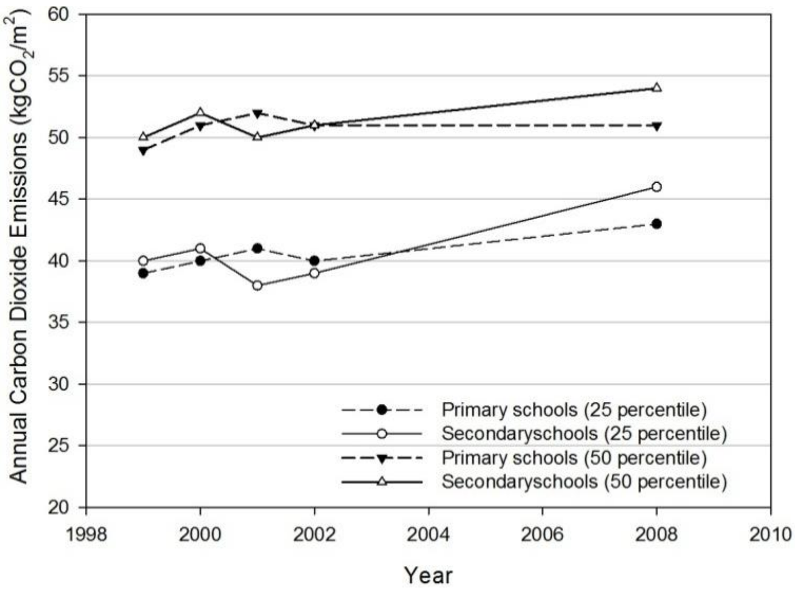


Figure 2.22. UK school CO_2 emissions 1999-2002 & 2008. Adapted from: (Godoy-Shimizu et al., 2011). Data sources: (DfES, 2003b) and DEC database 2008-09.

As discussed in section 2.2.1, there has been a trend for increasing ambient temperatures, and predictions for even warmer conditions in the future (Jenkins et al., 2009b). Therefore, it is likely that existing schools may consider resorting to mechanical ventilation and cooling to achieve comfort outside the heating season. Such a shift would mark the onset of a transition from a heating-driven to a cooling-led energy use with implications for carbon emissions. If retrofitting of mechanical ventilation and cooling is adopted, the increase in electricity consumption may not be offset by fossil fuel reductions, which, as seen in Figure 2.21, was already the case over recent years from appliance usage (Godoy-Shimizu et al., 2011). The following section presents an investigation conducted within this work that explored the thermal conditions in 4 post-war schools in Southampton outside the heating season in terms of their overheating risk and occupant satisfaction.

2.4 Evaluation of the thermal conditions in 4 case study schools outside the heating season

Based on the analysis of the parameters affecting the indoor thermal environment (section 2.2), UK schools run the risk of overheating outside the heating season due to factors such as the trend for warmer summer temperatures, changes in their surrounding environment, their form which often compromises ventilation, their large glazed surfaces, the high occupancy density and the inadequacy of available controls. Furthermore, the post-war light-weight schools have a higher overheating risk compared to the Victorian buildings, due to their low thermal mass and highly glazed facades. This was previously demonstrated by a post-occupancy survey in 3 school buildings from different construction phases (late 1800s, 1970, 2004), which highlighted significant differences in the level of satisfaction of the occupants (school staff) with the thermal environment (Bunn and Leaman, 2007). The new school, constructed under recent building standards, overall received the highest comfort scores from the teaching and administration staff, followed by the Victorian building which was also assessed as comfortable both in winter and summer. The highly-glazed light-weight school of the early 1970s received low scores both in winter and summer for being too cold and too hot respectively.

In order to evaluate the thermal environment and overheating risk of post-war schools and the way this is perceived by the occupants, four case study schools in Southampton were investigated. The schools were studied in terms of the parameters or the combination of parameters that may affect their indoor thermal conditions. The study comprised two components: (i) an aerial photo analysis of the schools and their surrounding environment and (ii) a questionnaire survey of the teachers.

The aerial photo analysis, which is highlighted in Figure 2.23, included:

- the surrounding urban environment (urban density level, building heights, adjacency to roads/parks/fields/water).
- the school grounds (density level, greenery/hard surfaces, location of the building within the school grounds, shape of the school grounds in relation to the orientation)
- the building (form, shape, roof cover)
- the classrooms (materials, window/wall ratio, shading conditions)

The area within a 100m radius of the schools was studied since the local microclimate of this area was considered as influential for the building performance.

The questionnaire surveys were conducted in October and November 2010. The teachers of the 4 schools were requested to complete an 11 question survey investigating their perception of their individual classroom's thermal environment (the questionnaire is included in Appendix A). The teachers were asked for a retrospective evaluation of their classroom and if they had been in that classroom for less than 1 year, they were asked to answer for their previous classroom (within the same school). Most of the questions were closed type questions (fixed-response). The survey forms were filled in face-to-face with the respondents in an interview style. The aim of the questionnaire was to identify the following:

- when, where and under which circumstances overheating occurs
- the duration of overheating occurrences in the school/classroom
- the teachers' understanding of the factors which cause overheating
- the mitigation measures taken to date with respect to overheating
- the teachers' perceived impact of overheating on pupils

2.4.1 Schools' description and aerial-photo analysis

The schools are located in Southampton, in the South of the UK, and were constructed during the period of the 1950s-1980s. As discussed previously in section 2.2.1, the South of England is the warmest region in the UK and is characterised by the highest number of hours of sunshine annually (Figure 2.9). Furthermore, in Southampton the mean summer temperature has experienced a rising trend over the last four decades and in 2006 reached 18.7°C (Figure 2.12), which is more than 2°C higher than the baseline summer mean temperature of Southampton, T=16.4°C (1961-1990) (Met Office, 2012). This means that all 4 case study buildings, which were constructed before 1980, often experience much higher temperatures than those they were designed for.

The four schools used in this study are denoted as A, B, C and D in Figure 2.23. They share their school grounds in pairs and are surrounded by residential areas of a relatively low density with detached 2-storey houses. The schools are not shaded by surrounding buildings or trees. Vegetation is limited to grass surfaces with few trees in the school grounds. The outdoor space material surrounding the buildings is mainly tarmac, covering 58 and 68% of the open spaces for schools A, B and C,D respectively (excluding sports fields).

School A is a compact one-storey building with an assembly hall in the centre and the classrooms located around it. School B consists of two parts which create an enclosed yard, a 2-storey L shaped building housing the classrooms and a 1-storey building with the remaining school spaces. Schools C and D both consist of linear sections. The building parts which face southeast (SE) accommodate the classrooms. In school D the classroom part has 2 storeys.

Schools A and B were built in 1978 using a light-weight construction with steel frames and pre-fabricated concrete panels. The other two schools (C and D) were constructed in 1950 using a brick cavity wall system. This means that both of the typical post-war construction types described in section 2.1.2.3 were included in the study. 40 to 60% of the façades are glazed in all four schools (Figure 2.24). Windows in schools A and B are single glazed whilst they are double glazed in schools C and D. All buildings are internally shaded with blinds or curtains. In schools C and D most classrooms face SE while in school A most classrooms are open to two orientations and in school B half of the classrooms face North-East (NE) and half South-East (SE). This is shown in Figure 2.25.

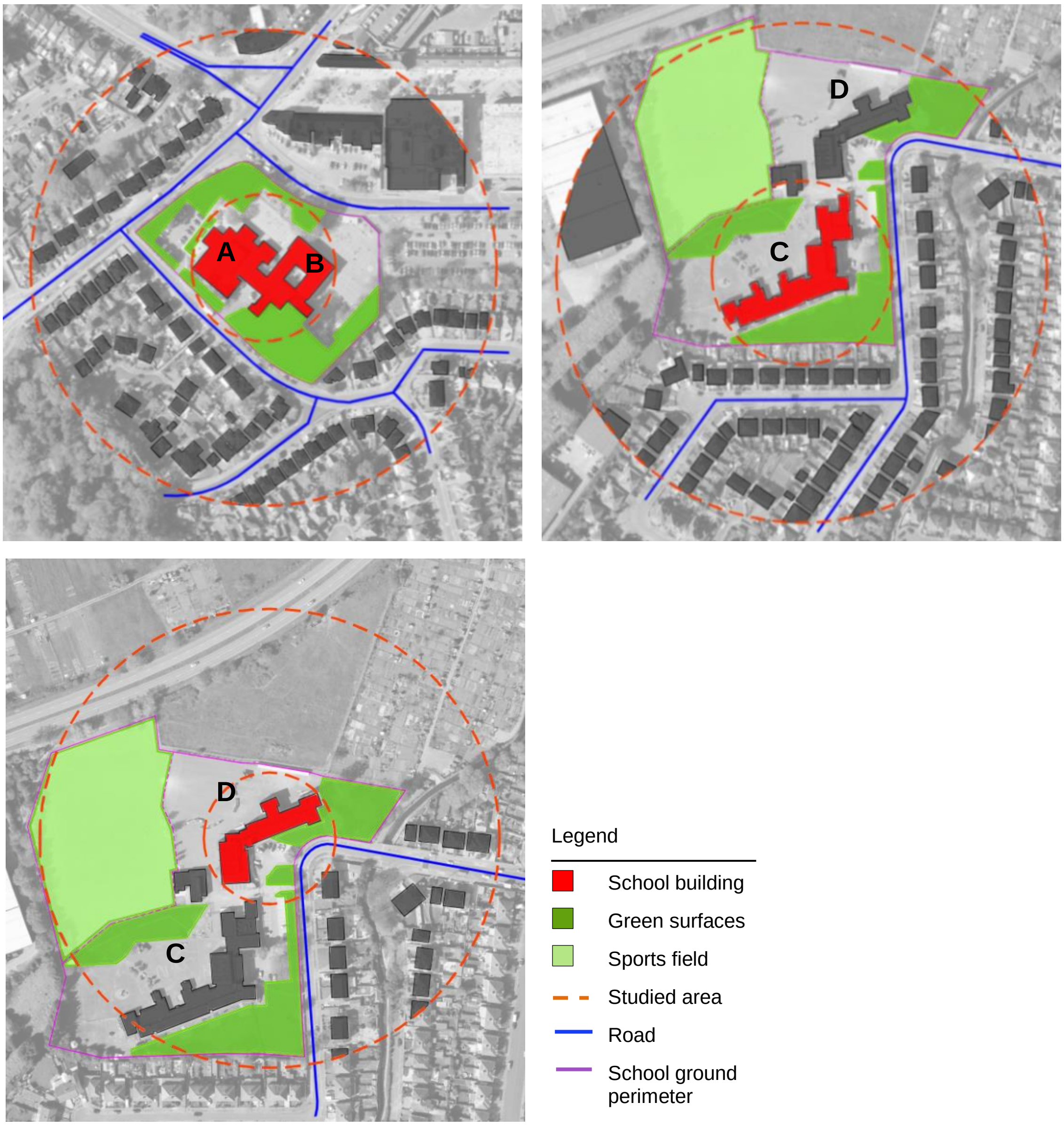


Figure 2.23. Analysis of the main urban characteristics of the schools (image source: Google Earth).

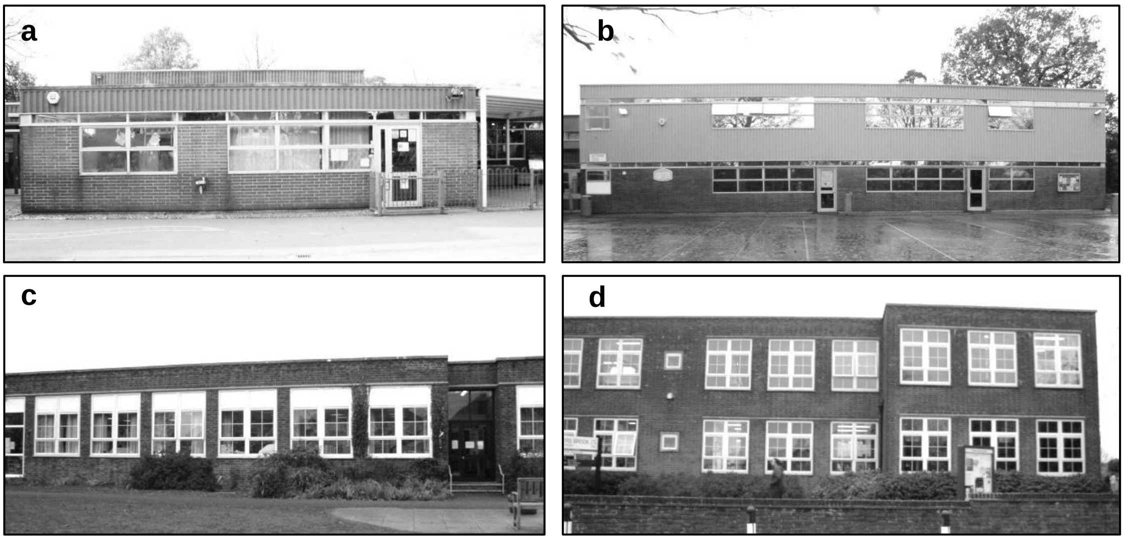


Figure 2.24. Schools' facades: (a) North-East elevation of school A, (b) South-East elevation of school B, (c) South-East elevation of school C and (d) South-East elevation of school D.

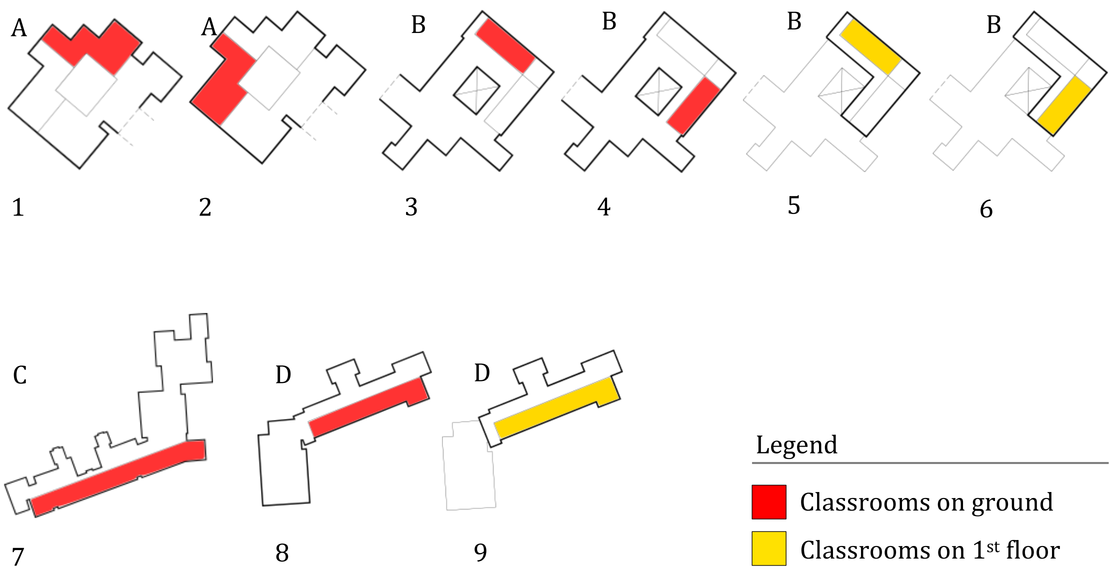


Figure 2.25. Classroom clusters of the case study schools.

From the aerial photo analysis 9 classroom clusters were identified based on construction, orientation, storey and surrounding environment (Figure 2.25). Clusters 5 and 6 (school B) appear to have the highest potential risk of overheating. Their NE and SE orientation in combination with the outdoor tarmac surfaces, a flat bitumen roof, a light-weight construction, single glazing and a lack of wind exposure are parameters which may drive overheating in the classrooms. Ground floor clusters 3 and 4 have the same characteristics as 5 and 6 apart from the missing heat absorption from the roof. In school A (clusters 1 and 2) the classrooms benefit from 2 facades due to the building form which increases their cross-flow ventilation potential. Cluster 2 is adjacent to a small green area and it is relatively exposed to prevailing SW winds. However, the light-weight construction, single glazing and flat roof indicate a high risk of summer overheating later in the day. Schools C and D (clusters 7-9) benefit from the cavity wall system and double glazing but the large SE oriented windows and the lack of ventilation and shading suggest high penetration of solar radiation.

2.4.2 Questionnaire survey results

50 teachers completed questionnaires across the 4 schools for their individual classroom. Their responses are analysed below and subsequently compared with the outcomes of the aerial photo analysis.

2.4.2.1 Thermal performance of the classrooms

The teachers were asked to consider their classroom's thermal performance for the occupancy period from April to October 2010[4]. As shown in Figure 2.26, June and July were considered as the months with the greatest overheating occurrence, whilst May and September were perceived as less problematic, but nevertheless about half of the teachers stated that the classroom is either 'warm' or 'too warm'. April and October were generally perceived as acceptable. It should be noted however that the teachers might have been influenced by the general perception of the climatic variations throughout the year.

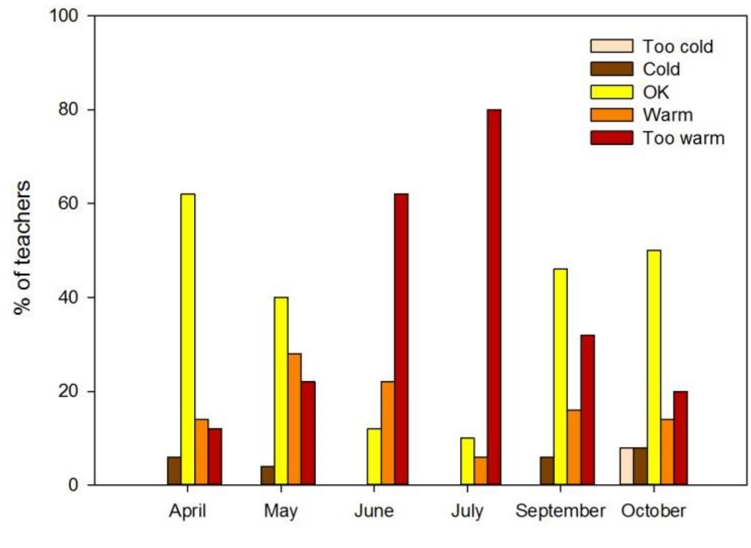


Figure 2.26. 4 school study: Teachers' perceived classroom temperature conditions from April-October (retrospective evaluation).

[4] In the UK, the summer school holidays are from the last week of July to the first week of September inclusive.

When comparing individual responses in relation to the classroom clusters described in section 2.4.1 (Figure 2.25), a high variation in responses on a single façade orientation was identified for the months of April, May, September and October. In some cases, the temperature of adjacent classrooms with exactly the same characteristics was assessed as 'OK' by one respondent and as 'too warm' by another. This suggests that in the spring and autumn months individual variation in perception appears to be more significant for thermal perception than absolute classroom temperatures.

2.4.2.2 Overheating occurrence

The teachers were asked about the magnitude and duration of overheating in their school and classroom. As shown in Figure 2.27, 80% of the teachers stated that outside the heating season (in summer) more than 60% of their school's classrooms experience overheating. In winter the responses vary. One of the reasons for this variation was found to be that in schools A and B the heating system is controllable at the classroom level and some teachers switch it off when temperatures are too high.

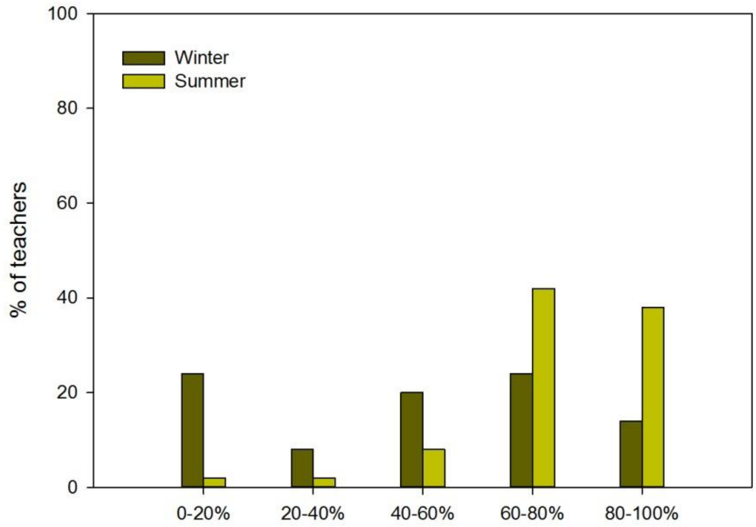


Figure 2.27. 4 school study: Teachers' perceived percentage of the school's classrooms that have experienced overheating.

Almost 60% of the respondents stated that overheating occurrences outside the heating season last for more than a week (Figure 2.28). For the heating season the responses are less clear. 30% of the teachers voted for 'not applicable' and about 25% for 'more than a week'.

The teachers were also asked to assess the frequency of overheating occurrences in various school spaces (Figure 2.29). For the classrooms, 80% of the teachers agreed that overheating occurs 'very often', while for the assembly hall, circulation areas and library the responses are less pronounced. This difference in perception may be related to the characteristics of the classrooms (high occupancy density, large windows, small window openings, internal gains etc), as described in section 2.2, but it may also be due to the stronger concern of the teachers for the spaces where most of the school activities take place.

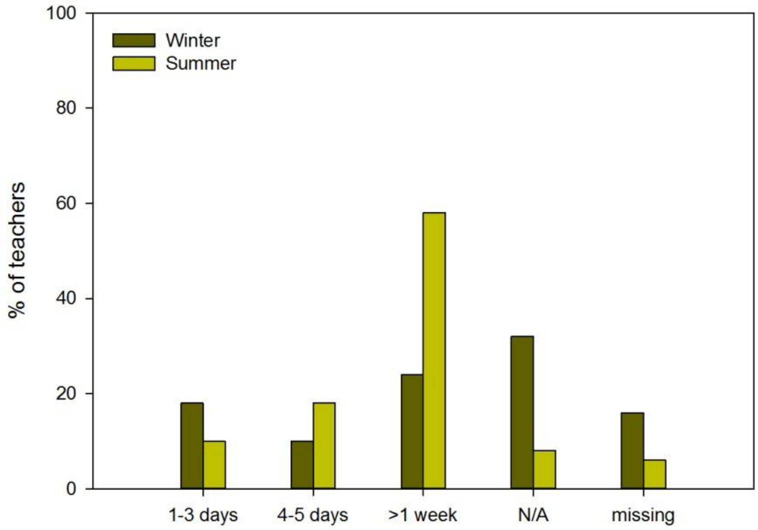


Figure 2.28. 4 school study: Teachers' perceived duration of overheating occurrences in their classrooms.

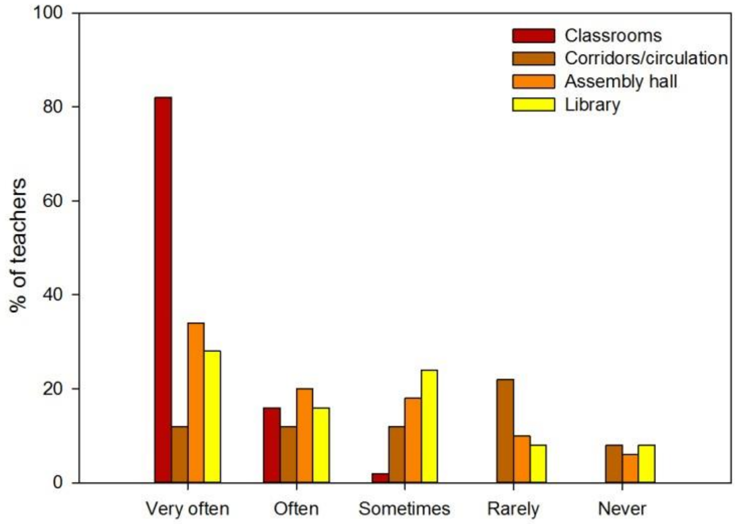


Figure 2.29. 4 school study: Teachers' perceived overheating occurrence in different school spaces.

Figure 2.30 shows the months which were perceived to cause greatest classroom overheating during the school occupancy periods. Multiple answers were possible and, as expected, June and July were indicated by almost all respondents as the two months with the greatest overheating problems.

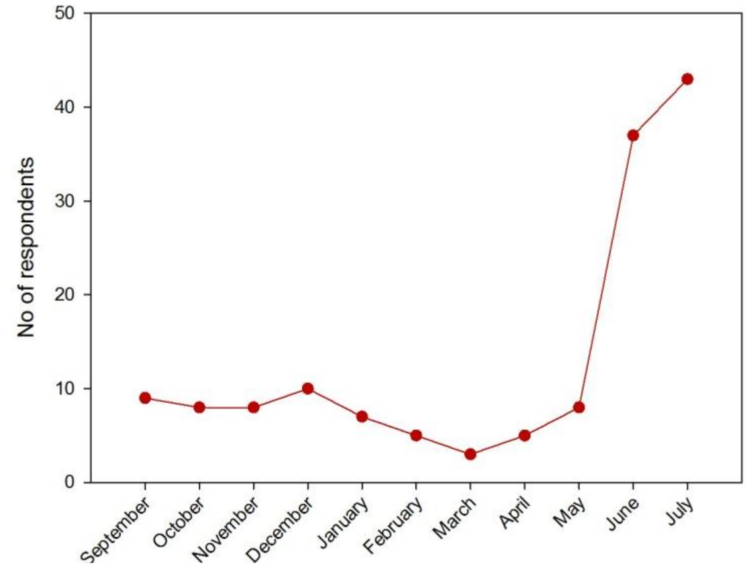


Figure 2.30. 4 school study: Months perceived to cause greatest overheating according to teachers' responses (School year: Sept '09-July '10).

2.4.2.3 Possible causes of overheating and mitigation measures

In an open question, the teachers indicated the factors which they believe to drive overheating in their classroom (Figure 2.31). Poor ventilation, a poorly controlled heating system and the number of pupils were the most frequent answers followed by room size and not-openable windows.

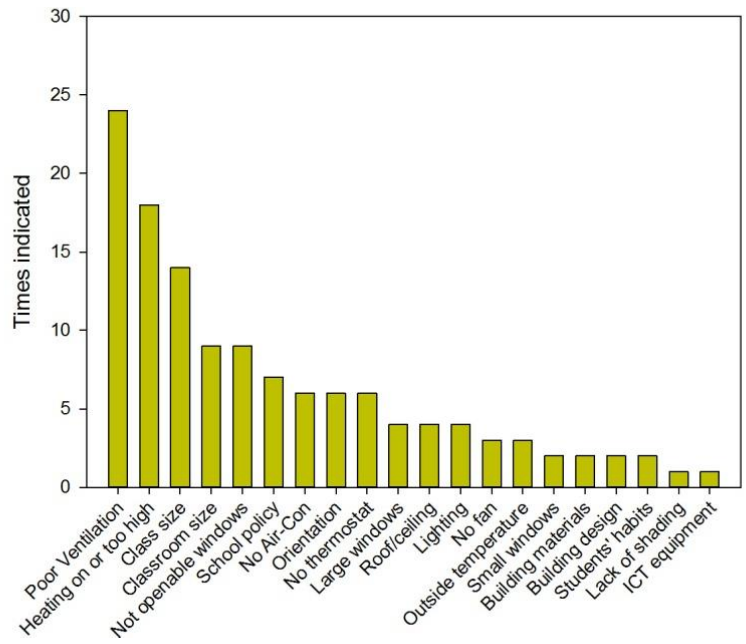


Figure 2.31. 4 school study: Causes for overheating of their classroom according to teachers.

Achieving appropriate ventilation is a problem in many classrooms as cross ventilation is not possible. Also, in all 4 schools the windows open only to a certain extent and the internal shading obstructs the air flow. This is a common problem with internal shading systems. The heating system was often highlighted as an issue because some teachers cannot control it in their classroom or they weren't aware that they could.

The pupils' habits and behaviour towards heat stress were identified as a point of concern. According to some teachers, children may be clearly too warm and yet do not take off their jumpers or ask for help. Teachers felt that children's perception of heat is different from adults and that this should be taken into account when school buildings' thermal conditions are studied. This highlights the importance of children's perception when looking at the thermal conditions in schools, as they are the main occupants.

Figure 2.32 shows the measures taken by the teachers when overheating occurs. The question was fixed-response with the opportunity to add further measures. All teachers selected window opening and almost everyone drinking of water.

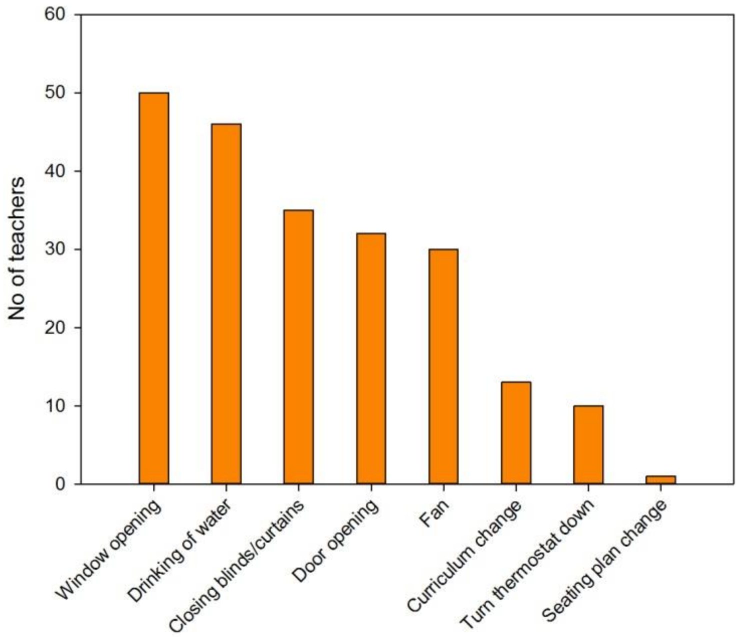


Figure 2.32. 4 school study: Mitigation measures taken by teachers when overheating occurs.

2.4.2.4 Impacts on pupils' learning experience

The teachers were asked to score 9 factors in terms of their impact on pupils' learning experience, using a scale of 0-5, 0 representing no impact and 5 standing for a highly detrimental impact. As shown in Figure 2.33, summer overheating gathered the largest number of 5 and 4 scores. This is followed by a wet lunch break and the class size (number of occupants in classroom). However, it should be taken into account that this result may have been affected by the specific interest of the survey in summer overheating.

Teachers were also asked whether pupils have complained about excessively high temperatures (Figure 2.34). 50% of them said that this was 'very often' the case outside the heating season and some noted that children may not complain even though they feel discomfort.

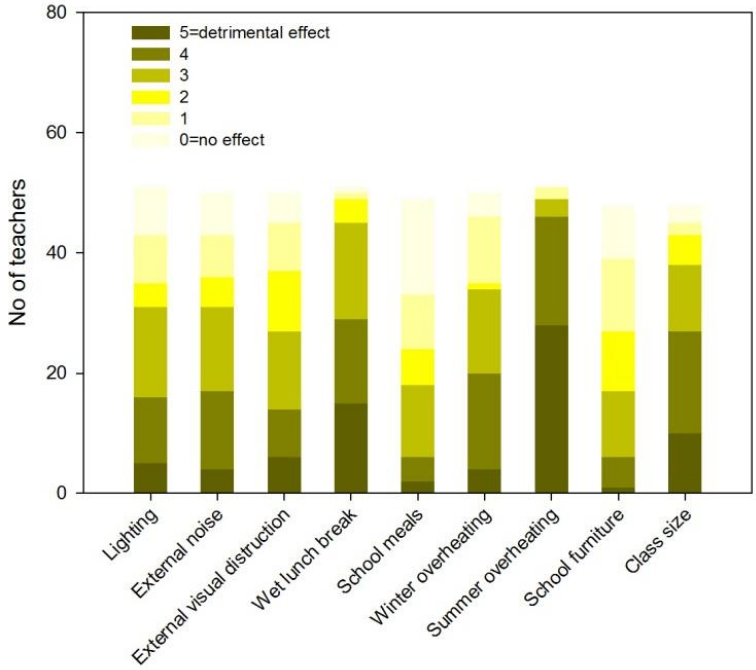


Figure 2.33. 4 school study: Teachers' perceived effect of different factors on pupils' learning experience on a scale of 'no effect' to 'detrimental effect'.

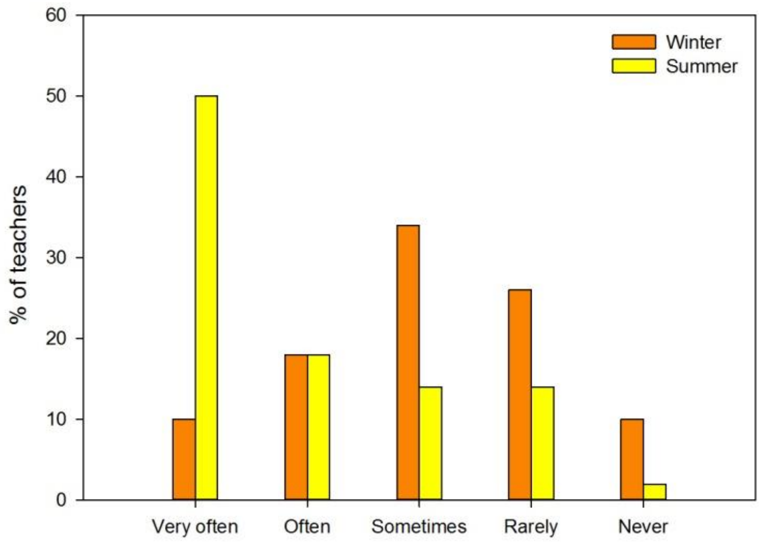


Figure 2.34. 4 school study: Frequency of complaints from children about excessively high temperatures in classroom according to teachers.

2.4.3 Overheating risk evaluation and individual perception

The analysis of the parameters which impact on the classrooms' thermal conditions, as discussed in section 2.2, provided a comprehensive initial assessment of the overheating potential of these spaces (section 2.4.1) suggesting a high overheating risk within all schools. This was also verified by the teachers' survey responses. However, a detailed comparison at the classroom level showed variations in individual responses of teachers for the spring and autumn months, highlighting the importance of individual perception and impacts of, for example, building orientation. Furthermore, based on the teachers' observations, children may have a different thermal perception and response to adults. This means that, while school environments may be experiencing overheating issues, children, who are the main occupants, may have different thermal requirements than adults. The above suggests that it is necessary to look at children's perception of their classroom's thermal environment in order to obtain an understanding of their thermal sensation and preference as well as their behaviour towards temperature changes.

A significant amount of research has focused on occupant thermal perception and comfort. The main approaches and outcomes are analysed in chapter 3, in relation to thermal comfort guidelines for schools and existing research on children's thermal perception.

3. Indoor thermal comfort

Thermal comfort is "the condition of mind which expresses satisfaction with the thermal environment" (ASHRAE, 2010). It depends on multiple variables, with the most important being the air temperature; mean radiant temperature; relative air velocity; humidity; the activity level and thermal resistance of clothing (Figure 3.1) (Fanger, 1970). There are large variations from person to person on the perception of comfortable conditions due to psychological and physiological factors, which makes it difficult to satisfy everyone in a space (ASHRAE, 2010). However, a space should provide thermal conditions found acceptable by most of the occupants. Additionally, the occupant comfort conditions determine to a great extent the energy consumption of buildings (Nicol et al., 2012).

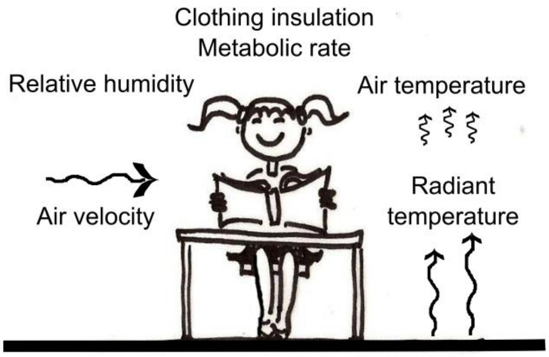


Figure 3.1. 5 key parameters affecting thermal comfort indoors

Thermal comfort in schools is essential, as the quality of a classroom environment is known to affect children's health, well-being and learning ability (EPA, 2003). Temperature is considered to be one of the most important indoor environmental comfort parameters as elevated temperatures may lead to a decline in productivity (Wargocki and Wyon, 2007). In the UK, thermal comfort in schools, in particular outside the heating season, has become an issue of concern as:

- Teachers have reported that they have been experiencing uncomfortably warm thermal conditions inside classrooms during recent summer periods (NASUWT, 2008). This was also observed in the teacher survey described in section 2.4.

- As analysed in section 2.4, parts of the existing school building stock are unsuitable for high external temperatures. Nevertheless, the life of the majority of these buildings will have to be extended further as new school projects have been cancelled due to public finance cuts (Hansard Parliamentary Debates, 2010).

- As discussed in section 2.2.1, predictions for the UK's climate indicate warmer summer temperatures in the future (Jenkins et al., 2009b), which will increase the overheating risk of naturally ventilated buildings (Nicol et al., 2009).

Extensive research has been conducted for a definition of commonly accepted criteria and comfort standards (ASHRAE, 2010, ISO, 2005, CEN, 2007). Based on studies with adults, mostly in offices, these comfort standards also provide comfort criteria for school environments. The two main approaches developed over the years and adopted in international standards, (1) the heat-balance (Fanger, 1970) and (2) the adaptive comfort approach (de Dear and Brager, 1998, Nicol and Humphreys, 2002), and the extension of the most commonly used heat-balance model (Fanger and Toftum, 2002) are analysed below.

3.1 Thermal comfort approaches

3.1.1 Heat balance approach

Research on the heat balance mathematical models investigated ways to simulate human thermal sensation relating physiological with environmental and personal factors (Lee and Strand, 2001). They are based on body heat balance and on thermal sensations reported by people during experiments in climate-controlled spaces (CIBSE, 2006). The most well-known models are: Fanger's PMV model (Fanger, 1970), the Pierce Two-Node Model (Gagge et al., 1971) and the multi-node Fiala model (Fiala, 1998). As W. Byron acknowledges, Fanger's model is the one mostly used in practice because it is the most thoroughly documented and has remained essentially unchanged since its first publication (Byron W, 2002). The above mentioned heat balance models are described in detail below.

3.1.1.1 Fanger's PMV model

Fanger's model was developed in the 1960/70's based on the fact that "the human body employs physiological processes (e.g. sweating, shivering, regulating blood flow to the skin) in order to maintain a balance between the heat produced by metabolism and the heat lost from the body" (Charles, 2003). The balance between the heat production and the heat dissipation is expressed by the following equation (Fanger, 1970):

$$\mathbf{H - E_d - E_{sw} - E_{re} - L = K = R + C} \quad (3.1)$$

Where:

- H = internal heat production in the human body
- E_d = the heat loss by water vapour diffusion through the skin

- E_{sw} = the heat loss by evaporation of sweat from the surface of the skin
- E_{re} = the latent respiration heat loss
- L = the dry respiration heat loss
- K = the heat transfer from the skin to the outer surface of the clothed body
- R = the heat loss by radiation from the outer surface of the clothed body
- C = the heat loss by convection from the outer surface of the clothed body

By inserting the comfort expressions for skin temperature and sweat rate derived from experiments in the heat balance equation (3.1), the comfort equation was obtained, which includes variables such as the environmental parameters (air temperature, mean radiant temperature, relative air velocity and water vapour pressure) and personal variables (clothing insulation and metabolic rate) (Fanger, 1970). It indicates how the environmental parameters should be combined to achieve optimal thermal comfort for an average adult. However, the comfort equation cannot be used to evaluate the thermal sensation of people in indoor environments which do not satisfy the equation. For the association of the comfort equation with thermal sensation Fanger used data from laboratory and climate chamber experiments with American and Danish college age subjects (Fanger, 1970). In those studies, participants were dressed in specific clothing and completed standardised activities, while exposed to different thermal states. The environmental conditions were recorded and at the same time participants answered questions about how hot or cold they felt on the seven-point ASHRAE thermal sensation scale (Table 3.1).

Table 3.1. 7 point ASHRAE Thermal Sensation Scale

-3	-2	-2	0	+1	+2	+3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

From the comfort equation and the experiments the following model indices were deduced:

a) The Predicted Mean Vote (PMV). The PMV index gives the thermal sensation of a large group of people for a given combination of clothing insulation and metabolic rate and the four thermal environmental parameters: the air temperature; mean radiant temperature; relative air velocity and water vapour pressure (Fanger, 1970). It is evaluated on a seven-point scale such as the ASHRAE scale (Table 3.1). The PMV cannot be easily interpreted in practice as it does not imply whether a thermal environment could be expected to be acceptable or not (Fanger, 1970). Therefore, the predicted percentage of dissatisfied index (PPD) was developed.

b) The Predicted Percentage of Dissatisfied (PPD). The PPD index states the percentage of persons that can be expected to be dissatisfied within a given thermal environment. The relationship between percentage of dissatisfied and mean votes was derived from the thermal sensation votes of the experimental studies used for generating the PMV. The PPD principle is widely used to express the degree of thermal discomfort (CIBSE, 2005).

The PMV and PPD indices can be calculated using the equations (3.2) to (3.6), of ISO 7730 (ISO, 2005).

$$PMV = (0.303e^{-0.036M} + 0.028) \cdot \{(M - W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - p_a] - 0.42 \cdot [(M - W) - 58.15] - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\bar{t_r} + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\} \quad (3.2)$$

$$t_{cl} = 35.7 - 0.028 \cdot (M - W) - I_{cl} \cdot \{3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\} \quad (3.3)$$

$$h_c = \begin{cases} 2.38 \cdot |t_{cl} - t_a|^{0.25} & for \;\; 2.38 \cdot |t_{cl} - t_a|^{0.25} > 12.1 \cdot \sqrt{v_{ar}} \\ 12.1 \cdot \sqrt{v_{ar}} & for \;\; 2.38 \cdot |t_{cl} - t_a|^{0.25} < 12.1 \cdot \sqrt{v_{ar}} \end{cases} \quad (3.4)$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 \cdot I_{cl} & for \;\; I_{cl} \leq 0.078 m^2 \cdot K/W \\ 1.05 + 1.645 \cdot I_{cl} & for \;\; I_{cl} > 0.078 m^2 \cdot K/W \end{cases} \quad (3.5)$$

$$PPD = 100 - 95 \cdot e^{(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2)} \quad (3.6)$$

Where:

- M= metabolic rate, in watts per square metre (W/m^2)
- W= effective mechanical power, in watts per square metre (W/m^2)
- I_{cl}= clothing insulation, in square metres Kelvin per Watt (m^2*K/W)
- f_{cl}= clothing surface area factor
- t_a= air temperature, in degrees Celsius (^oC)
- $\bar{t_r}$= mean radiant temperature, in degrees Celsius (^oC)
- v_{ar}= relative air velocity, in metres per second (m/s)
- p_a= water vapour partial pressure, in Pascal (Pa)
- h_c= convective heat transfer coefficient, in watts per square metre Kelvin [W/(m^2*K)]
- t_{cl}= clothing surface temperature, in degrees Celsius (^oC)

The PMV model is considered to be the most simplified of its kind as it uses a one-dimensional approximation of the human body (Figure 3.2) and doesn't simulate transient thermal conditions or thermal regulation (Byron W, 2002).

3.1.1.2 Pierce Two-Node Model

The two node model was developed by the John B. Pierce Foundation at Yale University in the 1970s (Gagge et al., 1971, Gagge et al., 1986). One of the indices calculated with this model, the Effective Temperature (ET*), was adopted in ASHRAE Standard 55 for the definition of the comfort zone, which is one of the methods used for determining acceptable thermal conditions in indoor spaces (ASHRAE, 2010). The two-node model represents the body as two compartments, the body core and the skin layer. It describes how heat transfers between the environment, the skin, and the core body, when relative humidity is 50% (Gagge et al., 1971). Geometrically, the body is modelled as two concentric cylinders (Figure 3.2), a core cylinder and a thin skin cylinder surrounding it (Fountain and Huizenga, 1995).

The heat balance equation (Equation (3.1)) and equations for heat transfer between the environment and the body used in the two-node model are the same as in the PMV model (Doherty and Arens, 1988). However, unlike the PMV model, in the Pierce model actual physiological variables are estimated on a minute by minute basis until the user-specified exposure time is reached (Doherty and Arens, 1988). Starting from initial values for the physiological variables at time=0 the cylinder is exposed to a uniform environment, and the model iterates until the user-specified time period is reached (Fountain and Huizenga, 1997). After that period is reached, the final surface temperature and surface skin wettedness of the cylinder are used to calculate a standard effective temperature (SET*), a widely used thermal index (ASHRAE, 2009). SET* gives the opportunity to compare thermal environments at any combination of the physical input variables, but has the disadvantage of requiring "standard" people (Fountain and Huizenga, 1995).

The indices developed and used by the model are explained below:

a) The standard effective temperature (SET*). SET* represents the dry-bulb temperature of an imaginary uniform indoor space at 50% RH, in which the total heat loss from the skin of an imaginary sedentary subject (1.0 met), wearing 0.6 clo, in still air (<0.1 m/s) at sea level is the same as that from a person in the actual environment, with actual clothing and activity level (ASHRAE, 2010). Its numerical value represents "the thermal strain experienced by the cylinder relative to a 'standard' person in a 'standard' environment" (Fountain and Huizenga, 1995).

b) The TSENS. TSENS represents the model's prediction of a vote on the 7-point thermal sensation scale. It was developed using empirical functions derived from laboratory studies (Gagge et al., 1986).
c) The DISC. DISC represents the model's prediction of a vote on a scale of thermal discomfort (lntolerable, Very uncomfortable, Uncomfortable, Slightly uncomfortable, Comfortable) (Fountain and Huizenga, 1995).

3.1.1.3 Limitations of the PMV and 2-node heat-balance models

The main limitations of the steady-state heat-balance models are:

- The heat transfer coefficients are not known with certainty due to the irregular body shape and the heterogeneity of body tissue (Doherty and Arens, 1988).
- The estimation of the clothing insulation may vary significantly, not only between comfort models but also between individuals (Byron W, 2002)
- The models are only reliable for the conditions for which their empirical relationships were developed. It was shown that while the models may agree in steady state conditions they appear to disagree significantly in transient conditions (Byron W, 2002).
- Evaporation of sweat from the skin and convection of heat from internal sources to the skin, which are the two basic heat exchange relationships, vary with body temperature and psychological condition (Doherty and Arens, 1988)
- The models make the inherent assumption that "there is some predictable comfort response for a given physiological state of the body" (Byron W, 2002). However, comfort is a psychological response and other factors may affect it (Byron W, 2002).

In line with the final point above, heat-balance models have been criticised for being static and viewing occupants as passive recipients of the thermal environment (Brager and de Dear, 1998). This view was supported by field surveys which found that PMV often differs markedly from the actual mean vote, both for naturally ventilated and air-conditioned spaces (Humphreys and Nicol, 2002, Moujalled et al., 2008). The above mentioned limitations led to an update of the PMV model and to alternative thermal comfort approaches, such as sophisticated multi-segmental mathematical models of human thermoregulation (Stolwijk, 1971, Huizenga et al., 2001, Tanabe et al., 2002, Fiala et al., 2001) and the adaptive comfort model (de Dear and Brager, 1998, Nicol and Humphreys, 2002). The update to the PMV model, described as "extension", and the most developed multi-node model, the Fiala model, are analysed below.

3.1.1.4 Extension of the PMV model

In 2002, an update to the PMV model was introduced to address the warmer thermal sensations Fanger's PMV model predicted compared to the observed in naturally ventilated buildings in warm climates (Fanger and Toftum, 2002). This extension to PMV takes into account two factors which were considered to be responsible for the PMV overestimates: (i) the different expectations of the occupants in naturally ventilated buildings in those locations and (ii) the reduction in metabolic rate as a human adaptive mechanism when feeling warm. The model suggests the use of an expectancy factor, *e*, to be multiplied with the PMV to address the first issue (Table 3.2) and the use of a reduced metabolic rate for the second.

Table 3.2. Expectancy factors for non-air-conditioned buildings in warm climates (Fanger and Toftum, 2002)

Expectation	Classification of non-air-conditioned buildings		Expectancy factor, e
	Location	Warm periods	
High	In regions where air-conditioned buildings are common	Occurring briefly during the summer season	0.9-1.0
Moderate	In regions with some air-conditioned buildings	Summer season	0.7-0.9
Low	In regions with few air-conditioned buildings	All seasons	0.5-0.7

The extension of the PMV was validated using field studies and it was found to predict well people's thermal sensation (Fanger and Toftum, 2002). Since then, a number of field studies have found discrepancies with the actual sensation votes, with larger errors for lower temperatures (Wong and Khoo, 2003, Tablada et al., 2005, Zhang et al., 2007, Rajasekar and Ramachandraiah, 2010).

3.1.1.5 Multi-node dynamic Fiala model

Numerous models have been created over the past 40 years as an evolution of the 2-node models but have not been widely used due to lack of comprehensive validation, poor modelling of the heat exchange with the environment and limited range of applicability (Fiala et al., 2010). The Fiala model of human thermal physiology and comfort was developed in 1998 based on the multi-segmental simulation of the human thermal regulation (Fiala, 1998). The Fiala model is considered to be a new-generation multi-node model able to predict thermal responses to changing environments (Humphreys et al., 2007).

The model enables thermal influences to be analysed for transient and heterogeneous conditions taking into account both environmental influences and varying activity levels

(Fiala, 1998). It incorporates two interacting systems of thermoregulation: the controlling, active system and the controlled passive system. The passive system is a detailed representation of the human body with all its anatomic and thermo-physiological properties (Fiala et al., 1999). It includes a simulation of heat transfers that occur inside the human body and at its surface. The active system simulates the thermoregulatory responses of the central nervous system, e.g. shivering and sweat moisture excretion (Fiala et al., 2011). It was developed through regression analysis using measured responses obtained from steady and transient conditions (Fiala et al., 2001). The index derived by the Fiala model is termed 'Dynamic Thermal Sensation' (DTS). It is evaluated on the 7-point ASHRAE scale in line with the PMV and TSENS described above (Fiala and Lomas, 2001).

The overall comfort model has been developed using experimentally observed thermal sensation votes from over 2000 male and female subjects (Fiala et al., 2011). It represents an average person with a body surface area of 1.85 m^2, body weight of 73.4 kg, and body fat content of 14%. It has been investigated whether the model can be adapted in order to apply to bodies of elderly people and it was found that it can, but only after changes are made to the model to address old people's physiology (Novieto and Zhang, 2010). However, there is no reference to a potential application of the model to children. Validation of the model is still required in every day environments (Humphreys et al., 2007) in order to gain confidence in its predictive abilities. Furthermore, an important limitation of this simulation model is the fact that it does not take into account the human behaviour and the interaction between the building and the occupant (Nicol et al., 2012).

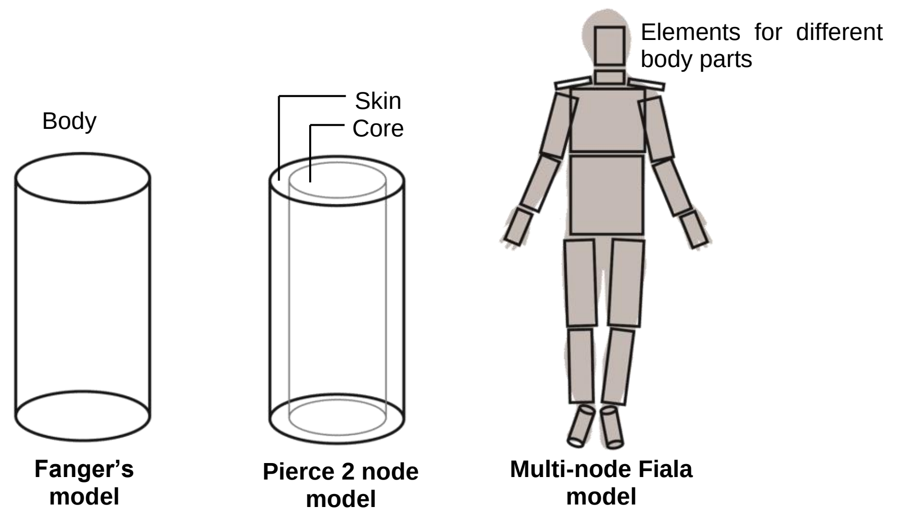


Figure 3.2. Geometrical representation of the described heat balance models [representation of Fiala model adapted from: (Fiala et al., 2010)]

3.1.2 Adaptive comfort approach

As mentioned in section 3.1.1, a comparison of the predicted thermal sensation votes from the widely used Fanger PMV model with actual thermal sensation votes from field studies revealed a systematic bias, especially in relation to hot conditions (Humphreys, 1996). In addition, a number of field surveys showed that, while the PMV model was found to be satisfactory in predicting thermal sensation for air-conditioned buildings, it predicted warmer thermal sensations in naturally ventilated buildings (Brager and de Dear, 1998) where occupants were tolerant to a wider range of temperatures. These discrepancies are attributed to the ability of people to adapt to changing conditions in their environment (Nicol and Humphreys, 1973, Nicol and Humphreys, 2002). The climate controlled chambers, used for establishing the heat-balance models, do not include any adaptive measures. This led to the development of the so-called adaptive comfort model, which states that apart from the environmental and personal parameters, thermal sensation also depends on the outdoor climate and the expectations it creates about the indoor environment (Humphreys, 1978, Auliciems, 1981).

As can be seen in Figure 3.3, the thermal adaptive mechanisms can be distinguished into three categories (de Dear and Brager, 1998):

a) **Behavioural**. The behavioural adjustments include actions which aim at improving the indoor climate or the body's thermal state and can be personal (clothing and posture changes, activity, moving to different locations), technological (opening/ closing windows or shades, controlling fans or HVAC systems) and cultural (schedule adjustments, dress code).
b) **Physiological**. Physiological adaptation includes all the physiological changes which result from the exposure to climate, and which lead to greater tolerance towards the climatic conditions. There are two subcategories of physiological adaptation: genetic adaptation (intergenerational alterations beyond the individual's lifetime) and acclimatisation (changes in the physiological thermoregulation system over a period of days or weeks, in response to exposure to environmental factors).
c) **Psychological**. Psychological adaptation refers to changed perception due to past experience. Having lower indoor climate expectations results in a greater tolerance of the occupants towards temperature fluctuations.

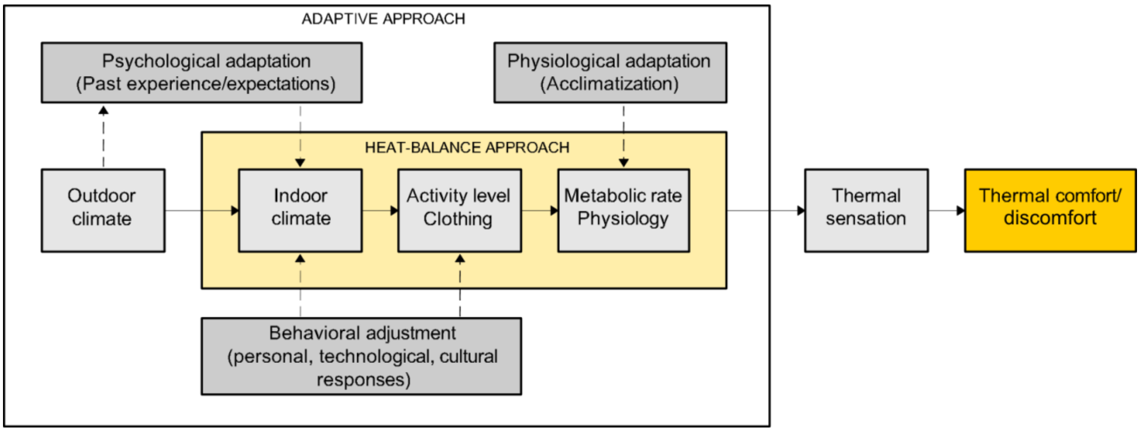


Figure 3.3. Representation of the adaptive mechanisms

It has been concluded that physiological acclimatisation doesn't significantly affect thermal adaptation under 'moderate' thermal conditions as they typically occur in buildings, while behavioural adjustment and expectations have much greater impact (Brager and de Dear, 1998).

In order to assess the acceptability of a thermal environment the adaptive comfort model uses the findings from field surveys (Humphreys et al., 2007). Table 3.3 summarises details of key published comfort field studies. The research method includes people's subjective rating of their thermal environment together with simultaneous measurements of the environmental variables. An analysis of human subjective response to the indoor climate is conducted in relation to outdoor meteorological factors (de Dear and Brager, 1998) and the comfort temperature is deduced through regression analysis of the collected data. For the use of the adaptive comfort model in practice, control algorithms have been developed which relate the comfort temperature to the monthly mean outdoor temperature (Humphreys, 1978), mean monthly effective temperature ET* (de Dear and Brager, 1998) or the running mean outdoor temperature[5] (McCartney and Nicol, 2002).

Table 3.3. Key worldwide comfort field studies (1995-2011)

	Reference	Location	Sample	Participants	Obser. No	Ventilation type	Occupancy pattern	Time period
1	(Oseland, 1995)	UK	Ad	30	1,080	NV+AC	office, chamber, residential	1995
2	(De Dear et al., 1997)	9 countries worldwide	Ad	20,693	22,000	various	office, few school clrs	Various periods in 1985-1996

[5] exponentially weighted mean outside temperature

	Reference	Location	Sample	Participants	Obser. No	Ventilation type	Occupancy pattern	Time period
3	(Nicol et al., 1999)	Pakistan	Ad	25 and 846	7,000	NV	residential, commercial, office	1993–1994, 1995–1996
4	(Raja et al., 2001)	UK	Ad	909	5,000	10NV+ 5AC	office	1996-1997
5	(McCartney and Nicol, 2002) SCATs	UK, France, Sweden, Greece, Portugal	Ad	840	4,500	various	office	12/1997-12/2000
6	(Kwok and Chun, 2003)	Japan	St	74	-	1NV+1AC	school	late summer 2000
7	(Wong and Khoo, 2003)	Singapore	St+Ad	506	-	MV (fans)	school	21 and 24 August 2001
8	(Bouden and Ghrab, 2005)	Tunisia	Ad	200	-	NV	residential	1 year
9	(Hwang et al., 2006)	Taiwan	Ad	944	1,290	NV+ AC	university (26 AC & 10 NV clrs)	-
10	(Zhang et al., 2007)	China	U-St	1,273	-	NV	university	March 24 to April 23 2005
11	(Corgnati et al., 2007)	Italy	U-St+St	427	-	NV	university and high school	Jan- April 2002
12	(Moujalled et al., 2008)	France	Ad	-	330	5 NV	office	August-Sept 2004 and March 2005
13	(Hwang et al., 2009)	Taiwan	St	1,614	3,700	NV	schools	09/2005-01/2006
14	(Al-Rashidi et al., 2009)	Kuwait	St (11-17)	336	336	Hybrid AC	schools (14 clrs)	13-22/11/ 2005
15	(Corgnati et al., 2009)	Italy	U-St	230	-	NV	university (2 clrs)	Sept-Oct 2006, May 2007
16	(Rajasekar and Ramachandraiah, 2010)	India	Ad	295	331	NV	residential	April-May and Nov-Dec 2009
17	(Indraganti and Rao, 2010)	India	Ad	113	4,000	NV	residential	May, June, July
18	(Mors et al., 2011)	Nether-lands	P (9-11)	79	2,000	NV+ Hybrid	schools (3 clrs)	24 days in winter,sprin g,summer 2010)

Notes:

- Observ. No = approximate number of observations (each observation comprised a subjective thermal sensation rating and corresponding measurements of the environmental variables)
- Ad= Adults, St= High school students, U-st=University students, P=pupils
- Clrs=classrooms
- AC=Air conditioned, NV=Naturally ventilated, Hybrid=occasional use of AC

3.1.2.1 Strengths and limitations of the adaptive model of thermal comfort

Compared to the static heat balance models, the adaptive comfort model allows higher maximum operative[6] temperatures as the outdoor temperature rises (de Dear and Brager, 1998). This suggests that if the adaptive comfort approach guided the formulation of building comfort standards, the energy use for heating and cooling could be reduced without compromising thermal comfort (Humphreys et al., 2007). As an example, in a test performed in a UK office building with an automated control system the calculated savings by using temperature limits based on the adaptive comfort model were approximately 30% of the cooling load corresponding to the fixed temperature set-point previously used (McCartney and Nicol, 2002). Building simulations of an office in another study showed that the application of the adaptive comfort limits in summer in combination with night purge ventilation, predicted acceptable thermal conditions during a large part of the occupied time (Moujalled et al., 2008). Similarly, thermal simulations of a typical office suggested that an advanced version of the office with a combination of strategies such as better insulation, over-window shading, new control strategies and the application of adaptive comfort limits could achieve close to zero energy demand for heating and cooling (Tuohy et al., 2010). However, the existing adaptive comfort standards (ASHRAE55 and EN15251, see also sections 3.2.2 and 3.2.3) use different comfort limit ranges which result in different potential energy demands. Indeed, for moderate climates it has been shown that ASHRAE55 does not result in energy savings compared to the fixed temperature set-points used before, whilst EN15251, which has higher upper temperature limits, can result in a cooling energy reduction of 12% (Sourbron and Helsen, 2011).

The adaptive comfort model is considered to be a useful simplistic tool which however does not explain why specific conditions would be found acceptable or comfortable by the occupants (de Dear, 2011). Other limitations related to the adaptive comfort model include issues such as whether someone who has air-conditioning at home would then accept higher temperatures in his or her office or whether the higher temperatures would have a negative impact on productivity, even though they are considered acceptable (Olesen, 2004).

By considering only the operative temperature, the adaptive comfort model has been criticised for disregarding other parameters which have a well-known direct impact on ther-

[6] The 'operative temperature' (T_{op}) is a weighted average of the air temperature and the mean radiant temperature (CIBSE, 2006). It is used as an index which expresses their joint effect.

mal sensation such as the air velocity, relative humidity, metabolic rate and clothing insulation, which are incorporated in the PMV model (Fanger and Toftum, 2002). However, it has been shown that the inclusion of the above variables does not improve the overall predictive power of the model, instead it can cause systematic biases due to measurement errors, errors related to the equation itself or to the steady-state nature of the model (Humphreys and Nicol, 2002, McCartney and Nicol, 2002). Therefore, the operative temperature, the index used by the adaptive comfort model, is considered as sufficient for the assessment of many indoor environments (Humphreys et al., 2007).

The adaptive comfort model is based on different principles and methodology compared to the heat-balance model, as can be seen in the summarising Table 3.4. However, the heat-balance model accounts for some behavioural adaptation such as changing clothing and metabolic rate (de Dear and Brager, 1998). In that sense, the adaptive model of thermal comfort has been considered as "complementary" to the heat-balance model, including the impact of other forms of adaptation on thermal response (Behavioural, physiological and psychological) (de Dear and Brager, 2002) . Expanding on this, "a variable indoor temperature standard can successfully combine features of both static and adaptive models by incorporating behavioural, physiological, and psychological modes of thermal adaptation" (de Dear and Brager, 1998).

Table 3.4. Main characteristics of the PMV, extended PMV and the adaptive comfort models

	PMV model	Extended PMV	Adaptive model
Basic principle	body heat balance	body heat balance, occupant expectations and metabolic rate adaptation	human adaptation to changing conditions
Environmental input in comfort equations	indoor environment immediately surrounding the occupants (air temperature, relative air velocity, mean radiant temperature, relative humidity)	same as PMV. The resulting PMV multiplied with expectancy factor in non-air-conditioned buildings in warm climates	outdoor thermal environment
Required information on occupants	clothing insulation and metabolic rates	same as PMV, reduced metabolic rate if necessary	-
Methodology for model generation	surveys in climate-controlled chambers	same as PMV	field surveys

3.2 Standards and guidelines for thermal comfort

Current international standards for the indoor thermal environment include "ISO 7730:2005 Ergonomics of the thermal environment- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria" (ISO, 2005) and "ASHRAE Standard 55-Thermal Environmental Conditions for Human Occupancy" (ASHRAE, 2010). At the European level there is "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" (CEN, 2007). In the Netherlands, the guideline "ISSO 74- Adaptive Temperature Limits guideline (ATG)" [7] was developed in 2004 based on the adaptive comfort approach (ISSO, 2004). In the UK, CIBSE gives guidance on thermal comfort in "CIBSE Guide A: Environmental design" (CIBSE, 2006). These documents are discussed and compared below in terms of their approach to thermal comfort and their recommended comfort criteria. The analysis is mainly focused on the time outside the heating season and naturally ventilated buildings which are the main areas of interest for this research. However, for comparison the analysis also includes information on the heating season.

3.2.1 EN ISO 7730

ISO 7730 is based on the heat balance model. It describes the calculation method for the PMV and PPD indices developed by Fanger (1970) (see chapter 3.1.1), and gives the criteria for thermal comfort in moderate thermal environments for three levels of acceptability A, B and C. These categories are based on 3 acceptability levels of the Percentage of People Dissatisfied (PPD), which are: 6%, 10% and 15% for categories A, B and C respectively, as can be seen in Table 3.5. The ISO 7730 comfort criteria consider:

- whole body thermal comfort, using the PMV and PPD indices
- local discomfort: a) due to draught, using the draught rate (DR), b) due to vertical air temperature difference, cool or warm floor or radiant temperature asymmetry, using the percentage of dissatisfied (PD) calculated from 3 different equations (ISO, 2005).

[7] ISSO (Instituut voor Studie en Stimulering van Onderzoek op het gebied van gebouwinstallaties) is the Netherlands Institute for Research of Building Services which produces technical guidelines and other tools to support the Dutch industry (http://www.isso.nl/)

Table 3.5. Thermal comfort criteria for the 3 categories of thermal environment (ISO, 2005)

Category	Thermal state of the body as a whole		Local discomfort			
	PPD %	PMV	DR* %	PD* % Caused by		
				vertical air temperature difference	warm or cool floor	radiant asymmetry
A	<6	-0,2<PMV<+0,2	<10	<3	<10	<5
B	<10	-0,5<PMV<+0,5	<20	<5	<10	<5
C	<15	-0,7<PMV<+0,7	<30	<10	<15	<10

Notes:
* DR=Draught rate, PD=Percentage of dissatisfied due to local discomfort

The thermal environment categories A, B and C correspond to 94, 90 and 85% of satisfied occupants respectively. They have been widely adopted as an assessment classification of the acceptability of thermal conditions in spaces. However, a sensitivity analysis of the PMV to the 6 input parameters used for its calculation (air temperature, radiant temperature, air speed, relative humidity, metabolic rate and clothing insulation) showed that the PMV is significantly sensitive to some of the variables, which indicated that the classification bands of the PMV are too narrow to be reliable (d'Ambrosio Alfano et al., 2011).

By using the acceptable values of PMV in Table 3.5 and typical values of metabolic rate (1.2met), clothing insulation (1.0clo for winter and 0.5clo for summer), air speed and relative humidity the standard provides design values of operative temperature T_{op} for different kinds of spaces. For classrooms, the recommended operative temperatures are given in the summarised Table 3.7 on page 64.

ISO 7730 is the main thermal comfort standard developed by the International Standards Organisation (Olesen and Parsons, 2002) , which has, however, been questioned for its validity for predicting thermal comfort in every-day life and has been considered to require revision since 2002 (Humphreys and Nicol, 2002). Furthermore, since the establishment of the PMV model in 1970, research on human physiology and comfort has evolved (Olesen and Parsons, 2002). Dynamic models of human thermoregulation, such as the Fiala multi-node model (see section 3.1.1.5), represent more accurately the human thermoregulatory system than the PMV equation (Olesen and Parsons, 2002). In addition, ISO 7730 does not address the issue of adaptation in free-running buildings (see section 3.1.2), which has been included in other standards (EN 15251, ASHRAE 55), as analysed below.

3.2.2 EN 15251

European Standard EN 15251:2007 is entitled "Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics" (CEN, 2007). This standard provides different criteria for mechanically cooled buildings and buildings without mechanical cooling. For mechanically heated or cooled buildings the standard refers to ISO 7730 and provides the same comfort criteria, as summarised in Table 3.5, but with one more category of thermal environment, for PMV<-0,7 or PMV>+0,7 which corresponds to PPD>15%. The recommended design values of the operative temperature are given as minimum and maximum for the heating and cooling season respectively, the same as suggested by ISO 7730 (for classrooms see Table 3.7). For buildings which are not mechanically heated or cooled (free running) the standard provides a method based on the adaptive algorithm of the European study SCATs, described below.

3.2.2.1 European adaptive algorithm: the SCATs database

The SCATs Project was a year-round study in European offices, from December 1997 to December 2000. The field studies were performed in Greece, Portugal, the UK, France and Sweden (Figure 3.4). The aim of the project was to develop a method based on the adaptive comfort approach (see section 3.1.2) in order to decrease the energy use in air-conditioned buildings (McCartney and Nicol, 2002). Some details of these comfort field studies (sample type and size, number of observations, type of spaces) can be seen in Table 3.3 (comfort study No5).

Figure 3.4. The locations of the field studies in the SCATs database. (Note that in Sweden little data were gathered for buildings in free-running mode)

From the statistical analysis of all the collected data the relationship between the neutral temperature and outdoor temperature was derived. The exponentially weighted outdoor running mean T_{rm} was chosen as a suitable outdoor climate index as it is based on the adaptive comfort approach's assumption that comfort temperature is influenced by recent experiences (Olesen, 2007). T_{rm} is calculated by equation (3.7) (Nicol and Humphreys, 2010). (3.8) is the same equation simplified for a series of days. The standard also provides an approximate equation (3.9) for cases when long term records are not available (CEN, 2007).

$$T_{rm} = (1-a)\{T_{ed-1} + aT_{ed-2} + a^2T_{ed-3} \dots\} \quad (3.7)$$

$$T_{rm} = (1-a)T_{ed-1} + aT_{rm-1} \quad (3.8)$$

$$T_{rm} = (T_{ed-1} + 0.8T_{ed-2} + 0.6T_{ed-3} + 0.5T_{ed-4} + 0.4T_{ed-5} + 0.3T_{ed-6} + 0.2T_{ed-7})/3.8 \quad (3.9)$$

Where:

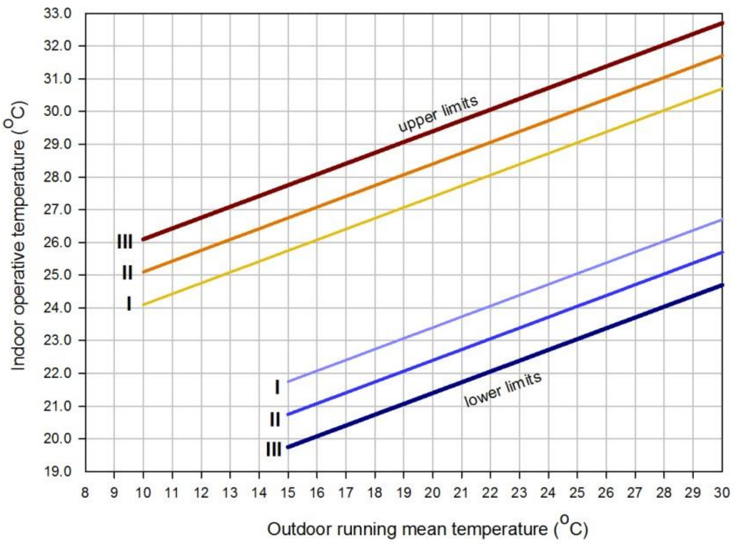
- T_{rm}= Exponentially weighted running mean of the outdoor temperature
- a is a constant between 0 and 1. Recommended=0.8
- T_{ed-1}=Daily mean outdoor temperature for the previous day
- T_{ed-2},…= Daily mean outdoor temperature for the day before and so forth
- T_{rm-1}= Exponentially weighted running mean of the outdoor temperature for the previous day

Equation (3.10) gives the relationship between the comfort temperature T_{comf} and T_{rm} as derived from the SCATs database.

$$T_{comf} = 0.33T_{rm} + 18.8 \quad (3.10)$$

Figure 3.5 shows the acceptability bands for 3 categories of buildings used in EN 15251, similar to those of ISO 7730 (A,B,C). The acceptability bands are: T_{comf} ±2, T_{comf} ±3 and T_{comf} ±4°C for categories I,II and III respectively.

EN 15251 was one of the standards developed to provide help in implementing the European Directive for Energy Performance of Buildings (EPBD) which was approved in 2002 (European Commission, 2002). The standard is addressed to the members of the European Union. However, it is not well known in Europe and internationally, even though it breaks new ground in recognising the different thermal expectations of occupants in naturally and air-conditioned buildings (Nicol and Wilson, 2011), similar to ASHRAE 55 analysed below. Furthermore, among the EU members, the Netherlands has its own adaptive guideline, developed and used since 2004 (van der Linden et al., 2006). This is described in section 3.2.4.



Category I - High level of expectation: recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons.

Category II - Normal level of expectation: to be used for new buildings and renovations.

Category III - An acceptable, moderate level of expectation: may be used for existing buildings.

Figure 3.5. Design values for the indoor operative temperature for naturally ventilated buildings as a function of the exponentially-weighted running mean of the outdoor temperature (CEN, 2007)

3.2.3 ASHRAE 55

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) has developed a thermal comfort standard for the specification of comfort criteria, “Standard 55: Thermal Environmental Conditions for Human Occupancy” (ASHRAE, 2010). It is intended primarily for office environments with sedentary or near sedentary activities as most of the data on which it is based is derived from office environments. However, it states that it can be applied to other building types, such as schools, “if it is applied judiciously”, without providing further explanation or guidance.

The main method provided by the standard for determining acceptable operative temperatures is the PMV/PPD application. The requirement set is PPD<10% which corresponds to -0.5<PMV<0.5 (Table 3.6). Unlike EN ISO 7730 and EN 15251, there is no different level of acceptability based on building category or level of expectation. In addition, ASHRAE-55 does not provide recommended design values for the operative temperature. Instead, it specifies a comfort zone which is generated for typical values of metabolic rate (1.1met), clothing insulation (0.5clo for summer and 1.0clo for winter) and air speed (0.10m/s). The standard also provides guidance on local thermal discomfort, radiant temperature asymmetry and draft, in line with ISO 7730 but again without space categories. However, the criteria match those recommended for a category B space from ISO 7730 (medium expectations) (see section 3.2.1).

Table 3.6. ASHRAE 55 requirement for indoor thermal comfort

Acceptable thermal environment	
PPD %	PMV range
<10	-0.5 <PMV< +0.5

In the latest versions of the standard, 2004 and 2010, ASHRAE has adopted the 'adaptive approach' as a method for defining the allowable indoor operative temperatures in naturally ventilated buildings relying principally on the use of opening windows to control the indoor temperatures. Initially, the method was stated as "optional" (ASHRAE, 2010) but this was recently removed (ASHRAE, 2012b). Its adaptive method is based on the comfort temperature equation which has been derived from the analysis of the ASHRAE worldwide database (de Dear, 1998) as described below.

3.2.3.1 ASHRAE adaptive algorithm: worldwide RP-884 Database

The RP-884 database was developed in the late 1990s from independent surveys around the world, unlike SCATs (section 3.2.2) which was created as part of one project with the procedures determined from the beginning for all participant countries. Nevertheless, the projects in the RP-884 database followed the same or similar measuring and surveying standards (De Dear et al., 1997). These standards were based on a protocol developed during the first thermal comfort studies of ASHRAE in the mid-1980s (de Dear and Brager, 2002). For the collation of the RP-884 database, the various raw data sets were categorised in 3 classes (I, II, III) based on the quality of instrumentation and survey procedures (De Dear et al., 1997). Most of the raw data belongs to classes II and I, which have the most stringent requirements.

The RP-884 database contains approximately 21,000 sets of raw data from 160 office buildings in 9 countries, as can be seen in Figure 3.6. Some information on the field studies is given in Table 3.3 (comfort study No2).

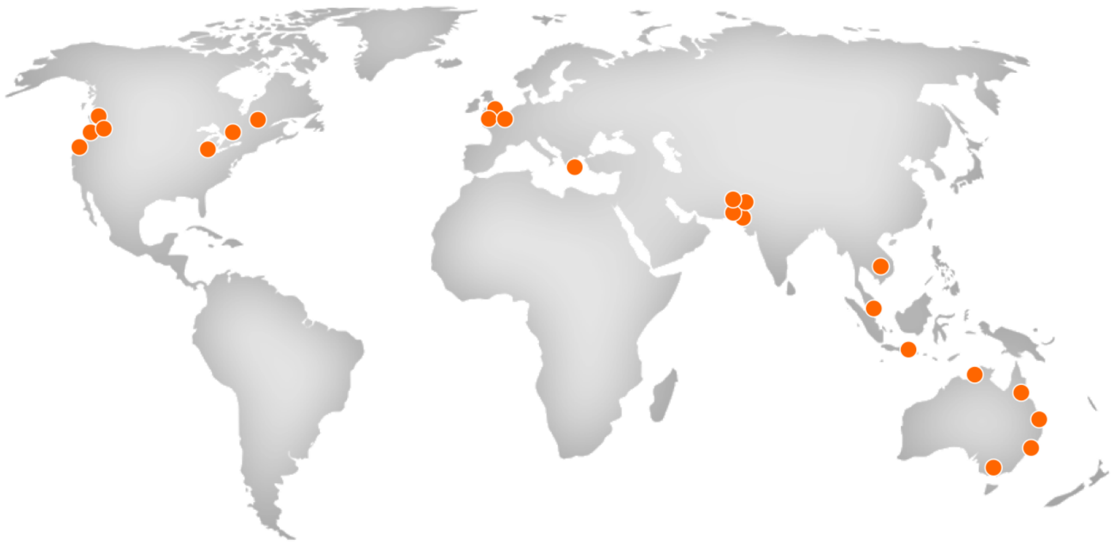


Figure 3.6. The locations of the field studies in the RP-884 database, adapted from (de Dear and Brager, 2002)

From the statistical analysis of the RP-884 database the adaptive equation (3.11) was developed, which initially related the comfort temperature T_{comf} with the mean monthly outdoor temperature (de Dear and Brager, 2001). This monthly time-scale was chosen for pragmatic reasons as it can be adopted more easily by practitioners compared to daily outdoor temperatures (de Dear and Brager, 2002). However, using the monthly mean has been criticised as being open to misinterpretation of the month period (e.g. it could refer to the calendar month or to 30 days before the day under investigation). Furthermore, it ignores variations within a month which could influence thermal adaptation (Nicol and Humphreys, 2010). Therefore, the time-scale recently changed to "prevailing mean outdoor air temperature", defined as the arithmetic mean of all of the mean daily outdoor air temperatures of "no fewer than 7 and no more than 30 sequential days prior to the day in question" (ASHRAE, 2012a). The revised standard also allows for weighting methods.

$$T_{comf} = 0.31T_{a,out} + 17.8 \quad (3.11)$$

Where T_{comf} is the comfort temperature and $T_{a,out}$ the prevailing mean outdoor temperature (previously "average of the mean monthly minimum and maximum daily air temperatures for the month in question").

Using the comfort temperature equation (3.11), the ASHRAE-55 adaptive comfort limits given in Figure 3.7 were derived. The graph includes two sets of operative temperature limits, one for 80% acceptability (T_{comf}±3.5°C) and one for 90% acceptability (T_{comf}±2.5 °C), with the latter being used when a higher standard of thermal comfort is required.

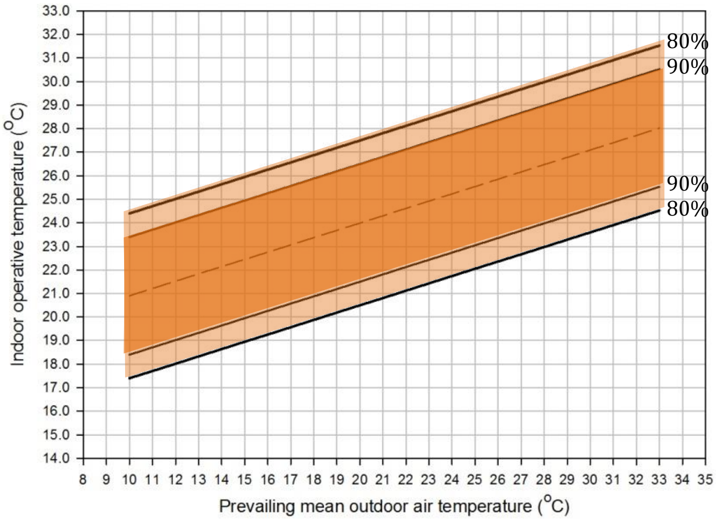


Figure 3.7. Acceptable operative temperature ranges for 90 and 80% acceptability in naturally ventilated spaces (ASHRAE, 2010)

ASHRAE standard 55 was first published in 1966 (ASHRAE, 2010) and is the most accepted standard for comfort in the US and well known worldwide. However, in Europe, EN 15251 is recommended, as it was based on data collected in European countries.

3.2.4 ISSO 74 Guideline

The Dutch ISSO 74 is an adaptive comfort guideline based on the ASHRAE worldwide database (Mors et al., 2011). Unlike ASHRAE 55 which uses the air-conditioned/naturally ventilated classification of buildings, ISSO 74 introduces the building/climate types Alpha and Beta as more suitable for the Netherlands (van der Linden et al., 2006). A simple method of applying this classification is shown in the flow chart of Figure 3.8. The reason for the development of this way of determining the building category is that most of the buildings in the Netherlands do not only use one of the two main conditioning regimes (air conditioning and natural ventilation) but a combination of them and other systems, such as passive façade ventilation systems (van der Linden et al., 2006). Therefore, this method gives the opportunity to assess combined options of occupant control rather than just the two options typically examined (no occupant control/air conditioning and occupant control/natural ventilation).

For the two new types, three acceptability levels are used, A, B and C, corresponding to 90, 80 and 65% of acceptance of the thermal environment. The least strict category (C) applies to existing buildings. Figure 3.9 shows the acceptable operative temperature ranges as a function of the outdoor running mean ($T_{e,ref}$) as calculated from equation (3.12) (van der Linden et al., 2006).

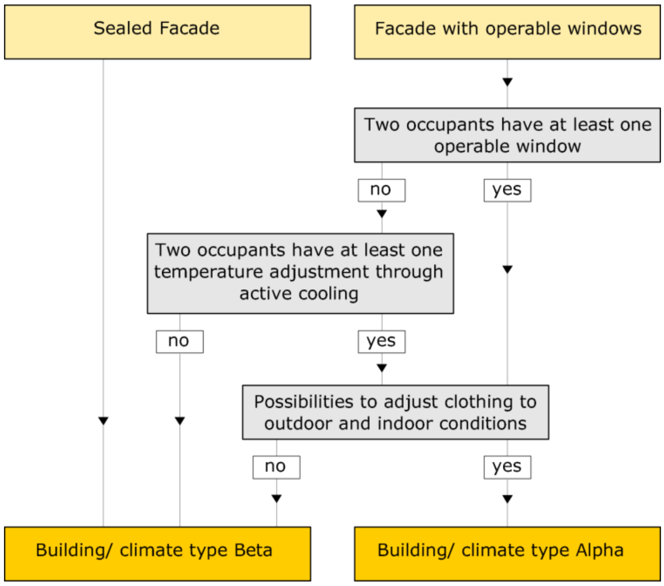


Figure 3.8. Flow chart determining building/ climate types Alpha or Beta, adapted from: (van der Linden et al., 2006).

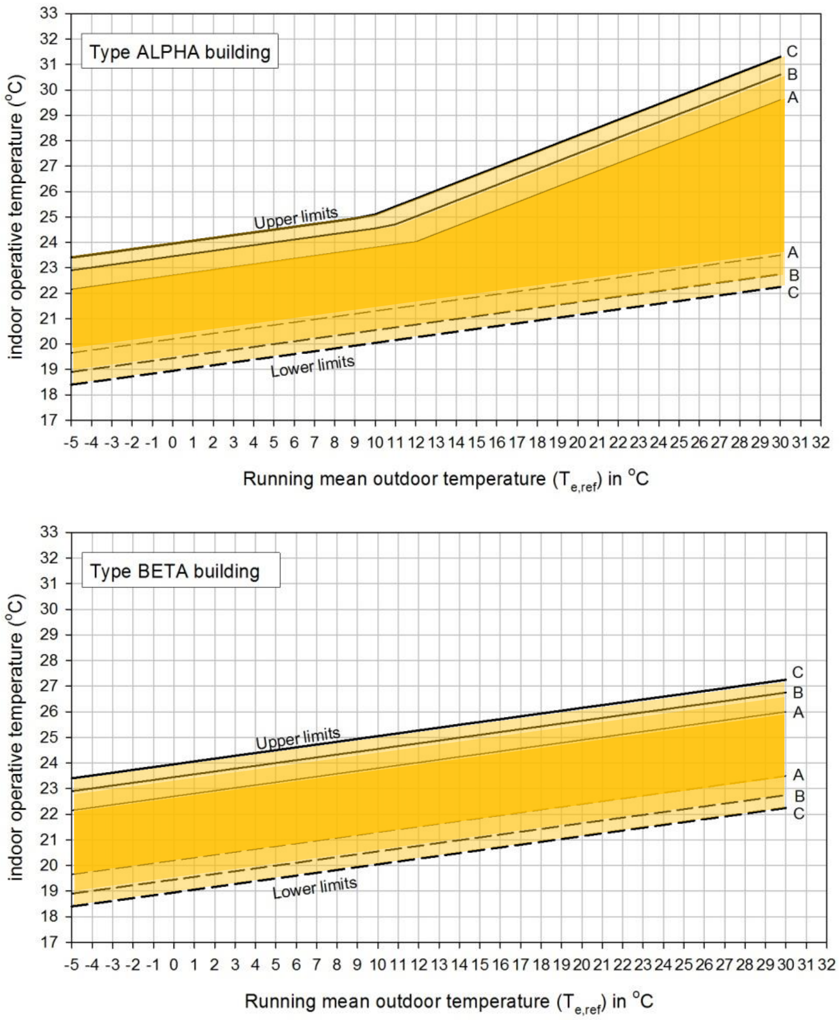


Figure 3.9. Allowed operative indoor temperatures for the building types ALPHA (upper) and BETA (bottom), adapted from: (van der Linden et al., 2006)

$$T_{e,ref} = (1T_{ed} + 0.8T_{ed-1} + 0.4T_{ed-2} + 0.2T_{ed-3})/2.4 \quad (3.12)$$

Where: T_{ed} is the daily mean air temperature of the day under study, T_{ed-1} the daily mean air temperature of the previous day and so forth.

ISSO 74 introduced a classification system which could be applied in other countries with similar building types and climate, such as the UK. However, the indoor climate distinction between type Alpha and Beta, based on the flowchart of Figure 3.8, is considered to still need further development (Kurvers et al., 2007, van der Linden et al., 2007). Furthermore, the guideline was based on the ASHRAE database which also includes data from tropical climates. This has been highlighted by the developers of the standard who noted that further research is required to address this issue (van der Linden et al., 2006).

3.2.5 CIBSE Guide A

In Guide A on environmental design, CIBSE (Chartered Institution of Building Services Engineers) provides design criteria for thermal comfort in buildings (CIBSE, 2006). For air conditioned buildings the criteria are based on the PMV model. Unlike ISO 7730, EN 15251 and ISSO 74, there is no categorisation of thermal environment and the recommended ranges of operative temperature correspond to $-0.25<PMV<0.25$ (PPD=6%) but can be adjusted for $-0.5<PMV<0.5$ (PPD=10%) if it is acceptable. For free-running buildings (nor heated or cooled at the time in question) different comfort temperatures are provided based on the adaptive comfort principle that people are more tolerant to higher temperatures during warm weather. The recommended values for teaching spaces (air-conditioned and free-running) and the indicated assumed values for metabolic rate and clothing insulation can be seen in Table 3.7 in section 3.4.1.

3.2.6 Limitations in the existing standards

- The criteria for thermal comfort provided by the standards are based on studies with adult subjects in climate chambers (ISO 7730) and offices (EN 15251, ASHRAE 55) (see sections 3.1.1 and 3.1.2). The focus of EN 15251 on workplaces has been identified as a limitation of the standard (Nicol and Wilson, 2011). In ASHRAE standard 55 (ASHRAE, 2010), it is suggested to apply the criteria to other building types "judiciously". However, there is no guidance on how this could be done.
- Existing thermal comfort standards are considered to be partly responsible for high building energy consumption by encouraging the use of air-conditioning

(Roaf et al., 2010). Comfort is often considered as a "product" driver for the heating and air-conditioning industry, which favours the use of mechanical means for the improvement of comfort (Nicol and Humphreys, 2009).

- The standards account for the different conditioning regimes by categorising buildings into naturally ventilated and air-conditioned. However, they do not take into account different construction types, e.g. building thermal mass and insulation values, or architectural features, e.g. layout, orientation of spaces, openings, shading devices, which also determine whether a building is capable of providing occupant thermal comfort.
- It is well accepted and stated in the Standards documents that it is difficult to satisfy everyone in a space. Therefore, levels of acceptability are used. However, the categories of acceptability level used in both ISO 7730 and EN 15251 have been questioned. The ISO 7730 classification was found to be unreliable due to the high PMV sensitivity to some of the input parameters (d'Ambrosio Alfano et al., 2011). The EN 15251 categories are associated with occupant expectations and have been criticised to relate "high expectation" to a closely controlled thermal environment (Nicol and Humphreys, 2009).
- The existence of different approaches and standards for the indoor thermal comfort highlights its complexity and the difficulty to produce general rules applicable in every location and any thermal environment. Furthermore, a wide range of disciplines are involved in thermal comfort research, which constitutes its strength but also leads to different approaches (Nicol, 1995).

3.3 Overheating criteria

The focus of this study is on comfort in naturally ventilated UK schools outside the heating season. As discussed in section 2.2.1, in the UK, over the last 30 years there has been a trend towards warmer summers. This has created a major concern for existing naturally ventilated buildings as it increases their overheating risk. Several overheating criteria have been developed, as described below. The first two are based on fixed overheating thresholds, whilst the third is based on the adaptive model of thermal comfort. Specific overheating criteria developed for schools are described in section 3.4.2.

CIBSE provides overheating thresholds for free-running buildings in the UK. Overheating is related to the building type and is expressed in terms of a benchmark temperature that should not be exceeded for a designated number of hours or percentage of the year. In TM36 (CIBSE, 2005) three building types (offices, schools and dwellings) were examined and overheating was defined as “the exceedance of more than 1% of occupied hours in a year over the higher temperature benchmark”, indicating a failure of the building to control overheating risk. The discomfort temperature benchmark for non-air conditioned non-domestic buildings was specified as 28^{o}C (CIBSE, 2006). The above criterion is also suggested by Approved document L2A (new buildings other than dwellings) for the specification of overheating (The Building Regulations Part L, 2010).

EST (Energy Saving Trust) introduced an alternative measure for quantifying overheating which is the number of degree hours above a threshold temperature (EST, 2005). If the threshold is set at 27^{o}C then a temperature of 30^{o}C for one hour corresponds to 3 degree hours. EST set this measure to replace CIBSE’s criterion which “does not convey the full extent of the impact on occupants” (EST, 2005).

Furthermore, “the risk and magnitude of overheating can be calculated according to the amount by which the operative temperature for any given hour or day exceeds the predicted comfort temperature for that day” (Nicol et al., 2009). The comfort temperature is calculated using equation (3.10), which was derived from statistical analysis of the SCATs data (see section 3.2.2) from office building field studies (Nicol and Humphreys, 2007). The likelihood of overheating is then calculated using equation (3.13) (Nicol et al., 2009).

$$P = e^{(0.4734 \cdot \Delta T - 2.607)} / \left\{1 + e^{(0.4734 \cdot \Delta T - 2.607)}\right\} \qquad (3.13)$$

Where P is the proportion of respondents voting ‘warm’ or ‘hot’ on the 7-point ASHRAE scale and ΔT the difference between the actual operative temperature and the comfort temperature. The above equation was derived from logistic regression analysis of the SCATs database (Nicol and Humphreys, 2007). The main advantage of this approach is that it takes into account the greater impact of a sharp rise in outdoor temperatures on thermal comfort than that of an extended warm spell.

3.4 Thermal comfort in schools

Thermal comfort in school classrooms is essential for the pupils’ productivity (Wyon, 1970). “Even though the human organism is highly adaptive, a student cannot attend, perceive, or process information easily when his or her physical environment is uncomfortable” (Knirk, 1979). Temperature is considered to be the most important indoor air quality parameter in buildings (Jaakkola, 2006). The combined effect of temperature and humidity has been proved to impact on performance and attention (Mendell and Heath, 2005). It has been shown that the impact of the indoor environmental conditions is stronger on children's schoolwork performance than on adults' office work (Wargocki and Wyon, 2013). Therefore, children appear to be more sensitive to the indoor environment than adults. A field intervention experiment in two classes of 10-year-old children has shown that reducing temperatures in summer and increasing ventilation rates leads to better performance of schoolwork (Wargocki et al., 2005). The more complex the task, the more likely its accomplishment will worsen with heat (Enander and Hygge, 1990) Also, tasks requiring concentration and clear thinking are negatively affected by heat stress (Wyon et al., 1979). Based on a summary of research findings on the effects of temperature on school work (Wargocki and Wyon, 2007), the pupil's performance is significantly lower at both 27°C and 30°C than at 20°C. Clearly, sustaining classroom temperatures within acceptable limits is crucial for a child's learning ability therefore child specific thermal criteria are necessary. The following section looks at existing criteria for school environments, with a focus on the non-heating season.

3.4.1 Existing comfort criteria for school environments

In the UK, specific guidelines for the thermal conditions in schools can be found in Building Bulletins (BB) 87 (DfES, 2003a) and 101 (DfES, 2006). Table 3.7 summarises the indoor operative temperatures recommended for teaching spaces by the previously described Standards and the BB guidelines.

Table 3.7. Design values of the operative temperature for teaching spaces

Standard /Guide	Type of space	Met*	Clo*		Category/ acceptability	Operative temperature T_{op} range (°C)	
			C-s*	H-s*		C-s*	H-s*
ISO 7730	ALL	1.2	0.5	1.0	A (PPD<6)	24.5±1.0	22.0±1.0
					B (PPD<10)	24.5±1.5	22.0±2.0
					C (PPD<15)	24.5±2.5	22.0±3.0
EN 15251	AC*	Same as ISO 7730				Same as ISO 7730	
	FR*				I (strictest)	$0.33T_{rm}$+18.8±2	Same as AC
ASHRAE 55	AC*	1.1	0.5	1.0	PPD<10	PMV-based range of T_{op} and RH	
	FR*	-	-	-	90% accept	$0.31T_m$+17.8±2.5	Same as AC
					80% accept	$0.31T_m$+17.8±3.5	
CIBSE	AC	1.4	0.65	1.0	PPD<10	22.0±1.0	20.0±1.0
	FR	-	-	-	-	25(+3)	Same as AC
BB 87	ALL	-	-	-	Low activity	24±4	21
					normal	24±4	18
					High activity	24±4	15

Notes:

- *C-s =Cooling season, H-s= Heating season, Met=Metabolic rate, Clo=Clothing insulation, AC=Air conditioned, FR=Free running
- ASHRAE- Standard 55 does not provide criteria by building type therefore the general criteria are considered applicable for school environments
- CIBSE's recommended operative temperatures for air-conditioned teaching spaces were calculated for higher met and clo values. However, guidance is provided for their adjustment for different values.

As can be seen in Table 3.7, in the cooling season (highlighted in grey) the recommended operative temperature based on the PMV model of the standards and guides ranges from 24 to 25°C with a maximum threshold of 28°C (ISO 7730). These PMV-based criteria are similar or even the same as those suggested for office spaces by the same standards (ISO, 2005, CIBSE, 2006, DfES, 2003a). Therefore, there is essentially no differentiation for the building and occupant type. There is a reference to very young children in the adaptive comfort standard EN 15251 (Category I- high level of expectation) but there is no definition of what ages are considered as "very young" (CEN, 2007). Furthermore, the adaptive comfort standards EN 15251 and ASHRAE-55, described in sections 3.2.2 and 3.2.3, were based on surveys of adults, not children, mainly in offices.

Even though the standards do not differentiate the assessment method for classroom and office environments, comparison between them suggests that the thermal environment and the occupant use may be significantly different. The main differences include:

- The main occupants, children, do not control their thermal environment, e.g. open or close windows/doors/blinds, the teachers are responsible for this. Therefore, it appears questionable whether the definitions for naturally ventilated spaces provided in the standards, such as: "Occupant controlled naturally conditioned spaces are those spaces where the thermal conditions of the space *are regulated primarily by the occupants* through opening and closing of windows" (ASHRAE, 2010) are valid.
- Compared with adults, children have a higher resting metabolic rate per kilogram body weight (Holliday, 1971).
- School children take limited adaptive action to adjust to the indoor thermal environment during class hours (Hwang et al., 2009). They can add or remove layers of clothing but cannot freely open or close windows or adjust their activity level (Corgnati et al., 2009).

- Even though they can add or remove layers of clothing, as mentioned above, children might neglect to do it (Humphreys, 1977). In addition, in the UK there is a school uniform policy which means that the available clothing choices are limited.
- The windows in schools open to a small extent for security reasons and to avoid injuries caused by projecting parts (The Building Regulations Part K, 2010).
- It is sometimes undesirable to open windows in classrooms due to external noise or pollution, especially in urban schools (Jenkins et al., 2009a).

Table 3.8 compares the main characteristics of climate chambers, offices, university classrooms and schools. In general, climate chambers are significantly different to everyday environments and the impact of this on thermal sensation of occupants has been thoroughly discussed in the past (Humphreys and Nicol, 2002). Furthermore, the everyday environments of offices, universities and school classrooms are different to an extent that suggests that occupants probably adapt to different thermal conditions (Table 3.8). The school day of pupils includes diverse activities in densely occupied classrooms where adaptive action is limited, as well as outdoor playtime at least twice a day. It is likely that pupils' thermal perception is influenced by this different daily routine. Therefore, there is no assurance that the described comfort standards are also optimal for pupil comfort or performance (NRC(US), 2007).

Table 3.8. Typical characteristics of offices, chambers, schools and university classrooms

	Climate chamber	**Office space**	**University classroom**	**School classroom**
Occupants	Adults	Adults	Adults	Children
Occupancy density	Varies	10 m^2/p (BCO, 2009)	Depending on the class can be very high	High (approx. 2.2 m^2/p)
Occupancy profile	Only for the survey time	8am-5pm with 1h lunch break	Students visit the room for the lecture hours (usually 1 to 2h)	9am-3pm with 2 major breaks, morning and lunch break
Typical layout	Restricted and controlled space	Usually open plan large areas	Lecture theatres or seminar rooms	Classrooms of approx. 60m^2
Environmental control/ action	None	Generally possible but depends on availability/ proximity	Limited during the lectures but possible	Main users (pupils) don't take action, the teacher does
Activities	Depends on the experiment	Desk-based	Lecture or workshop	Diverse during a day: maths, arts, physical education, literacy, playtime/ sports

3.4.2 Existing overheating criteria for school environments

For the issue of overheating in UK schools, two of the Building bulletins published by the 'Department of Children, Schools and Families' provide criteria, (i) Building bulletin 87- 'Guidelines for Environmental Design in Schools' (DfES, 2003a) and (ii) BB 101- 'Ventilation of School Buildings' (DfES, 2006). The criteria include overheating thresholds based on the fixed temperature approach (section 3.3), as described below.

(i) According to Building Bulleting 87 (DfES, 2003a), classroom overheating occurs when the indoor air temperature exceeds 28°C. Further to the definition of overheating, BB 87 determines an allowable degree of overheating occurrence at 80 occupied hours per year, normally outside the heating season, from May to September (DfES, 2003a).

(ii) Building Bulletin 101 (DfES, 2006) defines three conditions which apply outside the heating season for the occupied period of 09:00 to 15:30, Monday to Friday, from 1st May to 30th September. BB 101 states that:

a) "There should be no more than 120 hours when the air temperature in the classroom rises above 28°C
b) The average internal to external temperature difference should not exceed 5°C (i.e. the internal air temperature should be no more than 5°C above the external air temperature on average).
c) The internal air temperature when the space is occupied should not exceed 32°C."

If two of these three criteria are met, then, based on BB 101, there is no overheating issue.

In a recent study (Montazami and Nicol, 2012) the above fixed thresholds were compared to the overheating criteria based on the adaptive thermal comfort principle (Nicol et al., 2009), as analysed in section 3.3, and with teachers' estimates of pupils' thermal comfort in classrooms. It was found that the adaptive comfort overheating criterion better reflected the teachers' responses, whilst the fixed benchmarks were too lenient and therefore could constitute a potential reason for overheating occurrence in schools designed based on these standards. Following this study, a new guideline for schools was developed (Johnston and Partners, 2012) based on the adaptive comfort temperature limits given in EN 15251 (see section 3.2.2) (Montazami and Nicol, 2013). BB101 is planned to be updated in 2013 to include this new guideline, which uses three criteria to assess the risk of overheating, as stated below.

During the five summer months (May-September):

a) $H_e \leq 3\%$ of the total occupied hours or $H_e \leq 40$ hours, whichever is smaller, where:
   H_e (Hours of exceedance): the number of hours where T_{op} exceeds T_{max} by 1K
   T_{op}: the measured/predicted operative temperature
   T_{max}: the maximum acceptable operative temperature according to EN 15251 (CEN, 2007)
b) $W_e \leq 10.0$
   Where W_e (Weighted exceedance): the sum of the weighted exceedance for each degree K above T_{max} (1K, 2K, 3K), calculated using equations (3.14) and (3.15).

$$We = \sum He_{(1,2,3)} \cdot (\Delta T)^2_{(1,2,3)} \tag{3.14}$$

$$\Delta T = T_{op} - T_{max} \tag{3.15}$$

   Where H_{e1} is the number of hours that ΔT=+1K, etc. ΔT is rounded to the nearest integer.
c) ΔT < 4K at any time
   where ΔT is calculated using equation (3.15)

If two of these criteria are exceeded, then there is a risk of overheating in classrooms.

A. Montazami and F. Nicol compared this new guideline with the fixed thresholds of BB87 and BB101 and with the Nicol criterion described in section 3.3 (Montazami and Nicol, 2013). It was found that the new guideline is more stringent than the fixed thresholds relating better to occupants' dissatisfaction as expressed by the teachers' responses. However, it did not fully reflect the teachers' estimate of pupils' thermal response. It appears necessary to further investigate the new guideline in relation to pupils' thermal responses in order to make sure that the criteria correspond to their specific requirements.

3.4.3 Previous studies on children thermal comfort

Research studies conducted in schools in tropical and subtropical regions investigated the applicability of the ASHRAE specifications to those different climates (Hwang et al., 2009, Kwok and Chun, 2003, Wong and Khoo, 2003, Zhang et al., 2007) (see Table 3.9 for details). They focused on the potential impact of the different climates on thermal comfort and on the comparison between naturally and air-conditioned buildings. The age factor was not analysed in detail. It was found that the ASHRAE standard could not accurately predict the conditions in free-running buildings in the local climate. Another study in the hot and dry Kuwait found discrepancies with both the PMV and the adaptive models; however the studied classrooms were in hybrid air-conditioned mode, therefore neither of the models was fully applicable (Al-Rashidi et al., 2009).

In the UK, there is a lack of studies related to children's thermal comfort (Humphreys et al., 2007). Published data from school studies dates back to the 1970's with the results mainly related to the impact of clothing insulation on thermal comfort (Humphreys, 1973, Humphreys, 1977). On a European level there is a recent study with a small sample of children (79) conducted in the Netherlands which investigated the application of PMV charts and the clothing adaptation of children (Mors et al., 2011). It was found that existing standards underestimated children's thermal sensation.

Table 3.9. Thermal comfort field studies in school classrooms

Reference	Country	Climate	Ventilation	Age group
(Humphreys, 1973)	UK	Temperate	NV[1]	12-17
(Humphreys, 1977)	UK	Temperate	NV	7-11
(Wong and Khoo, 2003)	Singapore	Tropical	NV	13-17 26-50 (13 teachers)
(Kwok and Chun, 2003)	Japan	Sub-tropical	NV+AC[2]	13-17
(Corgnati et al., 2007)	Italy	Mediterranean	NV	12-23
(Hwang et al., 2009)	Taiwan	Sub-tropical	NV	11-17
(Al-Rashidi et al., 2009)	Kuwait	Desert	MM[3]	11-17
(Mors et al., 2011)	Netherlands	Temperate	NV	9-11
(Liang et al., 2012)	Taiwan	Sub-tropical	NV	12-17

[1] NV=Natural ventilation, [2]AC= Air-conditioning, [3]MM=Mixed mode ventilation

This study seeks to contribute to the understanding of the thermal perception of young children in classrooms which, as analysed in section 2.4.3, is essential for the assessment of indoor thermal environments. The study follows a field-survey methodology similar to that used in adult surveys, but with amendments, where necessary, in order to appropriately correspond to children (comprehensible questionnaire, interest-stimulating process) and school environments (appropriate survey times within the diverse school schedule). The method is described in detail in chapter 4.

4. Field study of thermal comfort in classrooms: case study details and research methodology

For the assessment of the thermal comfort sensation of pupils, field studies were conducted in naturally ventilated primary school classrooms in Southampton, UK. The studies included: a) thermal comfort surveys and b) classroom long-term environmental monitoring. In order to ensure that the results sufficiently represent the actual conditions in UK schools, it was decided to base the work on two typical UK school types as case studies, a post-war light-weight school and a Victorian school. Primary schools were selected for this research as the teachers and pupils remain in the same classroom during the school hours ensuring uniformity in terms of occupancy. Figure 4.1 shows the methodological pathways that were followed for the case study schools, with the full methodology being described in detail in section 4.2.

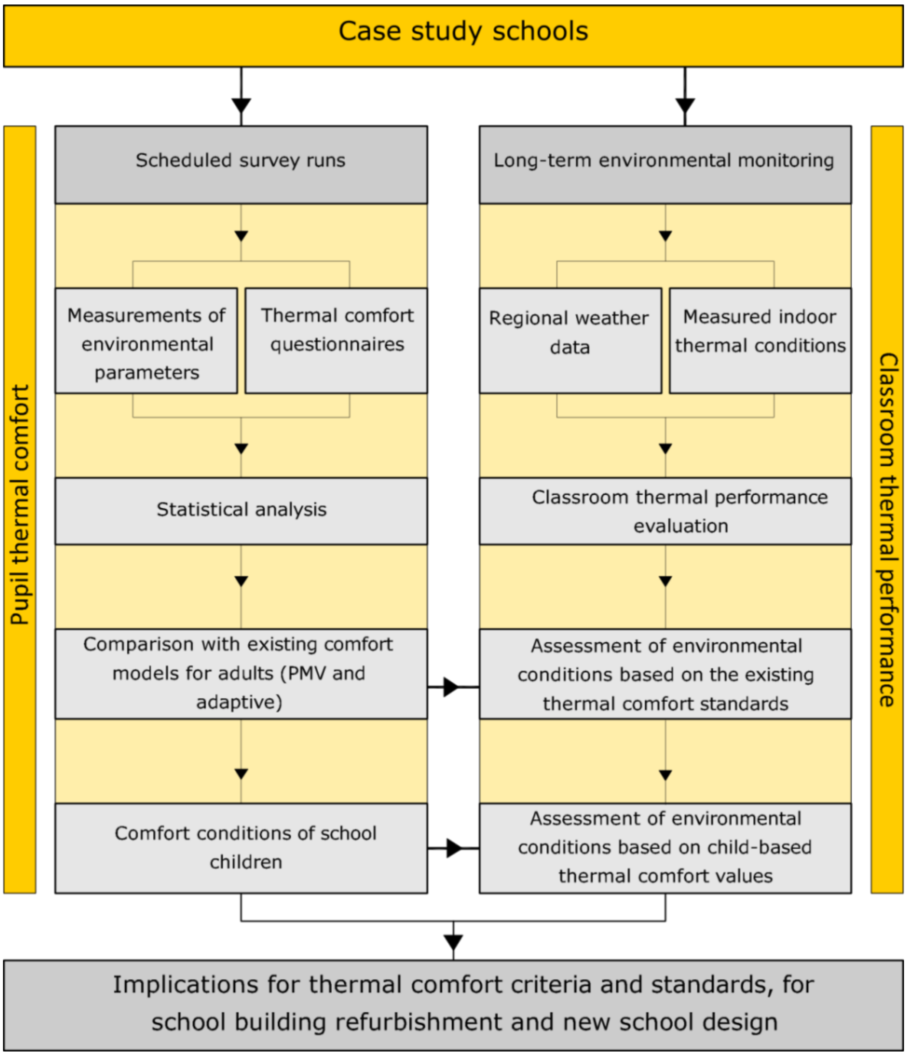


Figure 4.1. Flowchart of the research methodology

4.1 Case study schools

The core field study of this research was conducted in a post-war school in 2011. This selection was based on the high risk of overheating that post-war schools were found to experience, as analysed in chapter 2. Therefore, this building gave the opportunity to look at a potentially critical case for the summer season. The second case study was conducted in a Victorian school in 2012. The two case studies were analysed separately in order to minimise the impact of potentially different school policies and school characteristics (construction, materials) on pupils' overall thermal sensation and preference trends. The second case study was undertaken in order to be able to compare between different school construction types and building environments and their impact on thermal sensation and comfort in classrooms.

4.1.1 Location and climate of Southampton

The city of Southampton (50.9° N, 1.4° W) is located on the southern coastline of England, near continental Europe (Figure 4.2). It has a temperate climate which is type Cfb in the Köppen classification (Kottek et al., 2006), standing for: warm temperate (C), fully humid (f) with warm summers (b).

Figure 4.2. Location of Southampton on the UK map.

Due to its southern location, Southampton experiences milder winters and hotter summers than most northern UK cities. The average monthly temperature is between 5.5 and 18°C (Figure 4.3). The lowest temperature, on monthly average, occurs in February (mean daily minimum=2.6°C) and the highest in July (mean daily maximum=22.4°C). Figure 4.3 shows the 2011 and 2012 monthly averages of daily maxima and minima for the survey months March to July in relation to the 1981-2010 averages. It can be seen that the average minimum and maximum temperatures of the survey months are overall slightly lower that the 1981-2010 averages.

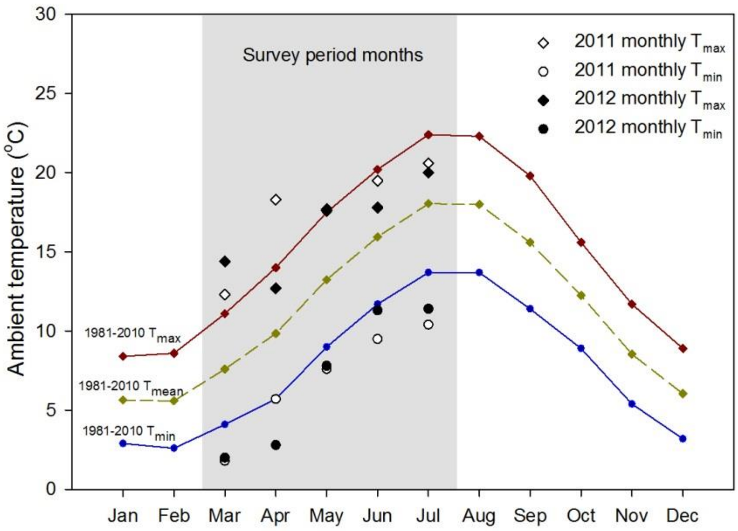


Figure 4.3. 1981-2010 averages of daily minimum, daily maximum and average monthly ambient temperature in Southampton, UK (data from Met Office). The data points show the monthly averages of the daily minimum and daily maximum temperatures for the survey months of 2011 and 2012 (data from http://www.southamptonweather.co.uk/)

Southampton is one of the sunniest cities in the UK with the average monthly sunshine hours reaching 230h in July. Overall, the months April, May, June, July and August are the sunniest, with a range of average sunshine hours between 180 and 230h. As can be seen in Figure 4.4, in the years 2011 and 2012 that the survey took place, the monthly averages of hours of sunshine for the months May-July were lower than the 1981-2010 average, especially in 2012. In June 2012, the average hours of sunshine was half that of the 1981-2010 period average. Overall, it appears that the summer months of 2011 and 2012 were milder compared to the average summer conditions of the past 30 years.

The rainiest months in Southampton are January, October, November and December, with an average precipitation of around 90mm (Figure 4.5). The driest month is July, with an average precipitation of around 40mm. Therefore, July is the driest and sunniest month.

This is important given that school summer term ends in the end of July therefore there is a risk of pupils experiencing warm conditions in schools. Overall, the survey months, March- July, are the warmest and driest of a school year.

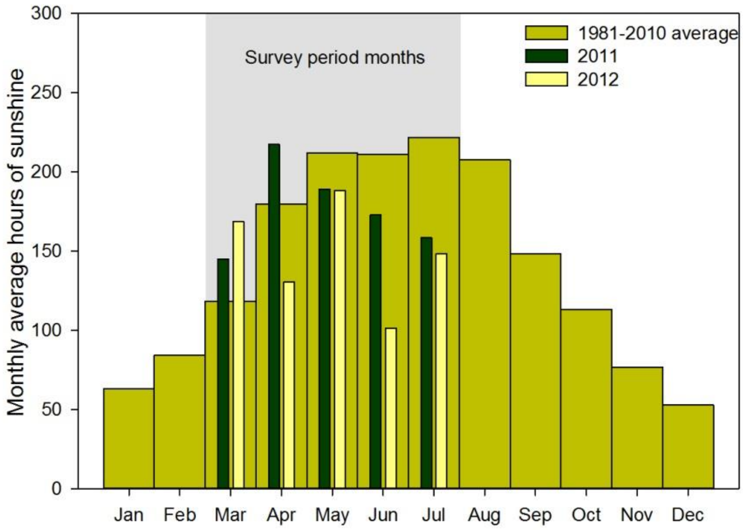


Figure 4.4. 1981-2010 average of monthly hours of sunshine in Southampton, UK (data from Met Office data).

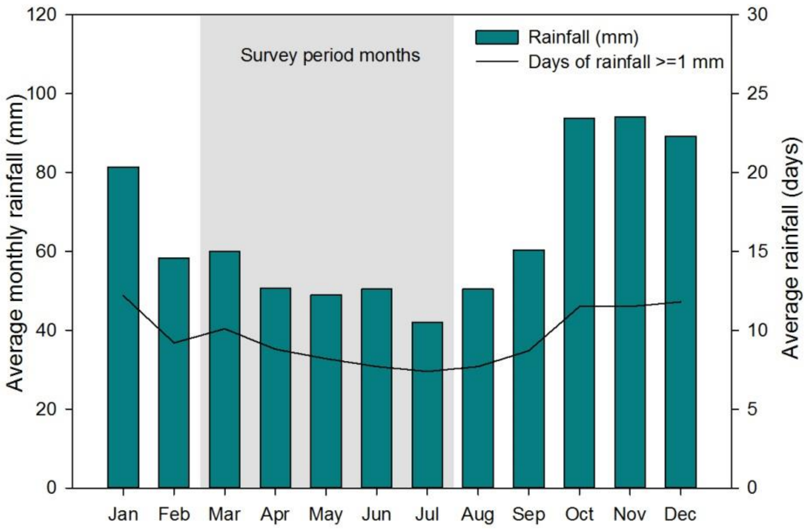


Figure 4.5. 1981-2010 average monthly rainfall in Southampton, UK (data from Met Office).

As can be seen in the wind roses of Figure 4.6, the prevailing winds during winter, summer and autumn blow from the West, whilst in spring the direction varies, with additional prevailing North-East and Southern winds. It should be noted however that the wind speeds given in Figure 4.6 apply to a height of 10m above ground where there are no obstructions and as such are not representative of the wind speeds at the building height of the investigated school buildings.

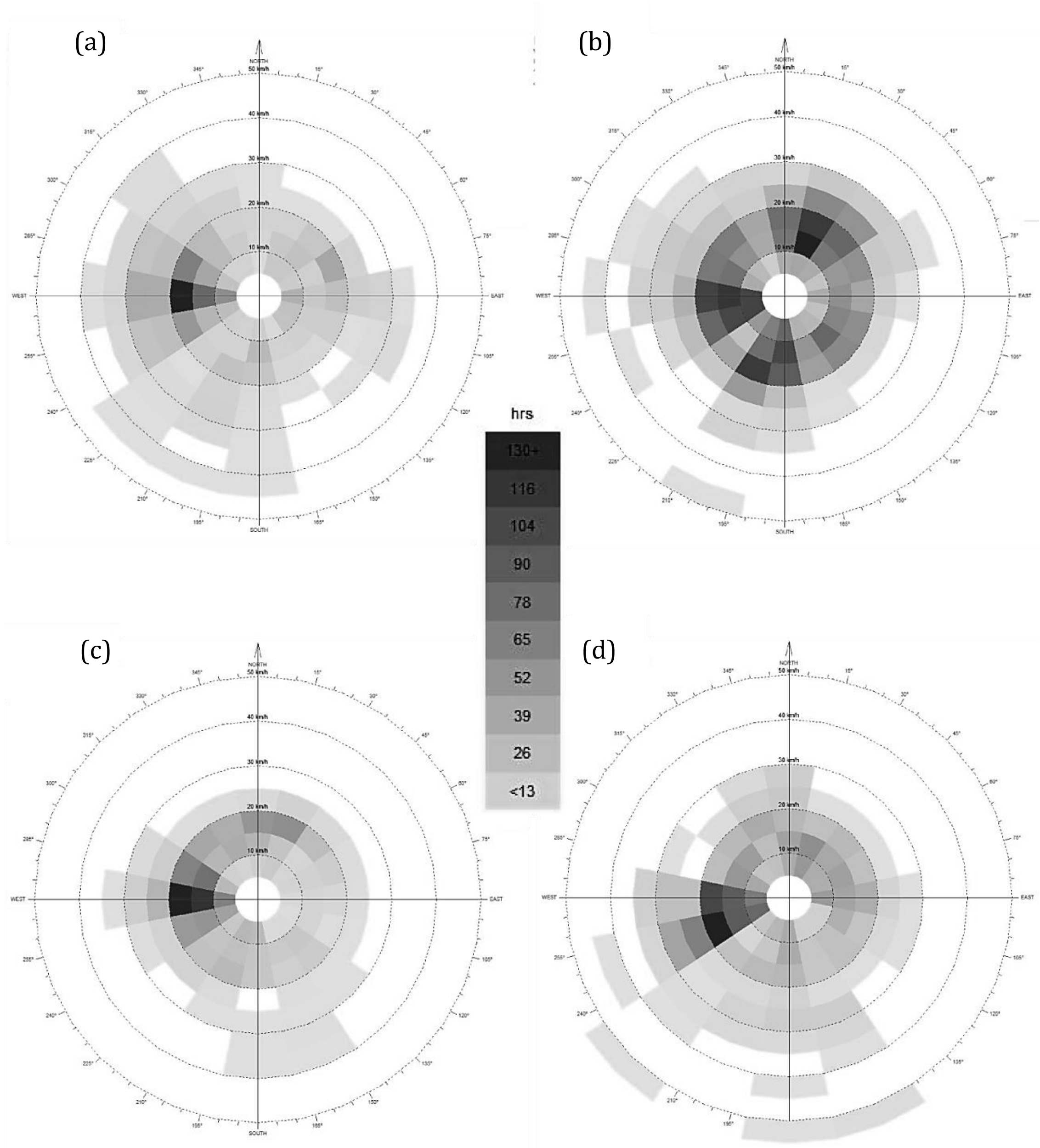


Figure 4.6. Wind roses for (a) winter and (b) spring (c) summer and (d) autumn in Southampton (generated with Autodesk Weather Tool 2009, using Southampton TRY file-Typical Reference Year from CIBSE/ Met Office data).

4.1.2 Case study 1 - Post-war light-weight school building

Building A on the aerial view given in Figure 4.7 (left) shows the post-war case study building, which is one of the four schools studied in section 2.4. It has around 235 enrolled pupils aged 5-11 (2011 data). It was constructed in 1978 using a light-weight steel frame construction (Figure 4.8, left) and pre-fabricated concrete panels. The building is attached to an infant school which was constructed during the same period (building B in Figure 4.7 left). As shown, the case study building consists of two parts which create an enclosed courtyard (Figure 4.8, right): a 2-storey L shaped building housing 8 classrooms and computer spaces and a 1-storey building with offices, the hall and kitchen. The study was conducted in all 8 classrooms (numbered spaces 1-8 in Figure 4.7 right), located in the L-shaped building part, where most of the school activities take place. The building has single-glazed, top-hung outward opening windows with reflective window film and is internally shaded with manually operated blinds (Figure 4.9, left).

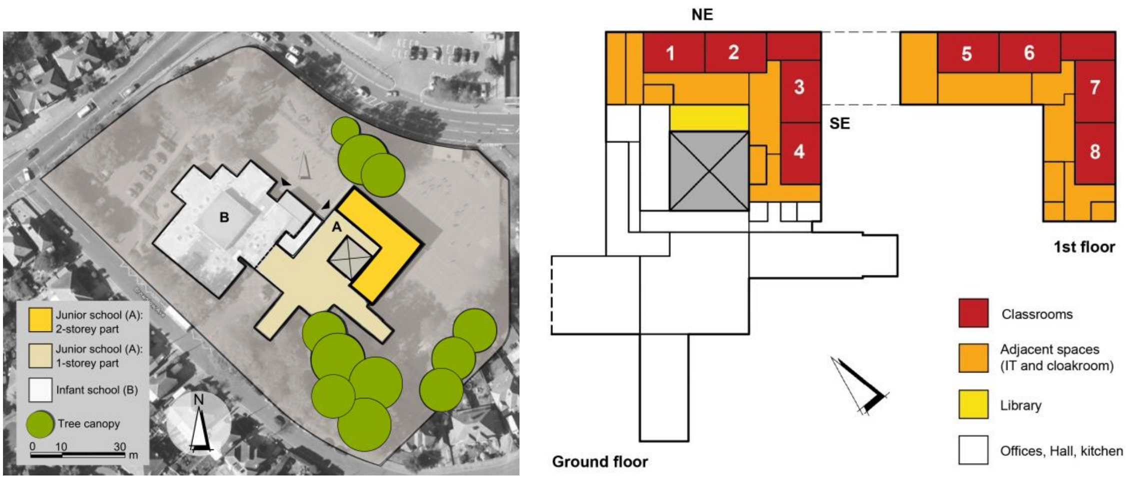


Figure 4.7. Post war case study school. Left: Infant (B) and primary (A) school (Adapted from: Google Earth), right: schematic plans of the surveyed school (A).

Figure 4.8. left: School corridor with exposed steel frame work construction, right: Enclosed courtyard for outdoor class activities and breaks.

The specific building was chosen as the main case study because it is a typical example of a light-weight post war school building in the UK and has reported overheating incidents in the past. Furthermore, from the overheating risk evaluation of section 2.4 it was determined that this building has the highest potential of overheating compared to the other 3 buildings of the same survey. Based on the previous building analysis, this is probably related to characteristics such as: morning solar gains due to the North-East and South-East orientation of the classrooms, a glazing to façade wall ratio of approximately 40% (Figure 4.10), large outdoor tarmac areas, a lack of vegetation and shading, the flat bitumen roof, the light-weight construction, single glazing and a lack of wind exposure (Teli et al., 2011).

Figure 4.9. left: view of a 4-pane window with manually operated blinds, right: Outdoor space covered with tarmac.

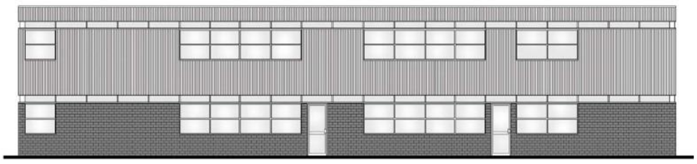


Figure 4.10. SE elevation drawing of the post-war case study school

4.1.3 Case study 2 - Victorian heavy-weight school building

The second case study building is shown on the aerial view given in Figure 4.11. It was founded in 1884 as a junior school and became a primary school in 2010. It has around 400 enrolled pupils aged 5-11 (2012 data). This study is focussed on the junior school (pupils' age 7-11) which is located in the Victorian building denoted with 'A' in Figure 4.11. Buildings B to E accommodate the infant school classrooms and were built at different periods, as can be seen in Figure 4.12 (D: secondary Victorian building, C: 1970s extension, B and E: recently built modular buildings).

The case study school (Building 'A', Figure 4.11) comprises of 11 classrooms. As can be seen in Figure 4.13, most school spaces and 7 classrooms are located on the ground floor and only 4 classrooms and the staff room are on the 1st floor. The study was conducted in all 11 junior school classrooms (numbered spaces 1-11 in Figure 4.13). As can be seen, the building spaces create an enclosed open space for outdoor activities and circulation (linkage between school spaces). The adjacent outdoor spaces are mostly covered in tarmac (Figure 4.14, left) and there is limited vegetation and few trees near the school ground boundaries (tree canopies in Figure 4.11).

Figure 4.11. Victorian case study school. Infant (B-E) and primary (A) school (Adapted from: Google Earth).

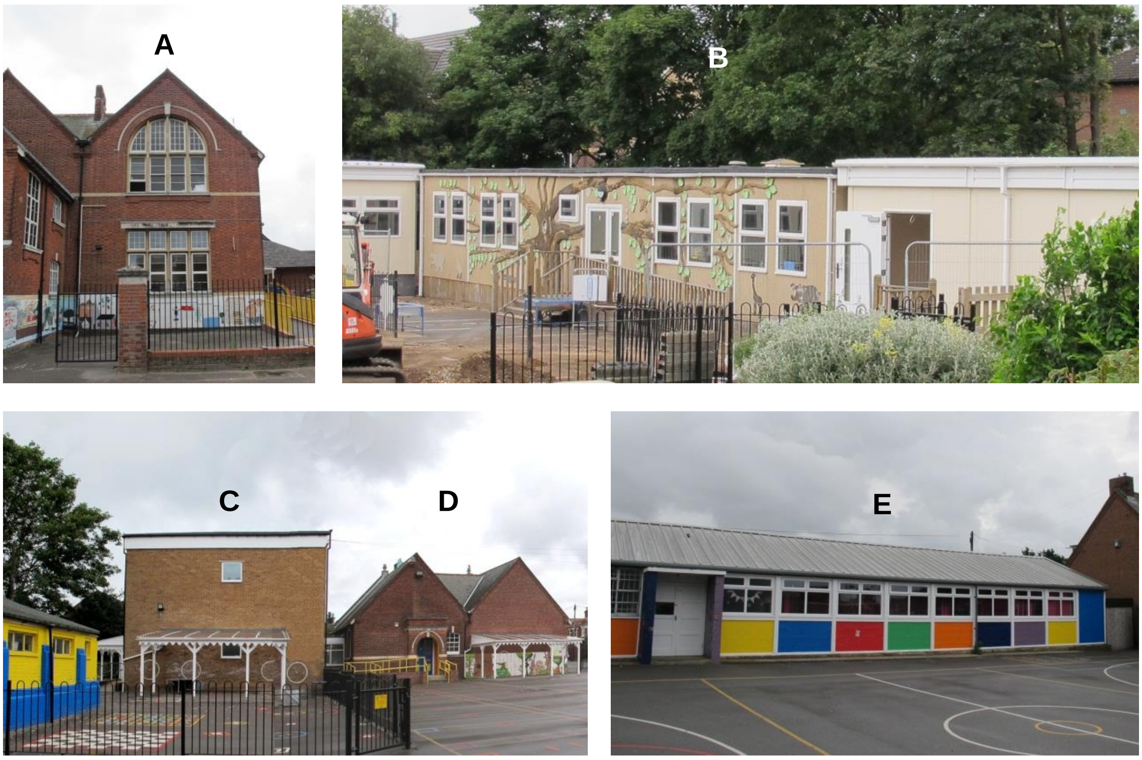


Figure 4.12. Buildings A-E of the school complex. Building A is the case study building.

The building was built using the cavity wall system with red bricks and pitched roof covered with slate tiles (Figure 4.14, right), following the typical Victorian school construction described in section 2.1.1. The classrooms have single-glazed sash windows with vertically sliding panels and, above them, one row of top-hung outward opening windows. Only one classroom (classroom 10) has internal shading blinds and in 4 classrooms (classrooms 3, 5, 6, 9) improvised shading solutions have been applied, such as carton boards and canvas posters on parts of the glazing area (Figure 4.15). The glazing to wall ratio in classrooms is approximately 25% (Figure 4.16). The classrooms have ceilings with a height of 3.7 m at the lowest point and 5.6 m at the highest point.

Figure 4.13. Victorian case study school: schematic plans

Figure 4.14. left: Large tarmac area outside buildings B and C of the school complex, right: Part of the case study Victorian building.

Overall, based on questionnaire surveys of teachers and staff, the building is comfortable in spring and autumn but its performance varies in winter and summer depending on the location of a space inside the building (Grob, 2011). For instance, some classrooms were assessed as too cold in winter and others as too warm. For the summer period, most were assessed by the teachers as too warm but some were even found to be cold. This is probably due to the different orientations of the classrooms (Figure 4.13), in comparison to the post-war school, where half of the classrooms are facing NE (north-east) and half SE (south-east). A detailed comparison of the two schools is conducted in chapter 8.

Figure 4.15. Window shading of 6 classrooms: a. shading blinds, b. canvas posters, c. fabric panels, d-e. carton boards, f. no shading.

Figure 4.16. NE elevation drawing of the Victorian case study school

4.2 Thermal comfort surveys and environmental monitoring methodology

Pupil questionnaire surveys and simultaneous measurements of the indoor environmental variables (as per ISO 7726 (ISO, 2001)) were conducted in both schools in line with standard methods used in adult surveys (Humphreys et al., 2007). Furthermore, in order to assess the overall thermal conditions in the classrooms outside the heating season the dry bulb temperature and relative humidity were monitored at 5 minute intervals during the survey periods, from March to August (2011 in the post-war school and 2012 in the Victorian school).

The surveys were carried out during 2-day visits to the schools, approximately every two weeks depending on the planned school activities (Figure 4.17). Material used during the surveys (forms and observation sheets) are included in Appendix C.

For reasons of clarity, in the text the following terms will be used:

- "test": a 2-day visit to the school
- “survey”: each classroom investigation

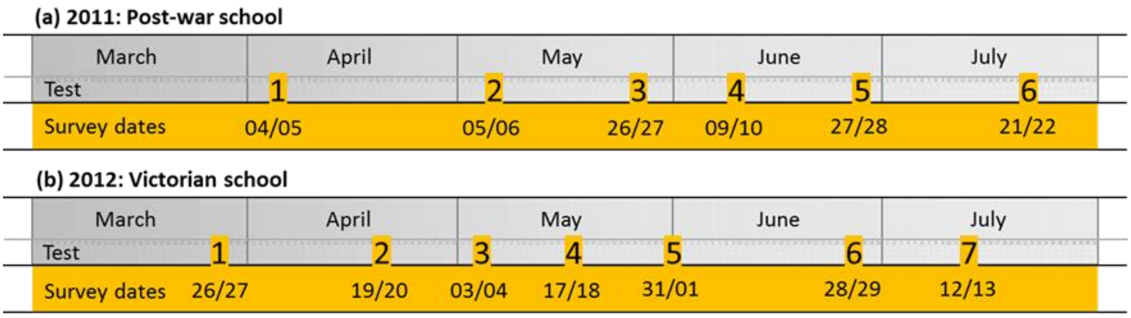


Figure 4.17. Dates of the tests conducted over 2-day visits to the case study schools in 2011(post-war school) and 2012 (Victorian school), from March to July.

(a) Post-war school: Approximately 230 pupils aged 7-11 in all 8 classrooms were surveyed 6 times (6 tests) and a total of 1314 responses were gathered. The field studies were carried out on 12 days outside the heating season, from April to July 2011, as shown in Figure 4.17. 4 surveys were conducted per day, i.e. 8 surveys per test and 48 surveys in total.

(b) Victorian school: Approximately 330 pupils aged 7-11 in 11 classrooms were surveyed a minimum of 6 times, while some were surveyed 7 times (7 tests, Figure 4.17). A total of 1676 responses were gathered on 14 survey days. However, in 3 of the tests the heating was on over some time, due to the exceptionally cool early summer (Met Office, 2012). Overall, 36 surveys were conducted in free-running classrooms and 33 in classrooms with the heating on during parts of the day, 69 surveys in total.

4.2.1 Survey questionnaire

The survey questionnaire, which is provided in Appendix A, was checked by the teachers prior to the study in order to be comprehensible to children. Visual stimuli (coloured sketches) were used as a way to retain children's interest and simple wording, as lack of interest and incomprehensible wording are the main factors which have been found to impact on the reliability of survey results in studies involving children (Borgers et al., 2000, Bell, 2007). The questionnaire included questions about:

a) the thermal sensation vote (TSV) of the respondent towards the indoor thermal environment, based on the 7-point ASHRAE thermal sensation scale (cold, cool, slightly cool, neutral, slightly warm, warm, hot)

b) the thermal preference vote (TPV) based on a 7-point scale (a lot colder, colder, a bit colder, no change, a bit warmer, warmer, a lot warmer)

c) the feeling of comfort

d) clothing information (whether the respondent was wearing a jumper (pullover) while answering the questionnaire)

e) the feeling of tiredness

f) the activity of the respondent prior to the questionnaire

A slightly amended version of the ASHRAE scale (Table 4.1) was chosen for the thermal sensation vote (TSV) assessment even though some research suggests that the Bedford scale (much too cool, too cool, comfortably cool, comfortable, comfortably warm, too warm, much too warm) might be more appropriate for the evaluation of the acceptability of the thermal environment (Wong and Khoo, 2003). The reason for this choice was that the ASHRAE scale was considered easier for young children to understand which was crucial for the reliability of the results. The ASHRAE scale was even simplified based on the teachers' comments/advice. The options "slightly cool", "slightly warm" and "neutral" were replaced by "a bit cool", "a bit warm" and "OK". As can be seen in Table 4.1, for the assessment of the thermal preference vote (TPV) a 7-point scale was applied instead of the commonly used 3-point scale. This was done in order to facilitate comparison with the thermal sensation votes (TSV).

Table 4.1. The ASHRAE and Bedford thermal sensation scales and the scales used in the questionnaire survey of this study

ASHRAE thermal sensation scale	Bedford thermal sensation scale	TSV scale (this study)	TPV scale (this study)
(+3) Hot	(+3) Much too warm	(+3) Hot	(+3) A lot warmer
(+2) Warm	(+2) Too warm	(+2) Warm	(+2) Warmer
(+1) Slightly warm	(+1) Comfortably warm	(+1) A bit warm	(+1) A bit warmer
(0) Neutral	(0) Comfortable	(0) OK	(0) No change
(-1) Slightly cool	(-1) Comfortably cool	(-1) A bit cool	(-1) A bit colder
(-2) Cool	(-2) Too cool	(-2) Cool	(-2) Colder
(-3) Cold	(-3) Much too cool	(-3) Cold	(-3) A lot colder

The children were not asked about their perception of thermal acceptability, humidity or air speed as undertaken in most similar adult surveys, because teachers found these questions difficult for 7-11 year olds to comprehend. Also, the questionnaire did not include a question about the clothes children were wearing during the survey as this would make the form too time consuming and go beyond the children's attention span. After discussion with the teachers, it was decided to include a simple question about whether they wore their jumper, as this changes their clothing insulation substantially and is one of the limited adaptive actions the children can take during the school day.

During the first school visits in the post-war school in 2011, the pupils showed a strong interest in the equipment and the survey process. However, after the second survey visit, the children showed some discontent about having to repeat the questionnaire. In order to keep the children engaged, a sticker booklet was prepared and handed out to each pupil along with an indoor thermometer for every classroom. The booklet included individual research tasks related to the indoor climate, such as keeping a log of the classroom's air temperature on a sunny, cloudy and rainy day (Appendix B). These tasks were specifically tailored towards different age groups: i.e. Years 3 & 4 and Years 5 & 6. Each time a task was completed or a thermal comfort survey was undertaken, the children received a reward sticker. This process managed to ensure pupils' interest during the remaining tests and was also adopted for the 2012 surveys in the Victorian school.

4.2.2 Measurements of environmental variables

During the surveys, the physical parameters which affect thermal comfort were recorded in line with the standards provided in ISO 7726 "Ergonomics of the thermal environment - Instruments for measuring physical quantities" (ISO, 2001). The equipment was placed as centrally in the classrooms as possible without disturbing the class activities and far from any heat sources such as projectors or computers. The measurements were taken at a height of 1.1m as recommended by ISO 7726 (ISO, 2001). A multi-functional measuring instrument was used (Testo 400) with probes which measured: air speed, ambient air temperature and humidity, radiant temperature (globe thermometer Ø 150 mm) and CO_2 concentration. Table 4.2 summarises the characteristics of the equipment and Figure 4.18 shows the measuring instruments, as they were set up during the surveys. The probe used for measuring air velocity is specifically designed for the small velocities typical of a classroom. Due to the small time constant of the probe, the mean air velocity value was determined from a series of individual readings, as suggested by Fanger (Fanger, 1970). Due to the response time of the globe thermometer, which is about 20 to 30 minutes, the instruments were set up in the room about 1 hour before the survey.

Table 4.2. Specifications of the measuring equipment

Probe	Meas. Range	Resolution	Accuracy
Humidity and air temperature	0 to100 %RH -20 to +70 °C	0.1% RH 0.1 °C	±2 %RH[1] (2 to 98%RH) ±0.4 °C (-10 to 50°C) ±0.5 °C (remaining range)
Air speed (hot-wire sensor)	0 to 5 m/s	0.01m/s	±(0.03 m/s ± 4% of m.v.[2])
Radiant temperature (Ø globe: approx. 150 mm)	0 to +120 °C	0.1 °C	± 0.5 °C (0 to 50 °C) ± 1 °C (50 to 120 °C)
CO_2	0 to 10,000 ppm CO_2	1ppm	50 ppm ±2% of m.v.[2] (0 to 5000 ppm) 100 ppm ±3% of m.v.[2] (remaining range)

Notes:

[1] RH: Relative humidity

[2] m.v.: measured value. In these cases, accuracy is the sum of both an absolute minimal and a percentage of the measured value.

In order to check whether the globe temperature measured by the globe thermometer corresponds to the mean radiant temperature as specified in the manufacturer's handbook, the instrument was tested under a range of conditions of air temperature and air velocity. Equation (4.1) was used to calculate the mean radiant temperature T_r (Nicol et al., 2012), using the measured values of globe temperature T_g, air velocity v, air temperature T_a and the globe's diameter d=150mm.

$$T_r = \left[\left(T_g + 273\right)^4 + (1.2 \cdot 10^8 d^{-0.4}) v^{0.6} \left(T_g - T_a\right)\right]^{0.25} - 273 \qquad (4.1)$$

Table 4.3 shows the calculated T_r for measured values of T_g, T_a and v. It can be seen that the globe temperature corresponds to the radiant temperature and starts departing from the calculated value of T_r at v=0.7m/s. Therefore, for v≤0.7m/s the globe temperature is equal to the radiant temperature T_r.

Table 4.3. Test measurements: Calculation of T_r using the globe thermometer

V (m/s)	T_g (°C)	T_a (°C)	d (mm)	T_r (°C)
0.05	23.2	22.0	150	**23.2**
0.60	22.8	22.4	150	**22.8**
0.70	22.9	22.4	150	**23.0**
0.30	23.2	22.7	150	**23.2**
0.07	23.3	22.3	150	**23.3**
0.04	24.1	23.5	150	**24.1**

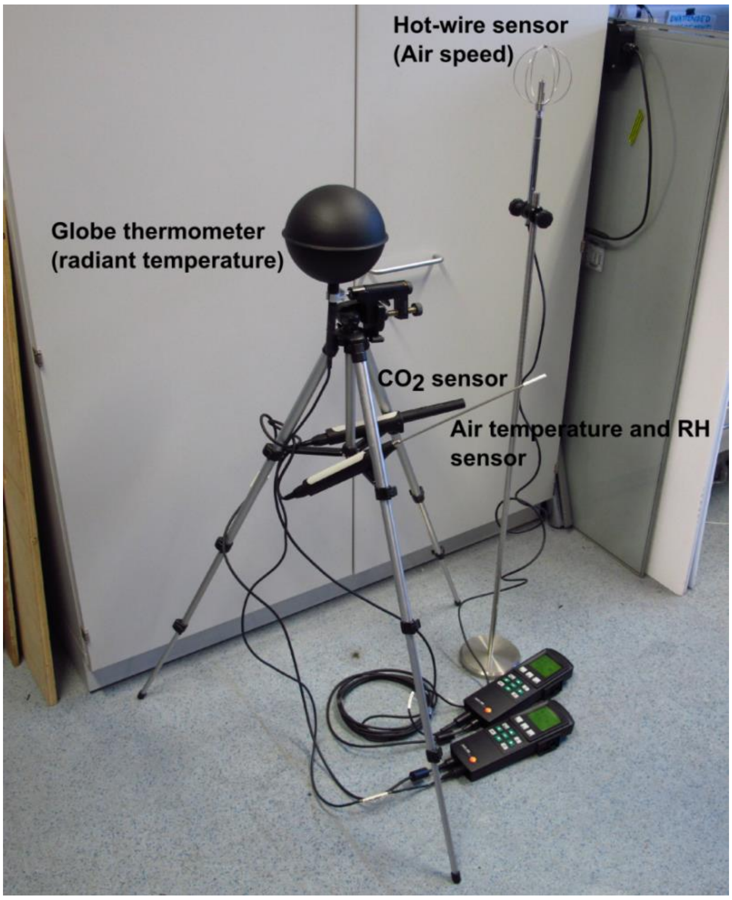


Figure 4.18. The equipment used during the pupil surveys.

4.2.3 Calculation of operative temperature (T_{op})

Operative temperature is the thermal index used throughout this study as it is the one mostly used for the assessment of the indoor environment in standards and guides (ASHRAE, 2010, CEN, 2007, ISO, 2005, CIBSE, 2006) (see also chapter 3). The operative temperature is the weighted average of the air temperature and the mean radiant temperature (CIBSE, 2006) and expresses their combined effect. The weights depend on the convective and the radiant heat-transfer coefficients of the clothed body of the occupant. The operative temperature is calculated using Equation (4.2) (CIBSE, 2006).

$$T_{op} = \frac{T_a \cdot \sqrt{10v} + T_r}{1 + \sqrt{10v}} \tag{4.2}$$

Where T_{op} is the operative temperature (°C), T_a the air temperature (°C), T_r the mean radiant temperature (°C) and v is the air speed (m/s).

At indoor air speeds at or below 0.1 m/s operative temperature may be taken from equation (4.3) (Nicol and Humphreys, 2010), as natural convection is assumed to be equivalent to v=0.1 m/s.

$$\mathrm{T_{op}} = 1/2\mathrm{T_{air}} + 1/2\mathrm{T_r} \tag{4.3}$$

Where T_{air} is the air temperature and T_r the radiant temperature.

In this study both equations were used, based on whether air speed was below or above 0.1 m/s.

5. Post-war school: Thermal environment and pupil perception

5.1 Classroom thermal environment

Table 5.1, which is organised by classroom, gives the mean, standard deviation, minimum and maximum values of each environmental parameter measured during the surveys and the mean thermal sensation vote ($TSV_{(mean)}$). The operative temperatures (T_{op}) ranged from 19.2°C to 28.9°C, relative humidity (RH) was within 40-60% and the air speed rarely exceeded 0.1m/s. The CO_2 concentration was mostly within 400-2,500ppm, except for 2 surveys where it reached 3,500 and 4,000ppm as a result of the windows being shut due to low ambient temperatures.

Table 5.1. Mean, standard deviation, minimum and maximum values of the main environmental parameters and mean Thermal Sensation Votes ($TSV_{(mean)}$) of the classrooms during the surveys

Classroom	1	2	3	4	5	6	7	8
Operative temperature (°C)								
Mean	22.8	23.3	22.5	22.1	23.6	24.4	24.1	24.1
S.D.	1.5	0.9	1.5	1.0	2.4	2.5	2.8	2.4
min	20.8	21.9	20.5	21.0	20.1	20.8	19.2	20.5
max	25.1	25.0	24.0	23.9	28.1	28.9	27.9	27.5
Relative humidity (%)								
Mean (%)	56.6	55.1	52.9	56.3	54.7	54.2	55.4	55.8
S.D.	6.5	5.5	6.9	6.9	4.9	4.6	3.9	5.0
min	46.5	47.0	39.3	40.9	47.5	46.7	48.2	46.1
max	66.5	63.1	60.4	62.0	60.9	59.6	59.2	60.8
Air speed (m/sec)								
Mean	0.07	0.08	0.06	0.07	0.09	0.09	0.08	0.12
S.D.	0.02	0.01	0.02	0.01	0.02	0.03	0.03	0.04
min	0.04	0.05	0.04	0.06	0.08	0.05	0.04	0.09
max	0.11	0.09	0.10	0.09	0.13	0.14	0.12	0.22
CO_2 (ppm)								
Mean	1,594	1,598	932	1,093	1,070	1,097	876	916
S.D.	1141	1027	436	714	506	618	256	415
min	750	500	400	450	500	450	500	550
max	4,000	3,500	1,700	2,500	1,800	2,000	1,200	1,700
TSV								
Mean	0.9	0.3	0.4	0.2	0.5	0.6	1.2	1.3
S.D.	1.2	1.4	1.5	1.5	1.6	1.6	1.4	1.3

5.2 Pupils' understanding of the thermal comfort questionnaire

The children generally considered the questionnaire as straightforward and easy to fill in. However, during the data processing, some inconsistent responses were found in the dataset, such as cases where a pupil wished it was warmer while feeling hot. These cases were identified by adding the thermal sensation (TSV) and thermal preference (TPV) scale values (Table 4.1). The cases where (TSV+TPV)<-3 or (TSV+TPV)>3 were regarded as inconsistent, based on the fact that thermal sensation votes within [-3,-2] and [+2,+3] are considered to express dissatisfaction (Fanger, 1970) and one wouldn't wish to enhance that sensation. The inconsistent cases were excluded from the analysis of pupils' thermal sensation and preference as it wouldn't be possible to distinguish which answer (TSV or TPV), actually reflected the pupils' thermal response (Figure 5.1). This approach of excluding data on the grounds of incoherent responses is consistent with previous thermal comfort studies in university classrooms conducted by Corgnati et al (Corgnati et al., 2009). However, based on previous research, a "neutral" sensation is not always the preferred thermal state (Wong and Khoo, 2003, Kwok and Chun, 2003). Therefore, only the extreme cases were excluded. The above cases constituted 7% of the gathered responses (103 of 1314 responses). 52% of the responses discussed below were given by girls and 48% by boys.

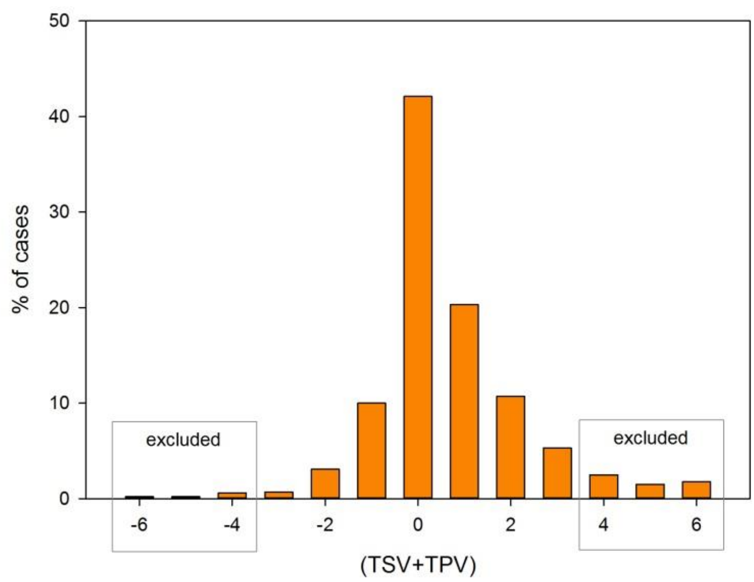


Figure 5.1. Post-war school: Relative distribution of the responses according to the sum of TSV and TPV (TSV+TPV) with the excluded cases from the dataset highlighted

As can be seen in Table 5.2, the incoherent cases are distributed quite uniformly within the 6 tests. This indicates that the inconsistency is not related to a lack of familiarity of the pupils with the questionnaire, as this would have meant more inconsistent responses in the first tests. In terms of their distribution within the 8 classrooms, the largest numbers of inconsistent responses appeared in classrooms 3, 6 and 8, which correspond to ages of 10, 7 and 8 years respectively. This eliminates the possibility that young age was responsible for the difficulty in providing coherent responses to the questionnaire. It is likely that these cases are related to individual parameters or classroom conditions, such as a difficult task prior to the survey that might had affected the ability of some pupils to match their thermal sensation with their preferred thermal condition.

Table 5.2. Post war school: cross-tabulation of inconsistent responses based on classroom number and test number (In brackets the total number of pupils participating in the survey)

		Test No						
		1	2	3	4	5	6	Total
Classroom number	**1**	3 (28)	0 (28)	1 (28)	2 (26)	3 (26)	1 (27)	10
	2	3 (30)	0 (26)	2 (28)	0 (26)	2 (26)	2 (27)	9
	3	2 (30)	7 (28)	4 (27)	5 (23)	2 (27)	4 (28)	24
	4	2 (28)	1 (24)	2 (27)	1 (29)	0 (28)	1 (29)	7
	5	0 (28)	0 (29)	3 (24)	2 (27)	0 (28)	1 (30)	6
	6	5 (27)	5 (27)	3 (27)	2 (28)	3 (27)	2 (29)	20
	7	1 (29)	0 (28)	2 (24)	5 (29)	1 (25)	2 (28)	11
	8	3 (30)	1 (24)	1 (27)	4 (28)	5 (28)	2 (29)	16
Total		19	14	18	21	16	15	103

Overall, based on the limited amount of inconsistent and missing values and the pupils' general attitude during the surveys, it can be concluded that the children of all ages were capable of understanding and filling in the questionnaire, which suggests that it is suitable for primary school children.

5.3 Relation between subjective assessment and measured variables

In order to investigate the relationship between the measured parameters and the subjective assessment of the classrooms' thermal environment, a correlation matrix of all the variables was created. This matrix, which is shown in Table 5.3, also includes the inconsistent cases discussed in section 5.2 above in order to investigate whether their occurrence is randomly distributed or associated with a specific question. For each correlation, the table includes the Pearson correlation coefficient (top value), its significance (middle value) and the number of observations (bottom value). The variables are grouped into four categories, the subjective assessment votes, the indoor environmental variables, personal parameters and outdoor climatic variables. The outdoor climatic variables were taken from the meteorological station of the National Oceanographic Centre in Southampton (NOCS) and correspond to the time of the surveys.

Table 5.3. Pearson correlations between the survey subjective and measured variables and their significance

Correlation matrix		Subjective assessment				Indoor environmental variables					Personal parameters			Outdoor climatic variables		
		TSV	TPV	Comfort (0,1)	Tiredness (0,1,2)	T_{op}	T_{air}	v	RH	CO_2	Gender	Jumper (Y/N)	Clo	T_{rm}	$T_{air(out)}$	$RH_{(out)}$
Subjective assessment	TSV		-0.50 .000 1301	-0.16 .000 1064	-0.03 .314 1301	0.33 .000 1302	0.33 .000 1302	0.13 .000 1302	-0.03 .349 1302	-0.14 .000 1302	0.02 .475 1283	-0.20 .000 1300	-0.20 .000 1302	0.19 .000 1302	0.28 .000 1302	-0.07 .007 1302
	TPV			0.19 .000 1075	0.00 .951 1312	-0.32 .000 1313	-0.32 .000 1313	-0.18 .000 1313	-0.03 .253 1313	0.19 .000 1313	-0.07 .018 1293	0.16 .000 1311	0.15 .000 1313	-0.24 .000 1313	-0.29 .000 1313	0.08 .004 1313
	Comfort (0,1)				-0.25 .000 1076	-0.16 .000 1076	-0.15 .000 1076	-0.03 .323 1076	-0.07 .023 1076	0.06 .061 1076	-0.04 .186 1056	0.10 .001 1075	0.10 .002 1076	-0.14 .000 1076	-0.17 .000 1076	0.02 .426 1076
	Tiredness (0,1,3)					-0.01 .718 1313	-0.02 .496 1313	-0.09 .001 1313	0.05 .048 1313	0.04 .199 1313	-0.06 .026 1293	0.01 .616 1312	0.00 .961 1313	0.00 .937 1313	0.01 .852 1313	0.03 .365 1313
Indoor environmental variables	T_{op}						0.99 .000 1314	0.17 .000 1314	0.01 .609 1314	-0.46 .000 1314	-0.01 .616 1294	-0.38 .000 1312	-0.38 .000 1314	0.65 .000 1314	0.84 .000 1314	-0.26 .000 1314
	T_{air}							0.18 .000 1314	0.01 .630 1314	-0.46 .000 1314	-0.01 .698 1294	-0.37 .000 1312	-0.38 .000 1314	0.64 .000 1314	0.85 .000 1314	-0.26 .000 1314
	v (air speed)								-0.12 .000 1314	-0.23 .000 1314	0.00 .954 1294	-0.16 .000 1312	-0.16 .000 1314	0.08 .005 1314	0.20 .000 1314	-0.14 .000 1314
	RH									0.35 .000 1314	0.04 .191 1294	0.04 .142 1312	0.05 .089 1314	0.05 .077 1314	-0.06 .027 1314	0.48 .000 1314
	CO_2										-0.03 .256 1294	0.28 .000 1312	0.27 .000 1314	-0.67 .000 1314	-0.61 .000 1314	0.17 .000 1314
Personal parameters	Gender											-0.15 .000 1293	0.06 .031 1294	0.00 .905 1294	-0.02 .420 1294	0.07 .007 1294
	Jumper (Y/N)												0.98 .000 1312	-0.29 .000 1312	-0.39 .000 1312	0.11 .000 1312
	Clo													-0.29 .000 1314	-0.39 .000 1314	0.13 .000 1314
Outdoor climatic variables	T_{rm}														0.79 .000 1314	-0.45 .000 1314
	$T_{air(out)}$															-0.43 .000 1314
	$RH_{(out)}$															

Correlation coefficient range
0.01-0.20
0.21-0.40
0.41-0.60
0.61-0.80
0.81-1.00

Notes: Values, from top to bottom, represent: the correlation coefficient, its significance (2-tailed), the number of observations.

The 'feeling of comfort', 'gender' and 'jumper' are nominal variables with values: Comfort: Yes=1 No=0, Gender: girl=1 boy=2, Jumper: Yes=1 No=0.

T_{op}=operative temperature, T_{air}=indoor air temperature, v=air speed, RH=indoor relative humidity, T_{rm}=outdoor running mean, $T_{air(out)}$=outdoor air temperature during the survey, $RH_{(out)}$=outdoor relative humidity during the survey

It can be seen that, for the subjective assessment votes, there is a relatively strong negative correlation between thermal sensation vote (TSV) and thermal preference vote (TPV), as would be expected. However, the negative correlation between TSV and feeling of overall comfort of pupils is considerably weak. Similarly, the correlation of the feeling of comfort with the thermal preference vote (TPV) is weak, whereas it is slightly stronger with the feeling of tiredness. It seems that pupils' perception of overall comfort was more associated with their feeling of tiredness rather than their thermal sensation. However, the overall difference is small.

The TSV and TPV are similarly correlated to the indoor and outdoor temperatures, whilst the feelings of overall comfort and tiredness appear to have no significant relation to these parameters, reinforcing the previous observation. For comparison, the correlation was repeated including the inconsistent cases. The TSV had a slightly stronger correlation to the indoor temperature (r=0.38, compared to r=-0.35 for TPV) but the difference is small. Overall, the TSV and TPV appear to be the most effective indicators of the pupils' thermal response. Furthermore, as can be seen in the correlation matrix, TSV and TPV are similarly correlated to the other variables. This means that the scales (thermal sensation and preference) are equally effective and consistent with the parameters affecting thermal comfort.

5.4 Pupils' thermal sensation and preference

Figure 5.2 shows the distribution of the thermal sensation votes (TSVs) and thermal preference votes (TPVs) for the entire sample, after the exclusion of inconsistent cases. It can be seen that the TSVs are centred on 'OK' (0) with an apparent shift towards warm thermal sensations. The TPVs are centred on '0' ('No change') and '-1' ('A bit cooler') with almost symmetrical distribution of the votes around them. Overall, over the survey period the pupils evaluated their thermal environment mostly as warm, but their thermal preference was more diverse.

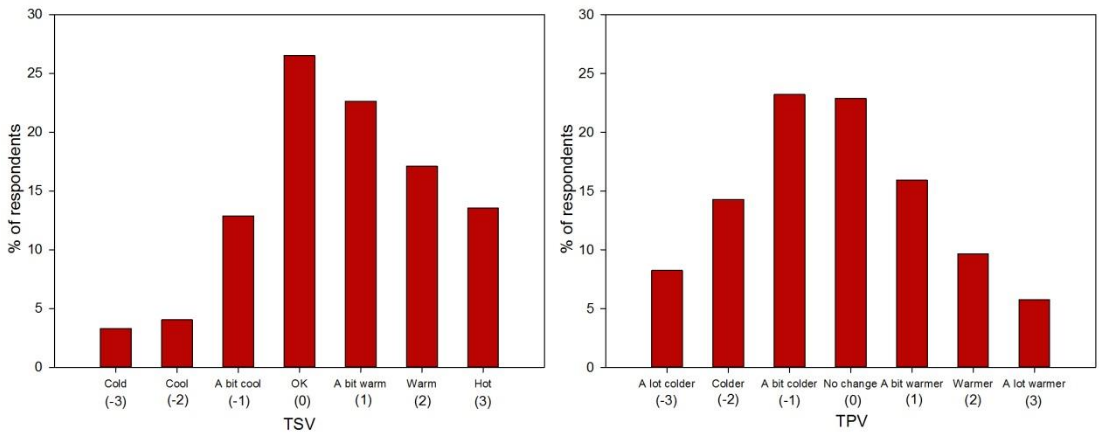


Figure 5.2. Relative frequency of Thermal Sensation Votes (TSVs) (Left) and Thermal Preference Votes (TPVs) (Right) from all 48 surveys

Figure 5.3 shows the $TSV_{(mean)}$ for every survey in relation to the operative temperature of the classroom. As shown in the graph, for the same operative temperature, $TSV_{(mean)}$ may differ by as much as 2 scale points. The scatter is generally quite large for operative temperatures of 20 to 24°C but the correlation, with r^2=0.545, is satisfactory for this type of thermal comfort field survey data (Wong and Khoo, 2003, Zhang et al., 2007, Raja et al., 2001) and p.129 in (Nicol et al., 2012). The above suggests that the mean thermal sensation of the pupils is affected by the room temperature variations. The regression gradient is 0.27 scale units/°C, which is lower than the mean regression gradient from recent field data with adult subjects (0.37 scale units/°C) (Humphreys et al., 2007), derived from the de Dear (de Dear, 1998) and the SCATs (McCartney and Nicol, 2002) databases. This suggests that children are slightly less sensitive to temperature changes, which agrees with the findings of Humphreys (Humphreys, 1977). However, it can also be attributed to the prolonged survey period of this study which might have led to more complete thermal adaptation (Humphreys et al., 2007).

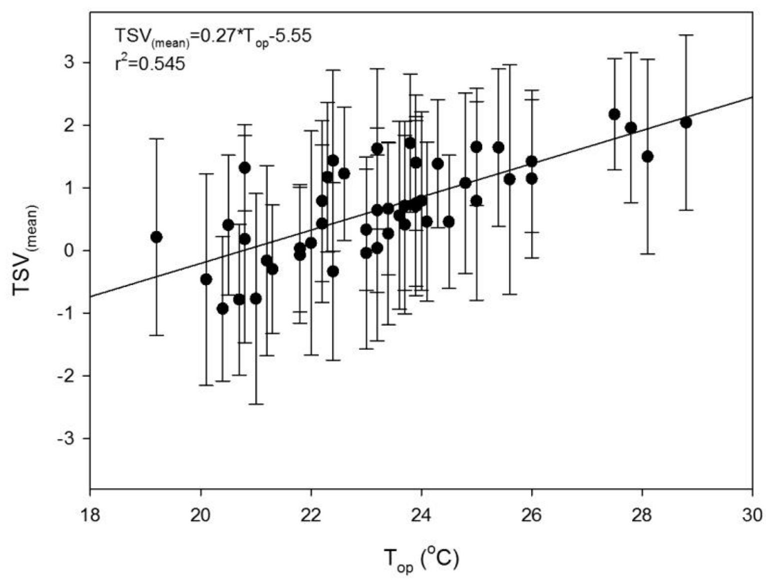


Figure 5.3. Mean Thermal Sensation votes per survey (TSV(mean)) with standard deviations, against the classroom's operative temperature

Looking at the thermal sensation votes in detail, a large variation can be identified within surveys. The standard deviation of the TSV was calculated for all surveys and ranged from 0.7 to 1.8 scale units (see Figure 5.3), with a mean of 1.5, which is larger than the mean value of 1.07 scale units, calculated from studies with adults (Humphreys et al., 2007). The variation within the surveys can be seen exemplarily in Figure 5.4, which shows the distribution of individual votes per survey of Test 1, where the operative temperatures ranged between 19.2-21.8°C. In most classrooms the votes cover the whole range of the sensation scale (from hot to cold). Similar observations were made by Humphreys, who suggested the different activity levels of individual children over the school day as a possible explanation (Humphreys, 1977). This argument is strengthened by the fact that, during breaks, children engage in different activities which may have an impact on their thermal perception.

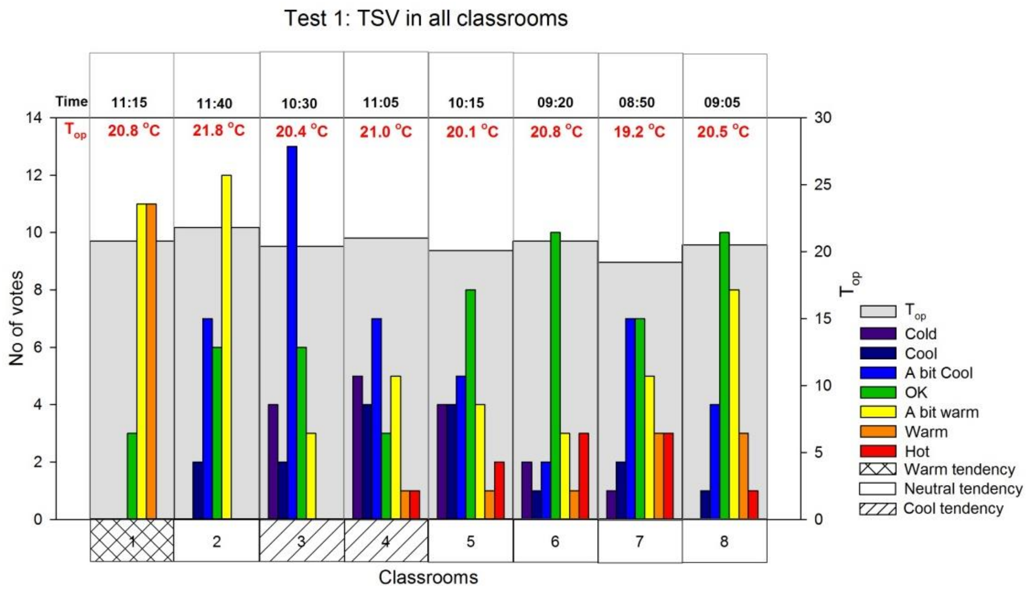


Figure 5.4. Distribution of Thermal Sensation votes (TSV) of Test 1 in relation to the operative temperature T_{op} (°C). The temperature tendency in the classroom is based on the weighted proportion of 'warm' votes [1,2,3], 'OK' votes [0] and 'cool' votes [-3,-2,-1] per survey

The distributions of thermal sensation votes of all surveys within the 6 tests are included in Appendix D, along with a diagrammatical explanation of the graphs.

Figure 5.5 shows the thermal sensation votes (TSV) of (a) girls and (b) boys, against the classroom's operative temperature. The diameter of a circle represents the weighted number of responses at the corresponding operative temperature. The regression lines suggest low correlations, with (a) r^2= 0.135 and (b) r^2= 0.143 respectively, due to the large variation in the pupils' TSVs. However, the narrow 95% confidence intervals enable a comparison of thermal sensation trends between genders. This also applies to Figure 5.6, which shows the thermal preference vote (TPV) trends according to gender. As can be seen in Figure 5.5, the distributions of votes according to operative temperature and the TSV regression lines are almost identical. This means that there was no significant difference in thermal sensation between male and female pupils, which generally agrees with literature referring to both child (Humphreys, 1977) and adult subjects (Fanger, 1970, Parsons, 2002) where only small differences were found. Where differences have been found in adults, they included female subjects being less satisfied with room temperatures and being more sensitive to both cool and warm conditions (Karjalainen, 2007). In this study however, based on the thermal preference vote (TPV) male pupils were found to be more sensitive to high temperatures compared to female pupils. This can be seen in Figure 5.6, which shows that, at high temperatures, boys clearly preferred far cooler environments compared to girls, reaching about one preference scale point difference. This could be related to a general tendency found in females to prefer higher temperatures than males (Karjalainen, 2007) or to the fact that female subjects have been found to adjust their clothing to the indoor temperatures faster than male subjects do (Hwang et al., 2006). The preference of boys towards cooler environments can constitute useful information for control measures in order to avoid pupil thermal dissatisfaction, such as, for instance, re-location of pupils in the classroom.

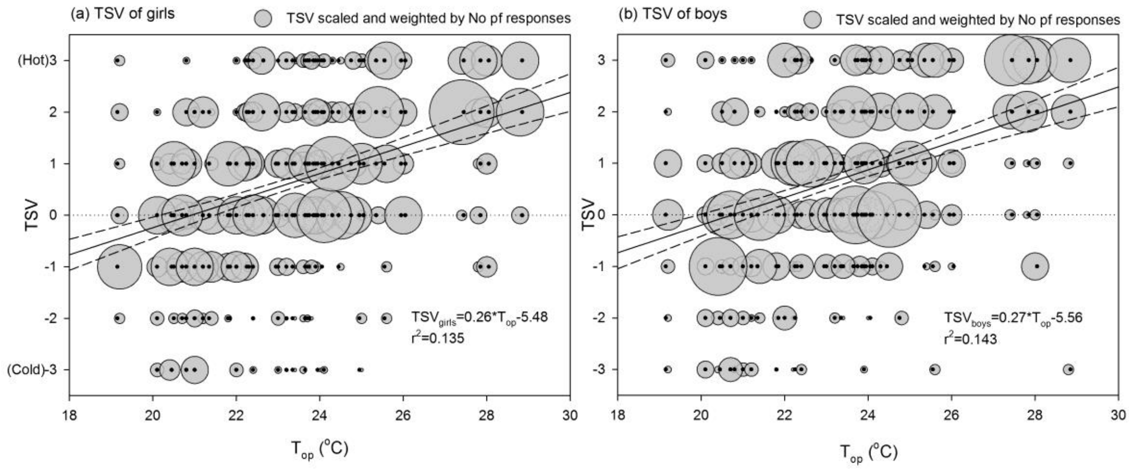


Figure 5.5. Thermal sensation votes (TSV) weighted by number of responses against the classroom's operative temperature (T_{op}), per gender: (a) girls and (b) boys. The weighted number of responses is proportional to the diameter of the circle

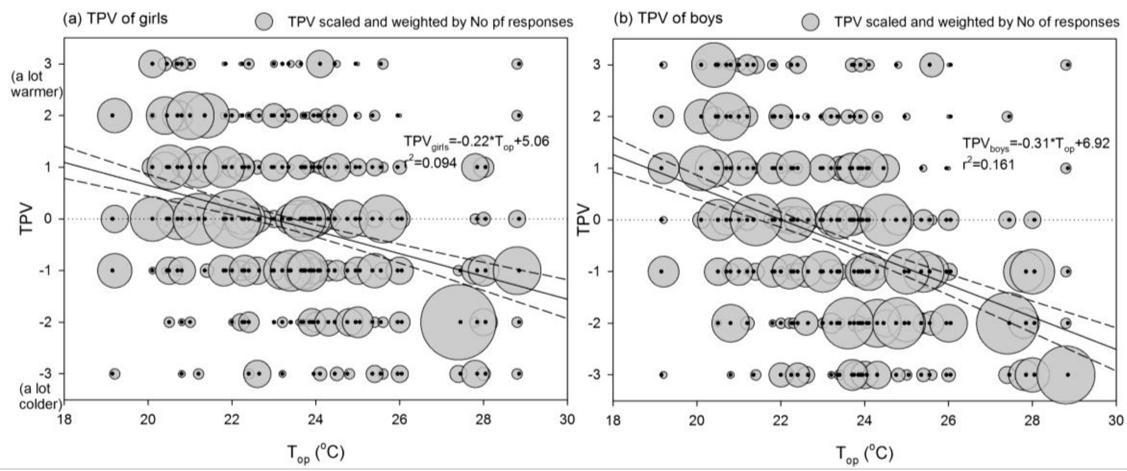


Figure 5.6. Thermal preference votes (TPV) weighted by number of responses against the classroom's operative temperature (T_{op}), per gender: (a) girls and (b) boys. The weighted number of responses is proportional to the diameter of the circle

5.5 Perception of overall comfort and tiredness

The pupils were asked whether they were feeling comfortable during the survey (Question 3 on the survey form, Appendix A). The aim of this question was to identify the perceived impact of the thermal sensation on the overall comfort of the pupils. Figure 5.7 shows their responses in relation to their thermal sensation votes. The distribution is centred around “OK” with about 70% of the pupils who voted “OK” feeling comfortable, which suggests that a thermal sensation around “OK” was generally associated with overall comfort. Of the children that would be considered as cold dissatisfied, i.e. voting -2 and -3, 45% and 25% respectively felt comfortable. Furthermore, 43% of those who voted TSV=+3 (“hot”), which is generally considered to express warm dissatisfaction, stated that they were feeling comfortable. Similarly, 30% of the pupils that felt thermally satisfied (TSV: 0, “OK”) said that they were not feeling comfortable. This does not appear to be plausible. This means that some pupils may feel hot but still say that they are comfortable. This finding could have several explanations, such as, that children may not associate extreme thermal sensations with overall discomfort which is also supported by the weak correlation found between the thermal sensation votes and the overall comfort responses (see section 5.3, Table 5.3).

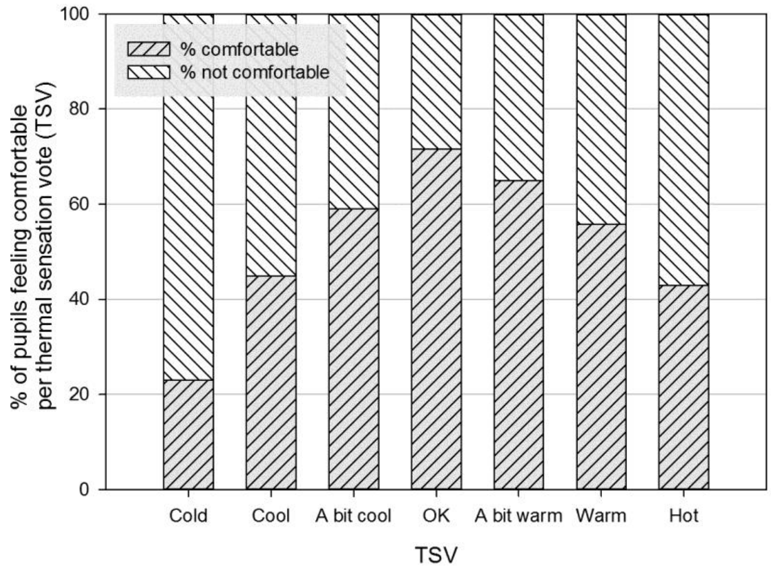


Figure 5.7. Percentage of pupils feeling comfortable per thermal sensation vote

Furthermore, it is possible that children’s perception of overall comfort is strongly affected by other parameters, such as the class activity, their psychological condition or time of the day, rather than their thermal sensation. Also, it could be related to a tendency of children not to express dissatisfaction when they feel thermal discomfort, which was reported by teachers in a previous survey (Teli et al., 2011). Overall, it appears necessary to rely on information other than the perception of overall comfort in order to capture the conditions children consider as thermally acceptable. As discussed in section 5.3, thermal sensation and preference votes appear to provide more detailed information on the tendencies of the pupils' thermal perception than the overall feeling of comfort.

Figure 5.8 shows the relative frequency of the pupils' feeling of tiredness ('very tired', 'a bit tired', 'not tired') per survey, in relation to the CO_2 concentration at the survey time [see Figure 5.8(a)], the operative temperature (T_{op}) [see Figure 5.8(b)], the mean Thermal Sensation Vote ($TSV_{(mean)}$) of the pupils [see Figure 5.8(c)] and the time of the day the survey took place [see Figure 5.8(d)]. Overall, as can be seen in Figure 5.8(a), (b) and (c), there is a large scatter and a weak correlation of the percentage of pupils feeling tired in relation to the above factors. The weakest correlation can be seen with the CO_2 concentration and can be attributed to the fact that the CO_2 measurements reflect the instant CO_2 level during the surveys whilst the feeling of tiredness often results from a more prolonged exposure to an influential factor. As can be seen in Figure 5.8, the percentage of pupils stating that they felt 'very tired' is within 0-40% and appears to be independent of the mean thermal sensation, but positively, although weakly, correlated with the CO_2 level and operative temperature. The strongest correlation is found to be with the operative temperature (Figure 5.8(b)): when the operative temperature increases the percentage of pupils that stated that they were feeling 'a bit tired' decreases, which is offset by the increase in the percentage of pupils feeling 'very tired' and 'not tired'. The increase of pupils voting for 'not tired' at higher temperatures could be related to the fact that under warm conditions windows are usually opened, keeping the CO_2 concentration at lower levels. This highlights the interrelation of the factors affecting pupils' perception of tiredness.

As can be seen in Figure 5.8(d), the distribution profiles of the votes in relation to breaks are similar, which suggests that the pupils' feeling of tiredness was not related to the time of the day the survey was conducted. Overall, the majority of the pupils felt "a bit tired" regardless of the time of the day, which could be attributed to a general predisposition towards school activities and tasks. The results indicate that the pupils' feeling of tiredness is weakly related to the factors examined here, although the operative temperature appears to have a more profound impact on tiredness, compared to CO_2, thermal sensation and time of the day.

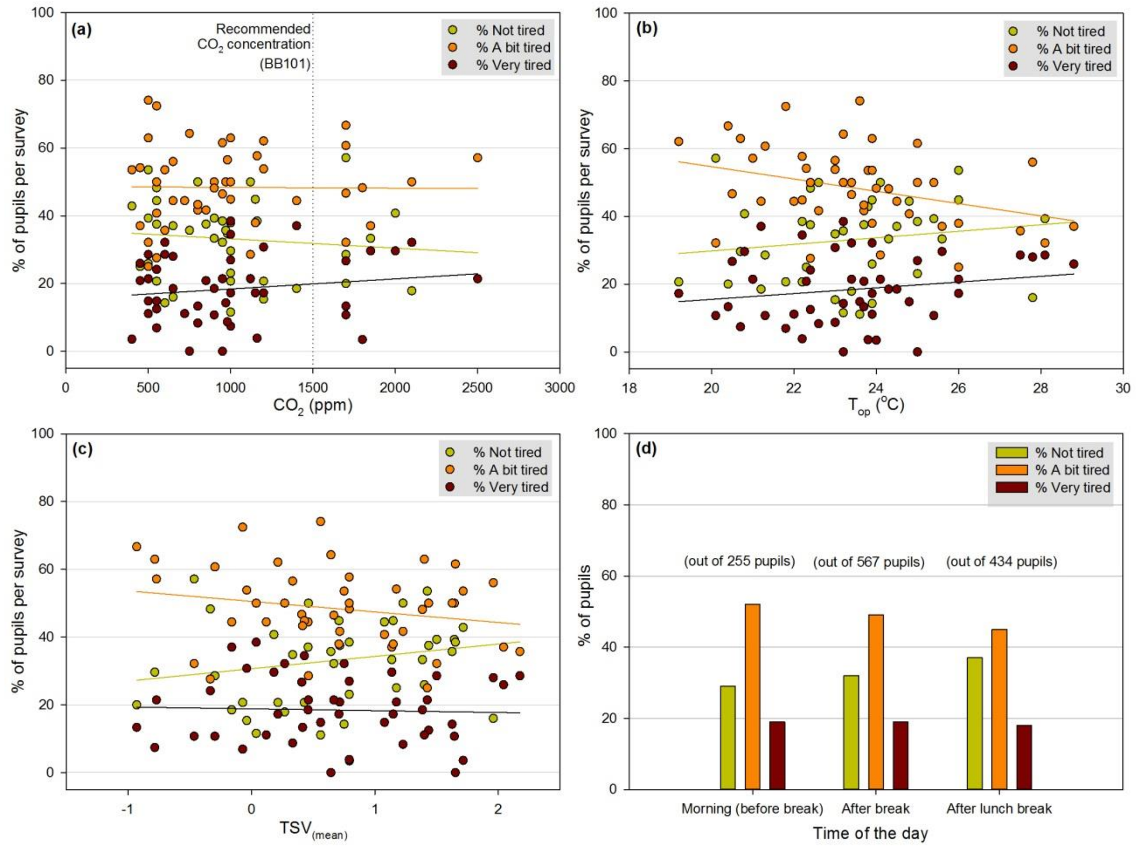


Figure 5.8. Percentage of pupils feeling 'very tired', 'a bit tired' and 'not tired' per survey, in relation to (a) CO_2 concentration, (b) Operative temperature (T_{op}) and (c) Thermal sensation vote (TSV) and (d) distribution of votes for 'tired', 'a bit tired' and 'not tired' in relation to time of the day.

5.6 Section summary

The main outcomes from this section are the following:

- The surveyed primary school children aged 7-11 were capable of understanding simplified thermal sensation and preference rating scales.
- The thermal sensation and thermal preference votes were found to be similarly related to the environmental variables and therefore equally effective as thermal response indicators of the pupils' thermal response.
- The study reinforces Humphrey's observations (Humphreys, 1977) that there is a large variation in pupils' thermal sensation votes (mean standard deviation=1.5) which could be related to their diverse activity schedule. The variation is larger than that found in studies with adults in office environments (mean standard deviation =1.07) (Humphreys et al., 2007).
- No difference was determined in thermal sensation between girls and boys, which agrees with previous studies with child (Humphreys, 1977) and adult subjects

(Fanger, 1970, Parsons, 2002). However, significant differences were found for the thermal preference. At temperatures above 23°C boys preferred far cooler environments than girls.

- The pupils' perceived overall comfort is not always related to their thermal state, i.e. some may feel hot but state that they are feeling comfortable. Their feeling of tiredness has a weak correlation with the mean thermal sensation, CO_2 and time of the day and slightly stronger correlation with the classroom's operative temperature.

These results suggest that school children have a different thermal perception to adults and this could have implications for thermal comfort standards (ISO, 2005, CEN, 2007, ASHRAE, 2010) which are based on comfort models developed using studies with adult subjects, as discussed in section 3.2. This issue is addressed in the following chapter, by comparing the survey results with predictions of the PMV and adaptive comfort models.

6. Post-war school: Thermal comfort survey results in comparison to comfort model predictions

6.1 Survey results and PMV model predictions according to ISO 7730

As analysed in section 3.2.1, the widely used thermal comfort standard ISO 7730 is based on the PMV model (ISO, 2005) which was originally developed by Fanger in 1970 on the basis of climate chamber experiments (Fanger, 1970). The validity of using the PMV model for naturally ventilated buildings has been questioned over recent years as occupants were found to be tolerant to a wider range of temperatures than predicted by the model (de Dear and Brager, 2002, Moujalled et al., 2008) (see also section 3.1.2 and "limitations of the PMV and 2-node heat-balance models" in section 3.1.1). There are studies that compare and thoroughly discuss deviations of the PMV predictions and actual mean thermal sensation votes from field studies with adults in offices (Humphreys and Nicol, 2002, de Dear and Brager, 1998). Nevertheless, the PMV model continues to be widely applied in thermal comfort assessments, including schools (ISO, 2005, ASHRAE, 2010, CEN, 2007). However, as the development of the PMV model did not encompass children, there is limited information on its general use for schools (Mors et al., 2011). Therefore, in order to bridge this gap, this section explores the applicability of the PMV model for children and school environments, examining parameters which may require adjustment or further investigation.

6.1.1 PMV/PPD calculation method

The PMV and PPD indices were calculated using the equations given in ISO 7730 (ISO, 2005). The environmental input parameters required for these calculations (ambient air temperature, mean radiant temperature, air velocity and partial water vapour pressure) were all measured during the surveys. The clothing insulation and metabolic rate of children, which are also required, were estimated as detailed below.

6.1.1.1 Clothing Insulation

Clothing insulation (clo) for children has been found to be similar to that of adults for the same season (Havenith, 2007) and therefore the 'clo' values were estimated using ISO 7730 (ISO, 2005). Pupils have a specific range of school uniform choices and they can decide whether to wear their jumper. The clothing values of all possible school uniform combinations observed during the surveys were determined and were found to be within a range of 0.30-0.49 'clo' when no jumper is worn (Table 6.1). The jumper adds 0.25 'clo' to the insulation value. For the calculation of the PMV/PPD indices a weighted average 'clo' value was calculated for each survey, using mean 'clo' values of 0.4 and 0.35 'clo' for boys and girls respectively and the questionnaire responses regarding the jumper. Minimum and maximum 'clo' values were also estimated for each survey, providing an 'error band' for the PMV prediction.

Table 6.1. School uniform combinations

Clothing combinations[1]	Clo[2]
Light dress-short sleeves, stockings, shoes	0.30
Light dress-short sleeves, stockings, boots	0.36
Light dress-short sleeves, socks, shoes	0.29
Light skirt, short sleeves shirt/blouse, stockings, shoes	0.36
Light skirt, short sleeves shirt/blouse, stockings, boots	0.46
Light skirt, short sleeves shirt/blouse, socks, shoes	0.39
Shorts, short sleeves shirt/blouse, socks, shoes	0.30
Normal trousers, short sleeves shirt/blouse, socks, shoes	0.49

Notes:
[1] All combinations include underwear, [2] Clo values estimated based on ISO 7730 (ISO, 2005)

6.1.1.2 Metabolic rate

The metabolic rate appears in the PMV formula (ISO, 2005) in two ways:

- As part of the empirical equation, with the value of the resting metabolic rate (RMR) of an average adult (58.15 W/m^2)
- As input variable, representing the physical activity level, expressed by the ratio of the metabolic rate during the activity to the resting metabolic rate. The unit used for this ratio is 'met'. It is defined as "the metabolic rate of a sedentary person (seated, quiet): 1met = 58.15 W/m^2 = 50 kcal/(h·m^2)" (ASHRAE, 2009).

The above clearly indicates that the PMV equation inherently corresponds to adult physiology. Furthermore, the metabolic rates per unit skin surface area for different activities provided in tables by commonly used standards represent typical values for an average adult (ISO, 2005, ASHRAE, 2010, ISO, 2004). These values are based on experiments conducted with adult subjects (ISO, 2004) and therefore cannot automatically be considered as suitable for children. Compared with adults, children have a higher resting metabolic rate per kilogram body weight, which declines during the growth years (Holliday, 1971). In addition, children engage in different activities during their school day. Therefore, a thermal comfort model specifically tailored towards the physiology of children appears to be required.

Few previous thermal comfort studies with children have made adjustments to the PMV model in order to address the difference in metabolic rates. However, Havenith (Havenith, 2007) determined metabolic rates for school activities to be within a range of 52-64 W/m^2 which is about 10% lower than the adults' equivalent for sedentary activities (office work) (70 W/m^2) (ISO, 2004). In a study of Kuwaiti classrooms (Al-Rashidi et al., 2009) the input 'met' was reduced by 10% in line with these findings. No account was however taken for the resting metabolic rate of children and both, the 'standard' PMV and the 'corrected' PMV failed to predict the actual thermal sensation. Another adjustment that has been previously used is the correction of the input 'met' value by accounting for the smaller body surface area of children (Wargocki and Wyon, 2007, Mors et al., 2011). In a study by Wargocki and Wyan (Wargocki and Wyon, 2007) the input 'met' was increased by 40%, whilst Mors et al (Mors et al., 2011) multiplied the adult 'met' by 1.73/1.14, which is based on the Mosteller formula for the calculation of the body surface area (1.73 m^2 for adults and 1.14 m^2 for 10 year olds) (Mosteller, 1987). Mors et al (Mors et al., 2011) found that the 'corrected' PMV underestimated the children's actual thermal sensation. Here, four metabolic rate adjustment approaches were investigated for the PMV calculations as described below.

Approach (a): *Application of the standard (unchanged) PMV model with the input 'met' value calculated from metabolic rates for children*

In this approach, the PMV equation was used as provided by ISO 7730 (ISO, 2005). The input 'met' value was derived from literature values for metabolic rates for classroom activities and an estimated resting metabolic rate (RMR) for children. This means that the model in essence predicted the thermal sensation of an adult under the given environmental conditions with a 'met' value that corresponds to children.

In the surveys presented here the comfort questionnaires were handed out after at least 15 minutes of classroom activities. Based on the results of Havenith (Havenith, 2007) a value of 58 W/m^2 was used as the metabolic rate for the physical activity level in all surveys as this represents the average value for typical primary school class activities (Table 6.2). However, it should be noted that these values were derived from measurements of a relatively small sample of 25 primary school children. More data on the metabolic rates of children during school lessons would be desirable in order to achieve higher confidence in the validity of these values.

Table 6.2. Metabolic rates for several class activities (Havenith, 2007)

Primary school activity	Metabolic rate (W/m^2)
1. Language, assignment	52
2. Writing task	53
3. Art	59
4. Drawing	62
5. Calculus	64
Average	58

The RMR of children has been measured in numerous studies over the past 20 years (Amorim, 2007) but there is no standard value for an 'average' child that could be used for the 'met' calculation. It was therefore decided to use data collated by Amorim (Amorim, 2007) in order to determine the average RMR for the same age group as the pupil sample (7-11 years old). 30 of the studies investigated by Amorim (Amorim, 2007) were within the given age group with $RMR_{(mean)}$ ranging from 1012-1420 kcal/day (Table 6.3). Each $RMR_{(mean)}$ value was weighted by the number of children in the study. Equation (6.1) gives the average RMR of these studies.

$$\text{Average RMR} = 1147.9\ \text{kcal/day} = 55.6\ \text{W} \rightarrow 55.6/1.14 = 48.8\ \text{W/m}^2 \qquad (6.1)$$

The resulting 'met' value is 58/48.8=1.2, which is equivalent to the adult value for sedentary office activity (ISO, 2004). This agrees with the outcome of research by Harrell et al (Harrell et al., 2005), where the ratio of activity energy expenditure to resting energy expenditure was found to be comparable in children and adults. Therefore, approach (a) in essence represents an unaltered use of the PMV calculation.

A comparison of the metabolic rates and physiological characteristics of adults and 10 year-old children is given in Table 6.4.

Table 6.3. Resting metabolic rates measured in numerous studies, adapted from (Amorim, 2007)

Researcher	Sample size (n)	age	gender	$RMR_{(mean)}$ in Kcal/day
Dietz et al. (1994)	18	10.4±1.1	F	1160, 1133 (2 studies)
Firouzbakhsh et al. (1993)	10	8-10	F	1092
	10	8-10	M	1158
Spadano et al. (2004)	10	9.9±1	F	1087
	26	9.9±1	F	1203
Hsu et al. (2003)	15	9.3±1.7	M/F	1223
Spadano et al. (2003)	17	8-12	F	1420
Maffeis et al. (1990)	14	8.6±1.1	M/F	1062
Maffeis et al. (1993)	48	7.6±1.5	M	1083
	49	7.8±1.2	F	1012
	10	8.6±0.4	M/F	1080
Roenmich et al. (2000)	14	10.9±1.0	F	1245
	13	10.2±1.4	F	1217
Spadano et al. (2005)	28	8-12	F	1249
Wurmser et al. (1998)	28	10.2±1.1	F	1203
	27	10.0±1.2	F	1070
Treuth et al. (2000)	30	8.5±0.4	F	1070
	44	8.5±0.4	F	1087
	27	8.5±0.4	F	1125
Klesges et al. (1993)	16	10.2±1.1	F	1254, 1358 (2 studies)
Amorim (2007)	14	10.1±1.4	F	1144, 1098, 1213, 1087, 1175, 1147, 1197, 1239 (8 studies)

Table 6.4. Physiological characteristics and metabolic rates of average adults and 10 year old children

	Average adult	Average pupil
Body weight[1] (kg)	70	35
Body surface area[2] (m^2)	1.73	1.14
Resting metabolic rate-RMR (W/m^2)	58.15 (1.45 W/kg)	48.8 (1.60 W/kg)
Metabolic rate of sedentary/ school activity (W/m^2)	70	58
'met' value of sedentary activity for PMV calculation	1.2	1.2

Notes:

[1] The average adult body weight is based on ISO8996 (ISO, 2004) and the average pupil's body weight on Havenith (Havenith, 2007)

[2] The body surface areas are based on the Mosteller formula (Mosteller, 1987)

Approach (b): *Application of the standard (unchanged) PMV model with body surface area correction of the input activity metabolic rate*

In this approach, the input metabolic rate of adults for sedentary activities was corrected for the reduced surface area of children, with the average adult's and child's surface areas taken as 1.73 m^2 and 1.14 m^2 respectively (Mosteller, 1987). The corrected metabolic rate is then received by multiplying the adult metabolic rate for sedentary activities, 70 W/m^2 (ISO, 2005), by 1.73/1.14=1.5. In this approach, the resting metabolic rate remains unchanged, therefore the resulting 'met' value is: $70 \cdot 1.5/58.15=1.8$.

This approach was used by Mors et al. (Mors et al., 2011) for obtaining a child adjusted 'met' input value for the PMV calculations. It should be noted however, that the use of adult values as baseline to estimate the metabolic rate of children has been criticised as a method which can lead to significant errors (Torun, 1983), as the relation between body weight and metabolic rate is non-linear and the ratio of body surface area per unit of mass changes substantially with age (Havenith, 2007). Therefore, using body weight or body surface area for 'downscaling' may not produce reliable 'met' values for children. This is also supported by the findings given in approach (a) above and highlights that the adjustment can only be seen at best as a 'correction' of the PMV equation.

Approach (c): *Body surface area correction of the input activity metabolic rate and resting metabolic rate, both in the 'met' calculation and inside the PMV equation*

In this approach, both the input activity (70 W/m^2) and the resting metabolic rate (58.15 W/m^2) are corrected for the reduced surface area of a child. The RMR then becomes: $58.15 \cdot 1.73/1.14 = 88.25$ W/m^2. This value is used in both the 'met' calculation and inside the PMV equation, replacing the adult RMR. The resulting 'met' is $70 \cdot 1.5/58.15 \cdot 1.5=1.2$. It needs to be highlighted however that, as in approach (b), the surface area 'correction' is only used as an adjustment factor for the PMV equation and that this does not suggest that the resting metabolic rate of children is 88.25 W/m^2. This would mean that in children the metabolic rate per m^2 is higher than for adults for the same activity, whilst, as discussed in approach (a), the opposite has been found to be the case (Havenith, 2007).

Approach (d): *Application of the calculated metabolic rates for children in the input 'met' calculation and inside the PMV equation*

In this approach, the 'met' value of 1.2 and the RMR of 48.8 W/m^2 calculated in approach (a) are used for the PMV calculation.

6.1.2 Comparison of the actual thermal sensation votes with the predictions of the PMV adjustment approaches

This section compares the thermal sensation data from the surveys in the post-war case study school with the predictions of approaches (a), (b), (c) and (d), described in 6.1.1.2. The top graphs of Figures 6.1 to 6.4 show the PMVs that were determined for the average 'clo' values in relation to the mean actual thermal sensation votes ($TSV_{(mean)}$) of the classroom surveys, plotted against the operative temperature (T_{op}). The bottom graphs of Figures 6.1 to 6.4 show the corresponding PPD for the average 'clo' values in relation to the actual percentages of dissatisfied (APD), plotted against the operative temperature. The actual percentage of dissatisfied (APD) was determined from the share of the -3 (cold), -2 (cool), +2 (warm) and +3 (hot) thermal sensation votes in relation to the overall sample size. This approach is based on the PPD definition given in common comfort standards (ISO, 2005, CEN, 2007, ASHRAE, 2010). The 'error bands' which are derived from using the minimum and maximum 'clo' values, discussed in section 6.1.1.1, are highlighted as grey shaded areas in the graphs.

Approach (a): S*tandard (unchanged) PMV model*

It can be clearly seen in Figure 6.1(a1) that under approach (a) the actual thermal sensation votes ($TSV_{(mean)}$) are higher than the calculated PMVs, which means that the children felt warmer than predicted by the PMV model. This discrepancy can reach up to 2.5 scale points. However, the PMV regression line is almost parallel and about 1.1 scale points lower than the $TSV_{(mean)}$ regression line. According to the $TSV_{(mean)}$ regression line, the neutral temperature (T_n)[8] is 20.8 °C, which is 4.2 °C lower than the neutral temperature predicted from the PMV regression line. Interestingly, this finding disagrees with the common notion that the PMV model overestimates the thermal sensation vote in naturally ventilated buildings (Humphreys, 1978) which originally led to the development of the adaptive comfort model in the 1970s (see section 3.1.2).

As can be seen in Figure 6.1(a2) there is a poor agreement between the actual percentage of people dissatisfied (APD) and the calculated PPD data with the two data sets showing no apparent correlation in their corresponding regression lines. Overall, Figure 6.1 shows

[8] According to the PMV model, neutral temperature corresponds to a neutral TSV

that the use of the PMV equation without any changes is ill suited to reflect the classroom survey data.

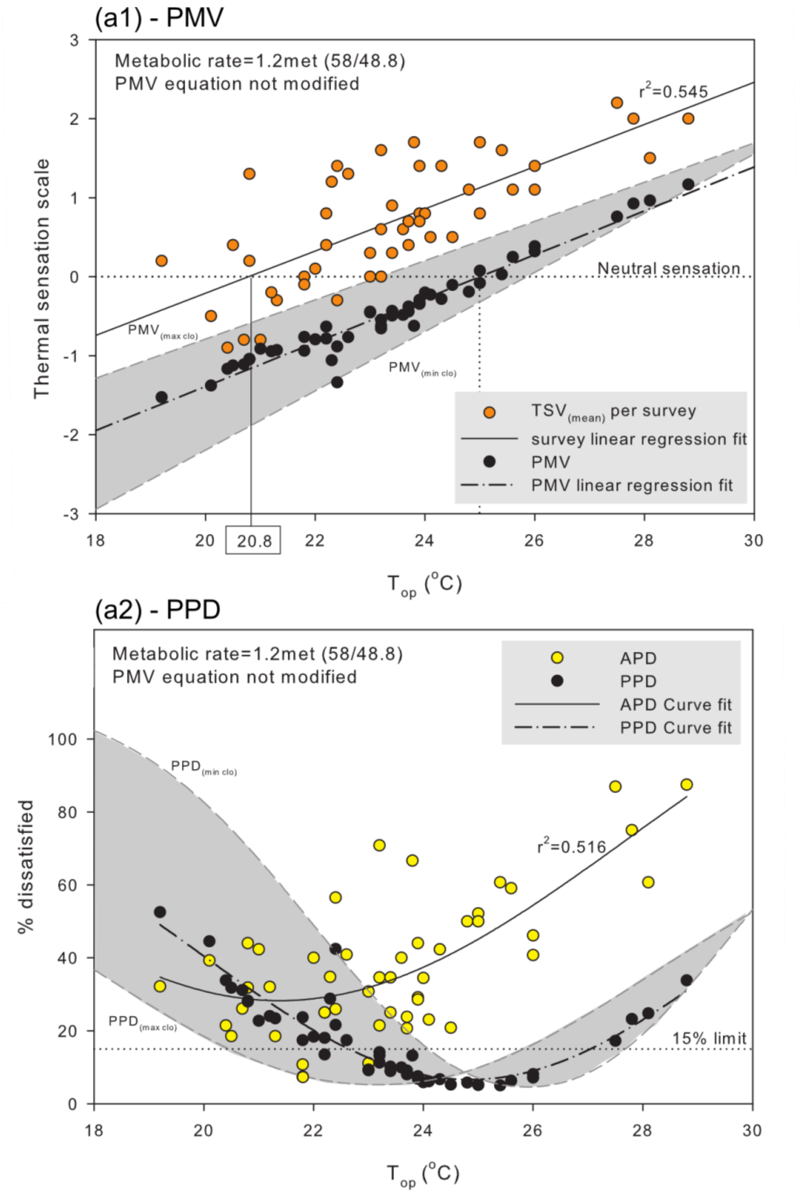


Figure 6.1. (a1): Actual mean thermal sensation vote (TSV(mean)) for each survey and calculated PMV against the operative temperature. (a2): Actual percentage of dissatisfied (APD) and calculated PPD against the operative temperature with curve fits. The grey shaded areas show the 'error bands' from using estimated minimum and maximum 'clo' values.

Approach (b): *Standard (unchanged) PMV model with input met correction*

Figure 6.2(b1) shows a better agreement between the predicted and the actual TSVs for approach (b) than approach (a). However, as a general tendency the approach (b) PMV model still underestimates the thermal sensation vote. This underestimation agrees with the results of Mors et al. (Mors et al., 2011) for school classrooms, where the error was found to be ranging from 0.5 to 1.5 thermal sensation scale points. Further to this, there is a clear mismatch between the linear regression line of the survey TSV and that of the PMV model, in particular for higher operative temperatures.

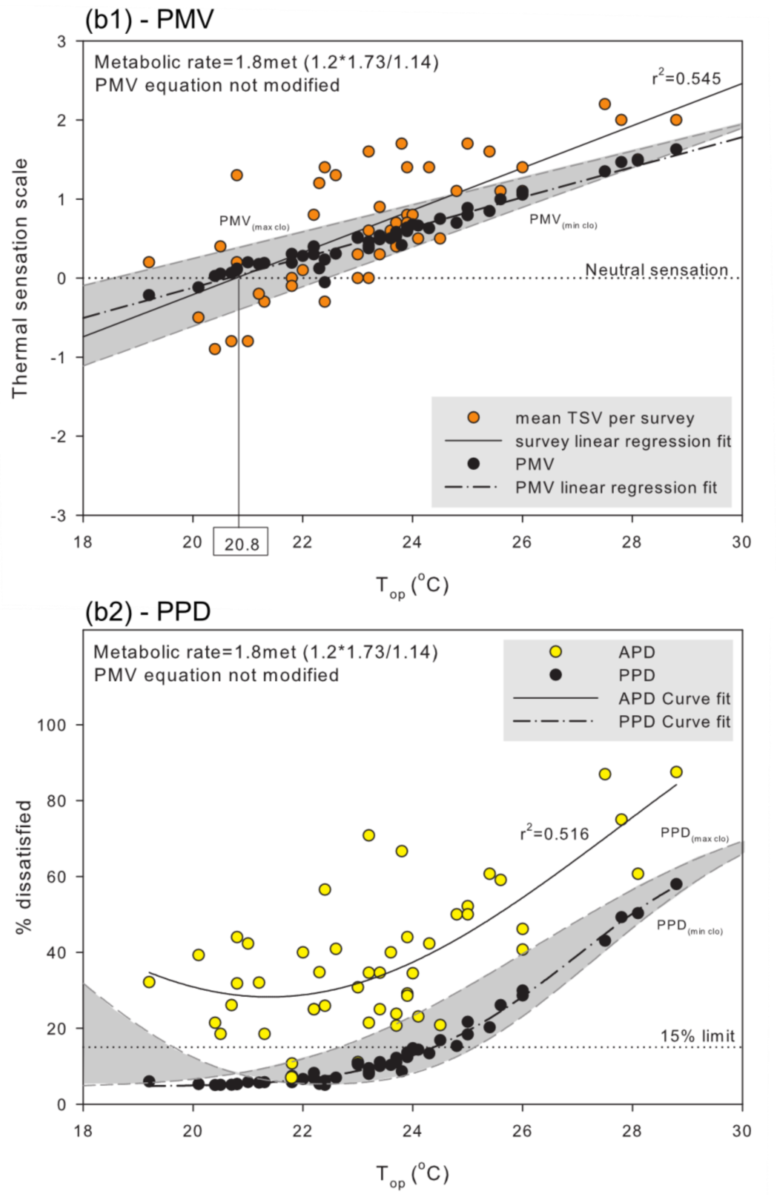


Figure 6.2. (b1): Actual mean thermal sensation vote (TSV(mean)) for each survey and calculated PMV against the operative temperature. (b2): Actual percentage of dissatisfied (APD) and calculated PPD against the operative temperature with curve fits. The grey shaded areas show the 'error bands' from using estimated minimum and maximum 'clo' values.

In addition, Figure 6.2(b2) highlights a large discrepancy between modelled and actual results for the PPD. Even though the curve fits have an almost parallel relationship, the PPD values are much lower than the APD values. This again indicates a limited suitability of this approach for replicating the survey results.

Approach (c): *RMR change inside the PMV equation and input met correction*

As can be seen in Figure 6.3(c1), the majority of the actual TSV points lie below the calculated PMV points with the actual TSV regression line falling almost on top of the $PMV_{(min\ clo)}$ regression line for temperatures below 25 °C. However, there is a generally better match between the actual TSV and PMV data than in approaches (a) and (b).

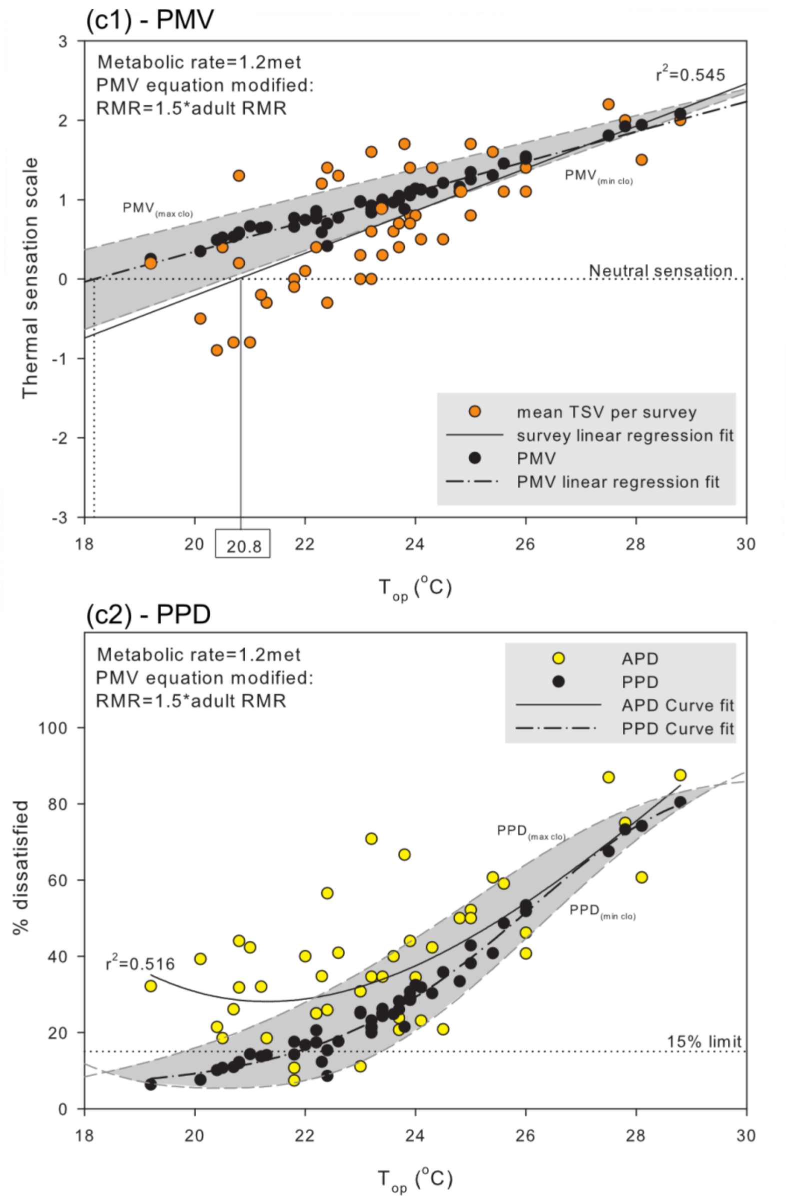


Figure 6.3. (c1): Actual mean thermal sensation vote (TSV(mean)) for each survey and calculated PMV against the operative temperature. (c2): Actual percentage of dissatisfied (APD) and calculated PPD against the operative temperature with curve fits. The grey shaded areas show the 'error bands' from using estimated minimum and maximum 'clo' values.

A better agreement than in the other two approaches can also be seen in the PPD/APD graph of Figure 6.3, which highlights that a large number of the APD points fall within the PPD range, yet with some large scatter at operative temperatures of about 20-24 °C. Of all the investigated approaches, approach (c) delivered the best match between the survey results and the calculated data.

The 'over-prediction' of the PMV under approach (c) is, in fact, what would be expected for a naturally ventilated building according to the adaptive approach to thermal comfort (de Dear and Brager, 2002). Following this observation, it appears reasonable to assume that the match between the adjusted PMV and $TSV_{(mean)}$ could potentially be greater in the case of a mechanically ventilated building. However, further research would be required to verify this.

Approach (d): *Calculated metabolic rates for children in the input 'met' calculation and inside the PMV equation*

Figure 6.4 (d1) shows a large deviation between the PMV calculation results of approach (d) and the actual TSVs and graph (d2) highlights a clear mismatch between the PPD and APD. The reason for the poor match of the calculated PMV data with the actual thermal sensation votes probably lies with the empirical nature of the PMV equation, which was derived from experiments with adults (Fanger, 1970). Conversely to approaches (a) to (c) which in essence represent a scaling of the PMV equation to represent children, approach (d) changes the equation directly with data from children. However, relationships between for example activity level and sweat rate may be different in children than adults, which means that a mere substitution of the RMR value with the equivalent RMR of children changes the balance in the equation, which can potentially lead to unreliable results.

It can be concluded that approach (a) suggests that children may be more sensitive to higher temperatures than adults, as the TSV is on average shifted by about 1.1 scale points, compared to the PMV as it would be calculated for adults under the same environmental conditions (Figure 6.1 (a)). The body surface area correction of the input activity metabolic rate in approach (b) gave a better prediction of the TSV than approach (a) but significantly underestimated the PPD. The body surface area correction of both the activity and the resting metabolic rate provided the most accurate prediction of the 3 approaches, but, comparing individual survey points, the difference between the predicted and the actual TSV values can be up to 1 scale point.

Overall, this investigation indicates that in view of the survey data presented here an adjustment of the PMV equation according to the principles of approach (c) seems to be the most reasonable approach to predict the thermal sensation of children under the PMV model.

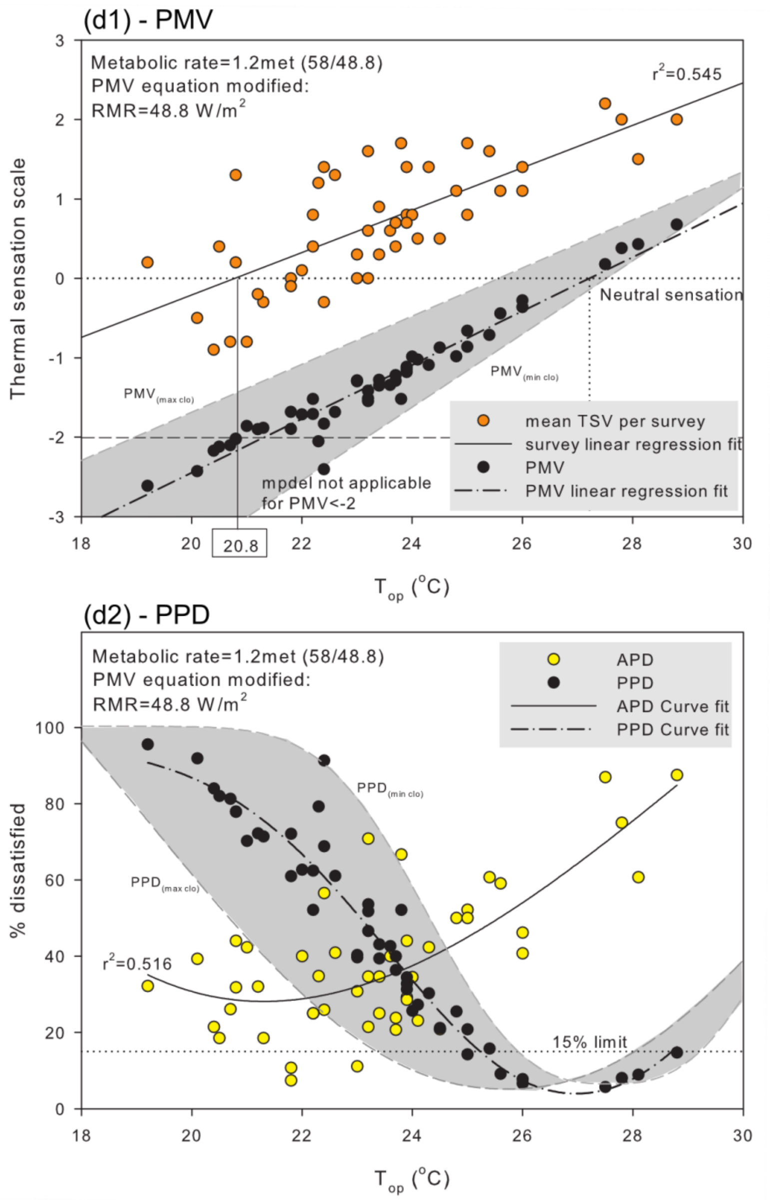


Figure 6.4. (d1): Actual mean thermal sensation vote (TSV(mean)) for each survey and calculated PMV against the operative temperature. (d2): Actual percentage of dissatisfied (APD) and calculated PPD against the operative temperature with curve fits. The grey shaded areas show the 'error bands' from using estimated minimum and maximum 'clo' values.

6.1.3 Surveyed thermal satisfaction and preference

It should be noted that a large variance was observed in the TSVs and APD between classroom surveys with similar operative temperatures (Figures 6.1-6.4). This highlights that other parameters apart from temperature may affect thermal sensation and satisfaction. The APD in all except 3 surveys was observed to be above the maximum acceptable limit of 15% set by ISO 7730 (ISO, 2005) for a Category C thermal environment, the least strict category. This can be seen more clearly in Figure 6.5, where the actual percentage of satisfied people is plotted in relation to the 3 minimum acceptability limit categories set by ISO 7730 (94, 90 and 85% acceptability). It should be noted however that the definition of the people dissatisfied as those who vote beyond the central three categories is questionable, as other research has found that some subjects may actually find the thermal environment acceptable even if they voted outside these categories (Wong and Khoo, 2003, Kwok and Chun, 2003). Therefore, the actual percentages of people dissatisfied (APD) may be overestimated. If this was the case, then the predictions of approach (c) could be considered to deliver a relatively close match of the PPD with the 'true' APD. Further to this, previous research has concluded that neutrality may not always be the preferred thermal state because a significant percentage of people voting within the 3 central categories of the thermal sensation vote (TSV) vote for warmer or cooler conditions on the 3-point McIntyre preference scale (Wong and Khoo, 2003, Zhang et al., 2007, Hwang et al., 2009, Kwok and Chun, 2003, Corgnati et al., 2007, Humphreys and Nicol, 2004, Hwang et al., 2006). This possibility is examined in the following with the responses form the pupil survey.

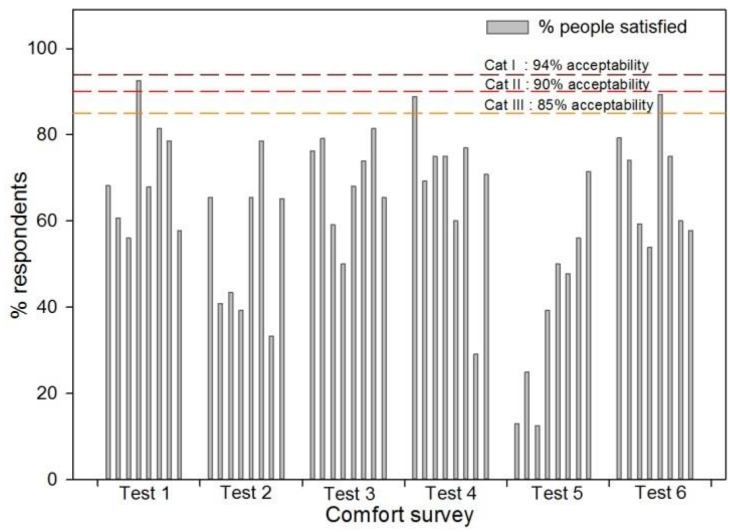


Figure 6.5. Percentage of survey respondents who voted -1, 0, +1 on the ASHRAE thermal sensation scale, i.e. are thermally satisfied (A test corresponds to a 2-day visit for surveying all 8 classrooms).

As seen in Figure 6.6, the majority of children voting for a specific thermal sensation preferred the conditions which would bring them to neutrality. Figure 6.7 shows the distribution of thermal preference votes (TPV) of the children who voted within the 3 central thermal sensation categories which are considered to correspond to thermal satisfaction. Most of the votes are within the 3 central categories of thermal preference (a bit colder, no change, a bit warmer), whilst only a few subjects would have preferred warmer or colder conditions. 30% of the pupils who voted within these categories (-1, 0, +1) answered that they did not want any change, whilst about 50% of them would have preferred slightly warmer or colder conditions. If a 3-point scale had been adopted and these two options were not available in the questionnaire, it is possible that those pupils who voted for a slight change in the thermal environment would have voted for a change (warmer, colder) rather than no change. This may to an extent explain why, in other studies where the 3-point McIntyre scale was used, thermal acceptability appears to be low (Wong and Khoo, 2003, Kwok and Chun, 2003). As can be seen in Table 6.5, in this study the percentage of satisfied children is essentially identical for both the thermal sensation and preference votes. (The pupils who voted “a bit warm”, “OK” or “a bit cool” on the thermal sensation scale and “a bit warmer”, “no change” or “a bit colder” on the thermal preference scale were considered as satisfied.) This implies that the APD results of the surveys are reflecting the true satisfaction levels reasonably well.

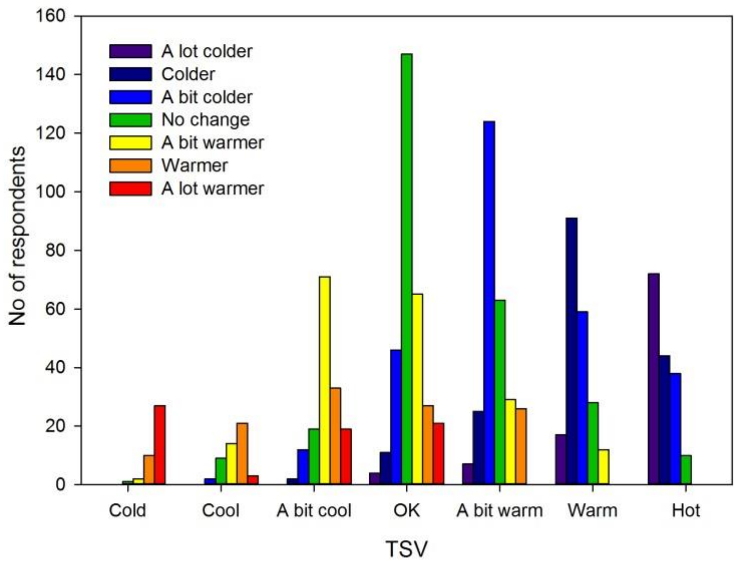


Figure 6.6. Thermal preference vote (TPV) by thermal sensation vote (TSV).

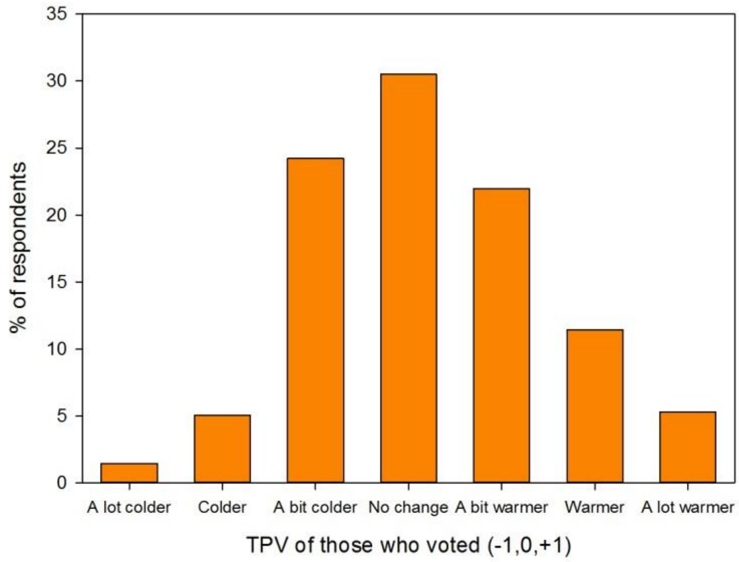


Figure 6.7. Thermal preference votes of the children who voted within the central 3 thermal sensation categories.

Table 6.5. Cross-tabulation of thermal satisfaction based on the TSVs and TPVs of all the surveys.

Assessment method	Cold dissatisfied	Satisfied	Warm dissatisfied
TSV	[-3,-2] 15%	62% [-1,0,+1]	[+2,+3] 23%
TPV	[+3,+2] 7%	62% [-1,0,+1]	[-2,-3] 31%

Figure 6.8 shows the preferred operative temperature T_p of the respondents in relation to the neutral operative temperature T_n discussed in section 6.1.2. The intersection of the $TPV_{(mean)}$ regression line with the horizontal line that corresponds to a "no change" preference (0 on the TPV scale) suggests a preferred operative temperature of the pupils at T_p=22.4 °C, which is about 1.6 °C higher than the estimated neutral temperature T_n=20.8 °C. This suggests that the pupils would generally prefer a slightly warmer thermal environment than the neutral. On the contrary, studies in hot and humid climates found the preferred temperature to be lower than the neutral (Hwang et al., 2006). The difference between this UK study and the Taiwan study is diagrammatically shown in Figure 6.9. The above indicates a potential influence of acclimatisation to different climates and variations in the cultural context on thermal sensation and preference. Overall, this finding appears to reinforce that neutrality may not be the desired condition.

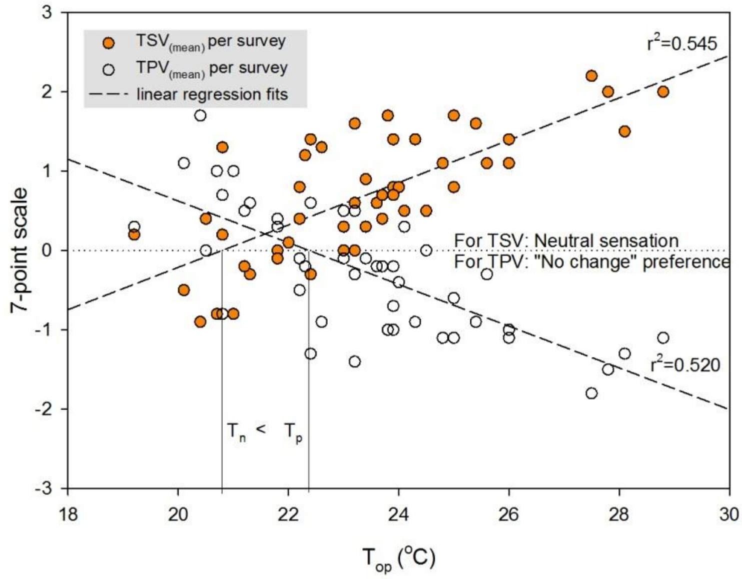


Figure 6.8. Mean thermal preference vote ($TPV_{(mean)}$) and mean thermal sensation vote ($TSV_{(mean)}$) for each survey plotted against the operative temperature (T_{op}).

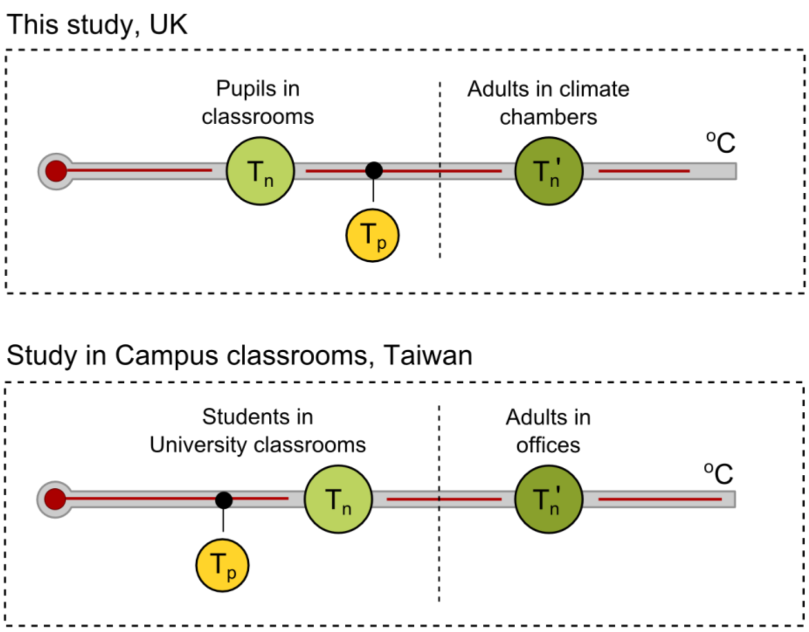


Figure 6.9. Diagram showing the relationship between neutral (T_n) and preferred (T_p) temperature in two field studies: this school study (UK) and a field study in University classrooms in Taiwan [Taiwan study:(Hwang et al., 2006)].

6.2 Survey results and the adaptive comfort model according to EN 15251

Figure 6.10 shows the operative temperatures determined during the surveys in relation to the recommended temperature limits given in Annex A of EN 15251 for buildings without mechanical cooling (CEN, 2007). The outdoor running mean temperature (T_{rm}) was calculated using the equation provided in EN 15251 (Equation (3.7) in section 3.2.2). The outdoor daily mean temperatures required for this calculation were derived from hourly data from the meteorological station of the National Oceanographic Centre in Southampton (NOCS). NOCS is located in Southampton docks, at a distance of 3km from both the investigated schools. The dashed lines in the graph correspond to the PMV-based operative temperature lower limits that apply for the heating season (CEN, 2007) and are included for comparison. The dotted line represents the comfort temperature in relation to the outdoor running mean which was the basis for deriving the upper and lower comfort zone limits of the EN 15251 diagram (Nicol and Humphreys, 2010).

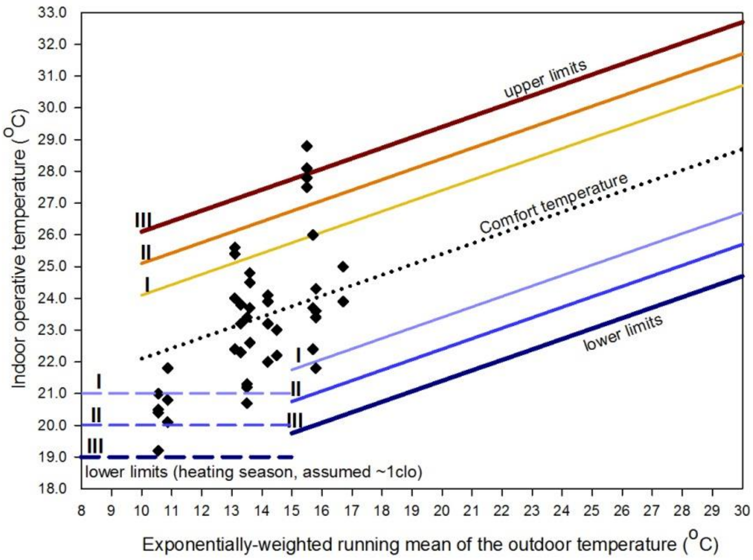


Figure 6.10. The survey operative temperatures on the EN 15251 diagram.

According to Figure 6.10, in all but 2 surveys the classrooms' operative temperature fell within the acceptability range for category III of EN 15251, which applies to "an acceptable, moderate level of expectation and may be used for existing buildings" (CEN, 2007). This category is considered to correspond to 85% of people satisfied. However, as discussed in section 6.1.3 above, the actual percentage of people satisfied (people who voted within the central 3 thermal sensation categories) was much lower, exceeding 80% in only 3 out of 48 surveys (Figure 6.5). Additionally, in 8 surveys the operative temperatures fell within the lower limits for the heating season (dashed lines), which are calculated with an assumed clothing insulation of 1.0 clo (CEN, 2007). This means that the pupils would be expected to feel cold as the average clo value determined during the surveys was around half the assumed clo of 1.0. However, the mean TSVs of these surveys were between -0.9 to 1.3, which means that the pupils had neutral to warm sensations rather than cold, as Figure 6.10 indirectly suggests.

6.2.1 Adaptive comfort temperature results in relation to standard adult values

In order to allow a direct comparison of the survey results with EN 15251 (CEN, 2007) the comfort temperature was calculated using the same method as applied in the SCATs (Smart Controls and Thermal comfort) database (McCartney and Nicol, 2002), since this database was used for developing the adaptive comfort equation underlying the building category limit equations given in Annex A of EN 15251 (CEN, 2007). The 'neutral' or 'comfort' temperature T_{comf} is defined as "the Operative Temperature at which either the average person will be thermally neutral or at which the largest proportion of a group of people will be comfortable" (Nicol and Humphreys, 2010). It is calculated using Equation (6.2) (Humphreys et al., 2007):

$$T_{comf} = T_{op} - TSV/b \qquad (6.2)$$

where T_{op} is the operative temperature, TSV the thermal sensation vote and b=0.5 a constant (Griffiths constant) (Nicol and Humphreys, 2010). The above equation can be applied using individual thermal sensation votes (TSV) or the mean value of a group of votes ($TSV_{(mean)}$).

As can be seen in Figure 6.11 the regression line of the calculated T_{comf} data for the classroom survey runs is 2 °C lower than that produced by the adaptive comfort equation underlying the EN 15251 building category equations. This suggests that for the same outdoor running mean temperature the pupils would prefer a cooler environment than the subjects in the SCATs project. It should be noted that the 95% confidence intervals of the classroom survey regression line are relatively wide. Therefore, the slope cannot be assumed to express the precise relationship between the comfort temperature and the outdoor running mean. However, the best-fit line is almost parallel to the adaptive comfort equation line with an almost identical slope (0.33 as compared to 0.38). This suggests that, whilst the overall relationship between comfort temperature and outdoor running mean temperature may be identical for adults and children, children appear to have a lower 'feel warm' threshold.

The classroom survey regression line in Figure 6.11 shows a comfort temperature range of T_{comf}=20.7 to 23 °C in relation to an outdoor running mean temperature range of T_{rm}=10.6 to 16.7 °C. For comparison, the neutral temperature determined in section 6.1.2 from the relationship between the classroom survey TSVs and the operative temperature was 20.8 °C (Figures 6.1-6.4). This is almost equal to the adaptive comfort temperature for an outdoor running mean of T_{rm}=10.6 °C. The adaptive approach however, showed a tolerance of the pupils for temperatures up to about 23 °C when the outdoor running mean reached about 17 °C, which is 2 °C higher than the previously calculated static TSV neutral temperature. This highlights the higher flexibility of the adaptive comfort model in defining comfortable indoor thermal conditions by providing a wider range of acceptable temperatures compared to a static neutral temperature.

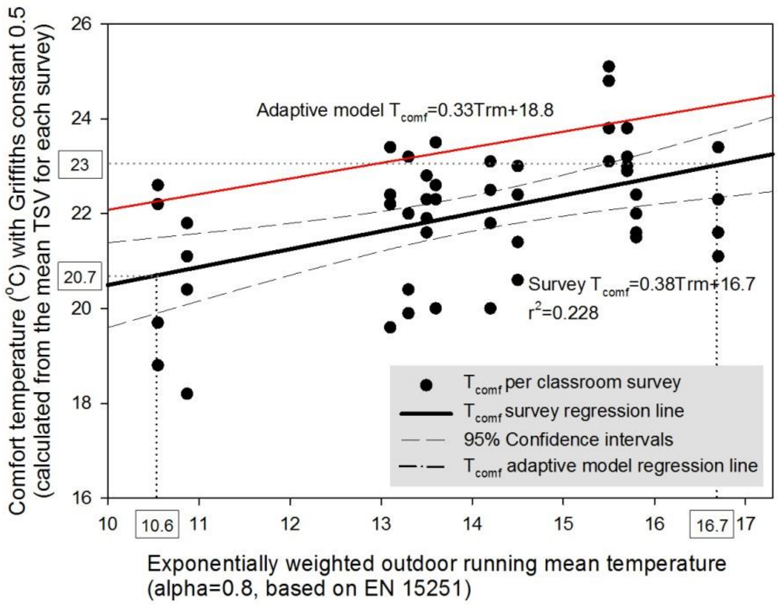


Figure 6.11. Operative temperatures of the survey runs plotted on the EN 15251 diagram (CEN, 2007) for acceptable indoor temperatures in buildings without mechanical cooling. (I, II and III correspond to building categories with different thermal performance requirements.)

The comfort temperature was also calculated for all the individual pupils' responses and plotted against the outdoor running mean temperature (Figure 6.12). The resulting regression line suggests a low correlation between the comfort temperature and the outdoor running mean with r^2=0.069, as the comfort temperatures vary significantly between the pupils for the same outdoor running mean. However the narrow 95% confidence intervals suggest that the slope of the line can be considered reliable (slope=0.44). The comfort regression lines of the entire SCATs database (used for setting up the building category limits in EN 15251) (Nicol and Humphreys, 2010) and of the SCATs UK database (McCartney and Nicol, 2002), are also included. The survey's comfort regression line is below both database regression lines but interestingly its slope is closer to the one of the whole database sample rather than that of the UK sample. However, a closer correlation to the UK database would be expected, as previous research has shown that the cultural context has a strong impact on the perception of air quality and thermal comfort (Humphreys et al., 2002). The absolute difference between the survey and the UK database is quite substantial as, at an outdoor running mean of T_{rm}=10 °C, the difference between the pupil survey's and SCATs-UK comfort temperature is 3.5 °C (Figure 6.12). This suggests a potentially stronger influence of the outdoor climate on the surveyed school children than adults. The reason for this may be the amount of time spent outdoors as the pupils frequently leave the building for breaks, which would not be the case for the subjects in the SCATs database. In conclusion, it appears that the current adaptive comfort approach may not be suited for assessing the preferred comfort conditions of school children.

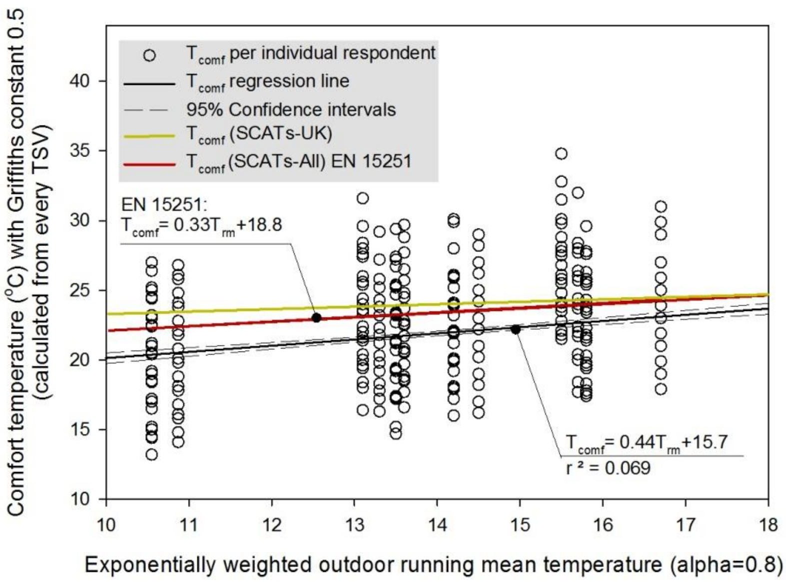


Figure 6.12. Calculated comfort (neutral) temperatures for the individual classroom surveys plotted against the exponentially weighted outdoor running mean temperature.

6.2.2 Adaptive behaviour in the classrooms

The classroom environment is generally controlled by the teachers and the only adaptation that children can take is the addition or removal of layers of clothing. Since in the UK pupils wear uniforms, their options for behavioural adaptation are limited. There are two options which address the seasonal change, winter and summer uniform, and over a day pupils can remove or add their jumper. Here, the adaptive behaviour of pupils is examined both for the prolonged period of the survey and in relation to the immediate reaction to thermal changes.

Long-term behavioural change: Figure 6.13 shows the relation of the survey mean clothing insulation with the classroom's operative temperature. There is an apparent decrease in mean clothing insulation at warmer operative temperatures, which is mostly related to the number of pupils deciding not to wear their jumper (pullover). This means that, over the prolonged survey period, pupils adapted their clothing to the temperature changes. This agrees with previous research in the Netherlands, where children adapted their clothing to the seasonal changes over the course of a year (Mors et al., 2011).

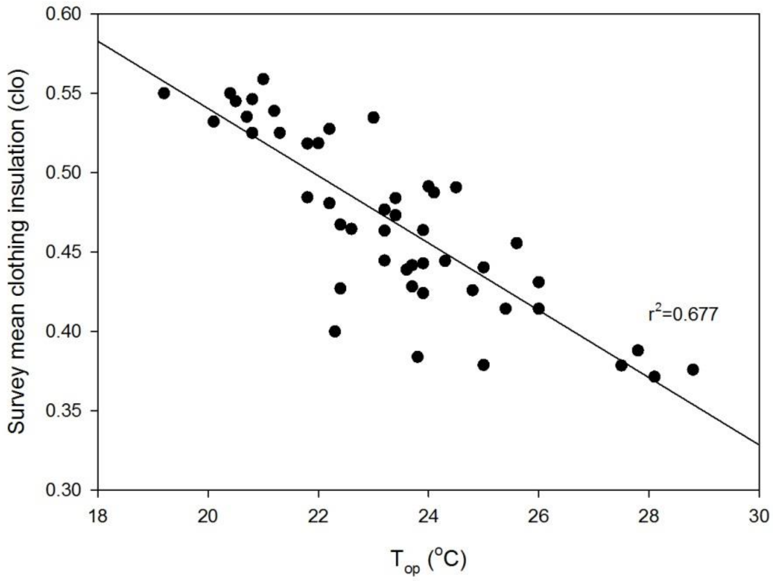


Figure 6.13. Survey mean clothing insulation against the classroom's operative temperature (T_{op}).

Immediate behavioural change: Looking at pupils' thermal sensation in relation to whether they were wearing their jumper during the survey, it appears that, within a day, children may not adapt their clothing to their thermal sensation. This agrees with other research with primary school children (Humphreys, 1977) and also corresponds to comments of teachers, as discussed in section 2.4.2.3, on possible causes of discomfort caused by overheating. As shown in Figure 6.14, about 15% of the children who voted "hot" and 25% of those who voted "warm" still wore their jumpers. Similarly, about half of the children that had a cold thermal sensation were not wearing their jumper during the classroom surveys (Figure 6.14). According to some teachers (section 2.4.2.3), children may be clearly too warm and yet do not take off their jumpers or ask for help (Teli et al., 2011). The limited adaptive opportunities in combination with the fact that children do not always adapt their clothing to their thermal sensation over a day could explain to an extent the warm thermal sensation tendency of the pupils observed in this study (see also sections 6.1.2 and 6.2.1).

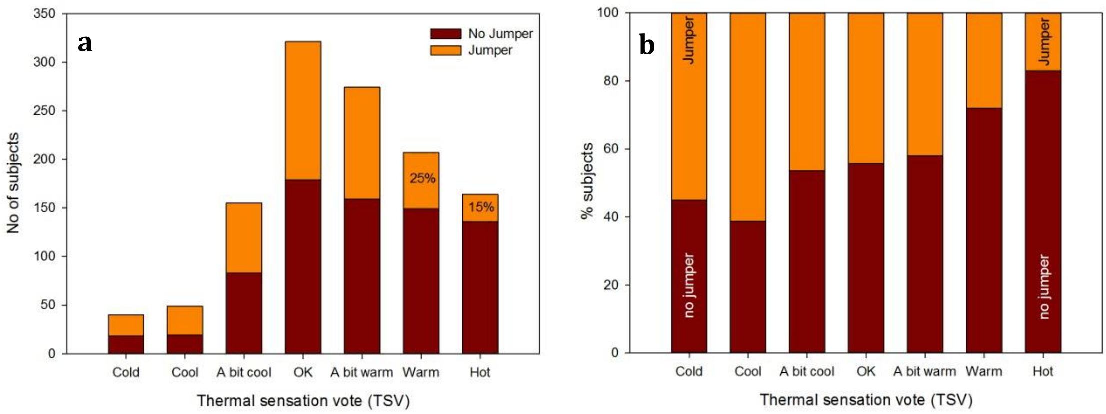


Figure 6.14. a) Distribution of the Thermal sensation votes from all the comfort surveys by number of children wearing their jumper, b) Percentage of subjects voting for each sensation wearing their jumper or not.

6.2.3 Comparison of the long term classroom thermal performance with accepted adaptive comfort temperature limits

In order to assess the overall thermal performance of the naturally ventilated case study school building it is necessary to compare the long term classroom thermal performance outside the heating season with the indoor operative temperature limits given in Annex A of EN 15251 (CEN, 2007) (see also Figure 6.10). Following the specifications of EN 15251, each classroom would need to meet the requirements of a Category III thermal environment which is defined as "an acceptable, moderate level of expectation and may be used for existing buildings". It was decided to examine the logged thermal conditions of the warmest of the 8 classrooms (classroom 6 in Figure 4.7- right hand side) for the period from mid-March to mid-August 2011. In order to do this, the operative temperature for this period is required, which is calculated using the measured air temperature and radiant temperature as input values in Equations (4.2) (if air speed v>0.1 m/s) and (4.3) (if air speed v>0.1 m/s).

The radiant temperature however was only measured during the comfort surveys. To determine the radiant temperature at other time steps, the 136 sets of radiant (T_r) and air temperature (T_{air}) measurements taken in the classroom during the surveys were correlated (Figure 6.15). The linear correlation which is given in equation (6.3) was strong with an r^2=0.939. Therefore, the required radiant temperature values were calculated using this equation.

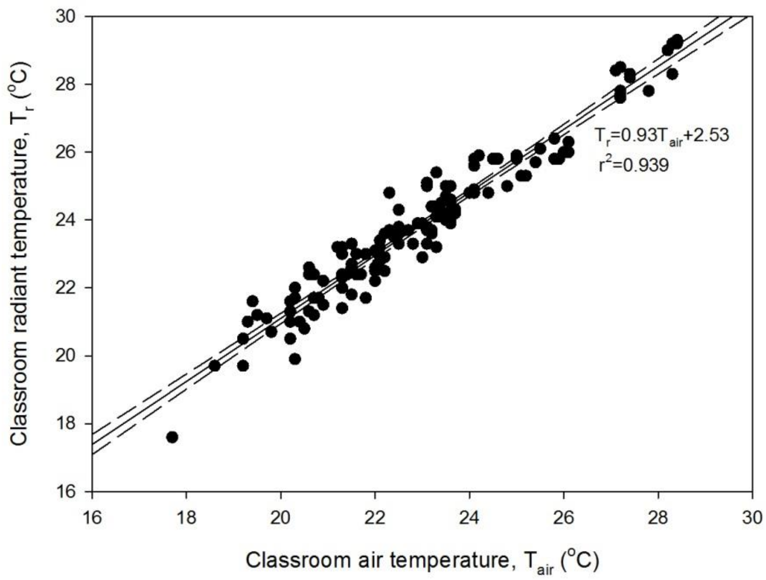


Figure 6.15. Measured radiant temperature plotted against the measured air temperature during the surveys.

$$T_r = 0.93 \cdot T_{air} + 2.53 \tag{6.3}$$

For comparison with the daily EN 15251 limits for Southampton in 2011, a daily value for the classroom operative temperature is required. This study is focused on the non-heating season, therefore the measured daily maximum indoor air temperature was used as reference value for the classroom T_{air} in equation (6.3), as this is the most critical point for a building's thermal performance during the day outside the heating season. The resulting operative temperature profile of classroom 6 is given in Figure 6.16.

As shown in Figure 6.16, the calculated operative temperature during occupied hours was mostly below the upper limit for a Category III indoor environment of EN 15251, whilst it frequently exceeded the upper limits for Category I and in some cases the limits for Category II. Figure 6.16 implies that from the end of March 2011 onwards children in this classroom were generally experiencing acceptable temperatures, according to Category III. However, as discussed in section 6.2.1, the survey results suggest that the comfort temperature regression line for the surveyed school is 2 °C lower than that of the equation underlying the EN 15251 categories (Figure 6.11). If this reduction is applied to the upper EN 15251 limits, the new limit for Category III overlaps with the current Category I upper limit (thick dashed line in Figure 6.16). It is evident that the estimated operative temperature frequently exceeds this adapted limit. This essentially means that, based on the survey results, the building would need to be considered as unsuitable for use without the adoption of mitigation measures.

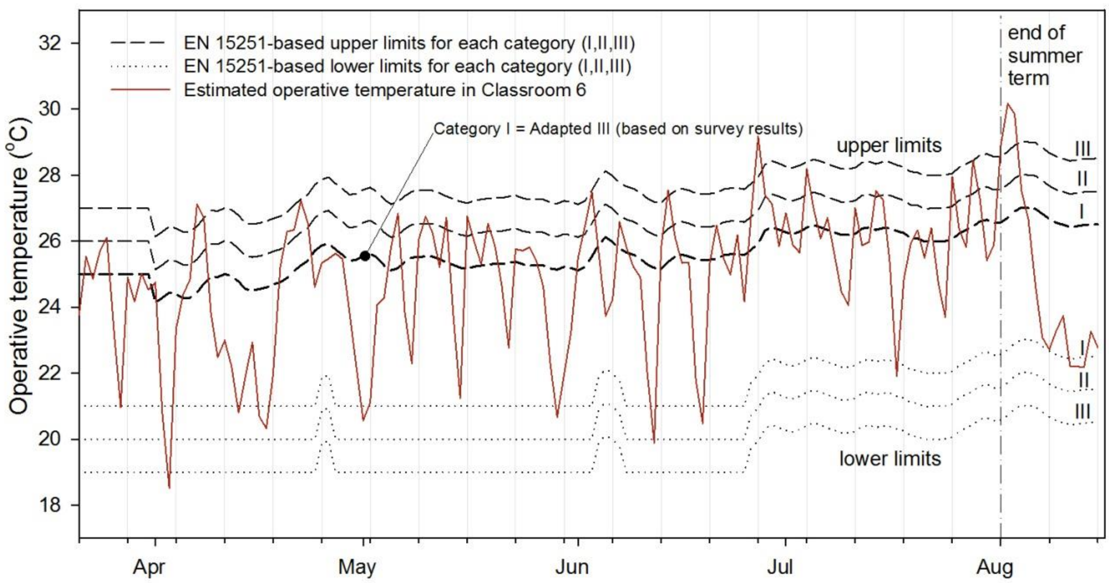


Figure 6.16. Estimated operative temperature for classroom 6 in relation to the operative temperature limits for the period of March-August 2011 as calculated from Annex A of EN 15251 (CEN, 2007), using the actual T_{rm}.

6.3 Survey results and overheating criteria

According to the analysis in the previous section of the measured thermal performance of the warmest classroom compared to the adaptive thermal comfort temperature limits, the case study school has a high potential of overheating. This section investigates whether this outcome agrees with the assessment of the school's overheating potential based on current overheating criteria applying to schools (see sections 3.3 and 3.4.1), by using the measured thermal performance of all school classrooms and the pupils' survey responses. The criteria under investigation include both fixed benchmarks (i-iii) and criteria based on the alternative approach to adaptive thermal comfort (iv-v), as listed below.

(i) BB 87 overheating criterion (DfES, 2003a)
(ii) BB 101 overheating criteria (DfES, 2006)
(iii) CIBSE overheating criterion (CIBSE, 2006)
(iv) Adaptive thermal comfort based Nicol criterion (Nicol et al., 2009).
(v) New DfE overheating criteria based on the adaptive comfort approach (Johnston and Partners, 2012)

For the comparison of the school's thermal performance with the above criteria the operative temperature (T_{op}) in every classroom was calculated for the monitoring period, including September, using equation (4.3) (section 4.2.3), with the measured air temperature and estimated radiant temperature from equation (6.3).

6.3.1 Fixed benchmarks

For the period mid-March to September (excluding August, which is holiday period) the number of hours when the operative temperature exceeded 28°C in each classroom was calculated, both for the 'occupied' (09:00-16:00) and 'unoccupied' hours. The results can be seen in Table 6.6 for two periods: a) the period 1 May - 30 September (excluding August), which is used in the Building Bulletins for the assessment of overheating (DfES, 2003a, DfES, 2006) and b) the whole monitoring period, 19 March – 30 September (excluding August) as the CIBSE criterion assesses the risk of overheating over the annual occupied hours (section 3.3).

Table 6.6. Number of hours when the operative temperature exceeded the threshold of 28°C in each classroom for comparison with fixed thresholds

		Classroom							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
a) 01/05-30/09	Unoccupied hours>28°C	0	0	0	0	4	10	5	6
	Occupied hours[1]>28oC	0	0	0	0	5	5	9	10
b) 19/03-30/09	Unoccupied hours >28oC	0	0	0	0	4	10	18	16
	Occupied hours[1]>28oC	0	0	0	0	5	5	9	10
Year	% of occupied hours in a year>28°C	0	0	0	0	0.4	0.4	0.6	0.7

Notes:

[1] Occupied hours correspond to the period of 09:00 to 16:00 on school days, in accordance with the guidelines (DfES, 2003a, DfES, 2006).

As can be seen in Table 6.6, the number of occupied hours that the indoor operative temperature exceeded 28°C in each classroom was way below the BB 87 and BB 101 limits, which are set to 80 occupied hours and 120 occupied hours respectively. According to BB 87, this is the only requirement and therefore, no overheating is assumed to have occurred. Unlike BB 87, BB 101 sets a combination of criteria (see section 3.4.2, a-c). Since the indoor air temperature never exceeded 32°C, two of the BB 101 criteria are met which means that, based on BB 101, there is no overheating issue. Finally, the CIBSE fixed overheating criterion is also met, as the percentage of occupied hours of threshold exceedance is below 1% in all classrooms (Table 6.6). However, the 1st floor South-East classrooms 7 and 8 are relatively close to the limit. Assuming a warmer summer, these 2 classrooms could potentially be assessed as 'overheated' by the CIBSE criterion. Overall, based on the existing criteria, the case study school can be assessed as not having overeating issues. However, this does not reflect the results of this field study, which showed that pupils frequently felt thermal discomfort from heat (see section 5.4).

Comparison between the two periods (a) and (b) of the occupied hours above 28°C shows no difference. However, the number of unoccupied hours above 28°C is much higher for classrooms 7 and 8 for the extended monitoring period. This threshold exceedance at 'un-occupied' hours during April occurred during the Easter holidays and on some occasions on school days after 16:00, which is considered to be out of the occupied period. This shows that the selection of the assessment period used in the Building Bulletins [period (a)] may lead to underestimation of the overheating risk of schools, as warm spells in April could occur and this could happen during school days. Furthermore, the low sun angle in April may exacerbate the risk of overheating during sunny days as the sun rays can reach deeper into classrooms. This can explain the threshold exceedance in the two top floor South-East classrooms 7 and 8.

For the calculation of the hours over 28°C of Table 6.6, the air temperature measurements taken at 5 minute intervals were used. The operative temperature was then calculated using equation (4.3) for each 5-min measurement and the sum for all the 5-min intervals where T_{op}>28°C was calculated. However, temperature measurements for overheating assessments are rarely taken at such small time-steps, whilst in thermal simulation modelling an hourly time-step is normally used. For comparison, the hours over 28°C were calculated after averaging the 5-min measurements to hourly air temperatures for the period (b). Table 6.7 shows the total number of hours exceeding the threshold based on both averaging options. As would be expected, using the hourly averages of the air temperature leads to a lower estimate of overheating hours. In combination with the lenient overheating thresholds used, this could significantly compromise the comfort conditions in classrooms designed following guidelines with fixed criteria.

Table 6.7. Total number of hours when the operative temperature exceeded the threshold of 28°C (occupied and unoccupied) in every classroom for 2 averaging options

Total hours>28°C	**Classroom**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Option A: Average of the hours>28 °C	0	0	0	0	9	15	27	26
Option B: Average of the 5-min T_{air}	0	0	0	0	8	15	23	25

Further to the above problems of the fixed thresholds, there is also the limitation of not taking into account the human adaptive mechanism and the potentially stronger impact of a rapid temperature rise on occupants compared to a gradual increase (section 3.3). This is addressed in the alternative approaches of overheating assessment based on adaptive thermal comfort, the formula developed by Nicol et al (Nicol et al., 2009) and the new DfE guideline (Johnston and Partners, 2012), which are investigated below in relation to the survey results.

6.3.2 Adaptive thermal comfort based criteria

6.3.2.1 Nicol overheating criterion

The alternative criterion suggested by Nicol et al (Nicol et al., 2009) estimates the likelihood of overheating in relation to the departure of the actual (measured/predicted) operative temperature from the calculated comfort temperature using equation (3.13) (section 3.3). The likelihood of overheating is expressed by the proportion of people (P) voting 'warm' or 'hot' on the ASHRAE scale, which is generally considered to correspond to thermal discomfort from heat (Nicol et al., 2009).

The proportion of people dissatisfied 'P' ("predicted discomfort") from heat was estimated for the occupied hours of the case study school during the survey period using equation (3.13), for comparison with the survey results. Two calculation options for the prediction were taken:

(a) Use of the comfort temperature equation underlying the EN 15251 comfort limits (equation (3.10)).
(b) Use of the comfort temperature equation (6.4), which was derived from this survey (section 6.2.1):

$$T_{comf} = 0.44 \cdot T_{rm} + 15.7 \tag{6.4}$$

For each classroom, the difference between the operative temperature and the comfort temperature was calculated for the occupied hours from March to July, for both (a) and (b). The results were then used for calculating the predicted proportion of people dissatisfied, P_a and P_b using equation (3.13). The mean and maximum predicted percentages of dissatisfied subjects for each classroom and for both equations can be seen in Figure 6.17 and Figure 6.18 respectively, in comparison with the corresponding observed values (proportions of pupils who voted 'warm' or 'hot' on the 7-point thermal sensation scale during the surveys in each classroom). For the evaluation of the results, 3 levels of overheating were used, as used by Montazami and Nicol (Montazami and Nicol, 2012):

- Highly overheated classroom when: $P \geq 10\%$.
- Moderately overheated classroom when: $6\% \leq P < 10\%$.
- Slightly overheated when: $P < 6\%$.

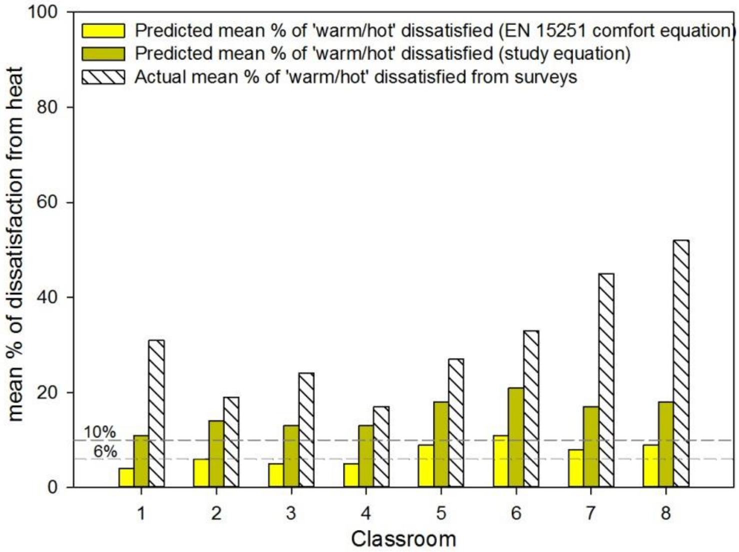


Figure 6.17. Predicted mean proportion of thermally dissatisfied subjects from heat based on adaptive thermal comfort, per classroom and for the occupied hours of the period March-July. The mean proportion of pupils voting 'warm' or 'hot' during the surveys is also depicted.

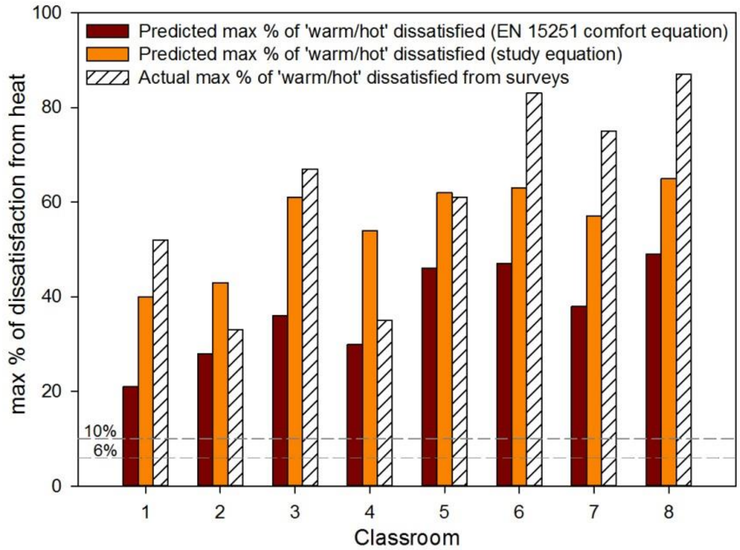


Figure 6.18. Predicted maximum proportion of thermally dissatisfied subjects from heat based on adaptive thermal comfort, per classroom and for the occupied hours of the period March-July. The maximum proportion of pupils voting 'warm' or 'hot' during the surveys is also depicted.

As can be seen in Figure 6.17, according to the results of calculation (a), using the EN 15251 equation, the ground floor classrooms 1-4 can be generally assessed as slightly overheating and the 1st floor classrooms as moderately overheating. This means that the Nicol criterion is stricter than the fixed thresholds used in CIBSE guide and Building bulletins 87 and 101, which did not predict any overheating issues (see section 6.3.1). Therefore, the adaptive comfort based overheating criterion provides a more realistic indication of the school's overheating risk compared to the fixed benchmarks, which was also highlighted by Montazami and Nicol, through comparison with teachers' responses (Montazami and Nicol, 2012). However, as discussed in section 6.2.1, the adult-based comfort temperature equation is not suitable for school children who were found to prefer lower temperatures than adults in offices. Subsequently, the likelihood of overheating based on case (a) potentially underestimates the actual overheating risk of the school classrooms.

Based on the results of calculation (b), which uses this study's comfort temperature equation, the predicted mean percentages of dissatisfied from heat exceed 10% in all classrooms, indicating that they all experienced overheating. The above prediction agrees with the observed mean percentages of pupils voting 'warm' or 'hot' during the surveys, which also exceed the 10% limit for highly overheated spaces. In fact, the exceedance is much greater than in the prediction. This discrepancy could be due to the fact that the mean observed percentages were derived from surveys within occupied hours and at specific times after at least 15 minutes of class activity, with full occupancy, which means that the classroom had been heated up. On the other hand, the predicted percentages correspond to measured operative temperatures at the period from 09:00 to 16:00, including breaktimes, physical education (PE) class, assembly time or music, which usually take place in other school spaces or outdoors, while the classrooms are kept cooler. This could also explain why there is a better agreement between the maximum predicted percentages of dissatisfied from heat based on calculation (b) and the observed maximum percentages from the surveys, as illustrated in Figure 6.18.

The fluctuations in the predicted hourly percentage of dissatisfied over the occupied hours from March to July can be seen in Figure 6.19 for two of the 8 classrooms (the coolest and warmest based on the prediction). The graphs show both prediction approaches: (a) using the EN 15251 comfort temperature equation and (b) using this study's comfort temperature equation. Under both calculations (a) and (b) the classrooms are often highly overheating. Furthermore, the proportions based on calculation (b) exceed by far the overheating levels of 6% and 10%. This finding corresponds to the critical thermal conditions found in classroom 6 which were assessed against the upper limit of the adapted Category III indoor environment derived from the school survey (Figure 6.16).

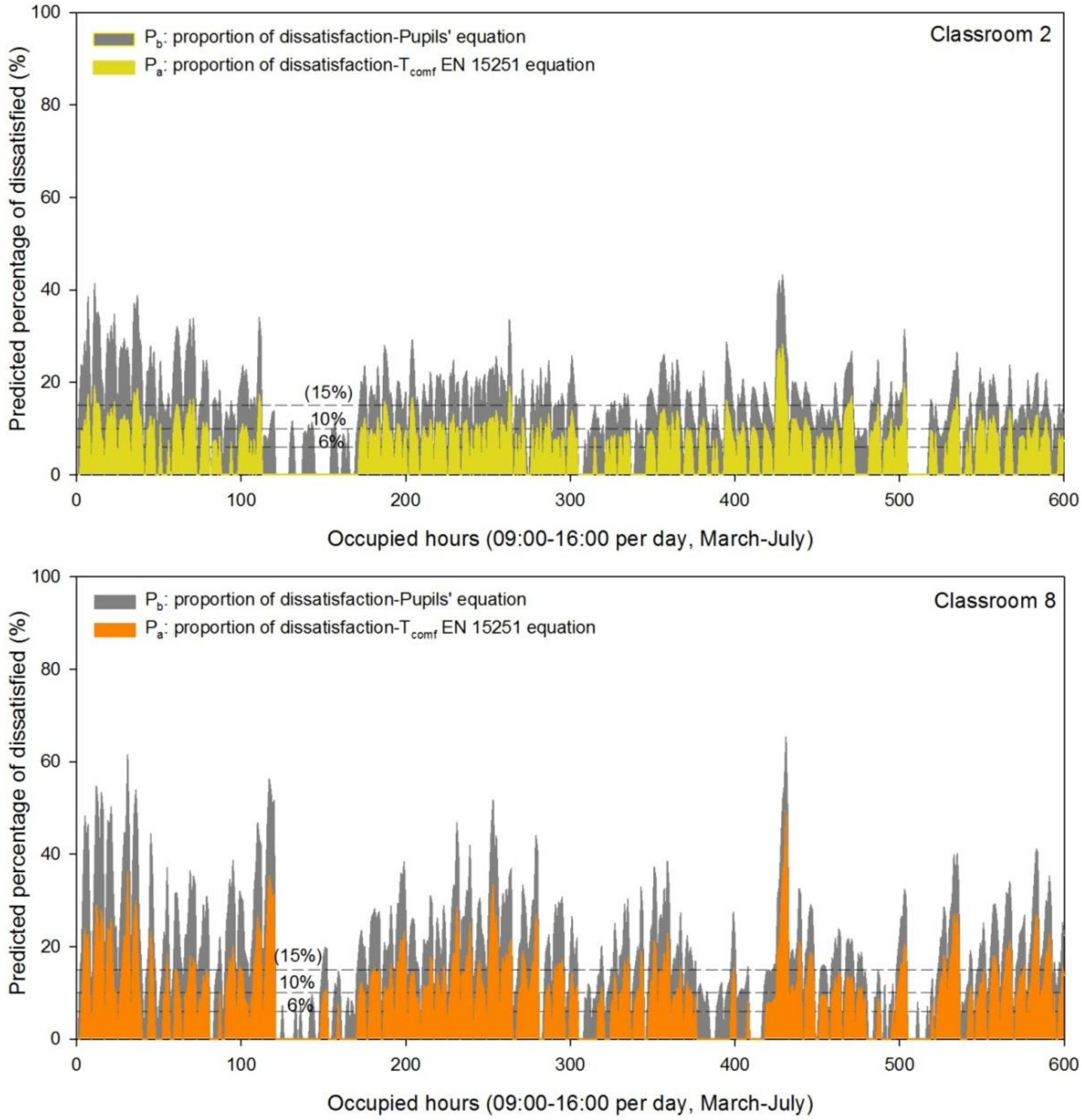


Figure 6.19. Predicted hourly percentage of dissatisfied pupils over the occupied hours of the monitoring period for classrooms 2-coolest (above) and 8-warmest (below).

6.3.2.2 DfE guideline

The new guideline for predicting overheating of the Department for Education (DfE) is based on the adaptive comfort temperature limits of EN 15251, as described in section 3.4.2. The DfE assessment period includes the occupied hours from May to September and the parameters that need to be calculated for these months are:

- $\Delta T = T_{op} - T_{max}$ (T_{op} =Measured operative temperature, T_{max} = maximum acceptable operative temperature)
- He: hours of exceedance of ΔT above 1°C
- We (weighted exceedance), as calculated using equation (3.14).

The new guideline, as published in the report of Cundall Johnston and Partners (Johnston and Partners, 2012), does not specify which building category of EN 15251 should be used for the calculation of T_{max} (I, II, or III). In the analysis of section 6.2.3, category III was used, which corresponds to "an acceptable, moderate level of expectation and may be used for existing buildings". However, Montazami and Nicol (2013) used category II as the category applying to 'normal buildings' for the assessment of the new guideline in relation to teachers' responses, as this category is used in CIBSE guide A (CIBSE, 2006). Since it is not specified in the guideline, category II is used here for direct comparison with the results in (Montazami and Nicol, 2013). However, it is clear that this is a limitation of the guideline. The overheating criteria are estimated for 2 assessment periods: (1) May to September, as required by the guideline and (2) the monitoring period from mid-March to September. T_{max} was calculated for two equation options:

(a) Using the maximum acceptable operative temperature equation found in EN 15251 for category II buildings (CEN, 2007).

$$T_{max} = 0.33 \cdot T_{rm} + 21.8 \tag{6.5}$$

(b) Using the maximum acceptable operative temperature equation derived from the comfort temperature equation (6.4) which was based on the pupil survey results, assuming a category II thermal environment (T_{max}=T_{comf}+3).

$$T_{max'} = 0.44 \cdot T_{rm} + 18.7 \tag{6.6}$$

The results for each of the assessment periods (1) and (2) and options (a) and (b) can be seen in Table 6.8. The new DfE guideline, applied exactly as recommended (option 1a), does not predict overheating in any of the school classrooms. This suggests that, based on the results of this study, the new guideline does not reflect pupils' needs, similar to the existing BB 87 and BB 101 criteria. Using the T_{max} equation deriving from the pupil survey (option 1b), the criteria become more stringent and the 1st floor classrooms 6-8 appear to have overheating issues. As indicated in section 6.3.1, there were warm days in April which are excluded from the overheating assessment of BB 87 and BB 101 as well as from the new guideline. The impact of this exclusion on the new guideline's assessment can be seen in the results of options 2a and 2b, where April is included in the assessment period. The criteria in 2a and 2b become more stringent, although using the EN 15251 equation for T_{max} suggests that only classroom 6 experiences overheating (2a). Option 2b included both an extended assessment period and the pupils' T_{max} equation. The results based on 2b suggest that all classrooms experienced overheating during the monitoring period (Table 6.8), which agrees with the case study results. It is clear that, unless the new DfE guideline adopts a children-based T_{max} equation or a more stringent category of thermal environment, it will underestimate the overheating potential of schools, similar to the existing BB87 and BB 101 guidelines.

Table 6.8. Overheating risk of all 8 classrooms based on the three criteria of the new DfE guideline, for options (a) and (b) of T_{max} calculation.

			Classroom							
1) May-September		Criteria	1	2	3	4	5	6	7	8
(a) EN15251	H_e (%)	<3	0%	0%	0%	0%	1%	2%	1%	1%
	W_{emax}	≤10	0	1	0	0	18	16	4	11
	$(\Delta T)_{max}$	<4	0	1	0	0	2	2	1	2
	Overheating		NO	NO	NO	NO	NO	NO	NO	NO
(b) Case study T_{max}	H_e (%)	<3	1%	2%	1%	1%	11%	16%	11%	14%
	W_{emax}	≤10	4	17	5	5	55	55	35	44
	$(\Delta T)_{max}$	<4	1	2	1	1	4	4	3	4
	Overheating		NO	NO	NO	NO	YES	YES	YES	YES
			Classroom							
2) end March-September		Criteria	1	2	3	4	5	6	7	8
(a) EN15251	H_e (%)	<3	0%	0%	0%	0%	1%	3%	1%	2%
	W_{emax}	≤10	0	1	1	1	18	16	5	11
	$(\Delta T)_{max}$	<4	0	1	1	1	2	2	1	2
	Overheating		NO	NO	NO	NO	NO	YES	NO	NO
(b) Study T_{max}	H_e (%)	<3	3%	4%	5%	5%	15%	21%	14%	18%
	W_{emax}	≤10	7	17	23	20	55	55	41	44
	$(\Delta T)_{max}$	<4	2	2	3	3	4	4	3	4
	Overheating		YES	YES	YES	YES	YES	YES	YES	YES

Notes: The occupied hours were 1) 608 (01/05-30/09) and 2) 760hrs (21/03- 30/09)

In summary, based on the results presented here, the existing fixed criteria do not reflect the way pupils experience their thermal environment. The adaptive comfort based Nicol formula provides a better indication of the overheating potential but it is still lenient as its calculation of the proportion of discomfort uses the adult based comfort temperature equation. Finally, the new DfE guideline, even though it is based on the adaptive comfort principle, appears to underestimate significantly the risk of overheating. It is clear that, the use of the child-based comfort temperature equation or the use of a more stringent category of thermal environment is necessary in order to assess the risk of overheating from a pupils' perspective.

Further to the above, the overheating assessment period should be extended to include the month of April, as it was shown that it is possible for a UK school to experience overheating during this transitional period when the sun enters classrooms from a low angle. Finally, the appropriate category of thermal environment for school buildings should be specified as it has a significant impact on the prediction of a school's overheating potential.

6.4 Section summary

The main outcomes of this section can be summarised as follows:

- The neutral temperature derived from the actual mean thermal sensation votes was about 4 °C lower than that predicted from the standard (unchanged) PMV model (see approach (a) in section 6.1.2), which highlights a significant difference between actual and predicted thermal sensation votes.
- The comparison between various adjustment approaches in the PMV model indicates that a surface area adjustment of the resting metabolic rate inside the PMV equation as well as the 'met' calculation appears to deliver reasonable values for school children's thermal sensation and satisfaction (see approach (c) in section 6.1.2).
- Pupils would generally prefer a slightly warmer thermal environment than their neutral (section 6.1.3).
- The adaptive comfort temperature values for children appear to be significantly lower than for adults with a 2 °C difference in this study. This highlights the need for further investigation on the applicability of the adaptive comfort model in its current form for children.
- Over long periods pupils adapt their clothing but not always within a day. The lack of immediate behavioural change and limited adaptive opportunities in classrooms may be related to their higher sensitivity to high temperatures.
- The fixed overheating thresholds which currently apply to schools were found to underestimate significantly the overheating potential in the investigated school since they imply that there was no overheating issue, while this study indicates a high risk of overheating based on pupils' responses.

- The adaptive comfort based Nicol formula better reflected the classrooms' overheating risk. However, it uses the adult-based comfort equation which, based on the results presented here, is not applicable to children. The use of child-based input data in the discomfort calculation appears to be necessary, as well as accounting for the variable school timetable. Similarly, the new DfE guideline should be updated to incorporate the results of this study; otherwise it may underestimate the risk of overheating. Finally, the overheating assessment period should be extended to include April.

The key outcome from this chapter is that it proves the hypothesis of section 5.6 that the differences in thermal perception found between adults in offices and pupils in classrooms (chapter 5) have implications for thermal comfort modelling. It has been shown that current comfort standards are ill suited for use in school environments without any adjustments. This stands in strong contrast to the common practice in the building industry. However, the differences between actual and modelled thermal sensation could also be related to the impact of the different building type (school instead of office) and its characteristics on thermal comfort rather than the fact that the subjects were children. The following section looks at this through the survey results.

7. Post-war school: Building type characteristics and thermal comfort in classrooms

Besides the environmental and personal parameters determined by the PMV model (Fanger, 1970) and the outdoor climate considered influential by the adaptive comfort model (Nicol and Humphreys, 2002, de Dear and Brager, 1998), there may be other parameters that influence whether an environment is perceived to be thermally comfortable or not, which are not captured by the calculations of comfort standards (Frontczak and Wargocki, 2011). In a school environment those parameters could be:

a) occupant related factors, such as

- the psychological condition of the pupils
- the potential influence of an established view amongst the teachers on the pupils' perception of the thermal conditions in the classrooms
- the pupils' disposition towards the activity undertaken
- the time of the day, especially in relation to school breaks
- controls and preferences of the teachers (e.g. blinds/curtains closed, door open)
- lack of adaptive opportunities

b) building related factors, such as

- the classroom orientation and glazing to wall ratio, with subsequent impact on solar gains
- the solar shading solution, operation and position (internal, external)
- the cross-ventilation potential of the classroom
- the floor level in the building (ground floor, top floor under the roof)
- the room and furniture layout (e.g. proximity to windows)
- the room's design characteristics (colouring, lighting)

7.1 Occupant related influential factors: controls and activities

The potential influence of occupant related parameters on thermal perception is supported by the survey results presented here. Figures 7.1-7.6 show the distribution of votes in all 48 surveys, grouped into the satisfaction categories (-3,-2: cold dissatisfied, -1, 0, +1: satisfied, +2, +3: warm dissatisfied), plotted in relation to the operative temperature at the time of the survey. The remaining environmental parameters, air speed and relative humidity, can be considered to have negligible influence on thermal comfort for this comparison as the air speeds during the surveys were similarly low, ranging between 0.04-0.13 m/s, and relative humidity variations are considered to have a low impact on thermal comfort under moderate temperatures (Toftum et al., 1998). The metabolic rate in all surveys can be considered similar since almost all were conducted after at least 15min of class activity. Finally, the four classrooms surveyed on the same day experienced the same outdoor climate. Therefore, in sets of 4, the surveys can be considered to have similar framework conditions. However, there are differences in thermal perception even between classrooms with similar operative temperatures. For example, as can be seen in Figure 7.4, classroom 3 in test 4 had a clearly higher percentage of satisfied respondents compared to the other three classrooms of the same test which had a similar or lower operative temperature. This high level of satisfaction could be related to the children's activity, as they had a computer class which they appeared to enjoy.

On the warmest day of the data set (test 5 on the 27/06/11), which had operative temperatures during the surveys between 27.5 and 28.8 °C, the percentage of children voting within the 3 central categories varied from 10-40% (Figure 7.5). This difference in votes could be related to the different measures taken by the teachers in order to improve the thermal conditions in the classroom. In classroom 6 there were 2 fans operating, the door and windows were open but the blinds were closed, obstructing airflow. By contrast, in classroom 5 the fan was off but the door and all windows, as well as the blinds, were open and therefore some cross-flow was created. The air speed was identical in both cases (0.1m/sec) and the CO_2 concentration similarly low (~500ppm). However, the percentage of satisfied pupils in classroom 5 was higher than in classroom 6 (Figure 7.5). One possible explanation is the difference in the air distribution between the two classrooms. In classroom 5 it was naturally driven whereas in classroom 6 it was achieved using fans, which may have led to some pupils experiencing unusually high or limited air flow.

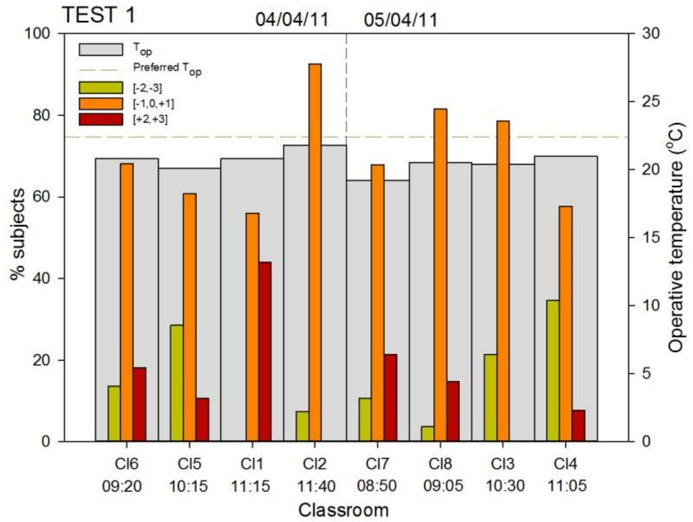


Figure 7.1. Grouped thermal sensation votes in relation to operative temperature of Test 1 surveys.

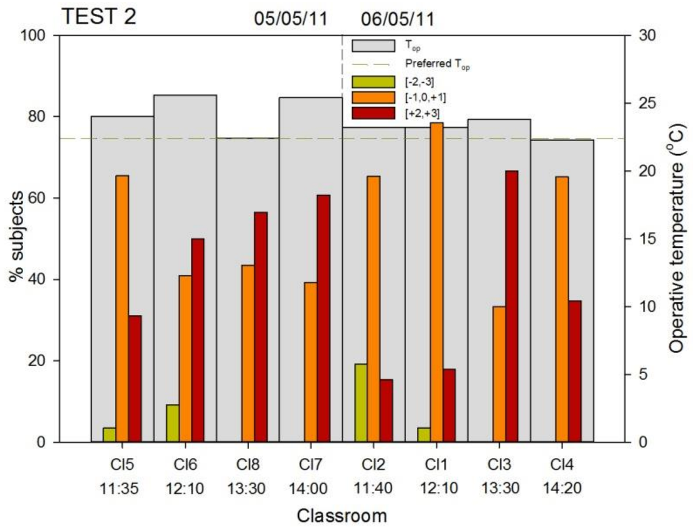


Figure 7.2. Grouped thermal sensation votes in relation to operative temperature of Test 2 surveys.

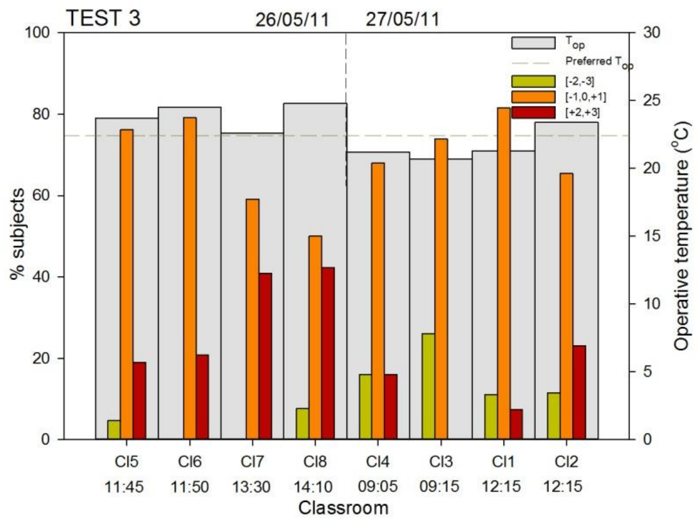


Figure 7.3. Grouped thermal sensation votes in relation to operative temperature of Test 3 surveys.

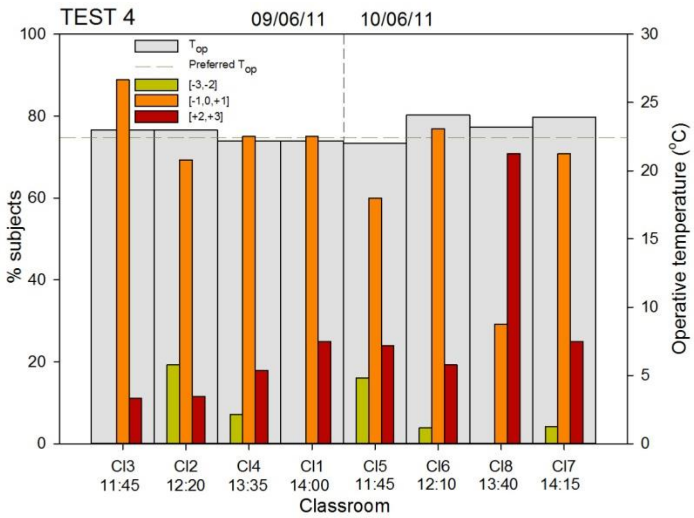


Figure 7.4. Grouped thermal sensation votes in relation to operative temperature of Test 4 surveys.

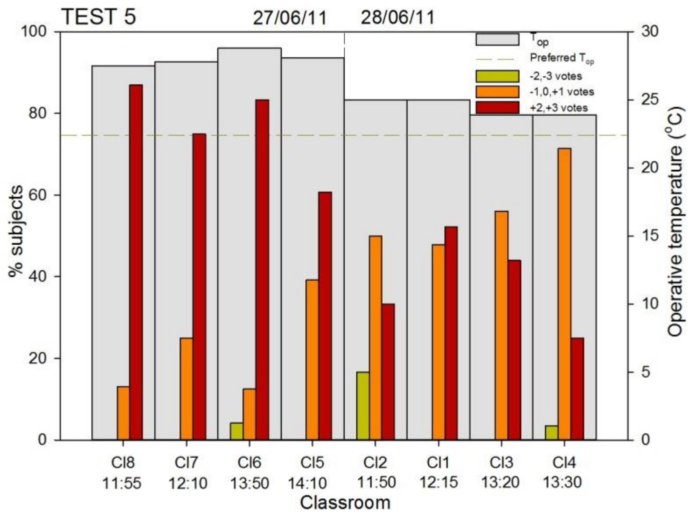


Figure 7.5. Grouped thermal sensation votes in relation to operative temperature of Test 5 surveys.

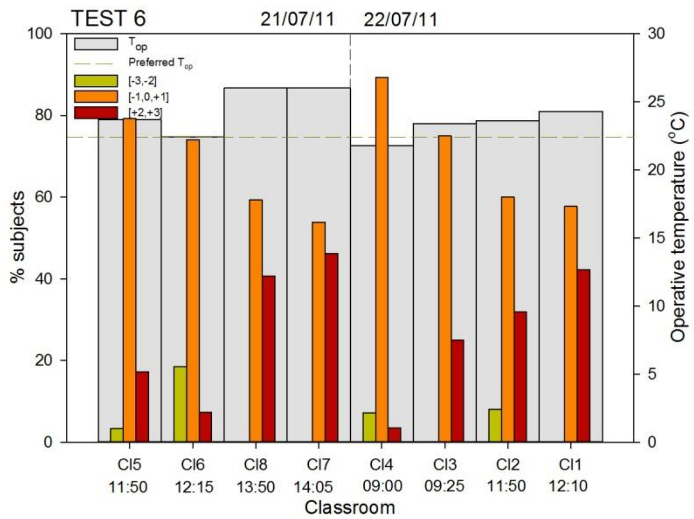


Figure 7.6. Grouped thermal sensation votes in relation to operative temperature of Test 6 surveys.

Table 7.1 highlights cases where major sensation differences were found between adjacent classrooms with identical building characteristics (pairs of classrooms as seen in Figure 7.7). The table, for each survey, includes: survey observations, operative temperature, PMV, and the mean actual thermal sensation vote ($TSV_{(mean)}$). The differences in operative temperatures and PMVs of adjacent classrooms generally agree in their relation to each other, whilst the actual mean thermal sensation votes ($TSV_{(mean)}$) disagree in most cases. For instance, classrooms 3 and 4 (Figure 7.8) of test 5 had the same operative temperature and PMV. However, the $TSV_{(mean)}$ shows a warmer sensation in classroom 3. A possible explanation for this could be the proximity of the survey in classroom 3 to the 'break time' or the fact that the door was open in classroom 4. However, in some cases no exact reasoning could be found. Only factors related to each classroom separately could explain such differences, e.g. a specific lesson or activity, the proximity to the break, a control action taken by the teacher (windows, blinds, door), the furniture layout or another individual characteristic. Furthermore, a prior activity is considered to affect thermal perception for approximately one hour (ASHRAE, 2010).

Overall, the role of teachers in creating or changing the classroom thermal environment appears to be significant in junior schools where pupils take no such action. Being in charge of all the activities that take place in the classroom, it would be difficult for teachers to constantly address pupils' thermal preferences as well. This means that there is need to investigate ways to efficiently control classrooms' thermal conditions in order to reflect pupils' needs without obstructing class activities.

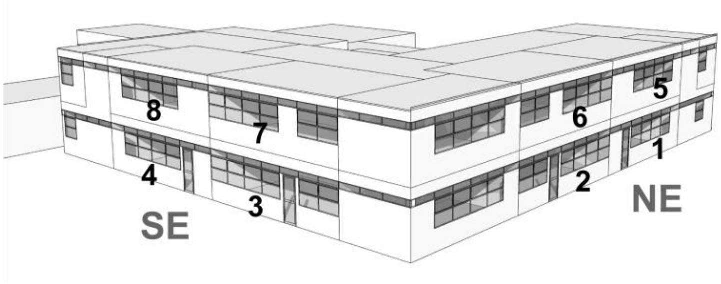


Figure 7.7. 3d model of the school building.

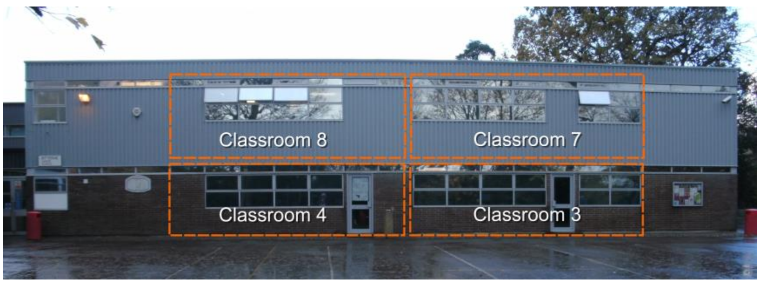


Figure 7.8. Photograph of the SE elevation with 2 pairs of classrooms (3 & 4 and 7 & 8).

Table 7.1. Adjacent classrooms with large differences in the TSV distribution

A/A	Test	Classroom	Activity/ breaks	Windows/ doors/ blinds/fans	Operative Temp. (°C)	PMV[1]	$TSV_{(mean)}$[2]
1	Test 1	Cl1	soon after the break	-	20.8	-1.0	1.3
		Cl2		-	21.8	-0.8	0.0
	Difference (Cl1-Cl2)				**-1.0**	**-0.2**	**1.3**
2	Test 2	Cl5	soon after the break	-	24.0	-0.2	0.8
		Cl6		-	25.6	0.2	1.1
	Difference (Cl5-Cl6)				**-1.6**	**-0.4**	**-0.3**
3	Test 2	Cl3	soon after the lunch break	-	23.8	-0.6	1.7
		Cl4	soon after PE[3]	-	22.3	-1.1	1.2
	Difference (Cl3-Cl4)				**1.5**	**0.5**	**0.5**
4	Test 4	Cl7		4 windows open	23.9	-0.3	0.7
		Cl8	after rainy lunch break	door open	23.2	-0.7	1.6
	Difference (Cl7-Cl8)				**0.7**	**0.4**	**-0.9**
5	Test 5	Cl1			25.0	0.1	1.7
		Cl2		windows open	25.0	-0.1	0.8
	Difference (Cl1-Cl2)				**0.0**	**0.2**	**0.9**
6	Test 5	Cl3	soon after the break		23.9	-0.3	1.4
		Cl4		door open	23.9	-0.3	0.8
	Difference (Cl3-Cl4)				**0.0**	**0.0**	**0.6**
7	Test 5	Cl5		Windows/ door open	28.1	1.0	1.5
		Cl6		blinds closed, fans on	28.8	1.2	2.0
	Difference (Cl5-Cl6)				**-0.7**	**-0.2**	**-0.5**

Notes:

[1] PMV calculated based on approach (a) in section 6.1.2.

[2] $TSV_{(mean)}$ is the mean of actual thermal sensation votes for each survey

[3] PE: Physical Education

7.2 Building related influential factors: orientation

The impact of building related characteristics on thermal comfort is especially relevant when investigating existing naturally ventilated buildings, since the occupants experience variations in the outdoor climate through the buildings they inhabit and their preferences are determined by this interaction (Nicol and Wilson, 2011). In the case study school, the main building-related characteristic that creates a distinctive difference between classrooms is orientation, as their size, layout and design characteristics are almost identical. Half of the classrooms are oriented towards the North-East (NE) and the remaining half towards the South-East (SE) (Figure 4.7, right). As can be seen in Figure 7.9 this results in different solar penetration profiles. For large parts of the year both façades receive low standing morning sun, yet the extent of exposure time is considerably longer for the SE orientation, especially during school hours. Based on this, the SE classrooms would be expected to experience higher indoor temperatures but, as can be seen in Table 7.2, the hourly mean air temperatures of the investigated 1st floor classrooms for the occupied time (school hours) were quite similar. Furthermore, the classroom with the highest hourly mean temperature for the occupied time was on the NE side of the building (classroom 6) and the classroom with the lowest hourly maximum air temperature on the SE side (classroom 7). This is probably due to the different control measures taken by the teachers that may outweigh the impact of solar radiation on the indoor thermal environment (see also section 7.1 on the role of teachers).

Figure 7.10 shows the individual thermal sensation votes of the pupils in the 1st floor classrooms according to classroom orientation (a-NE and b-SE) plotted against the operative temperature during the survey. The size of a circle on the plot represents the weighted number of responses for a specific thermal sensation vote at the corresponding operative temperature. It was decided to concentrate on the 1st floor classrooms for this analysis as these are the most exposed spaces. This also minimises the impact of other building characteristics on thermal perception, such as the impact of a floor slab to the ground. It can be seen that, at the same operative temperature, the pupils in the SE classrooms generally felt warmer than those in the NE classrooms. This results in lower comfort temperatures for the SE classrooms, as highlighted in Figure 7.11, which shows the calculated comfort temperatures for the 1st floor classrooms according to orientation, plotted against the outdoor running mean temperature.

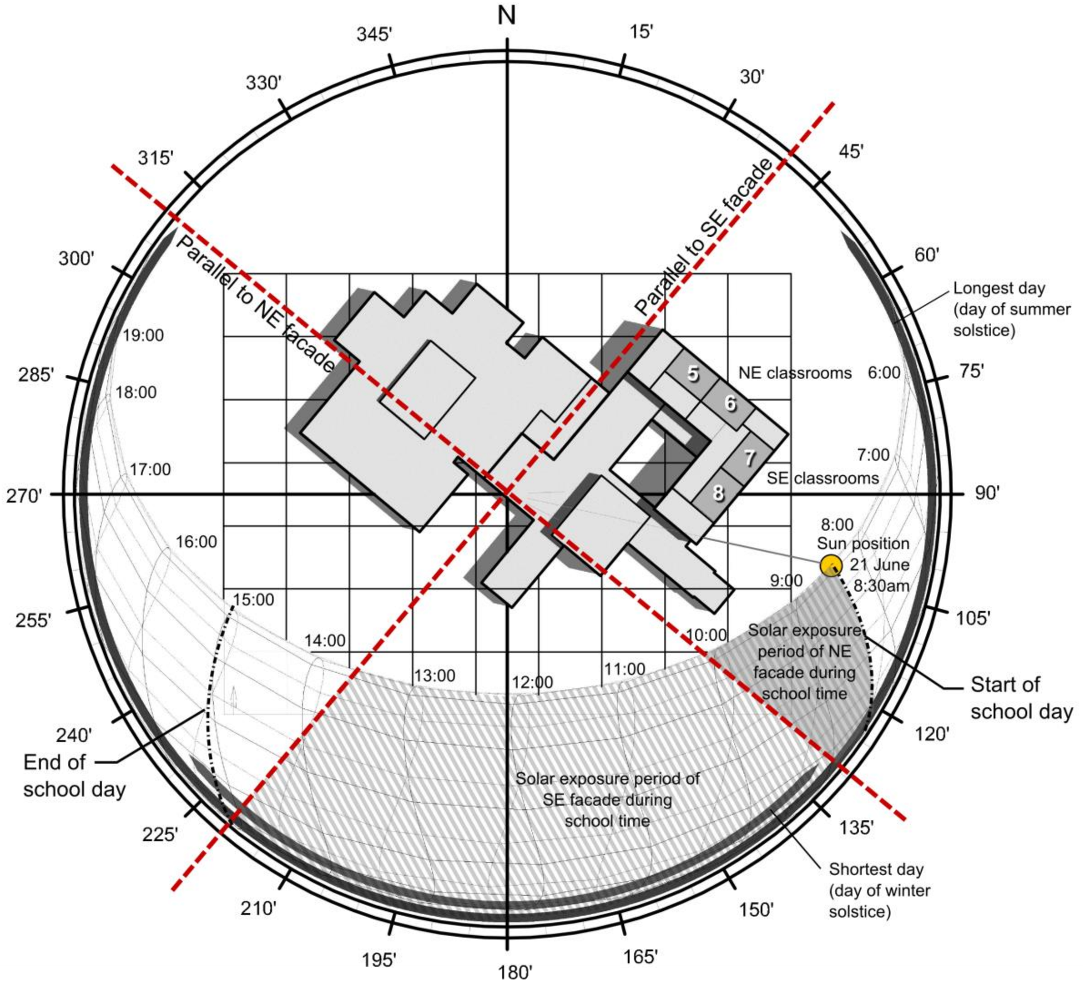


Figure 7.9. Spherical projection sun-path diagram for the school showing the year-round solar exposure period during school hours for the NE and SE oriented classrooms.

Table 7.2. Mean, maximum hourly dry bulb temperatures and standard deviations of all 8 classrooms, for the occupied hours (9:00-16:00) of the monitoring period (April to July 2011).

Location	Ground floor				1st floor			
	NE		SE		NE		SE	
Classroom	1	2	3	4	5	6	7	8
Mean hourly dry bulb temperature	22.3	22.9	22.7	22.6	23.4	23.8	23.3	23.3
Standard deviation	1.7	1.5	1.5	1.5	1.8	1.8	1.9	2.0
Max hourly dry bulb temperature (°C)	26.3	27.2	26.5	26.7	28.8	28.9	28.1	29.1

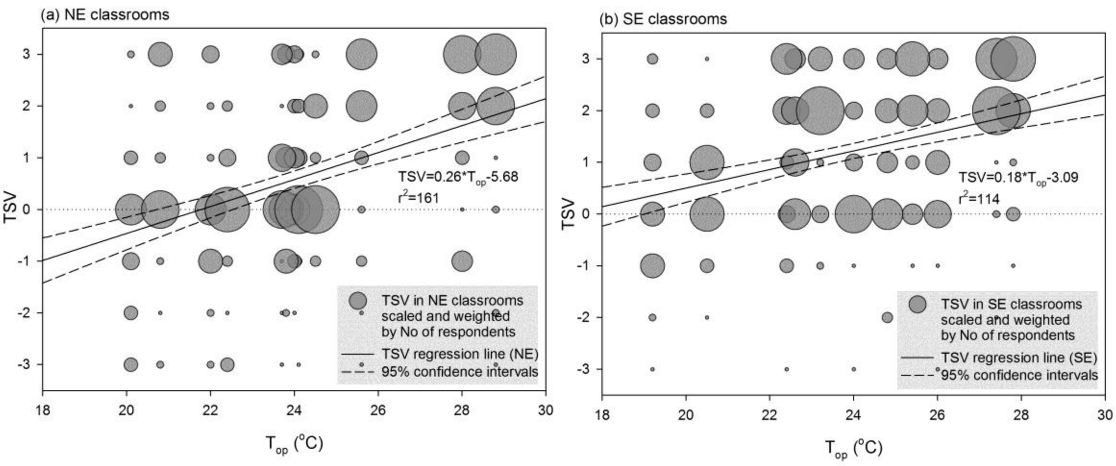


Figure 7.10. Thermal sensation Votes (TSV) of the 1st floor classrooms weighted by number of responses plotted against the operative temperature, according to orientation: (a) NE classrooms (5 & 6 in Figure 7.8) and (b) SE classrooms (7 & 8 in Figure 7.8). The weighted number of responses is proportional to the diameter of the circle.

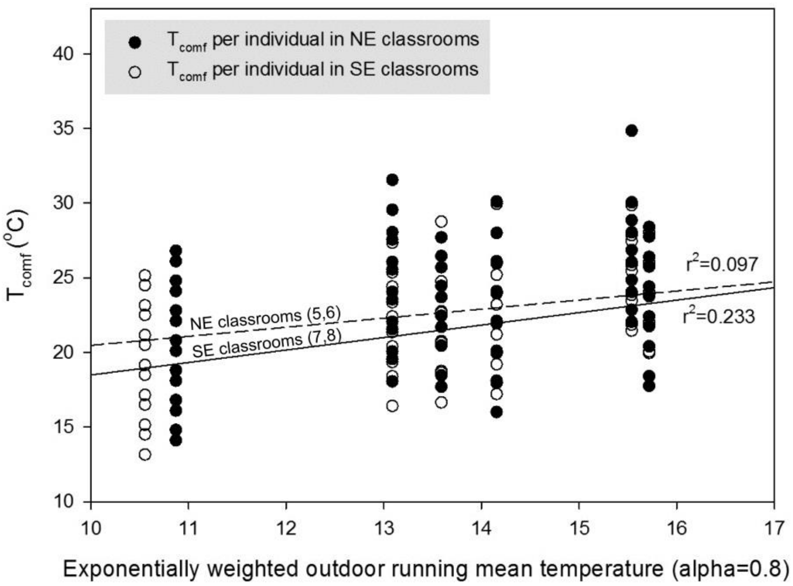


Figure 7.11. Calculated comfort temperature for each thermal sensation vote of the 1st floor classrooms per orientation (NE and SE), plotted against the exponentially weighted outdoor running mean temperature (T_{rm}).

This difference in thermal sensation trends between the investigated classrooms could be attributed to the different temperatures that occupants are used to ("customary temperatures"), an explanation based on work by Nicol and Humphreys (Nicol and Humphreys, 2009). This relationship is diagrammatically shown in Figure 7.12 which highlights the indirect influence of building characteristics on thermal perception through their impact on the indoor thermal environment. However, in the case study presented here, apart from classroom 6 (NE side) which had a slightly higher hourly mean air temperature

(+0.5°C), the mean and maximum hourly air temperatures of the classrooms on the 1st floor were essentially identical. This is unlikely to have led to pupils' adapting to higher temperatures and therefore feeling cooler than those on the SE side. The higher thermal sensation votes observed in the SE classrooms are probably due to the higher solar penetration in these classrooms (Figure 7.9), even though this did not result in higher indoor temperatures (Table 7.2). This potential direct influence of building characteristics on thermal perception is also shown in Figure 7.12.

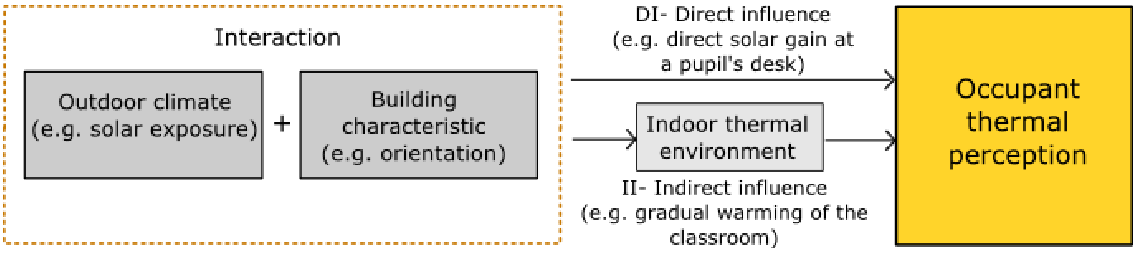


Figure 7.12. Schematic illustration of how building-related characteristics can influence occupant thermal perception: a) through determining the indoor thermal environment (II- indirect influence), b) through directly affecting thermal perception (DI-direct influence).

7.3 Section summary

The key points from section 7 are the following:

- The measures taken by the teachers to control the classroom's thermal environment affect to a great extent pupils' thermal comfort. This highlights the importance of adaptive behaviour in classrooms, which in schools is restricted to teachers who already have a heavy workload during class.
- Building related issues, such as orientation, may influence occupant thermal perception even in cases where they do not have an impact on the indoor environmental variables, such as air temperature. Building characteristics could also explain to an extent the difference found between the pupils' comfort temperatures and the adaptive comfort temperature equation underlying EN 15251 (see section 6.2.1).

A further investigation of the impact of building characteristics follows in chapter 8, through the comparison of the post-war school case study with the results from the Victorian school surveys.

8. Victorian school: Comparative analysis of the thermal comfort survey results with the post-war school

The study in the second school was conducted as a further step following the analysis presented in chapter 7 in order to investigate the impact of different school building types on pupils' thermal perception, through a comparative analysis between the 2 surveys. This second survey aimed to determine whether the findings from the first school were specific to the building and its occupants or whether there are indeed differences in thermal perception between adults and children. Table 8.1 provides an initial comparison of the main characteristics of the two schools.

Table 8.1. Comparison of the characteristics of the two case study buildings and their potential impact on classroom thermal environment

Characteristic	Post-war school	Victorian school	Impact on indoor environment/difference
Microclimatic profile	Similar residential areas/ lack of vegetation near the building/ tarmac on outdoor spaces		No difference
Building shape and form	Clear L-shaped form with classrooms towards 2 orientations	Complex arrangement of classrooms around a court-yard/ several different orientations/ building extrusions and recesses	Similar thermal environment in the post-war school classrooms / varying thermal environments in the Victorian school
Building fabric properties	Light-weight construction/ low albedo building envelope materials	Heavy-weight/ high thermal mass/ low albedo building envelope materials	Quick thermal response of building elements of post-war school/time-delayed response of the Victorian school
Classroom shape and form	Tight space/ low ceiling	High ceiling, large room volume, openness	Lower air speeds in post-war school (~0.06m/s), slightly higher in the Victorian school (~0.1m/s)
Occupant (teacher) controls/ availability	Window and door opening/ blinds/ fans	Window and door opening/ in some classrooms blinds and fans/ old window frames-some not openable	Similar controls/ in the Victorian school more limited availability
Glazing to wall ratio/ average window area per classroom	40%/ 7.0 m^2	25%/ 11.4 m^2	Larger glazed areas in the Victorian classrooms: more direct sunlight and solar radiation, but also higher fraction of wall area
Shading	Internal blinds	Variable: none/ internal blinds/ improvised shading	Less shading in the Victorian school

Room layout	Similar classroom layout/ desk arrangement		No difference
Classroom size/ density	46.2m^2 on average/ 1.7m^{2}pp	73.5m^2 on average/ 2.7m^{2}pp	Potentially higher internal gains in the densely occupied post-war school classrooms
Classroom design characteristics	Similar furniture/ light colours/ bright pictures and boards on the walls but the Victorian school has large light-coloured ceilings while the post-war school has suspended ceilings		Victorian classrooms are characterised by openness

Notes: pp=per person

As can be seen in Table 8.1, the post-war school appears to be more vulnerable to high temperatures due to its light-weight construction, less exposed thermal mass (ceilings), lower indoor air velocities and higher occupancy densities. The Victorian school is characterised by more limited occupant controls, due to its old age, and larger glazed areas per classroom, but also higher fraction of wall area. Overall, Table 8.1 suggests that pupils in the two schools experience different familiar (customary) thermal conditions, as was also discussed in section 2.2 which analysed the parameters affecting the indoor thermal environment in schools. The differences between the two classroom types can be seen in Figure 8.1, especially with regards to classroom volume.

Figure 8.1. left: post-war school classroom, right: Victorian school classroom

Further to the above comparison between the buildings, a comparison of the weather conditions over the two survey periods (March-July 2011 and 2012) highlights important differences. Figure 8.2 shows the daily mean, maximum and minimum dry bulb temperature for the period of March - July 2011 and 2012 in Southampton, UK. It can be seen that the outdoor temperature profile until the beginning of June of the two years was very different, with generally lower temperatures in 2012. Furthermore, while in 2011 there was a gradual temperature increase from March to May, in 2012 the temperature trend remained almost flat until May. This may have had an impact on pupils' thermal adaptation, which will be investigated in the following sections. The relatively cool April and May of 2012 also led to the heating system being switched on on many days until the end of May. Due to this, 3 out of 7 survey tests were conducted with the radiators on for at least parts of the school day.

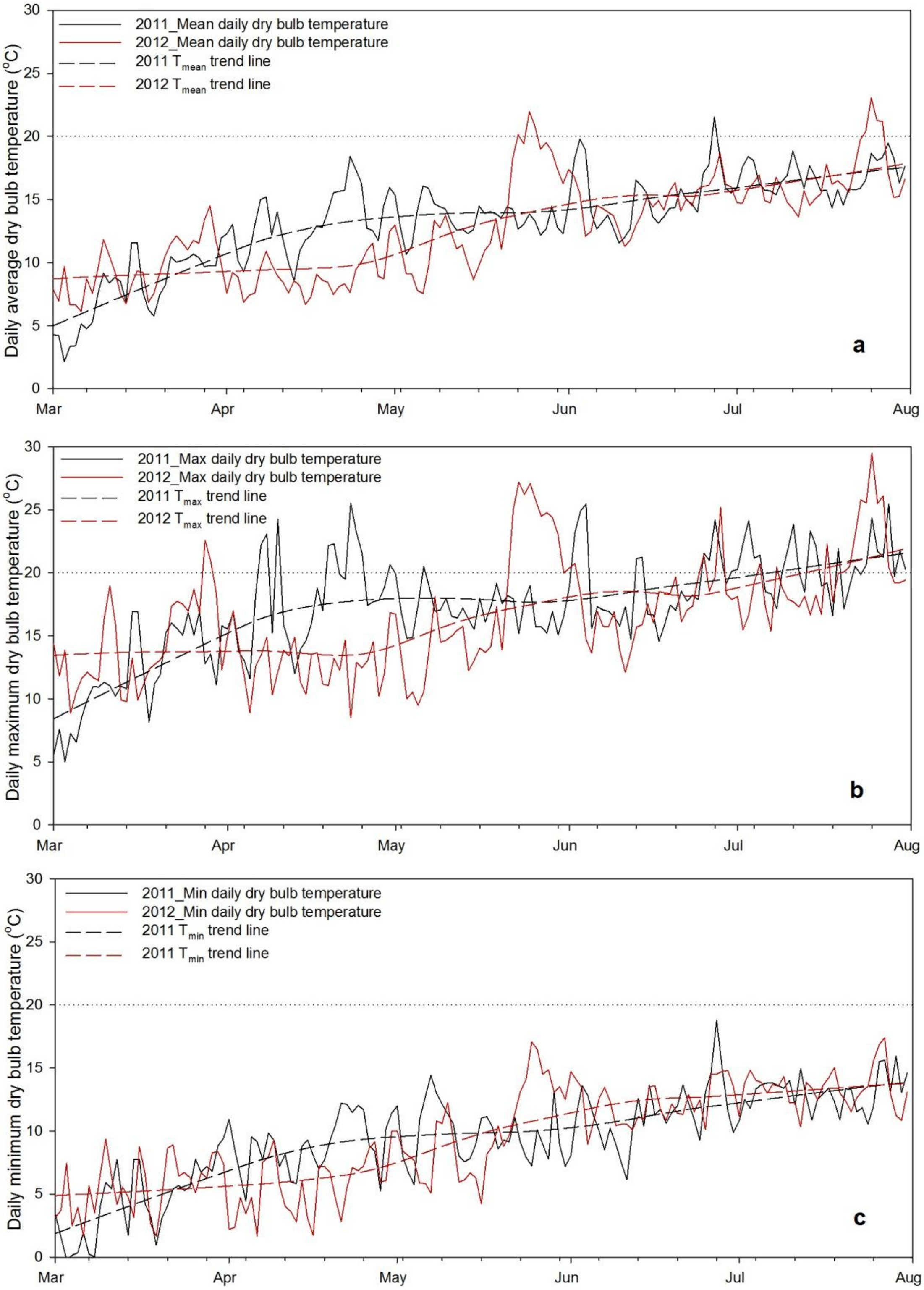


Figure 8.2. (a) Average, (b) maximum and (c) minimum daily outdoor dry bulb temperature from March to August in 2011 and 2012 (data from (NOCS))

As can be seen in Figure 8.2(b), the maximum daily dry bulb temperature in 2012 exceeded 20ºC on only a few occasions. In contrast, in 2011 this occurred on about 30 days from April to July. Furthermore, even though the trend lines almost match from around mid-June onwards, in 2011 the maximum daily dry bulb temperature exceeded 20ºC every week in July, which was not the case in 2012. In general, pupils in the Victorian school experienced lower outdoor temperatures which also affected their clothing levels, as will be discussed in following sections.

Apart from the relatively low temperatures, June and July 2012 were wetter than normal, with rainfall being almost twice the monthly average during June 2012 (198%) and 148% of the average during July 2012 (Met Office, 2012). This can be seen in Figure 8.3, with the anomaly for June 2011 (left) and June 2012 (right) in the entire of the UK, compared to the 1971-2000 average. Furthermore, sunshine levels were also significantly below normal in 2012 (70% of the average during June and 81% of the average during July). Overall, June and July 2012 have been considered as "generally cool, wet and dull" (Met Office, 2012).

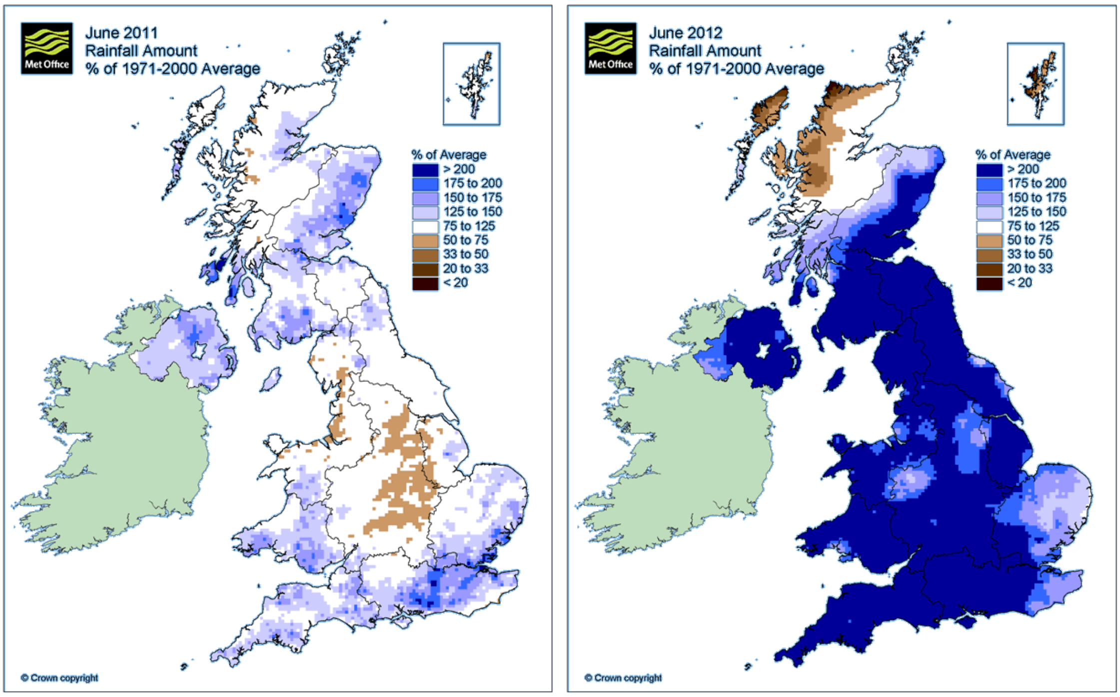


Figure 8.3. Map of rainfall percentage of the 1971-2000 average for June 2011 (left) and June 2012 (right) (images from Met Office: Contains public sector information licensed under the Open Government Licence v1.0).

The above analysis shows that there were distinctive differences in the building and annual climatic parameters that determined the indoor thermal environment (as described in section 2.2) in the two case study schools. The following section is focusing on the indoor thermal environment over the survey period and during the questionnaire surveys, comparing the environmental conditions in the two schools.

8.1 Classroom thermal environment

Inevitably, the weather anomalies which occurred during the survey period affected the Victorian school's indoor thermal environment and determined the operation time of the heating system. Figure 8.4 shows the relationship between the measured air temperature in the Victorian school classroom 1, given on Figure 4.13, and the ambient temperature, per month and at four time-steps of a day. Only one classroom was investigated for this analysis since the heating system is centrally controlled and therefore the results can be considered as representative of the heating regulation profile of all classrooms for the survey period.

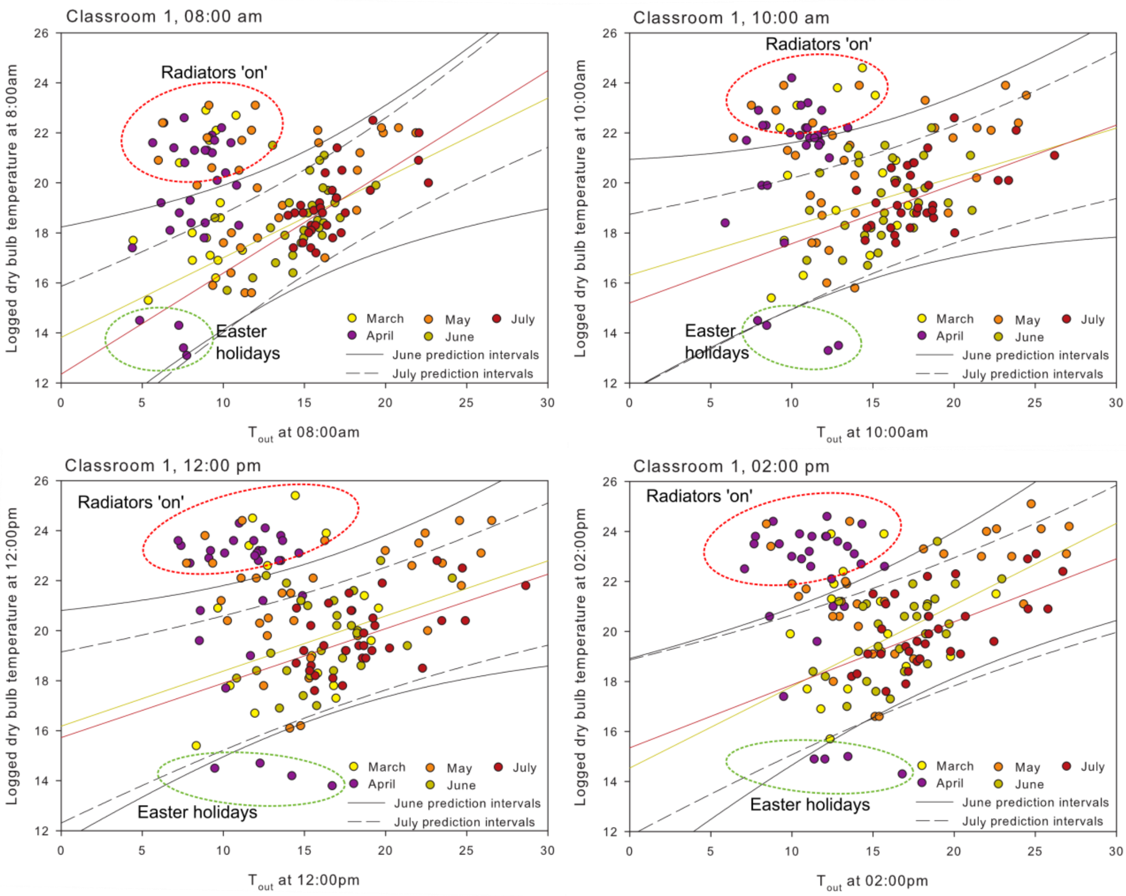


Figure 8.4. Logged dry bulb temperature of classroom 1 against the ambient dry bulb temperature at four time-steps: 08.00am, 10.00am, 12.00pm and 02.00pm, plotted per month from March to July 2012.

In June and July 2012 the building was in free-running mode. Therefore, the classroom temperature profiles of these months were used as a baseline in order to establish when the heating was switched on in the school. It can be seen that there are indoor temperatures in April and on a few days in March and May which were exceptionally high at ambient temperatures below 15°C, compared to the baseline profiles of June/July. This means that the radiators were switched 'on' over several days in April and on some days in March and May. However, this was not constantly the case but depended on the climatic conditions and in some cases the radiators were 'on' only for 1-3 hours each day, in order to bring the school temperatures to an acceptable level. Evidently, the end of the heating season or the exact free-running period of the building is not clearly defined. However, based on Figure 8.2, the rise in outdoor temperature after the first week of May could be considered to mark the starting point of the free-running period, since this also agrees with the results of Figure 8.4. Therefore, the 2 survey tests conducted in March and April and the first one in May could be attributed to a transitional period, when the radiators were occasionally switched on. The above is taken into account in the analyses presented in the following sections.

Table 8.2 gives, for every classroom in the Victorian school, the mean, standard deviation, minimum and maximum values of each environmental parameter measured during the surveys and of the mean thermal sensation vote per survey ($TSV_{(mean)}$), in accordance with Table 5.1 created for the post-war school. The operative temperatures (T_{op}) were calculated using the equations in section 4.2.3 and ranged from 17.5°C to 25.4°C, which is much lower than the T_{op} range in the post-war survey (19.2°C to 28.9°C). Relative humidity (RH) was within 47-82%, which is relatively high for indoor spaces but it is justifiable given the high rainfall during the survey period. Mean air speeds ranged from 0.07 to 0.12m/s, which is overall higher than in the post-war school classrooms, as highlighted in the comparative Table 8.1. The CO_2 concentration was within 700-2,900ppm, without extreme readings such as those of around 4,000ppm that occurred in the post-war school (Table 5.1). This is probably due to the large volume of the Victorian school classrooms (Table 8.1) which could also be related to the higher airflow measurements (Table 8.2).

Table 8.2. Mean, standard deviation, minimum and maximum values of the main environmental parameters and mean Thermal Sensation Votes ($TSV_{(mean)}$) of the classrooms during the Victorian school surveys.

Class-room	1	2	3	4	5	6	7	8	9	10	11
T_{op} (°C)											
Mean	21.8	21.4	21.5	22.5	20.7	21.6	20.9	22.9	22.4	22.9	22.1
S.D.	0.6	1.1	1.4	1.3	1.9	1.2	1.0	1.1	1.2	1.2	1.2
min	21.2	20.0	18.6	20.3	17.5	19.3	19.6	22.0	20.9	21.8	20.9
max	22.7	23.1	23.6	24.4	23.2	23.2	22.5	25.2	24.9	25.4	24.4
RH (%)											
Mean	56.9	56.6	63.9	54.0	60.7	61.8	60.6	61.5	60.4	60.1	62.6
S.D.	11.0	10.7	9.7	5.5	8.1	8.2	10.7	8.9	8.8	10.7	9.0
min	47.0	48.1	49.8	49.5	52.8	50.3	49.1	48.3	48.5	47.0	53.4
max	72.3	76.2	81.7	63.1	73.4	74.2	81.3	74.8	71.8	79.5	79.4
v (m/s)											
Mean	0.09	0.11	0.10	0.11	0.09	0.08	0.09	0.10	0.07	0.08	0.12
S.D.	0.03	0.03	0.02	0.03	0.02	0.02	0.01	0.01	0.01	0.03	0.03
min	0.05	0.07	0.07	0.07	0.07	0.06	0.07	0.08	0.06	0.05	0.09
max	0.13	0.16	0.14	0.16	0.13	0.14	0.10	0.12	0.10	0.13	0.18
CO_2 (ppm)											
Mean	1,043	1,272	1,264	1,444	1,415	1,296	1,121	1,582	1,183	1,676	1,808
S.D.	274	140	331	317	322	415	374	501	497	641	742
min	800	1,100	940	1,000	980	850	800	1,000	700	800	700
max	1,550	1,500	1,800	1,900	1,710	2,150	1,880	2,400	2,000	2,650	2,900
TSV											
Mean	-0.1	0.2	0.5	0.3	-0.2	0.2	-0.1	1.0	0.7	0.9	0.1
S.D.	1.5	1.5	1.5	1.2	1.6	1.7	1.4	1.4	1.4	1.4	1.3

The following sections seek to determine whether, apart from building related differences, there were also differences in pupils' thermal sensation and preference trends.

8.2 Thermal sensation and preference

From the pupil surveys a total of 1676 responses were gathered. From these responses, 165 were found to be inconsistent, with TSV+TPV <-3 or >3, and were excluded, as applied in the first case study school (see section 5.2, page 88). 30 of the inconsistent cases belonged to the first exclusion scenario (TSV+TPV <-3) and 135 in the second (TSV+TPV >+3). Overall, 9.8% of the gathered responses were excluded from the analysis, which is slightly more than that in the 2011 survey (7%).

There were also 78 missing responses on the survey forms (5% of the gathered responses). From these, 30 were thermal sensation votes (TSV) or thermal preference votes (TPV). More specifically, there were 27missing TSVs and only 3 missing TPVs. It appears that between the two, the thermal sensation question was more difficult than the thermal preference question for some pupils to respond to.

Figure 8.5 shows the relative frequency of the thermal sensation (left) and thermal preference votes (right). The TSV votes are centred on "OK" with an almost symmetrical distribution of the rest of the votes. There is a slight shift towards the warm side but not as strong as it was in the 2011 survey (Figure 5.2) as the indoor operative temperatures were lower this time, ranging from 17.5 to 25.4°C (instead of 19.2°C to 28.9°C). The distribution of the thermal preference votes (TPV) is generally diverse, with a stronger tendency towards a preference for warmer than cooler temperatures. This also agrees with the 2011 survey results (Figure 5.2).

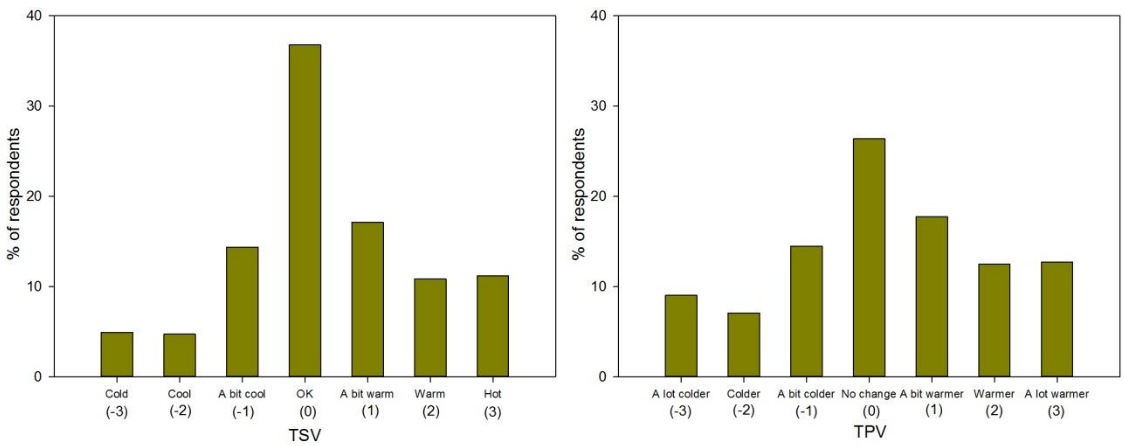


Figure 8.5. Relative frequency of Thermal Sensation Votes (TSVs) (Left) and Thermal Preference Votes (TPVs) (Right) from all 69 surveys in the Victorian school.

The mean thermal sensation votes ($TSV_{(mean)}$) of all surveys were calculated and compared to those of the post-war school survey. The comparison is considered valid since the survey periods and the frequency of the school visits were similar (Figure 4.17, chapter 4). Figure 8.6 shows the $TSV_{(mean)}$ of both surveys plotted against the operative temperature (T_{op}). It can be seen that the data points generally fit well and the regression lines are nearly identical. This means that the regression line equations reflect quite accurately the relationship between pupils' mean thermal sensation and the indoor operative temperature. Since the two regression lines are so similar, the datasets were combined to produce one equation for the prediction of the mean thermal sensation vote of school children. Equation (8.1) (r^2=0.5) was derived from the combined datasets and could be used for environmental conditions similar to those in the presented study periods.

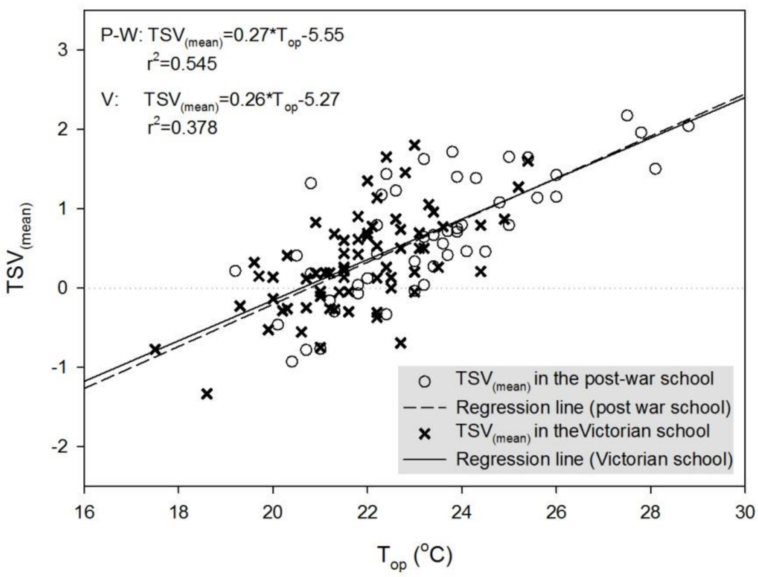


Figure 8.6. Mean thermal sensation votes ($TSV_{(mean)}$) of the 2011 and 2012 surveys with regression lines.

$$TSV_{mean} = 0.26 * T_{op} - 5.34 \quad (8.1)$$

Were TSV_{mean} is the mean thermal sensation vote and T_{op} the operative temperature.

Strong agreement was found between the two school surveys in the resulting neutral and preferred temperatures (T_n and T_p). As can be seen in Figure 8.7, the pupils of the second survey appear to have had a preference towards warmer than their neutral thermal state ($T_n < T_p$). This is the same as the pupils in the post-war school (section 6.1.3). Furthermore, this survey's values of the neutral (T_n) and the preferred (T_p) temperature are almost identical to the first survey values.

The standard deviations of $TSV_{(mean)}$ express the interpersonal differences within surveys and were also calculated for each survey. The results were found to be consistent with those of the post-war survey. The standard deviation values ranged from 0.8 to 2.0 scale units, which is slightly higher than those in the post-war school (0.7-1.8), but with an average of 1.5, which is exactly the same as in the post-war school survey. This result supports the argument made in the analysis of the first school survey that, in a school environment, occupants may engage in different activities which may impact on their individual thermal perception (also see section 5.4). On the contrary, in other everyday environments, such as offices, occupants experience mostly the same activity level throughout a day. This highlights the invalidity of generalised criteria for everyday environments without taking into account the particularities involved, especially with regards to the occupants.

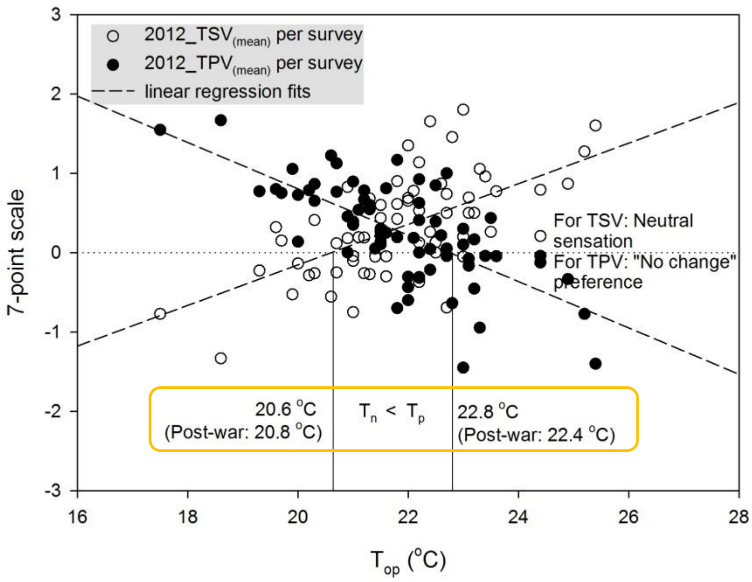


Figure 8.7. Mean thermal preference vote ($TPV_{(mean)}$) and mean thermal sensation vote ($TSV_{(mean)}$) for each survey in the Victorian school plotted against the operative temperature (T_{op}). The regression lines are also included.

Further to the variable schedule, the clothing change behaviour of pupils could also be a cause of interpersonal differences in thermal sensation. As discussed in section 6.2.2, pupils' response to thermal change through clothing was often not as immediate as it should have been in order to avoid thermal discomfort (page 118). This finding is also verified by the Victorian school survey responses on whether respondents were wearing their jumper during the surveys, as can be seen in Figure 8.8. In fact, the results are more critical than those from the post-war survey (Figure 6.14). This time, 51% of the children who voted 'hot' and 58% of those who voted 'warm' still wore their jumper (Figure 8.8), while in the post-war school survey the percentages were 15% and 25% respectively. A possible explanation for this may be the lower ambient temperatures occurred in 2012 compared to 2011, as analysed in the beginning of this chapter. Indeed, most of these responses were given in surveys conducted in April and May, after the lunch break. This means that children had stayed outside, at much lower temperatures than indoors, for about one hour before the survey and they most probably did not think of changing their clothing after coming back inside.

As can be seen in Figure 8.9, 69% of these pupils would prefer to feel cooler. This means that most of them were experiencing thermal discomfort without taking the simplest of actions to reverse this.

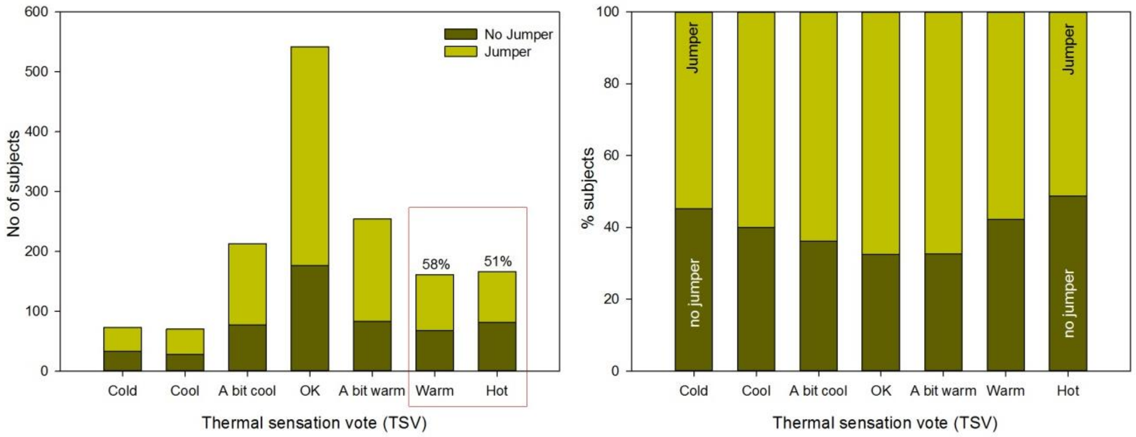


Figure 8.8. a) Distribution of Thermal sensation votes by number of children wearing their jumper, b) Percentage of subjects voting for each sensation wearing their jumper or not.

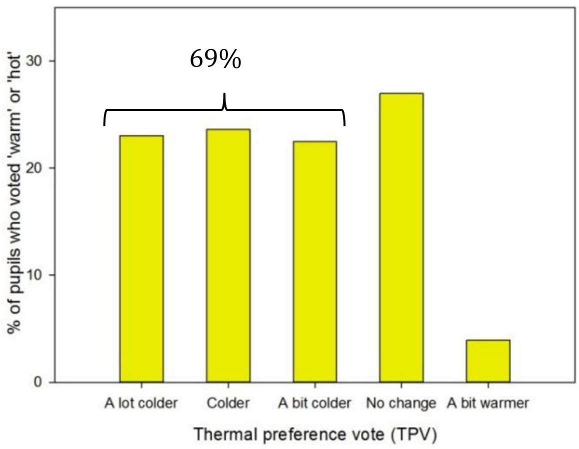


Figure 8.9. Distribution of the TPVs of pupils who voted 'warm' or 'hot' while wearing their jumper.

Overall, immediate behavioural thermoregulation, which is an important aspect of human interaction with the environment (Nicol et al., 2012), appears to be underdeveloped in primary school children. This highlights the importance of maintaining acceptable thermal conditions in classrooms, as counting on the main occupants' adaptive action is probably not an option in schools. Furthermore, as discussed earlier, the limited adaptive action of a number of pupils may lead to interpersonal differences, such as the ones observed in this study, which suggests that generalised criteria for every age group and indoor environment should be treated carefully.

8.3 Survey results and thermal comfort model predictions

8.3.1 PMV model (ISO 7730)

The Victorian school survey results were compared with the PMV model predictions following the same approach as for the post-war school survey, explained in section 6.1. The PMV and PPD indices were calculated using the measured environmental parameters, estimated clothing insulation values and the three (a-c) of the approaches examined in section 6.1.1 for determining the metabolic rate. Approach (d) was not included in this analysis as the results it produced (Figure 6.4) suggest that it is clearly not appropriate.

Table 8.3 shows the clothing insulation values of the main school uniform combinations observed during the surveys. The range of clothing combinations is narrower than in the post-war school survey, due to the lower outdoor and indoor temperatures and the higher rainfall which occurred in 2012 compared to 2011. In fact, only on a very few occasions summer uniforms with a total insulation value of around 0.30 clo (Table 8.3) were observed, which can be considered negligible. Therefore, based on the survey observations, it was decided to use a mean 'clo' value of 0.50 for both boys and girls and a mean value of 0.75 when the jumper was worn to reflect a mean clothing insulation value for each survey. Furthermore, in order to cover a wider range of potential clothing insulations, minimum and maximum 'clo' values were also used, estimated at 0.50 and 0.75 clo respectively. As discussed in section 6.1.1.1, the $PMV_{(min\ clo)}$ and $PMV_{(max\ clo)}$ are used as 'error' bands for the PMV prediction.

Table 8.3. Victorian school uniform combinations

Clothing combinations[1]	Clo[2]
Skirt, short sleeves polo, stockings, shoes	0.50
Skirt, short sleeves polo, socks, shoes	0.49
Light dress-short sleeves, stockings, shoes	0.30
Shorts, short sleeves sport shirt, socks, shoes	0.32
Normal trousers, short sleeves shirt/blouse, socks, shoes	0.51

Notes:
[1] All combinations include underwear, [2] Clo values estimated based on ISO 7730 (ISO, 2005)

The difference in survey mean clothing insulation values between the two school surveys can be seen in Figure 8.10. The scatter of mean 'clo' values is larger in the Victorian school surveys which can be attributed to the more variable outdoor climatic conditions that occurred in 2012 and the lower average T_{op} in the Victorian school. It can be seen that, the mean 'clo' regression slopes are identical (=- 0.02 clo/^{o}C) and therefore the rate of clo decrease as a function of the classroom operative temperature was generally the same between the two schools. However, there is a constant mean 'clo' difference of 0.15 as pupils in the Victorian school were dressed with slightly warmer clothing than in the post-war school survey. As discussed in section 8.2, the mean thermal sensation trend against operative temperature was essentially identical between the two school surveys (Figure 8.6) which means that this 'clo' difference of 0.15 had no impact on the pupils' overall thermal perception. This could be due to the overall lower radiant temperatures, or the slightly higher air velocities observed in the Victorian school, as pointed out in Table 8.1, which could have offset the impact of heavier clothing on thermal sensation. The potential impact of air velocity is investigated through the comparison with the PMV model, which accounts for both clothing and air velocity.

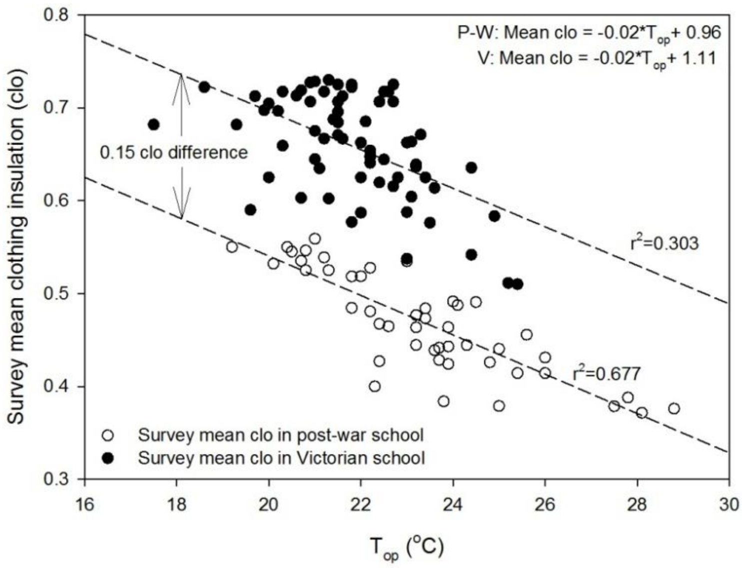


Figure 8.10. Mean clothing insulation per survey and by school, against the operative temperature.

For the metabolic rate, the approaches a-c (section 6.1.1.2) were followed and therefore 3 PMV / PPD predictions were produced and compared with the observed mean thermal sensation ($TSV_{(mean)}$) and actual percentage of dissatisfied (APD). In most surveys the comfort questionnaires were handed out after at least 15 minutes of classroom activities. Therefore a base value of 1.2 met was used corresponding to sedentary office activity (ISO, 2005). However, two surveys were conducted close after physical education class and break time and pupils were still quite active, therefore in these two cases a mean value of 1.5 met was used for 'light activity' (ISO, 2005). The results of the comparison with the PMV predictions are presented below.

Approach (a): *Standard (unchanged) PMV model*

As can be seen in Figure 8.11(a1), the actual mean thermal sensation votes are higher than the calculated PMVs, as was the case in the post-war school survey (Figure 6.1). The regression lines are again almost parallel, with the PMV being on average 0.75 scale points lower than the $TSV_{(mean)}$ regression line. This is less than the 1.1 scale points difference found in the post-war survey and is most probably due to the higher 'clo' values used for the PMV calculation leading to higher PMV values. This suggests that the PMV model is more sensitive to slight 'clo' changes than pupils' actual thermal sensation. The predicted neutral temperature T_n=23.6°C, is 3 °C higher than the T_n=20.6°C from the $TSV_{(mean)}$ line.

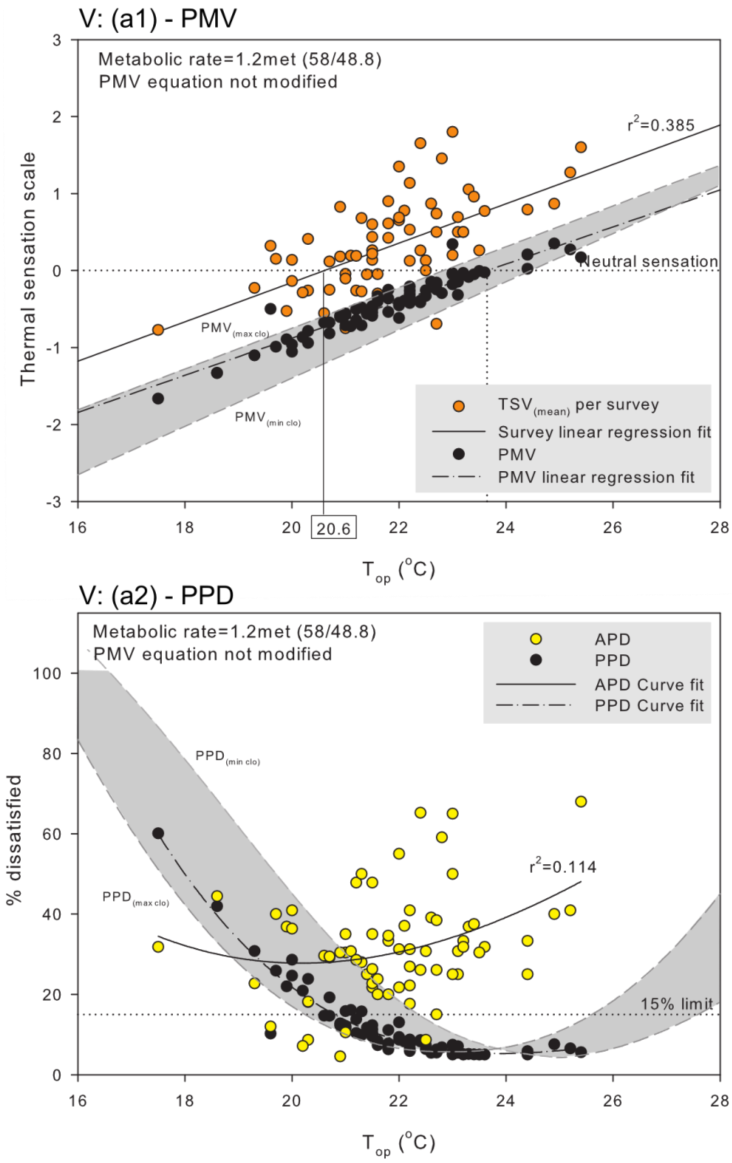


Figure 8.11. Victorian school: (a1): Actual mean thermal sensation vote (TSV(mean)) for each survey and calculated PMV against the operative temperature. (a2): Actual percentage of dissatisfied (APD) and calculated PPD against the operative temperature with curve fits. The grey shaded areas show the 'error bands' from using estimated min*i*mum and maximum 'clo' values.

Figure 8.11(a2) shows a poor match between the actual percentage of dissatisfied (APD) and the PPD, very similar to that found in the post-war school survey (Figure 6.1).

Approach (b): *Standard (unchanged) PMV model with input met correction*

Approach (b) shows once again a better agreement between TSVs and PMVs (Figure 8.12(b1)). However, the percentage of people dissatisfied shows a poor match with the observed results (Figure 8.12(b2)). Based on approach (b), most PPDs lie below the limit of 15% dissatisfied people for a category C thermal environment (ISO, 2005), which does not reflect the pupils' actual level of dissatisfaction.

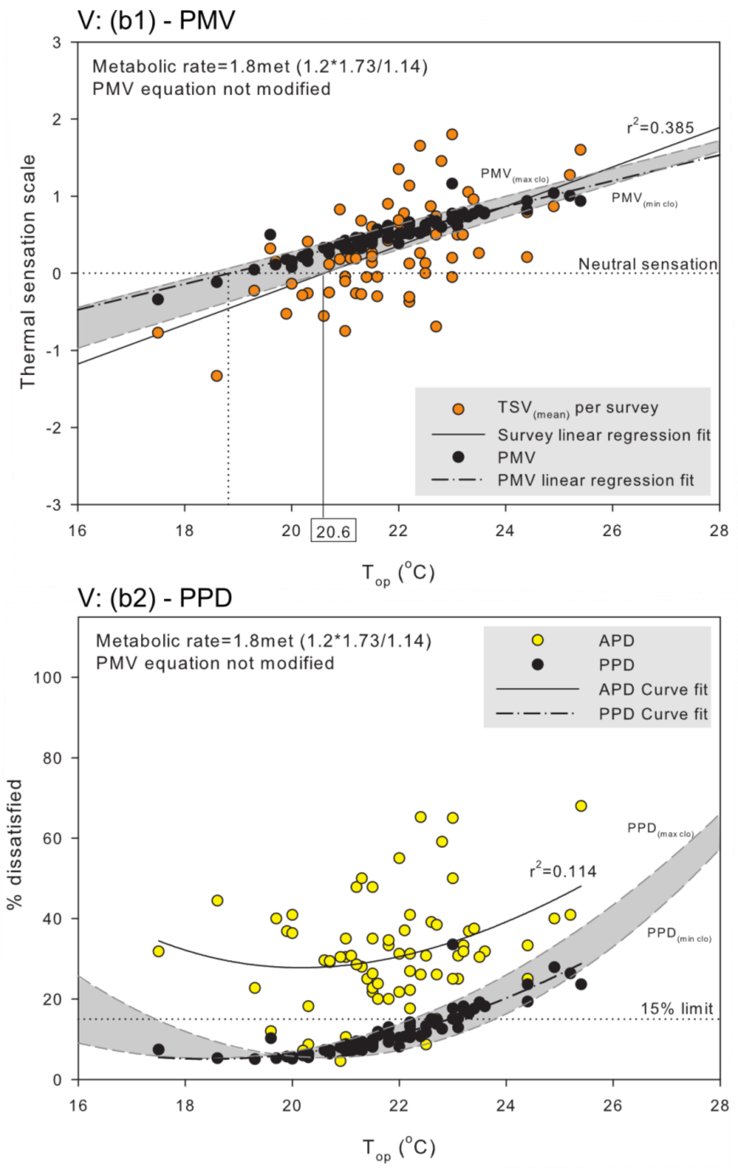


Figure 8.12. Victorian school: (b1): Actual mean thermal sensation vote (TSV(mean)) for each survey and calculated PMV against the operative temperature. (b2): Actual percentage of dissatisfied (APD) and calculated PPD against the operative temperature with curve fits. The grey shaded areas show the 'error bands' from using estimated minimum and maximum 'clo' values.

Approach (c): *RMR change inside the PMV equation and input met correction*

Of the 3 examined approaches, approach (c) again shows the best agreement with regards to both the PMV and PPD. However, as can be seen in Figure 8.13(c1), the $TSV_{(mean)}$ regression line is this time significantly lower than the PMV regression line. Therefore, the PMV model under approach (c) appears to overestimate pupils' thermal sensation in the Victorian school. Whether this can be attributed to climatic adaptation it is difficult to determine, as the building was in heated or free-running mode for an extended period.

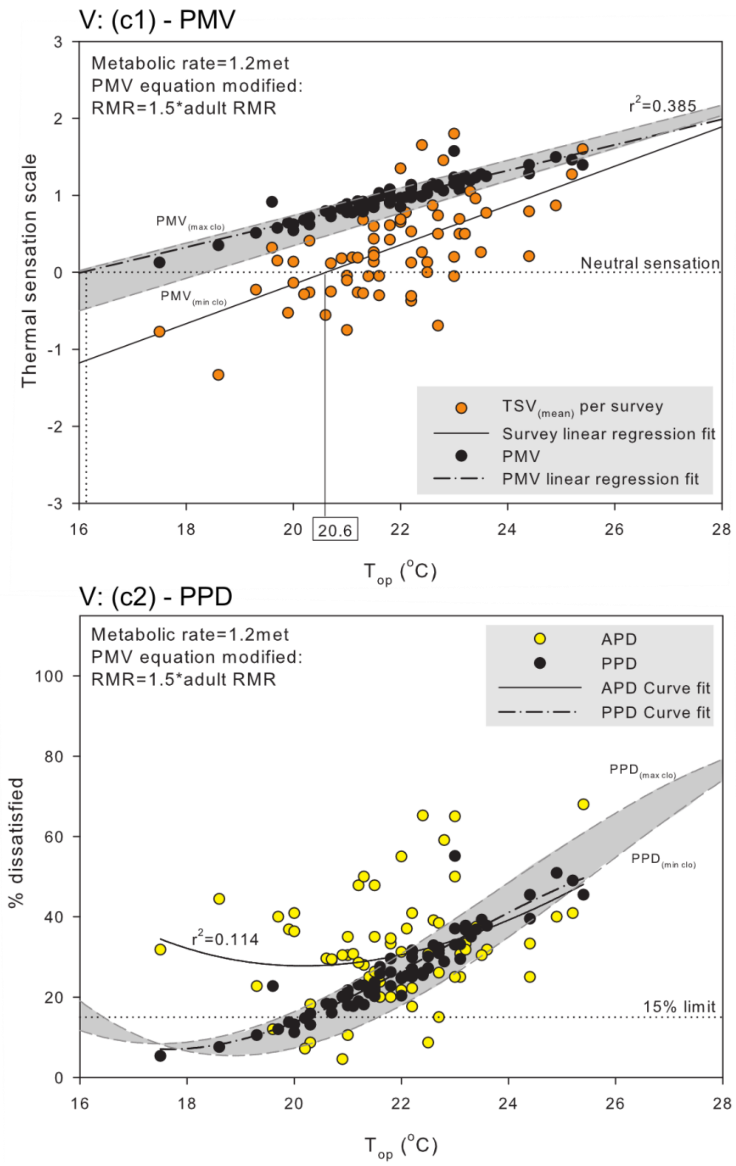


Figure 8.13. Victorian school: (c1): Actual mean thermal sensation vote (TSV(mean)) for each survey and calculated PMV against the operative temperature. (c2): Actual percentage of dissatisfied (APD) and calculated PPD against the operative temperature with curve fits. The grey shaded areas show the 'error bands' from using estimated minimum and maximum 'clo' values.

Overall, there are apparent similarities with the results from the post-war school survey in all three approaches. The Victorian school survey results support the limited suitability of the PMV model for predicting pupils' thermal response. However, the large scatter and narrow operative temperature range in the Victorian school survey make it difficult to assess with confidence the overall suitability of the adjustment approaches. The scatter in mean thermal sensation votes seems to support the argument made in chapter 7 that there are parameters other than the ones captured by the PMV calculations which affect pupils' thermal sensation during classes, such as teachers' controls (see section 7.1) or building related characteristics (section 7.2). Furthermore, the unusual weather conditions in 2012, with an extended cold period, might have affected pupils' climatic adaptation, as they did not have the chance to gradually adapt to warmer conditions. This is investigated in section 8.3.2 which focuses on the adaptive comfort model.

8.3.2 Adaptive comfort model (EN15251)

Figure 8.14 shows the operative temperatures during all 69 surveys conducted in the Victorian school in relation to the EN 15251 temperature limits for buildings without mechanical cooling (CEN, 2007). The required outdoor running mean was calculated as described in section 6.2, using equation (3.7) (page 55). The outdoor daily mean temperatures were derived from hourly data from the same meteorological station as used for the 2011 surveys, the National Oceanographic Centre in Southampton (NOCS), which is located 3km away from the school.

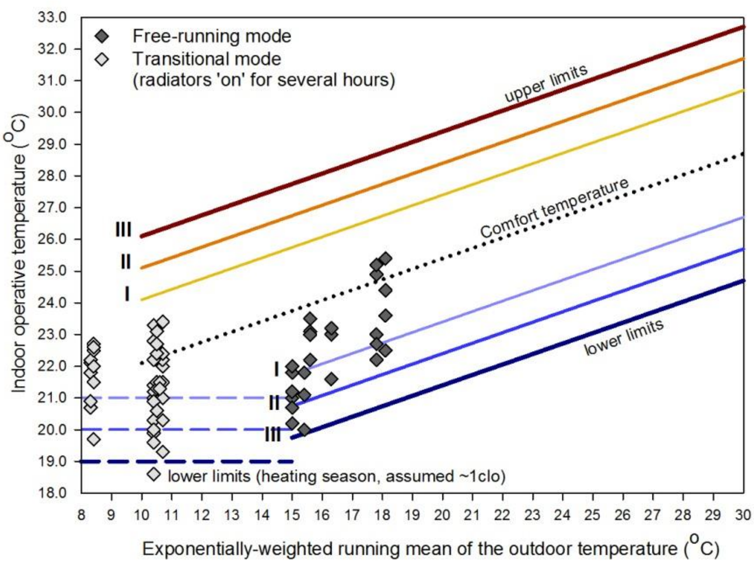


Figure 8.14. Victorian school: survey operative temperatures on the EN 15251 diagram.

The operative temperatures were grouped in two categories based on whether the surveys were conducted when the building was in free-running mode or in the transitional mode with the radiators occasionally switched on, as analysed in section 8.1. For the assessment of the classrooms' thermal environment during the transitional period the dashed limits of Figure 8.14 are used, which apply for the heating season (CEN, 2007). These temperature limits are PMV-based and are calculated with an assumed clothing insulation of 1.0 clo, higher than the 'clo' value of 0.75 mostly encountered during these surveys (section 8.3.1).

As can be seen in Figure 8.14, in all but 1 survey the operative temperature lies within the acceptability zone for category III of EN 15251 ("an acceptable, moderate level of expectation and may be used for existing buildings") (CEN, 2007), which is considered to correspond to 85% of thermally satisfied people. However, as can be seen in Figure 8.15, only in 6 surveys the actual percentage of satisfied exceeded 85%, similar to the post-war survey results (Figure 6.5).

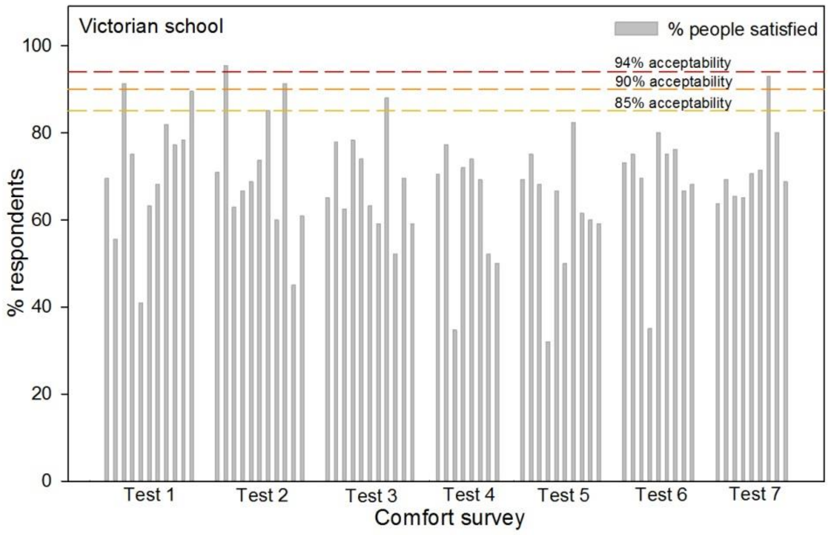


Figure 8.15. Percentage of thermally satisfied respondents (pupils who voted -1, 0, +1 on the thermal sensation scale).

Furthermore, most operative temperatures during the surveys fall below the EN 15251 comfort temperature line, within the lower temperature limits (Figure 8.14). However, in most cases, there are far more 'warm dissatisfied' pupils than 'cold dissatisfied'. An example can be seen in Figure 8.16, which shows the distribution of votes for the surveys of test 5, grouped into the satisfaction categories (-3,-2: cold dissatisfied / -1, 0, +1: satisfied / +2, +3: warm dissatisfied). In test 5 the building was in free-running mode and based on the EN 15251 diagram, the operative temperatures which occurred can be considered acceptable, falling near the lower limits. The grouped thermal sensation votes, however, of Figure 8.16 reveal that the pupils who felt 'warm' or 'hot' were more than those who voted 'cool' or 'cold'. The same result is obtained by examining the distributions of the other 6 tests, which have been included in Appendix D. Overall, the assessment of the classrooms' thermal environment as per EN 15251 shows an underestimation of pupils' thermal sensation, similar to the results of the post-war school survey (section 6.2).

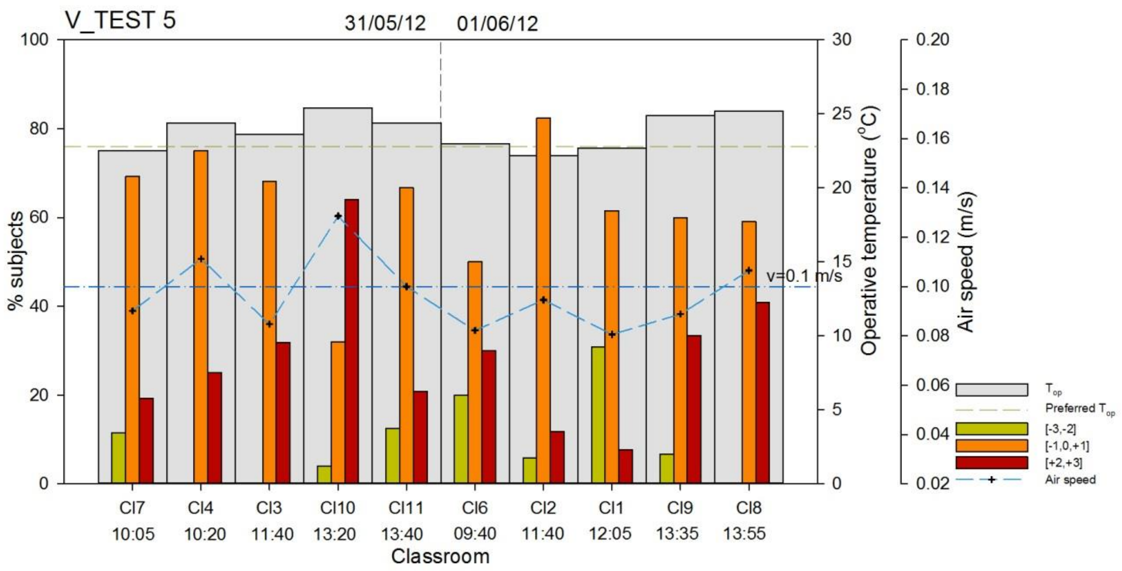


Figure 8.16. Grouped thermal sensation votes in relation to operative temperature of the Test 5 surveys in the Victorian school building.

Figure 8.17 compares the comfort temperatures (T_{comf}) from the Victorian school surveys with those from the post-war school survey and the EN 15251 comfort temperature line. The comfort temperatures were calculated for each individual response following the same process as described in section 6.2.1. It can be seen that the resulting regression line is lower than the EN 15251 comfort line which means that the pupils in the Victorian school would prefer lower temperatures than predicted using the adaptive comfort equation underlying the EN 15251 building category equations (CEN, 2007). At an outdoor running mean T_{rm}=10°C the difference in T_{comf} lines is 1.1°C and at T_{rm}=18°C the difference reaches 2.2°C. The average difference is 1.7°C, close to the 2°C estimated from the post-war school results. Therefore, the two surveys agree in their general outcome that school children appear to have lower comfort temperatures (approx.. 2°C) than adults in offices.

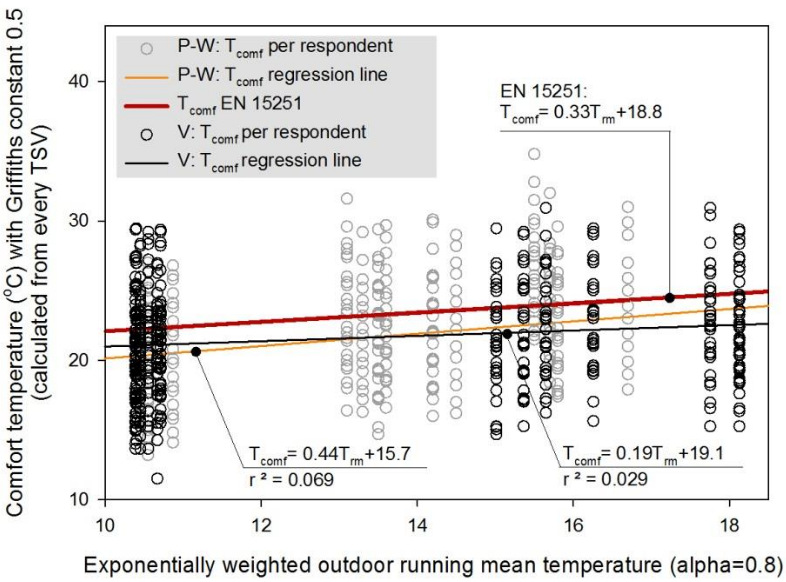


Figure 8.17. Calculated individual comfort temperature against the exponentially weighted outdoor running mean temperature of the 2012 and 2011 surveys (light grey) in relation to the EN 15251 comfort temperature line.

As can be seen in Figure 8.17, the comfort temperature regression lines of the two school surveys do not match well. The regression line of the Victorian school survey has a lower slope indicating a weaker relationship between pupils' comfort temperature and outdoor temperature change, or, in other words, a weaker climatic adaptation. This can be explained by the weather anomalies. 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 pupils. However, it can be seen in Figure 8.17 that there is a large gap in outdoor running means between 10.5 and 15.0°C due to the extended cold period followed by an almost immediate 'hot spell' in the end of May which marked the shift to warmer temperatures. The sudden shift from cold temperatures to a warm period meant that this year there was less of an opportunity for thermal adaptation as there was no gradual transition from cold to warm temperatures. This probably led to pupils being less tolerant to higher temperatures in 2012, which is reflected in the lower comfort temperatures in the Victorian school survey.

The above observation highlights that thermal adaptation is a dynamic process which greatly depends on the way and time weather changes occur. These parameters are not addressed in Figure 8.17, where only the relation of the comfort temperature to the outdoor running mean temperature change is illustrated. This should be taken into account when such results are to be used for producing comfort standards with exact temperature limits as it appears that annual variations may affect the comfort temperature trends.

8.3.3 Long-term classroom thermal performance in relation to adaptive comfort temperature limits

This section follows on the analysis of section 6.2.3 and compares the long term thermal performance of two classrooms outside the heating season 2012, with the operative temperature limits given in Annex A of EN 15251 (CEN, 2007). The two classrooms under investigation are classroom 6 of the post-war school (Figure 4.7, right), which was the one also examined in section 6.2.3 using 2011 data, and classroom 9 of the Victorian school (Figure 4.13), the warmest of the 11 classrooms. In 2012, monitoring in the post-war school was conducted in June and July. Therefore, the comparison covers these 2 months, which also correspond to the free-running mode of the Victorian school.

The classrooms' logged thermal conditions are investigated following the process described in section 6.2.3. The daily maximum operative temperature was calculated using the logged air temperatures and estimated radiant temperatures, for the period from mid-March to the end of July 2012 for classroom 9(V)[9] and for June-July 2012 for classroom 6 (P-W)[6]. For the estimation of the required radiant temperature in classroom 6(P-W) Equation (6.3) was used. For classroom 9(V), the corresponding equation was derived from the correlation between the measured air temperatures (T_{air}) and radiant temperatures (T_r) during the surveys in the Victorian school (218 sets of measurements) (Figure 8.18).

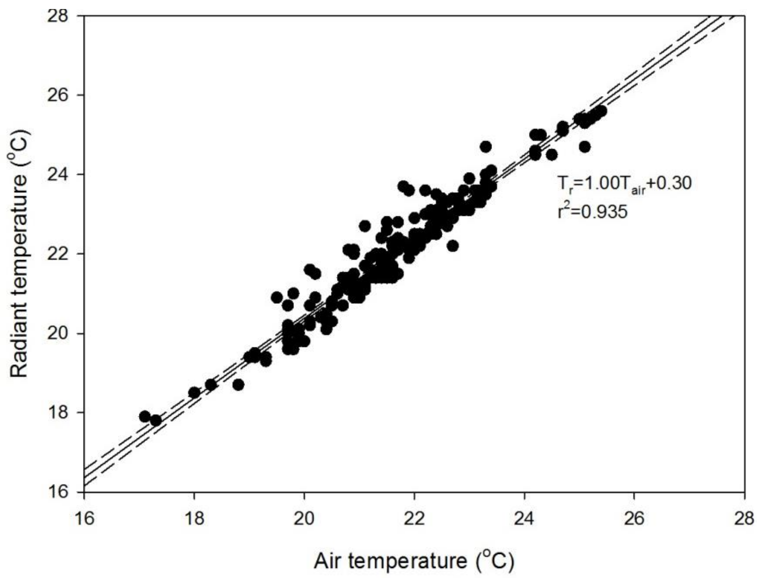


Figure 8.18. Victorian school: Measured radiant temperature plotted against the measured air temperature during the surveys.

[9] V: Victorian school, P-W: Post-war school

The linear correlation was strong (r^2=0.935) and Equation (8.2) was used for the calculation of the required radiant temperature in classroom 9(V).

$$T_r = T_{air} + 0.30 \qquad (8.2)$$

The operative temperature was then calculated using equation (4.3), for indoor air speeds below 0.1 m/s as, based on Table 8.2, the average air speed in classroom 9 during the surveys was 0.07 m/s and the maximum 0.1 m/s.

Figure 8.19 shows the resulting classroom operative temperatures for the survey period (March-July 2012). The operative temperature limits as per EN 15251 for the same period were calculated using the actual outdoor running means of Southampton (section 8.3.2) as input in the equations given in Annex A2 of EN 15251 (CEN, 2007). It can be seen that the Victorian school performs well, according to EN 15251 limits, always falling within the category III comfort zone (only at the weekends T_{op} occasionally falls below the lower limit). Even with the adapted upper limit for category III, which lies 2°C lower than the original (section 6.2.2), the Victorian school classroom basically remains within the acceptability limits and only during the hot spell at the end of May slightly exceeds the line. On the contrary, classroom 6 of the post-war school appears to frequently exceed the adapted upper limit, which concurs with the observations for 2011 (section 6.2.3).

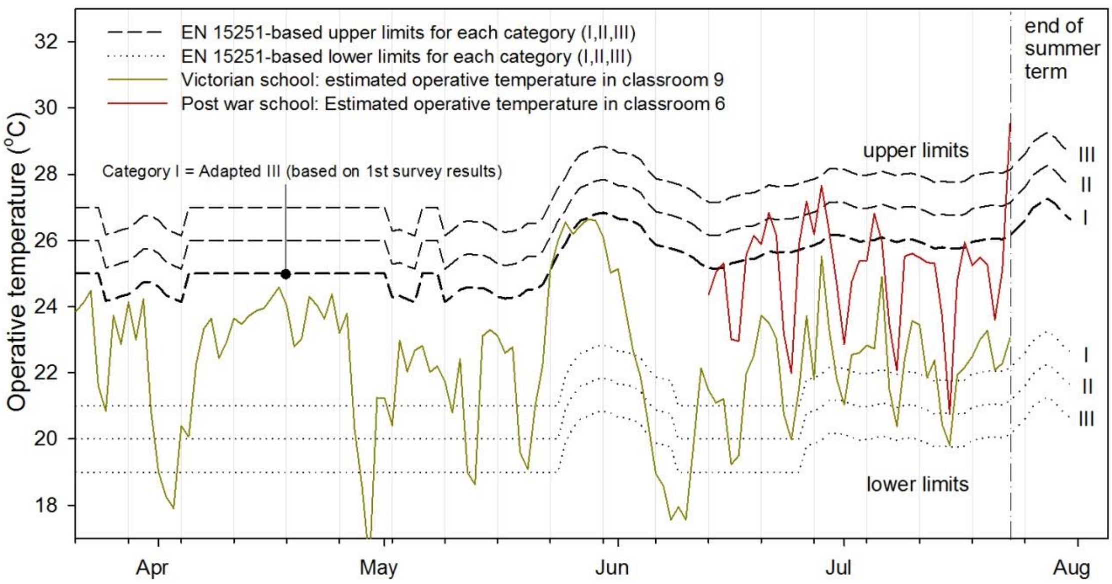


Figure 8.19. Estimated maximum daily operative temperature for classroom 9 of the Victorian school and classroom 6 of the post-war school in relation to the operative temperature limits for the period of March-August 2012 as calculated from Annex A of EN 15251 (CEN, 2007), using the actual T_{rm}.

The above observations highlight two important issues. First, the two schools performed in a very different way outside the heating season but even so, pupils were similarly sensitive to high temperatures and their general thermal sensation and preference trends agreed well. The second issue is the alarming performance of the light-weight school building in comparison with the adapted upper limit which is based on pupils' responses. Given the large number of this type of schools, as discussed in chapter 2, it is likely that many pupils in the UK experience unacceptably warm thermal conditions in classrooms outside the heating season.

8.4 Section summary

In this chapter the results from the post-war school survey were compared with those from the Victorian school survey. This helped to investigate whether the warmer thermal sensation of pupils in the post-war school survey compared to adults (chapter 6) was related to the specific type of school and/or the past experience of pupils in the school.

The results from the Victorian school show that, even though the school performs well outside the heating season and there was no concern about summer overheating occurrences, pupils once again felt warmer than would be expected. This suggests that the different construction type and subsequently cooler overall thermal environment had no impact on the general thermal sensation trend of the school children. However, as discussed in chapter 7, it is still possible that specific building characteristics, such as classroom orientation or teachers' control of the indoor environment could strongly affect the way pupils experience their everyday thermal environment and may lead to important differences in thermal sensation, at the school scale.

9. Thermal comfort in schools outside the heating season

9.1 Discussion

This research investigated the thermal performance of two typical UK school building types outside the heating season and their main occupants' thermal perception over the same period. This chapter discusses the implications of this work for both research and building design practice and how the findings could ultimately be used for the improvement of thermal comfort in classrooms outside the heating season.

9.1.1 Implications for thermal comfort research: surveying school children

Over recent years, there has been an increasing interest in children's perspective and rights which led to the realisation within research institutes and organisations that there is a need for more information deriving directly from children (Borgers et al., 2000). In thermal comfort studies, as discussed in section 3.4.3, children have rarely been surveyed. A possible explanation for this may be the lack of confidence on the ability of very young children to use thermal comfort rating scales for the assessment of their thermal sensation. This could be related to the common contention regarding children's ability to express their thoughts and feelings in a meaningful way (Walker, 2001).

Pupil participation in school building design projects has been found to be a complex process with time and cost implications. It requires qualified people capable of facilitating pupil involvement (den Besten et al., 2008). However, in cases where pupil 'voices' about their school buildings were considered, children showed good knowledge of their school environment and contributed positively to the planning process, supporting the promotion of their involvement (Ghaziani, 2008).

Humphreys (1977) investigated the ability of young children to vote on a thermal comfort rating scale prior to conducting his fieldwork on children in 1971. He found that many children under 7 years were capable of understanding a simply worded thermal sensation scale (Humphreys, 1977). Other research, in the field of Social Sciences, showed that children from approximately the age of seven can respond to survey questionnaires (Bell, 2007) but also highlighted that considerable care should be taken when designing questionnaires for children. Prerequisite for obtaining meaningful and valid information from young children is a child-centred methodology that matches the children's cognitive development (Borgers et al., 2000).

This research showed that primary school children, aged 7-11, were capable of understanding and answering thermal comfort related questions (see section 5.2). However, this study also highlighted that children's attention span is short and that they can easily lose interest if no action is taken to keep them engaged. The sticker booklets and indoor climate activities used in this study (Appendix B) proved to be valuable tools for the collection of data over the repeated survey runs.

It is evident from this study that when surveying pupils the methods and survey materials should be adapted to the particularities of school environments and the occupants' young age (see appendices A and B). Based on this research, the key issues that need to be addressed when surveying pupils in primary schools are the following:

- Planning of survey dates and times. Organising the school visits is necessary due to the diversity of the school schedule, which may also lead to changes in pupils' metabolic rates or even affect their ability to concentrate.

- Easy to understand, brief and stimulating questionnaire. The questionnaire should match pupils' attention span. The questionnaire in this study was approved by teachers and appeared to be easy for the children to respond to (Appendix A). Stimuli, such as colours and images, should be used as they contribute to a better understanding and concentration on the survey forms (Bell, 2007, Borgers et al., 2000).

- Engaging with pupils during the surveys. Preparing activities and small scale experiments was found to be a prerequisite for the collection of data.

9.1.2 Implications for thermal comfort standards and guides

This research compared pupils' reported thermal sensation with the predictions of comfort models used in international thermal comfort standards and guides (chapters 6 and 8). It was found that there are differences which suggest that current comfort criteria are inappropriate for use in school design and operation. The impact of the research results on current thermal comfort standards and guides, described in section 3.2, is summarised below.

9.1.2.1 PMV based criteria (ISO 7730, EN 15251, ASHRAE 55 and CIBSE guide A)

The PMV model has received criticism for being static and not reflecting the conditions in everyday environments (section 3.1.1). Nevertheless, it is still widely used in all thermal comfort standards as well as in thermal simulation software packages and building performance assessments. Therefore, an update of the standards is required in order to address the results of this research.

The post-war school survey results showed a difference of about 4°C between the neutral temperature derived from the model and that derived from the actual thermal sensation votes (section 6.1.2). The corresponding difference from the Victorian school survey results was 3°C (section 8.3.1). One of the reasons for these large differences may be the higher metabolic rate of children per kg body weight. One of the adjustment approaches to the input metabolic rate for the calculation of the PMV and PPD which were investigated, approach (c) in section 6.1.2, showed a relatively good agreement with the actual thermal sensation of pupils. The adjustment however needs further verification, especially during other periods of the year. It could then be used in standards and guides which are based on the PMV model, in order to better reflect pupils' sensation. In any case, it should be made clear in the above documents that school classrooms have special requirements and that the current adult based calculation routines should be treated with care in this particular environment.

9.1.2.2 Adaptive thermal comfort based criteria (EN 15251, ASHRAE 55, ISSO 74 Guideline, CIBSE Guide A)

Comparison of the results with the predictions based on the adaptive comfort model highlighted a difference of approximately 2°C between the predicted comfort temperature and the pupils' actual comfort temperature (sections 6.2 and 8.3.2). The analysis on the long-term and sort-term adaptive behaviour in classrooms showed that adaptive opportunities are limited in schools and mainly the responsibility of the teachers rather than the pupils. Standards and guides should incorporate specific sections describing these considerations, as well as adjustment of the adaptive comfort model to reflect the 2°C difference in comfort temperature.

9.1.2.3 Overheating criteria (BB 87, BB 101, CIBSE overheating criterion, Adaptive thermal comfort based Nicol criterion, new DfE guideline)

The overheating criteria currently used for schools were found to be too lenient which could pose risks for pupils during hot summers. The adaptive thermal comfort based Nicol criterion provided a better prediction of the overheating potential. However, this criterion was found to also be rather lenient due to the fact that it is based on the comfort equation derived from adult subjects. The new Dfe guideline also underestimated the overheating risk of the case study school due to the inappropriate adult-based equation. Therefore, a comfort temperature equation based on pupils' responses is necessary in order to assess the risk of overheating in schools. The comfort temperatures derived from this study can be used as a basis but more surveys with children will be required to achieve higher levels of confidence in order to feed into the standards.

9.1.2.4 UK Building Bulletins

Building Bulletins 87 and 101 which apply to UK school buildings will need to include new environmental guidelines to match the research results in accordance with the adjustments in the standards described above.

Overall, it is evident that child specific criteria need to be developed for school environments based on current and future research on pupils' thermal comfort. However, compliance with temperature criteria may not be enough to ensure thermal comfort. This research showed that thermal sensation trends may be influenced by other characteristics, such as occupant controls and activities (section 7.1) and classroom orientation (section 7.2). Therefore, along with thermal criteria, guidance on school building design and refurbishment should be given, tailored to match pupils' specific thermal sensation trends.

9.1.3 Implications for school design and refurbishment

As explained in the previous section, the results of this research suggest that in order to achieve good comfort conditions for children in classrooms outside the heating season different comfort criteria than those applied to adults' are required, with stricter upper temperature limits. This could have significant implications on energy demand in schools. In order to comply with the stricter upper limits for thermal comfort in summer many schools would probably require comfort cooling. The light-weight case study building presented in this study already exceeded the EN 15251 Category I and II comfort limits. Given the observed warmer sensation of the pupils and the predictions for warmer summer temperatures in the future (Jenkins et al., 2009b), this exceedance is likely to be exacerbated in the years to come. As discussed in section 2.3, it is likely that existing schools may consider installing mechanical ventilation and cooling to cope with warmer summer temperatures. However, this would conflict with the UK Government's goal to reduce greenhouse gas emissions by 80% by 2050 (UK Parliament, 2008). It appears necessary to explore appropriate passive cooling and solar control design techniques for school environments and investigate their potential to mitigate uncomfortably warm temperatures in classrooms. Challenges to be considered include compliance with health and safety rules of primary schools and matching with the young age of occupants and the special requirements of learning spaces, such as adequate natural lighting and good air quality. Discussion of potential cooling techniques for schools is included in Appendix E.

9.1.4 Future work

The potential of low-energy cooling measures to ensure thermal comfort in schools outside the heating season, mentioned in section 9.1.3 and included in Appendix E, needs to be an area of future research. Furthermore, this will require consideration of building resilience to warmer temperatures to address the predicted warmer future climate (Murphy et al., 2009). The risk of overheating of schools under future climates has partially been investigated by researchers through the use of fixed adult based overheating criteria and thermal simulation modelling (Jenkins et al., 2009a, Coley and Kershaw, 2008). However, as discussed in section 6.3, current overheating criteria for schools do not reflect the children's thermal tendencies. Therefore, future research will need to cover this important gap.

Suggested measures should also be tested against their impact on schoolwork performance, as they could have adverse effects, such as compromising day light penetration or leading to an increase of air pollutants (Wargocki and Wyon, 2013), parameters which are equally important for pupils' performance and health. Multidisciplinary research appears to be required to address these overlapping areas.

Finally, the results presented here are based on surveys conducted outside the heating season, which means that further investigation is required with respect to the applicability of the outcomes during the heating season and its implications. If the lower comfort temperatures of children outside the heating season also apply to the heating season, then this would suggest that lower temperatures could be acceptable. This could lead to energy savings in the heating season, which further highlights the significance of future research on this area. Overall, more surveys in schools are necessary in a wider climatic context, in order to verify the findings of this research and investigate the influence of parameters such as varying climatic and environmental conditions. Finally, thermal comfort surveys with children in the age group of 11-16 in the UK are necessary in order to investigate the way thermal comfort trends and preferences develop with age.

9.2 Conclusions

This research showed that both models used in existing thermal comfort standards (the PMV and adaptive comfort model) had a limited suitability for predicting the thermal comfort conditions in the surveyed schools as both did not accurately reflect the children's actual thermal sensation. The results suggest that children have a warmer thermal sensation than adults and would prefer an indoor thermal environment with lower temperatures compared to adults. Possible explanations for this may be the higher metabolic rate per kg body weight, the limited available adaptive opportunities in classrooms, the fact that children do not always adapt their clothing to their thermal sensation, or the influence of characteristics of their familiar indoor environments. Furthermore, the daily school schedule of children includes a lot of outdoor playing, unlike offices where occupants stay inside for most of the day. This variation of activity levels and the strong relationship with the outdoor climate may also influence children's thermal perception. The study presented here suggests that adjustments are required to both the thermo-physiological and the adaptive comfort model in order to appropriately reflect the thermal sensation of children.

Furthermore, this research showed that there are parameters other than those regulated by comfort standards which influence thermal perception in classrooms. Building characteristics, such as orientation, have a strong impact on building occupants' thermal perception even when they do not directly affect the thermal conditions. Occupant behaviour and teachers' control of the thermal environment also play a significant role. Considering the building characteristics which influence thermal comfort trends and a case-by-case approach appear to be necessary to achieve indoor thermal satisfaction, instead of merely complying with universal design criteria for thermal comfort.

The pupils' thermal sensation trends, as presented in this study, suggest that there may be temperature thresholds and subsequently overheating risks which are not currently addressed in policy documents, due to lack of detailed understanding of children's thermal response. This could have significant implications for pupils' performance and wellbeing, especially in relation to the potential changes to the global climate predicted in the future. According to the 2009 UK Climate Projections (UKCP09), under a medium emissions scenario, the summer mean temperature change for the UK in the 2020s is predicted to be about 1.5 ^{o}C while the summer mean daily maximum temperature change could be up to 3 ^{o}C, relative to the modelled 30 year baseline period 1961–1990 (Murphy et al., 2009). In view of these climate projections, the pupils' lower comfort temperatures, appear to be alarming for the children's future feeling of thermal comfort and work performance in classrooms, as these are strongly affected by increased temperatures (Wargocki and Wyon, 2007). The observed warm thermal tendency of pupils under current summer conditions suggests that there is already a high risk of thermal dissatisfaction from overheating, which may be exacerbated in the future. This means that school building design and refurbishment would need to follow strict guidelines, set according to child based thermal comfort standards. This will be a challenging task, considering that any measures taken to improve thermal comfort in schools should also comply with the UK Government's goal to reduce greenhouse gas emissions by 80% from 1990 levels by 2050 (UK Parliament, 2008) which would essentially exclude mechanical cooling from being implemented.

In conclusion, it appears necessary to set higher standards in school design and refurbishment in order to ensure the delivery of appropriate thermal comfort conditions for children. Our aim should be centred on investigating low and zero energy ways to achieve this.

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Appendices

Appendix A

Head teachers' and teachers' questionnaires

School ......: **(School name) Junior (B)**

Notes of surveyor

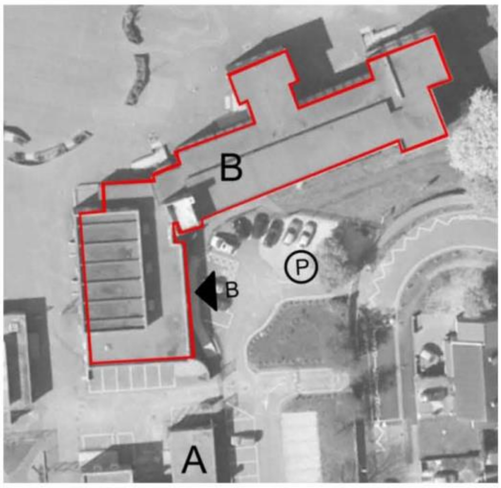
1) Surrounding buildings: >3 storeys (shade on map)

2) Building form

Compact ☐ Structured ☐ linear ☐ Enclosed courtyard ☐ Courtyard open on one side ☐

School ......: **(School name) Junior (B)**

Notes of surveyor



Comments

3) Construction type

Light-weight ☐ Heavy-weight ☐

4) Shading devices

Horizontal ☐ Vertical ☐ None ☐

Internal ☐ External ☐ Other (Please state) ☐ ....

Note on map, if variations

5) % glazing

<50% of the facade ☐ >50% of the facade ☐

Note on map, if variations

6) Façade colour

Light ☐ dark ☐ ....

7) Roof cover

Pitched (~degree on map) ☐ Tarmac/bitumen ☐ Metal sheeting ☐

Flat ☐ Tiled ☐ Other (state) ☐ ....

8) Building height (number of storeys on map)

School ......: **(School name) Junior (B)**

University of Southampton
School of Civil Engineering and the Environment

Overheating in schools-Head teachers' questionnaire

I am undertaking research in the School of Civil Engineering and the Environment at the University of Southampton. My project is looking at the potential for high temperatures in school classrooms in the summer months.

Please answer the following questions regarding your school, by ticking the boxes or writing the answer in the space provided.

School name

Number of Students ☐

Number of Classrooms ☐

School details

1) School's construction year

Pre 1914 ☐ 1914-1945 ☐ 1945-1960 ☐

1960-1970 ☐ 1970-1990 ☐ 1990 onwards ☐

2) Were there any of the changes below made to the main building?

Extension ☐ Additional building ☐ Change of use of parts of the building ☐

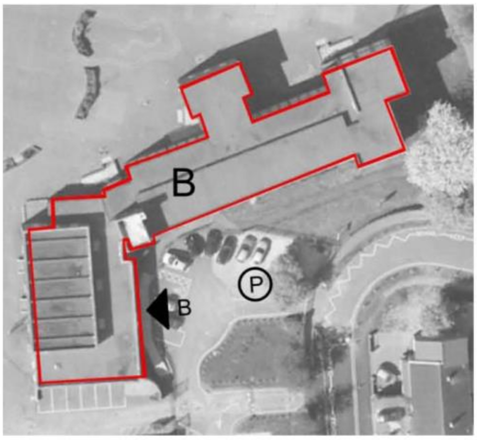
Roof cover replacement ☐ Internal layout changes ☐ Other (Please state) ☐ ....

If additional building sections were constructed, indicate the different building phases by putting numbers on the map, starting from the oldest to the newest.

(Note their construction year, if known)

If there was change of use or internal layout, indicate where in the building.

Comments ....
....
....
....



School ......: **(School name) Junior (B)**

UNIVERSITY OF Southampton
School of Civil Engineering and the Environment

3) When is the central heating on (heating season) in your school during the year? Shade the corresponding areas.

September	October	November	December	January	February
March	April	May	June	July	August

School performance

4) How do you think the school generally performs in terms of temperature during the following months?

	Too cold	Cold	OK	Warm	Too warm
April	☐	☐	☐	☐	☐
May	☐	☐	☐	☐	☐
June	☐	☐	☐	☐	☐
July	☐	☐	☐	☐	☐
September	☐	☐	☐	☐	☐
October	☐	☐	☐	☐	☐

5) Do the following spaces overheat during warm days?

	Very often	Often	Sometimes	Rarely	Never
Classrooms	☐	☐	☐	☐	☐
Computer Room	☐	☐	☐	☐	☐
Corridors/circulation	☐	☐	☐	☐	☐
Offices	☐	☐	☐	☐	☐
Assembly hall	☐	☐	☐	☐	☐
Library	☐	☐	☐	☐	☐

6) Are there ever complaints about excessively high temperatures in classrooms?

	Very often	Often	Sometimes	Rarely	Never
During the heating season (winter)	☐	☐	☐	☐	☐
Outside the heating season (Summer)	☐	☐	☐	☐	☐

7) Which months cause most overheating problems in your school (if any)?

September	October	November	December	January	February
March	April	May	June	July	August

Overheating in schools 2

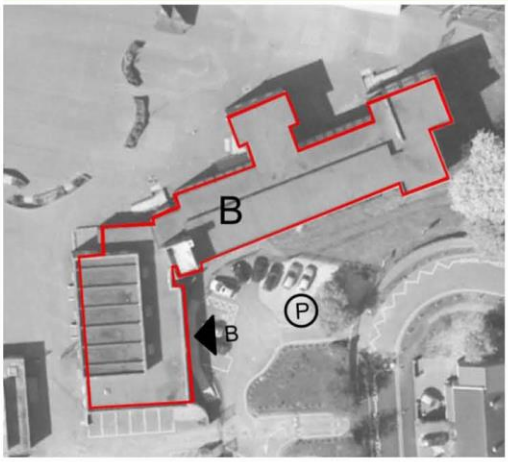
School ......: **(School name) Junior (B)**

UNIVERSITY OF Southampton
School of Civil Engineering and the Environment

8) What is the usual duration of overheating occurrences?

	1-3 days	4-5 days	More than 1 week	N/A
During the heating season (winter)	☐	☐	☐	☐
Outside the heating season (Summer)	☐	☐	☐	☐

9) Indicate which areas in the building overheat the most (if any).



Areas which mostly overheat

10) Which percentage of the school's classrooms has experienced overheating (if any)?

	0-20%	20-40%	40-60%	60-80%	80-100%
During the heating season (winter)	☐	☐	☐	☐	☐
Outside the heating season (Summer)	☐	☐	☐	☐	☐

11) Name the factors which you believe cause overheating in your school (if any)

1) .... 4) ....
2) .... 5) ....
3) .... 6) ....

12) What measures do you take in cases of increased temperature? Circle the most used.

Window opening ☐	Door opening ☐	Fan ☐
Drinking of water ☐	Closing Blinds/curtains ☐	Class interruption/break ☐
Clothing policy change ☐	Curriculum change ☐	Seating plan change ☐
Change heating strategy ☐	Other (Please state) ☐	

UNIVERSITY OF Southampton
School of Civil Engineering and the Environment

School ......: **(School name) Junior (B)**

13) Did you ever have to change the clothing policy during a warm spell?

YES ☐ NO ☐

If yes, how?...

....

....

Impact on students

14) From your experience, rate the following factors in terms of their detrimental effect on students' learning experience on a scale of 0-5, where 0=no impact, 5=highly detrimental.

Lighting conditions in the classroom	0	1	2	3	4	5
External noise	0	1	2	3	4	5
External visual distraction	0	1	2	3	4	5
Wet lunch break	0	1	2	3	4	5
Quality/availability of school meals	0	1	2	3	4	5
Winter overheating	0	1	2	3	4	5
Summer overheating	0	1	2	3	4	5
Quality of school furniture	0	1	2	3	4	5
Class size	0	1	2	3	4	5

Respondent's details

How many years have you been at this school?

0-1 ☐ 1-2 ☐ 3-5 ☐ More than 5 ☐

How many years have you been in the teaching profession?

0-5 ☐ 5-10 ☐ 10-20 ☐ More than 20 ☐

How many years have you been head teacher?

0-5 ☐ 5-10 ☐ 10-20 ☐ More than 20 ☐

If you have any further comments, please feel free to add them below:

....

....

....

Thank you very much for participating in this questionnaire.

School ......: **(School name) Junior(B)**

UNIVERSITY OF Southampton
School of Civil Engineering and the Environment

Overheating in schools- teachers' questionnaire

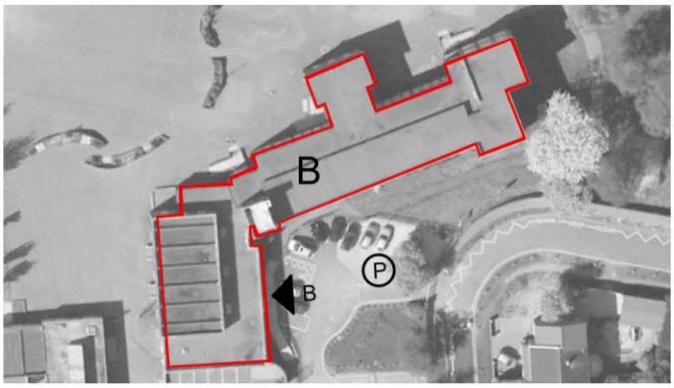
I am undertaking research in the School of Civil Engineering and the Environment at the University of Southampton. My project is looking at the potential for high temperatures in school classrooms in the summer months.

Please answer the following questions regarding your classroom (or form classroom, if secondary) and school, by ticking the boxes or writing the answer in the space provided.

Classroom ....

Number of Students in classroom ☐

1) Where in the school is your (form) classroom?



2) When is the central heating on (heating season) in your classroom during the year? Shade the corresponding areas.

September	October	November	December	January	February

March	April	May	June	July	August

3) How do you think the classroom generally performs in terms of temperature during the following months?

	Too cold	Cold	OK	Warm	Too warm
April	☐	☐	☐	☐	☐
May	☐	☐	☐	☐	☐
June	☐	☐	☐	☐	☐
July	☐	☐	☐	☐	☐
September	☐	☐	☐	☐	☐
October	☐	☐	☐	☐	☐

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School ......: **(School name) Junior(B)**

4) Have the students complained about excessively high temperatures in the classroom?

	Very often	Often	Sometimes	Rarely	Never
During the heating season (winter)	☐	☐	☐	☐	☐
Outside the heating season (Summer)	☐	☐	☐	☐	☐

5) Which months cause most overheating problems in your classroom? (if any)

September	October	November	December	January	February
March	April	May	June	July	August

6) What is the usual duration of overheating occurrences? (if any)

	1-3 days	4-5 days	More than 1 week	N/A
During the heating season (winter)	☐	☐	☐	☐
Outside the heating season (Summer)	☐	☐	☐	☐

7) Name the factors which you believe cause overheating in your classroom (if any)

1) .... 4) ....
2) .... 5) ....
3) .... 6) ....

8) What measures do you take in cases of increased temperature? Circle the most used.

Window opening ☐ Door opening ☐ Fan ☐

Drinking of water ☐ Closing Blinds/curtains ☐ Turn thermostat down ☐

Seating plan change ☐ Curriculum change ☐ Other (Please state) ☐
....

9) Do the following spaces in the school overheat during warm days?

	Very often	Often	Sometimes	Rarely	Never
Classrooms	☐	☐	☐	☐	☐
Computer Room	☐	☐	☐	☐	☐
Corridors/circulation	☐	☐	☐	☐	☐
Offices	☐	☐	☐	☐	☐
Assembly hall	☐	☐	☐	☐	☐
Library	☐	☐	☐	☐	☐

10) Which percentage of the school's classrooms has experienced overheating (if any)?

	0-20%	20-40%	40-60%	60-80%	80-100%
During the heating season (winter)	☐	☐	☐	☐	☐
Outside the heating season (Summer)	☐	☐	☐	☐	☐

School ......: **(School name) Junior(B)**

11) From your experience, rate the following factors in terms of their detrimental effect on students' learning experience on a scale of 0-5, where 0=no impact, 5=highly detrimental.

Lighting conditions in the classroom	0	1	2	3	4	5
External noise	0	1	2	3	4	5
External visual distraction	0	1	2	3	4	5
Wet lunch break	0	1	2	3	4	5
Quality/availability of school meals	0	1	2	3	4	5
Winter overheating	0	1	2	3	4	5
Summer overheating	0	1	2	3	4	5
Quality of school furniture	0	1	2	3	4	5
Class size	0	1	2	3	4	5

How many years have you been at this school?

0-1 years ☐ 1-2 years ☐ 3-5 years ☐ More than 5 ☐

How long have you been using this classroom?

0-1 years ☐ 1-2 years ☐ 3-5 years ☐ More than 5 ☐

If you have any further comments, please feel free to add them below:

....
....
....
....
....
....
....
....

Thank you very much for participating in this questionnaire.

Pupils' questionnaire

1

Comfort in classroom-pupil survey

UNIVERSITY OF Southampton
School of Civil Engineering and the Environment

I am a: Girl ☐ Boy ☐

1) How do you feel at the moment?

Cold	cool	A bit cool	OK	A bit warm	Warm	Hot
☐	☐	☐	☐	☐	☐	☐

2) Tick the box of the phrase you agree with:

AT THE MOMENT, IN THE CLASSROOM:

- I wish it was a lot colder ☐
- I wish it was colder ☐
- I wish it was a bit colder ☐
- I don't want any change ☐
- I wish it was a bit warmer ☐
- I wish it was warmer ☐
- I wish it was a lot warmer ☐

3) At the moment, do you feel comfortable?

Yes ☐ No ☐

4) At the moment, are you wearing your jumper?

Yes ☐ No ☐

5) Do you feel tired?

Very tired ☐ A bit tired ☐ I am not tired ☐

Please turn the page

Classroom No:......|Date:.../.../11

Thank you very much!

6) What were you doing in the last 30 minutes before the survey?

Class activity (reading, writing, maths, science, etc.) ☐

PE (Physical education, games) ☐

ICT (Computers) ☐

Playing outside/ running during break ☐

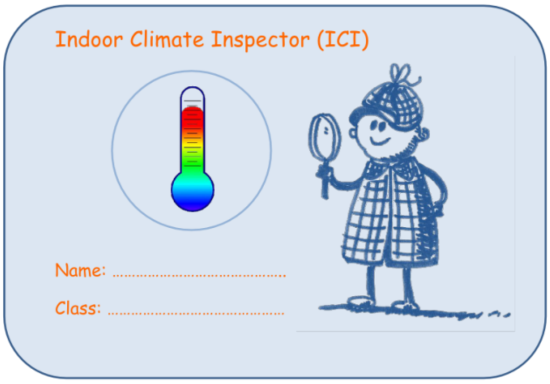
Relaxing during break ☐

Having lunch ☐

Thank you very much!

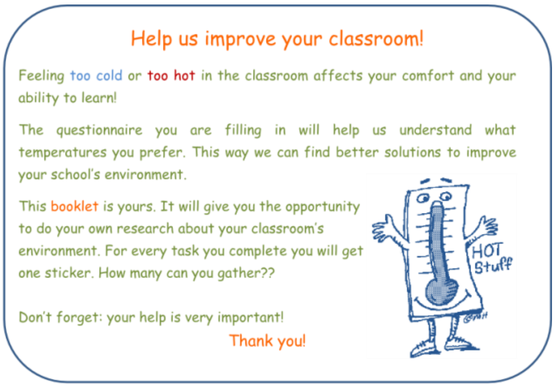
Appendix B

Pupils' sticker booklet


Indoor Climate Inspector (ICI)

Name: ....

Class: ....


Help us improve your classroom!

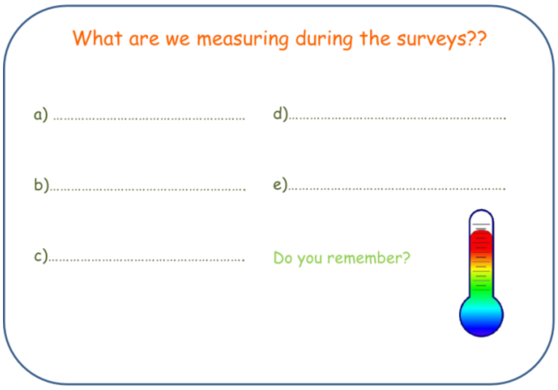
Feeling too cold or too hot in the classroom affects your comfort and your ability to learn!

The questionnaire you are filling in will help us understand what temperatures you prefer. This way we can find better solutions to improve your school's environment.

This booklet is yours. It will give you the opportunity to do your own research about your classroom's environment. For every task you complete you will get one sticker. How many can you gather??

Don't forget: your help is very important!

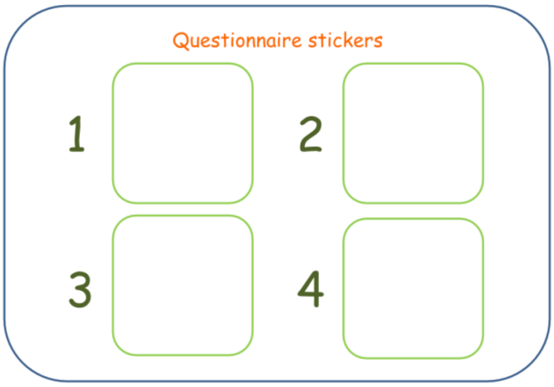
Thank you!


What are we measuring during the surveys??

a) .... d)..

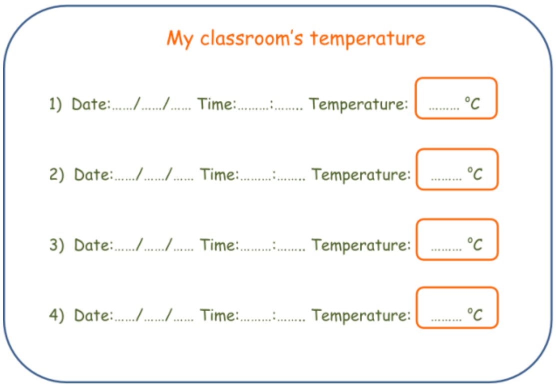
b).. e)..

c).. Do you remember?


Questionnaire stickers

1 2

3 4

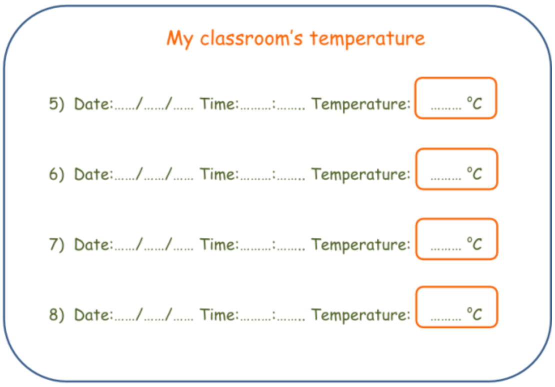

My classroom's temperature

1) Date:....../....../...... Time:........:........ Temperature: .... °C

2) Date:....../....../...... Time:........:........ Temperature: .... °C

3) Date:....../....../...... Time:........:........ Temperature: .... °C

4) Date:....../....../...... Time:........:........ Temperature: .... °C

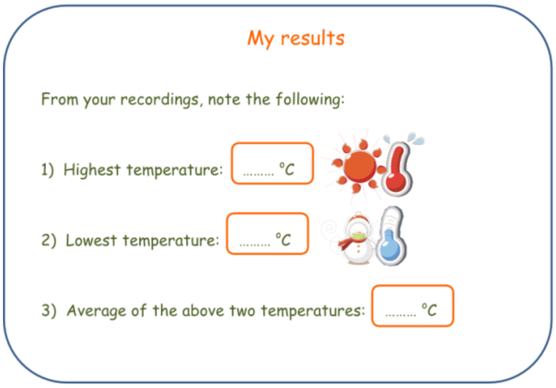

My classroom's temperature

5) Date:....../....../...... Time:........:........ Temperature: .... °C

6) Date:....../....../...... Time:........:........ Temperature: .... °C

7) Date:....../....../...... Time:........:........ Temperature: .... °C

8) Date:....../....../...... Time:........:........ Temperature: .... °C

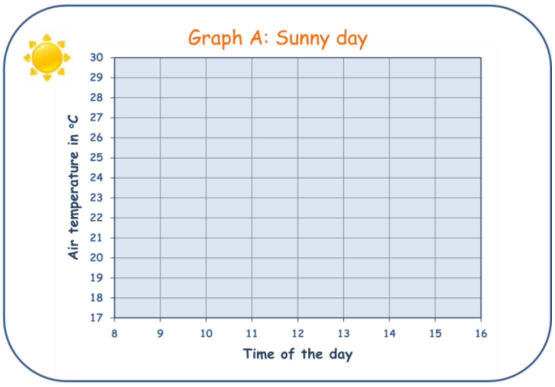

My results

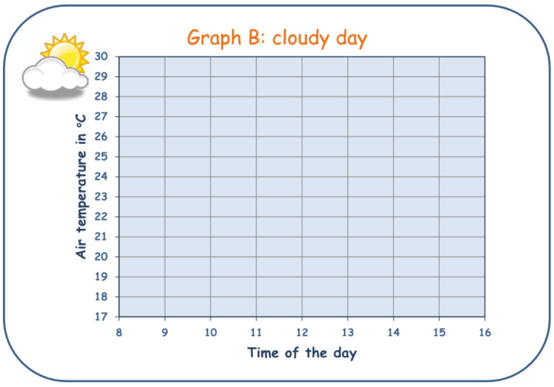
From your recordings, note the following:

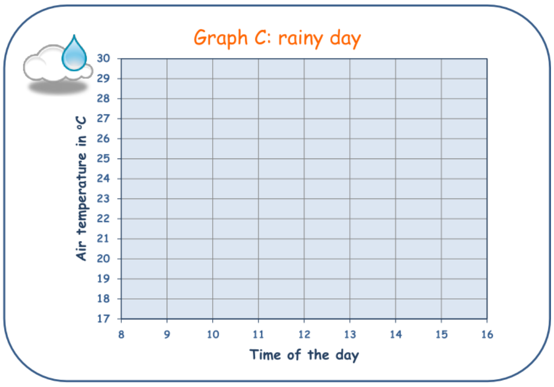
1) Highest temperature: .... °C

2) Lowest temperature: .... °C

3) Average of the above two temperatures: .... °C


Graph A: Sunny day





More stickers!

5 I noted all the measurements

6 I noted all 8 temperatures of my classroom

7 I noted my results

8 I created at least 2 graphs

University of Southampton
School of Civil Engineering and the Environment

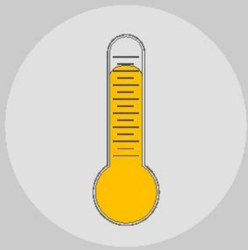
Stickers

Appendix C

Survey material

Participation letter for teachers

Thermal comfort in schools-Survey



Dear teacher,

I would like to invite you to participate in my research on pupils' thermal comfort in school classrooms. This study is being undertaken as part of research work towards obtaining the degree of Doctor of Philosophy (PhD) in the Faculty of Engineering and the Environment at the University of Southampton.

What this research is about:

The study focuses on the thermal environment of school classrooms and investigates the pupils' thermal comfort perception outside the heating season. The overall aim of this study is to contribute to the improvement of thermal comfort in learning environments through a better understanding of pupils' preferences.

What the research procedure includes and how you can help:

The research will be conducted by the PhD student, Ms Despoina Teli, through visits to the school in intervals of two weeks to 1 month, from March to July 2012. In every school visit the following will take place:

a) Pupil questionnaire surveys in 2-4 classrooms per visit with questions related to the indoor environmental conditions. The survey will last approximately <u>10 minutes</u> per classroom.

b) Recordings of indoor environmental variables using walk-through measuring equipment during the questionnaire surveys.

The same process will be repeated several times until the end of July (about 12 school visits in total). Your help and cooperation during the questionnaire surveys <u>will be valuable</u>.

Should you need any further information or have questions about this survey, please do not hesitate to contact me. Thank you in advance.

Sincerely,

Ms Despoina Teli, PhD student
Architect Dipl. Ing., Msc

Sustainable **E**nergy **R**esearch **G**roup- http://www.energy.soton.ac.uk/
Faculty of Engineering & the Environment

Tel: 023 8059 2134
Email: dt1e09@soton.ac.uk

Informative letter on temperature monitoring

Temperature monitoring in your classroom

UNIVERSITY OF Southampton
Engineering and the Environment

Dear teacher and pupils,

I would like to inform you that two small devices have been placed in your classroom as part of my research project on thermal comfort in schools. The devices measure the temperature and relative humidity in the classroom and look like the one in the picture below.

The devices were placed in a way so that they cause minimal disturbance to your class activities. Please do not remove them or change their location. Please contact me if you are not happy with the sensors being in your classroom or would like to change their position.

Should you need any further information or have questions about the devices, please do not hesitate to contact me. Thank you in advance for your cooperation.

Sincerely,

Ms Despina Teli, PhD researcher
Architect Dipl. Ing., Msc
Tel: 023 8059 2134
Email: dt1e09@soton.ac.uk

Sustainable **E**nergy **R**esearch **G**roup- http://www.energy.soton.ac.uk/
Faculty of Engineering & the Environment

UNIVERSITY OF Southampton
Engineering and the Environment

Survey timetable (for the head teacher's approval)

St Mark's CoE Primary school Survey

UNIVERSITY OF Southampton
Engineering and the Environment

Survey date: ……………………..

Please, let me know if you have any problems with the suggested survey times or if they overlap with an activity undertaken outside of the classroom (e.g. assembly, music). Thank you!

Despina Teli, PhD researcher
email: dt1e09@soton.ac.uk
mobile: 07935870982

		School day	Survey timetable
a.m.	08:40-08:55	Registration	
	08:55-09:25	Collective Worship	
a.m.	09:25-10:30	Class	SURVEYS 09:30 : class …. 09:45 : class ….
a.m.	10:30-10:45	break	
a.m./ p.m.	10:45-12:10	Class	SURVEYS 11:40 : class …. 11:55 : class ….
p.m.	12:10-01:00	Lunch break	
p.m.	01:00-15:00	Registration +Class	SURVEYS 01:30 : class …. 01:50 : class ….

Despoina Teli, PhD researcher [dt1e09@soton.ac.uk]
Sustainable Energy Research Group- http://www.energy.soton.ac.uk/
Faculty of Engineering & the Environment

Observation sheet

St Mark's CoE Primary school Survey

UNIVERSITY OF Southampton
Engineering and the Environment

Classroom: ....

No of pupils: ....

Date:	Time	Air temperature (TA)	Radiant temperature (TR)***	Relative humidity (RH)	Air speed (V)	CO_2
		°C	°C	%	m/sec	ppm
1 (during q)	..... :					
2 (before q)	..... :					
3 (after q)	..... :					
4	..... :					

***Globe a / b

Observations:

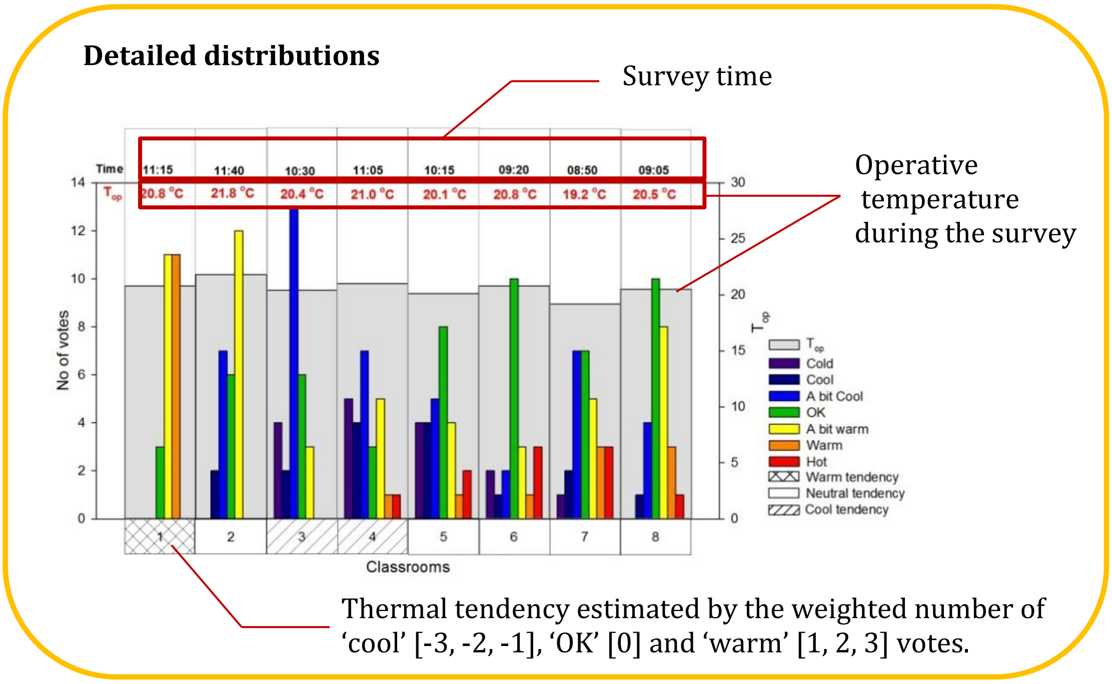
	Condition	Notes:
Windows	Number open: ..../.....	
Doors	Number open: ..../.....	
Blinds	Open/Closed % of glazing covered:	
Activity		Working silently, 1 child/teacher speaking, children working on tables, group work+ movement
Weather (Rain/Sun/overc)		
Artificial lighting	Lights on/off: ..../.....	
ICT	On/off	Projector, computer, other?
Clothing		
Other		Fans? Heating?

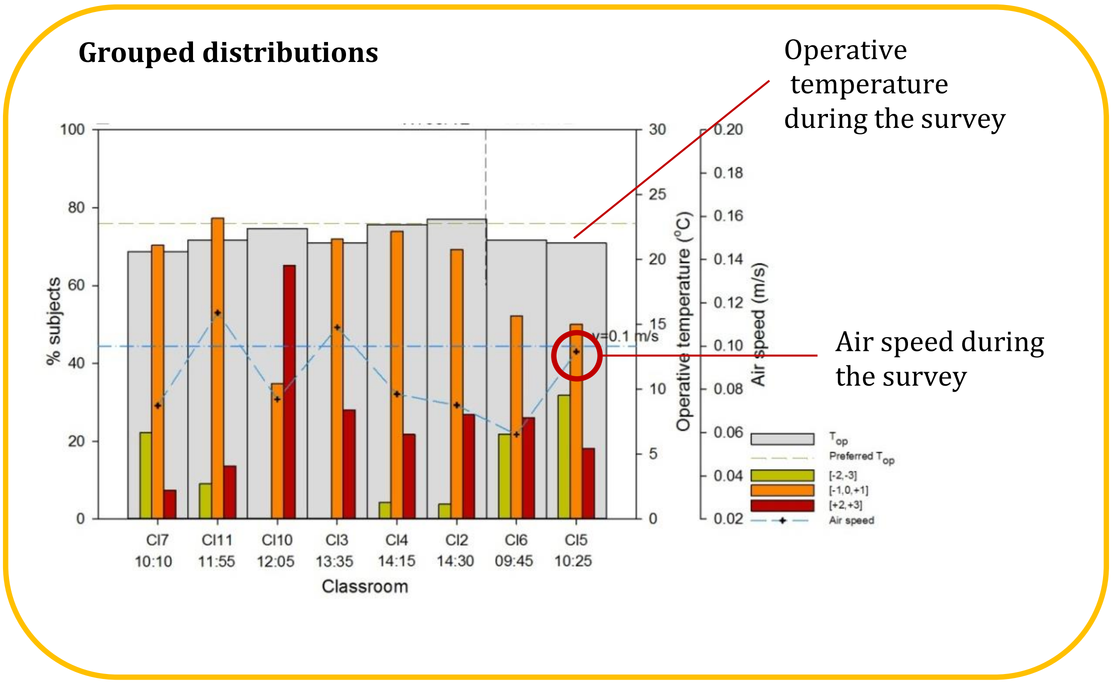
Despoina Teli, PhD student [dt1e09@soton.ac.uk]
Sustainable Energy Research Group - http://www.energy.soton.ac.uk/
Faculty of Engineering & the Environment

Appendix D

Thermal sensation distributions of all surveys, detailed and grouped

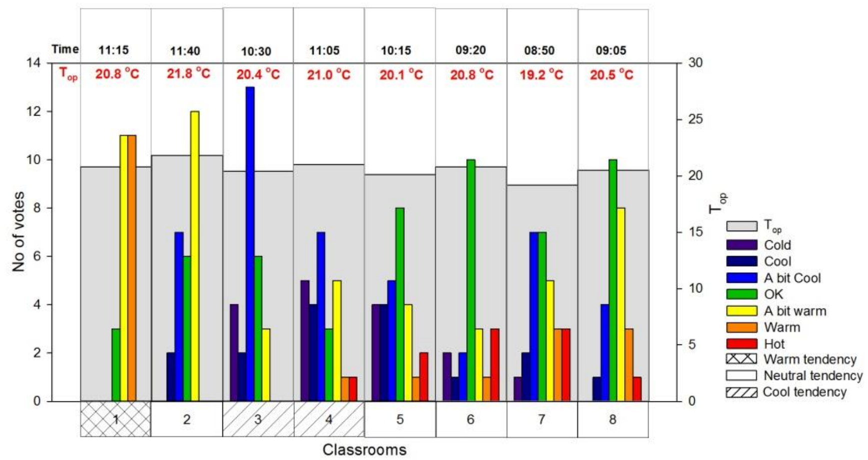
Explanation diagrams of the two graph types



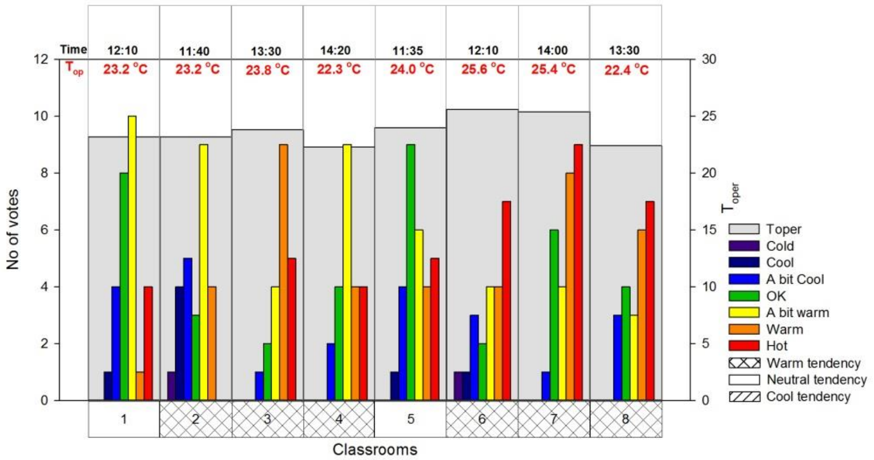


Post-war school survey: detailed TSV distributions

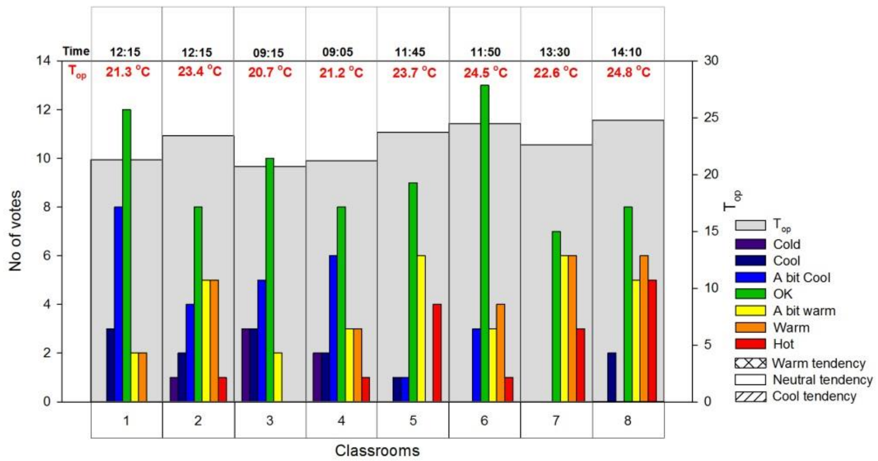
Test 1: TSV in all classrooms



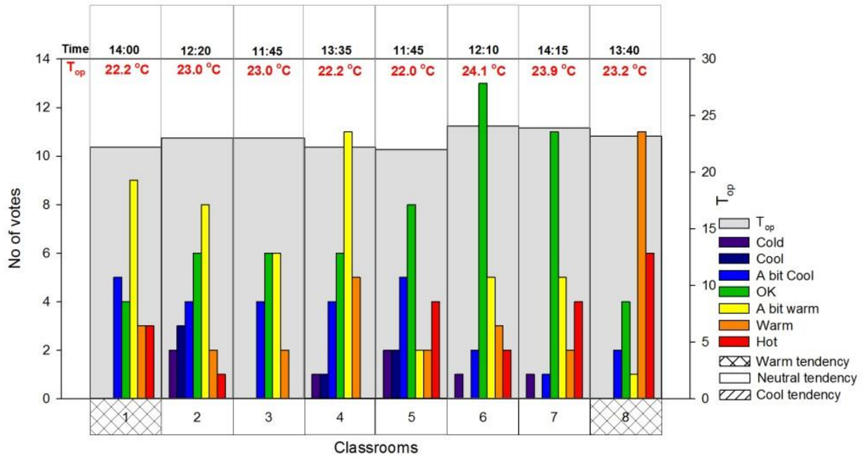
Test 2: TSV in all classrooms



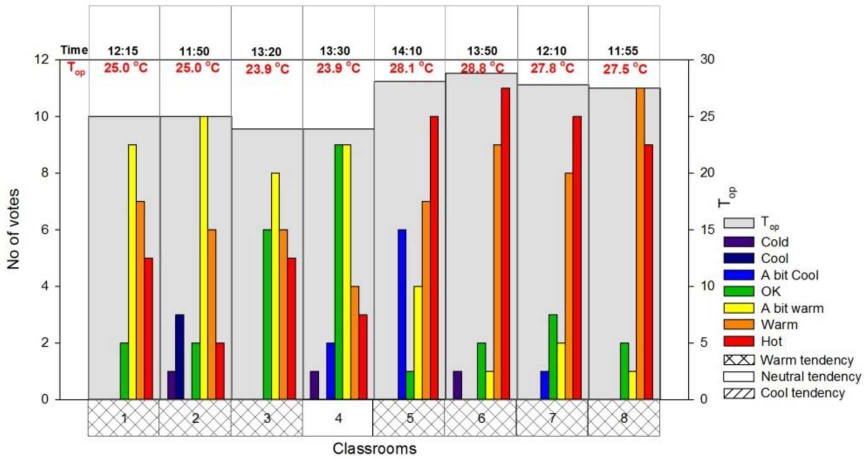
Test 3: TSV in all classrooms



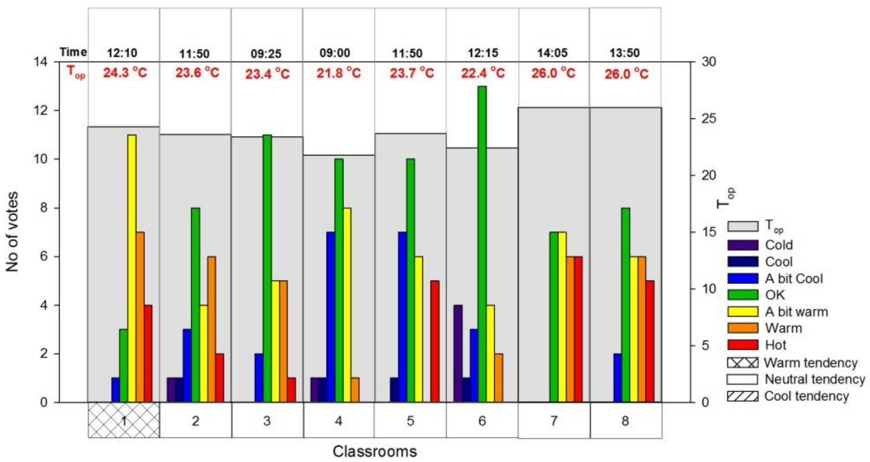
Test 4: TSV in all classrooms



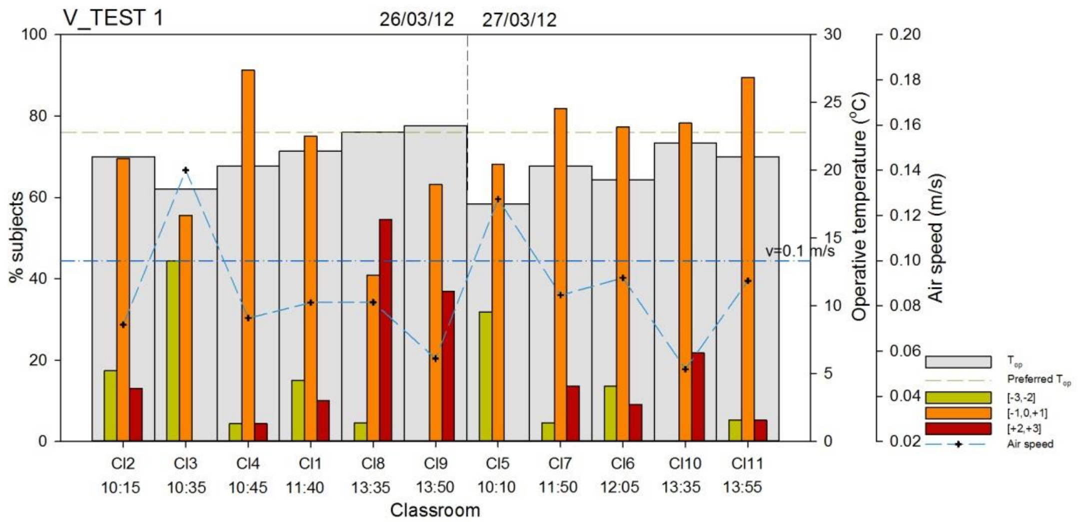
Test 5: TSV in all classrooms

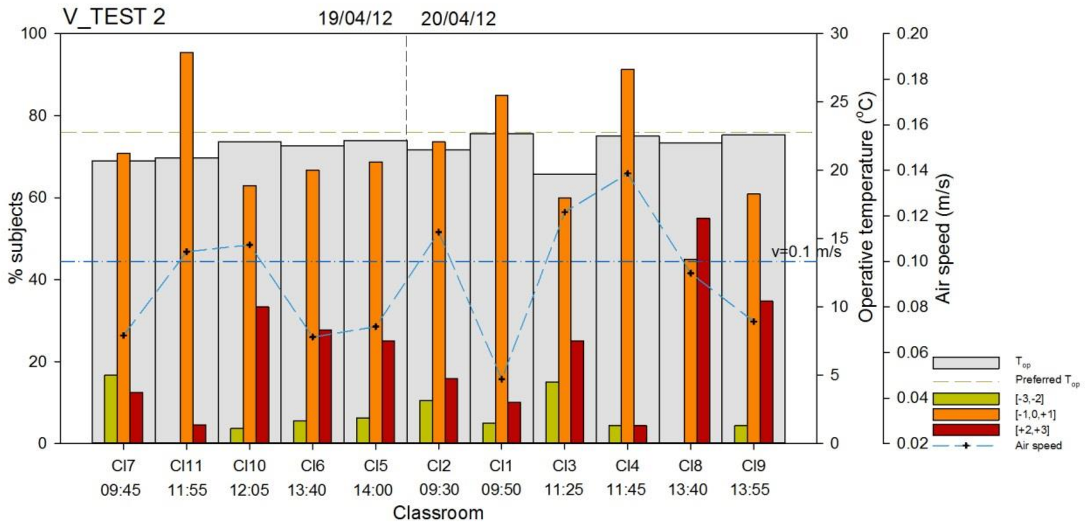


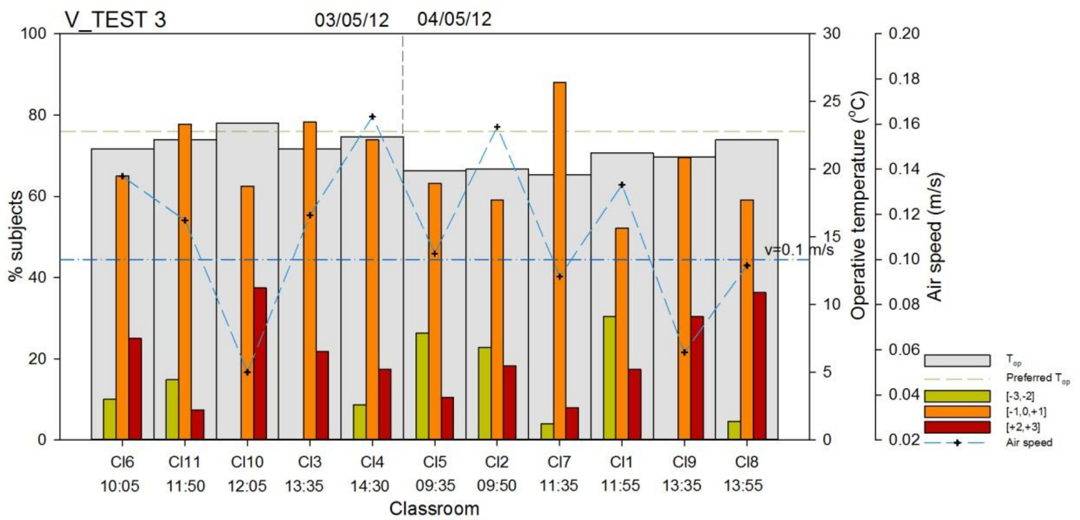
Test 6: TSV in all classrooms

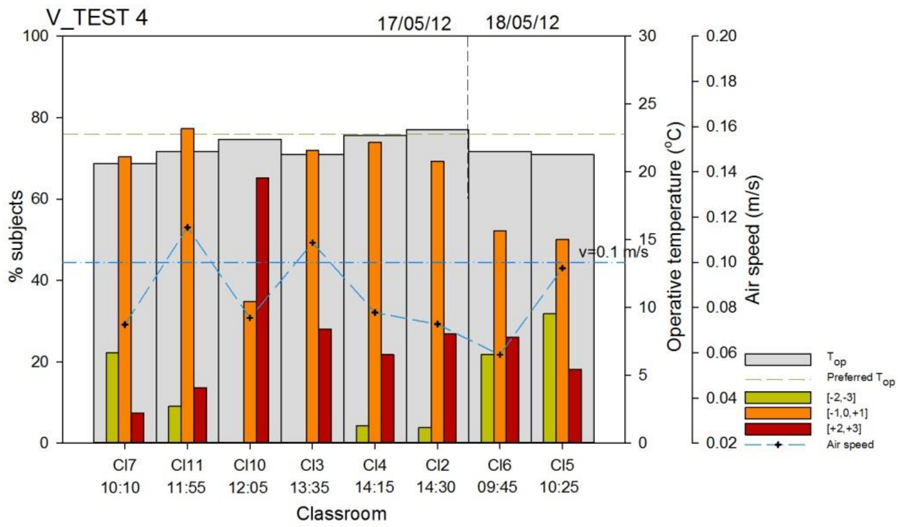


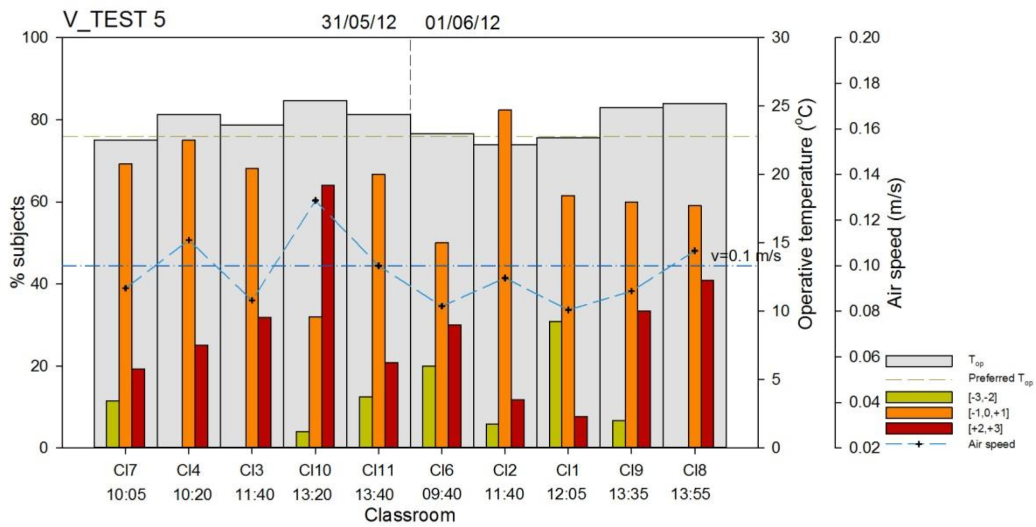
Victorian school survey: grouped TSVs (%)

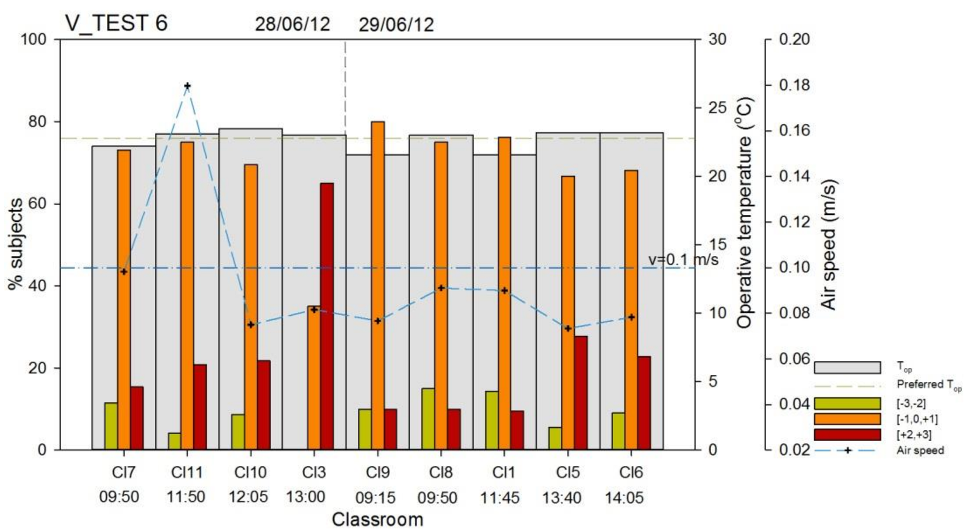


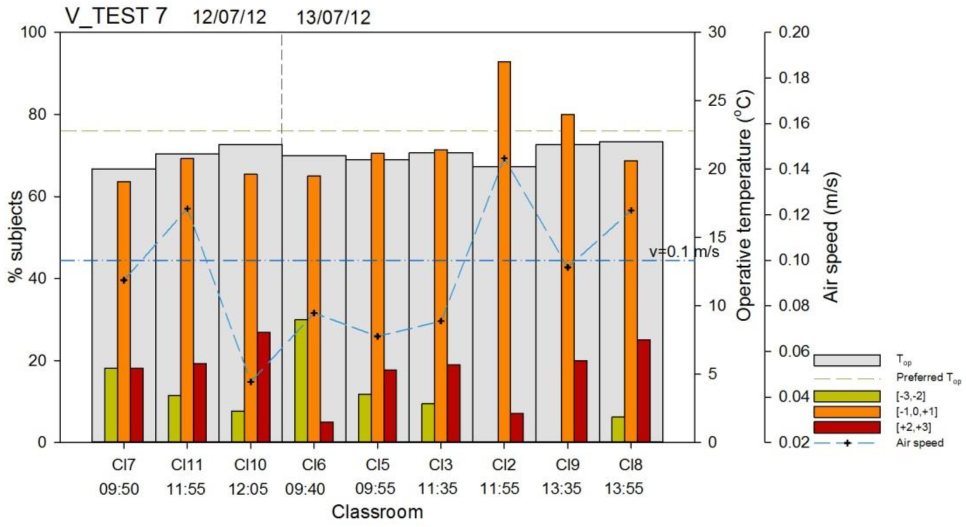




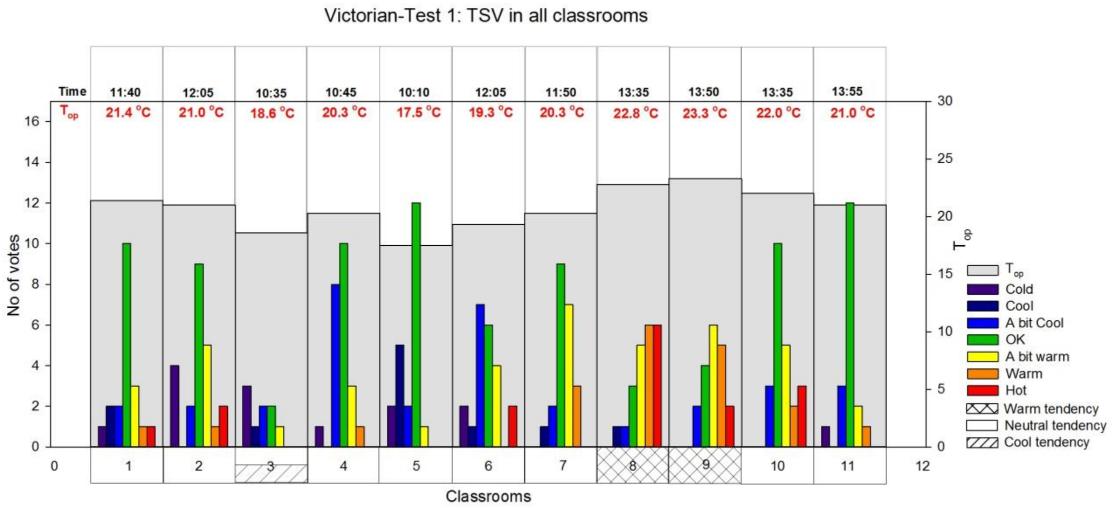

V_TEST 4
17/05/12
18/05/12
% subjects
Operative temperature (°C)
Air speed (m/s)
v=0.1 m/s
Cl7 10:10
Cl11 11:55
Cl10 12:05
Cl3 13:35
Cl4 14:15
Cl2 14:30
Cl6 09:45
Cl5 10:25
Classroom
Top
Preferred Top
[-2,-3]
[-1,0,+1]
[+2,+3]
Air speed

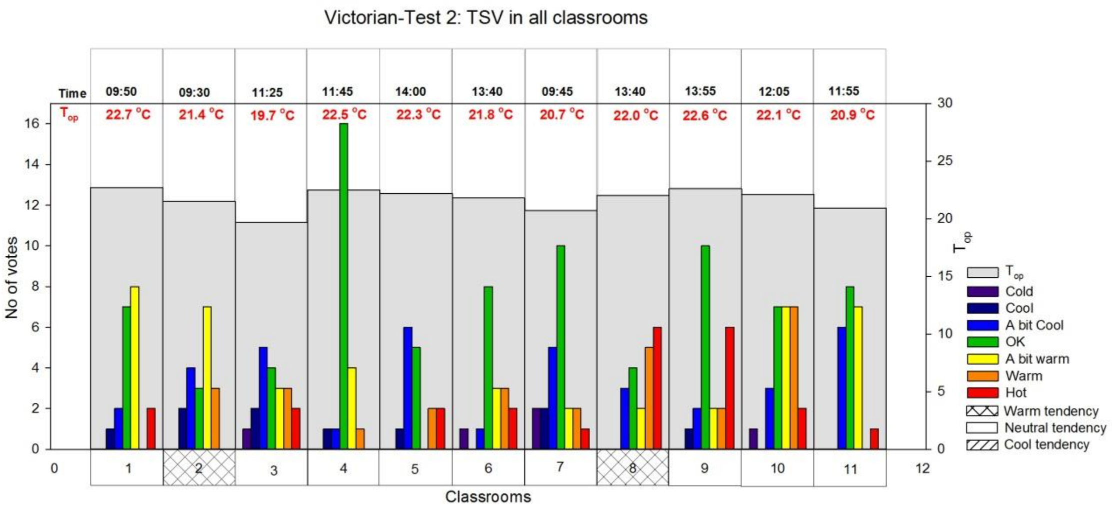

V_TEST 5
31/05/12
01/06/12
% subjects
Operative temperature (°C)
Air speed (m/s)
v=0.1 m/s
Cl7 10:05
Cl4 10:20
Cl3 11:40
Cl10 13:20
Cl11 13:40
Cl6 09:40
Cl2 11:40
Cl1 12:05
Cl9 13:35
Cl8 13:55
Classroom
Top
Preferred Top
[-3,-2]
[-1,0,+1]
[+2,+3]
Air speed


V_TEST 6
28/06/12
29/06/12
% subjects
Operative temperature (°C)
Air speed (m/s)
v=0.1 m/s
Cl7 09:50
Cl11 11:50
Cl10 12:05
Cl3 13:00
Cl9 09:15
Cl8 09:50
Cl1 11:45
Cl5 13:40
Cl6 14:05
Classroom
Top
Preferred Top
[-3,-2]
[-1,0,+1]
[+2,+3]
Air speed

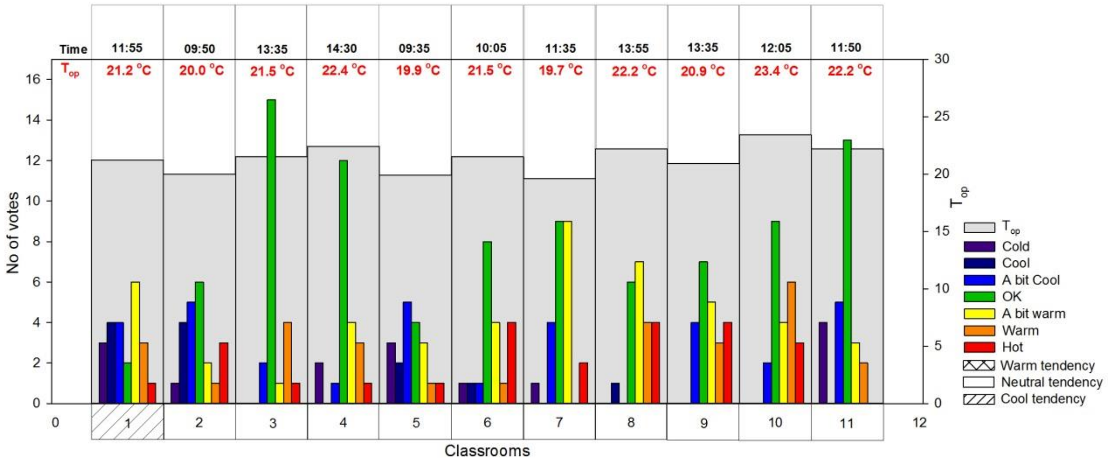


Victorian school survey: detailed TSV distributions

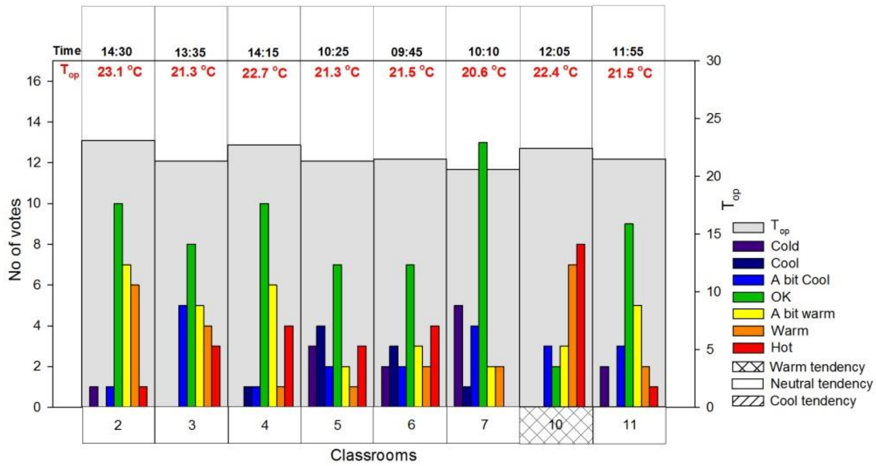




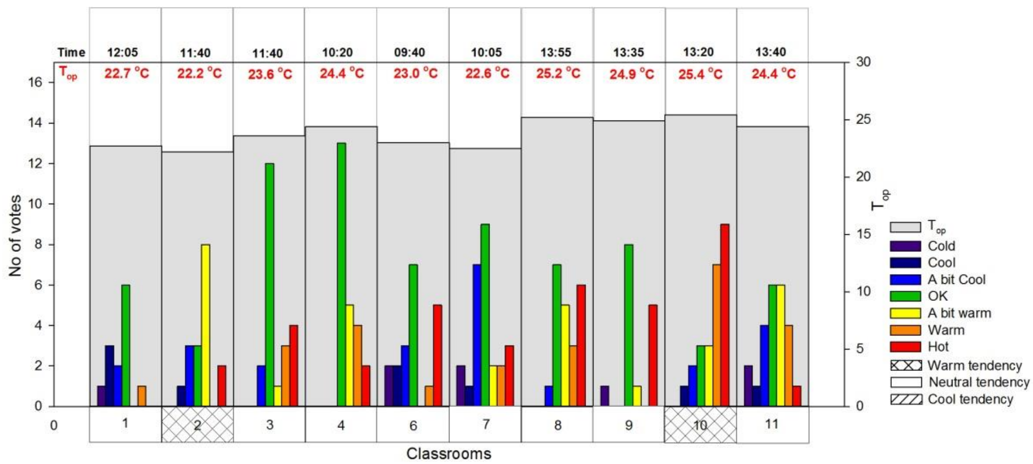
Victorian-Test 3: TSV in all classrooms

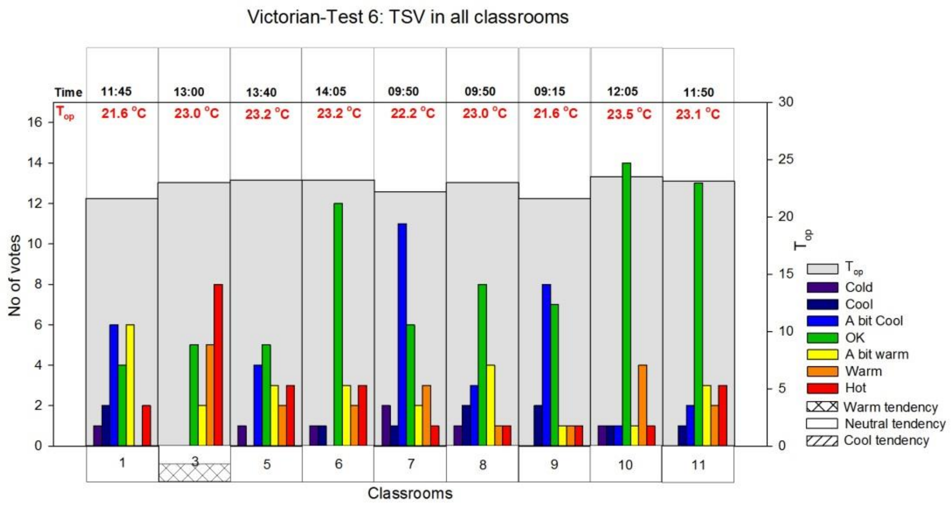


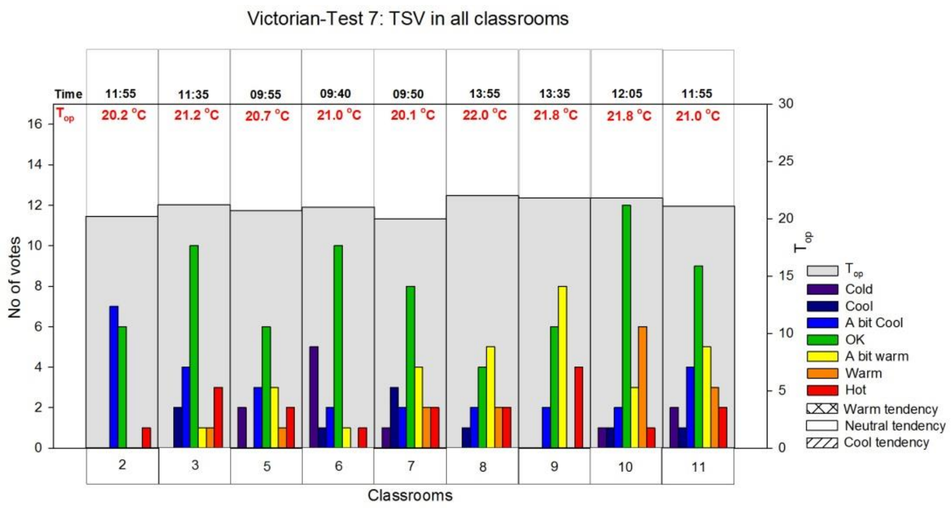
Victorian-Test 4: TSV in all classrooms



Victorian-Test 5: TSV in all classrooms




Victorian-Test 6: TSV in all classrooms
Time
11:45
13:00
13:40
14:05
09:50
09:50
09:15
12:05
11:50
T op
21.6 °C
23.0 °C
23.2 °C
23.2 °C
22.2 °C
23.0 °C
21.6 °C
23.5 °C
23.1 °C
No of votes
T op
Cold
Cool
A bit Cool
OK
A bit warm
Warm
Hot
Warm tendency
Neutral tendency
Cool tendency
1
3
5
6
7
8
9
10
11
Classrooms


Victorian-Test 7: TSV in all classrooms
Time
11:55
11:35
09:55
09:40
09:50
13:55
13:35
12:05
11:55
T op
20.2 °C
21.2 °C
20.7 °C
21.0 °C
20.1 °C
22.0 °C
21.8 °C
21.8 °C
21.0 °C
No of votes
T op
Cold
Cool
A bit Cool
OK
A bit warm
Warm
Hot
Warm tendency
Neutral tendency
Cool tendency
2
3
5
6
7
8
9
10
11
Classrooms

Appendix E

Passive and low-energy cooling and solar control techniques for school buildings

Natural ventilation

Ventilation in schools is an issue of increasing interest due to its association with air quality and subsequently with pupils' productivity and health (Daisey et al., 2003, Clements-Croome et al., 2008, Bakó-Biró et al., 2012). Daytime cross flow and night purge ventilation could be applied to schools to dissipate heat. However, there are limitations with regards to their implementation in school environments, as discussed below.

Natural ventilation during the day through window opening in schools often conflicts with the need for a quiet classroom environment, especially in urban areas. External noise may obstruct class activities or distract pupils, affecting their performance (Dockrell and Shield, 2006). Based on recent research, this is even more critical for schools near airports where natural ventilation through windows is insufficient and subsequently the risk of overheating and poor air quality is high (Montazami et al., 2012).

Cross flow in school buildings may not always be possible due to the school's layout. Typical Victorian classrooms open into a central hall (Figure 2.1) whilst most post-war classrooms open into corridors (Figure 2.4). As discussed in section 2.1.2.1, cross flow ventilation using clerestory windows was adopted only in early post-war school designs, up to about 1949. Therefore, in most cases cross flow is probably not an option. Furthermore, in most schools, such as in the post-war case study school described in this thesis, the windows only open to a small extent for safety reasons, which makes daytime natural ventilation even more challenging. Safety reasons could also prevent night time ventilation from being implemented, unless there are clerestory or ceiling windows in the classrooms that cannot be easily reached from the outside.

Potential solutions for natural ventilation in schools are windcatcher ventilators and solar chimneys. Windcatchers (Figure E.1) have been found to be capable of delivering airflow of at least 3 l/s (minimum requirement) in classrooms, combined with open windows (Jones and Kirby, 2010). However, research showed that the cooling effect of windcatchers over occupied hours is limited, unless it is coupled with night time purge ventilation through the use of windows and the windcatchers (Elmualim, 2006). This strategy however could conflict with school safety policies which is an important limitation. Solar chimneys (Figure E.2) have been found to reduce indoor temperatures (Khedari et al., 2000) and can be effective even in multi-storey buildings (Punyasompun et al., 2009). Therefore, this system could be used in schools, if the required conditions are met, such as appropriate orientation and wind direction and speed.

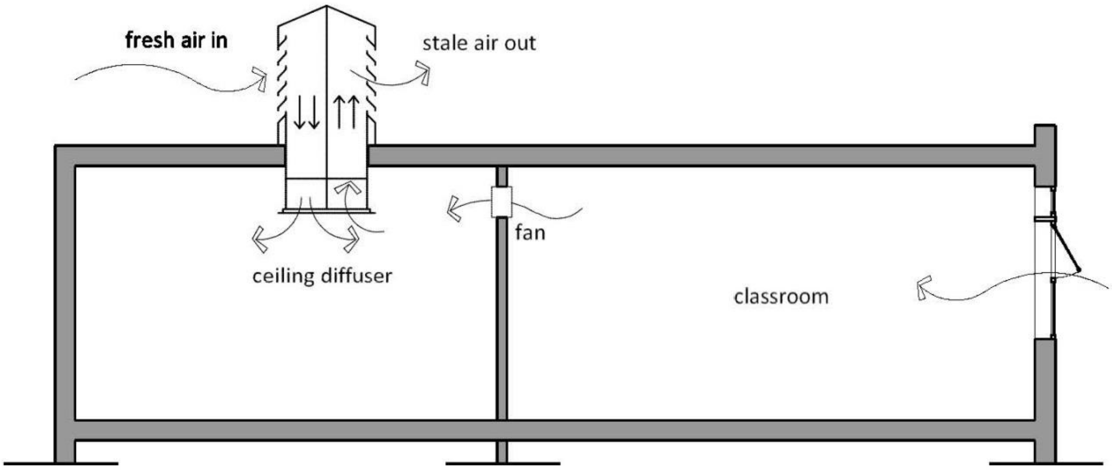


Figure E.1. Windcatcher system for use in schools.

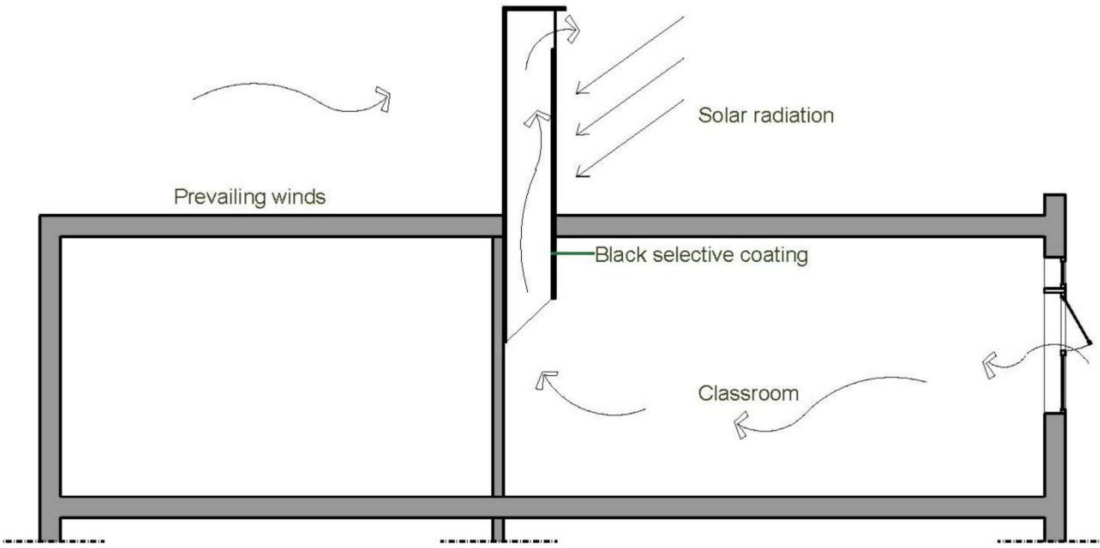


Figure E.2. Solar chimney example for use in classrooms.

Solar control and shading

This research showed that direct solar gains at pupils' desks may have a strong impact on pupils' perception leading to high thermal sensations, even when this is not coupled with higher temperatures than in classrooms with lower solar gains (section 7.2). Shading therefore appears to be necessary. However, there are specific requirements in schools related to shading solutions that need to be taken into account: a) provision for adequate daylight, b) safety risks, such as climbing over shading louvers (Figure E.3), c) impact on ventilation potential.

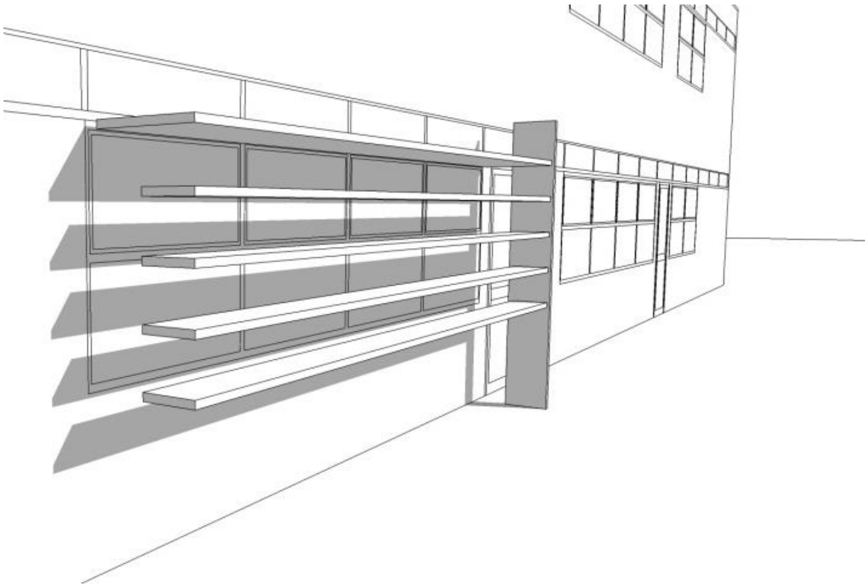


Figure E.3. Horizontal louvers at ground floor level.

Given the often large outdoor spaces in schools, landscaping could be used for shading, which would also improve air quality and the overall value of the schools' outdoor spaces (Figure E.4).

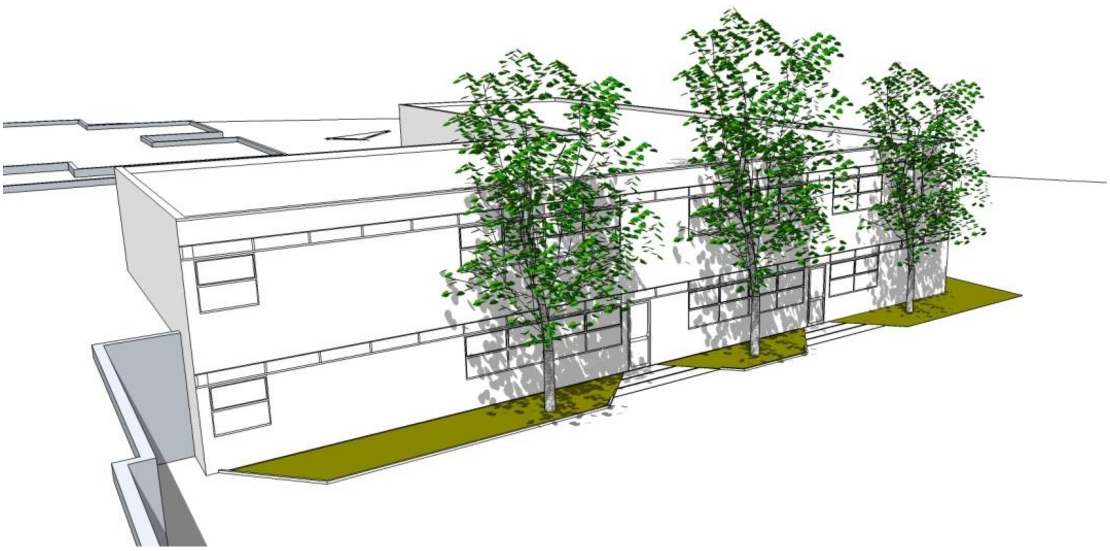


Figure E.4. Use of vegetation for classroom shading.

Building materials

As shown in section 8.3.3, in the heavy-weight Victorian school classrooms the operative temperature was significantly lower compared to the post-war light-weight school (Figure 8.19). Therefore, thermal capacity is an important parameter which should be taken into account in the design of new school buildings. Changing the construction materials in existing school buildings however, would not be an economically viable solution. In existing buildings, improvements could however be achieved by increasing the albedo (reflectivity) of the building façades (section 2.2.4). For example, research has found, through simulations, that white roofs and shade provided by trees in Los Angeles, USA, would decrease the cooling load by 18% (Rosenfeld et al., 1997). A combination of shading and light-coloured coatings in schools should therefore be investigated as a potential overheating mitigation measure.

Building layout design

Given the impact of solar radiation on pupils' perception found in this study, classroom orientation appears to be very important for thermal comfort in classrooms. Furthermore, the large variation in pupils' thermal sensation votes and gender differences in thermal preference reinforce the need for flexible layouts of learning environments which can be modified to match with individual thermal preferences (e.g. movable furniture, partitions, controllable shading).

Ground cooling

As discussed in this thesis, security is an important aspect in school buildings and affects the opening of windows for ventilation. A potentially safer ventilation system for schools is the earth-tube system, which uses the constant soil temperature at depths>2.0m to cool or heat the air passing through buried pipes (Lee and Strand, 2008). A design example of such an installation can be seen in Figure E.5 for the case study post-war school. However, such a system requires large open areas as the pipe length required is on average 50m (Darkwa et al., 2011). This supports their use in schools which usually have large school grounds. The cooling potential of earth-tube systems has been found to be significant and, under specific experimental conditions, savings of up to 50% of the cooling loads have been achieved (Lee and Strand, 2008). However, their cooling and heating potential is highly dependent on the local climate and soil conditions (Lee and Strand, 2008).

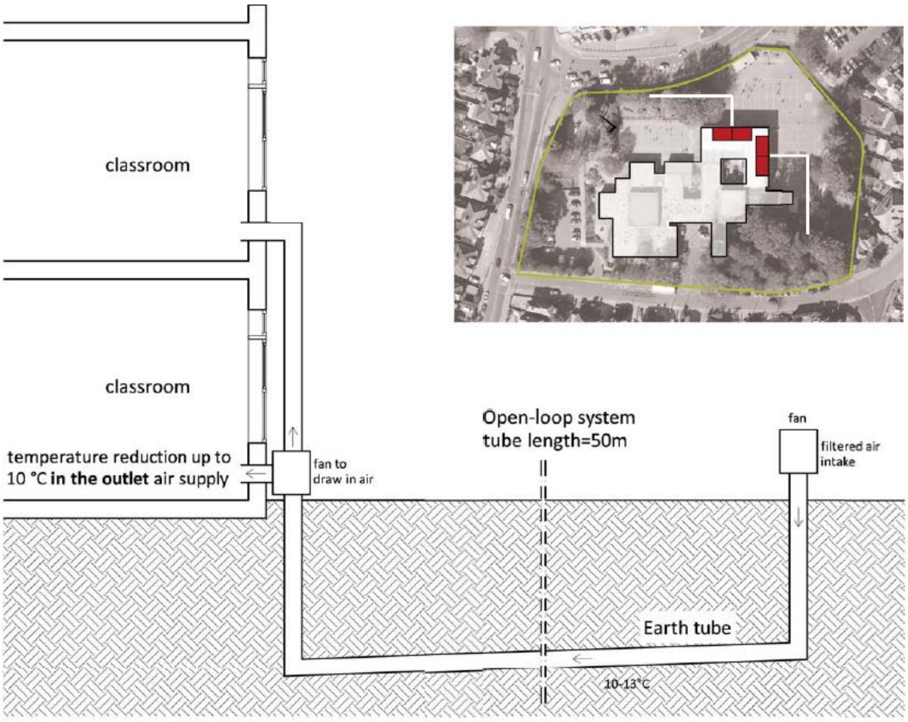


Figure E.5. Potential installation of an open-loop earth-tube ventilation system at the investigated post-war school building.

Occupant behaviour change and operational control management

In primary schools, classroom environments are mainly controlled by the teachers and caretakers. This study showed that pupils' overall feeling of comfort may not be related to their thermal state (section 5.5), which means that the teachers cannot count on the pupils' evaluation of their overall comfort for making decisions to change the thermal environment. Therefore, an appropriate management system is required, based on knowledge gained on pupils' specific requirements and comfort temperatures (chapter 6). This should be combined with seminars on children's thermal comfort response and preference for teachers and caretakers, in order to adapt their behaviour and environmental controls to children's specific needs.

Overall, the described passive and low energy cooling techniques could be used in schools to improve thermal comfort outside the heating season. However, the specific requirements of school spaces, such as safety and the diverse school day schedule, need to be taken into account. Furthermore, such measures should be implemented in ways that enhance the overall learning experience of children and improve the quality of learning spaces. External shading structures, for example, can create spaces for outdoor activities and social interaction (Figure E.6). Shading trees can also be used for educational purposes such as for getting familiarised with different plant species. A pond used for evaporative cooling could also provide material for experimentation and learning. Integrated solutions need to be investigated further, for quality school environments.

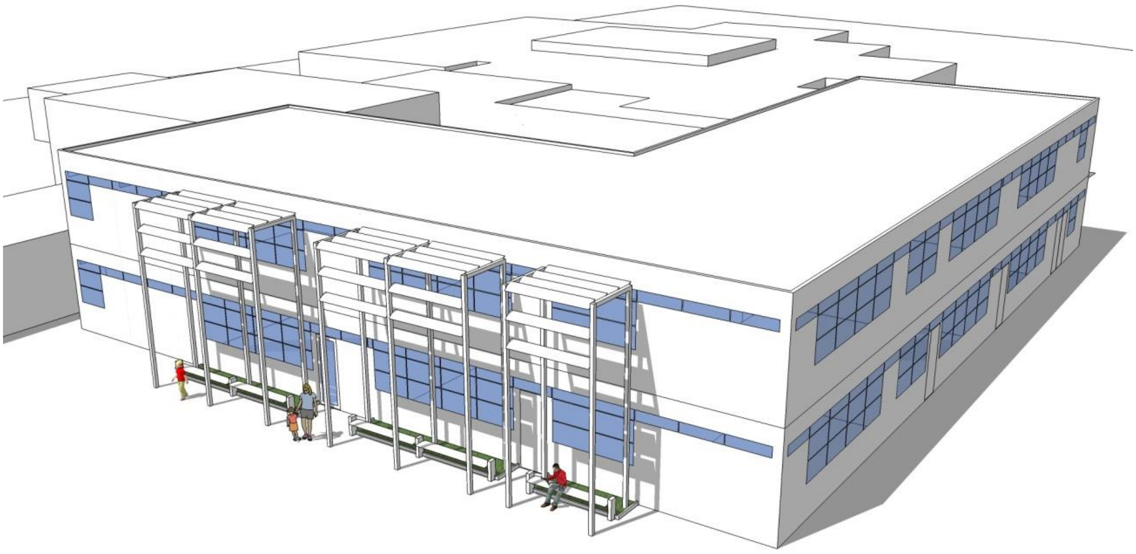


Figure E.6. Shading structure designed for the post-war case study building (constructed in 2011) which also accounted for outdoor seating space.