A PRACTICAL MODEL FOR THE ASSESSMENT OF THERMAL COMFORT IN TRAIN CARRIAGES

By

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TABLE OF CONTENTS

ABSTRACT

A practical model has been developed for the assessment of human thermal comfort in rail carriages. The PMV_{Model} is based upon the existing ISO 7730 standard for assessing moderate thermal environments (PMV: Fanger 1970), with correction factors to account for the extreme environmental stimuli that may be experienced by some passengers seated next to windows (i.e. exposure to direct solar radiation or the effects of a cold window). Three sets of laboratory experiments and four field trials were conducted. Environmental conditions and mean skin temperature were recorded and thermal rating questionnaires filled in by participants.

The PMV_{Solar} model (Hodder & Parsons, 2002) provided a corrective factor to account for the effects of direct solar radiation on thermal comfort whilst in neutral conditions. This model was tested in cool conditions (PMV = -1.5 ± 0.5) to ensure that it was applicable over a range on the ISO 7730 sensation scale. Eight male and eight female participants spent a 30 minute period of acclimatisation in a thermal chamber set to maintain PMV = -1.5 ± 0.5. They were then exposed to $600Wm^{-2}$ of solar radiation in the same environmental conditions. The mean increase in Actual Mean Vote (AMV) was 3.1 scale units, which was in keeping with predictive outputs from PMV_{Solar}.

Eight male participants were exposed for 30 minutes to a cold window of temperature 5 ± 1°C, in neutral conditions (PMV = 0 ± 0.5). The mean decrease in subjective sensation rating was 1 scale unit. Exposure was also found to create a thermal gradient across the body as well as draught. Existing models for assessing local discomfort (Draught and Radiant asymmetry) given in ISO 7730, were not found to accurately estimate the effects of the window.

Eight male participants were exposed on four separate occasions to 500 Wm^{-2} of solar radiation in neutral conditions (PMV = 0 ± 0.5), each time wearing each of a black/white, loose/tight shirt once. Clothing colour had a significant effect on thermal comfort. Clothing fit had no significant effect.

Four field trials, each using four male participants, were conducted between Loughborough and London St Pancras railway stations. The PMV_{Model} was found to perform better than the existing standard (ISO 7730) in terms of the relationship between the change in output and change in AMV. Pearson's correlations were conducted using data from laboratory experiments and field trials. Out of all models tested the PMV_{Model} was found to correlate best with AMV, and can be regarded as an accurate tool for the assessment of railway carriage environments.

STATEMENT OF DECLARATION

The work presented in this was part funded by the science faculty of Loughborough University and part funded by Rail Research United Kingdom (RRUK). The data collected by the Author was used, in addition with other data, to produce a practical model for the assessment of thermal comfort on rail carriages.

Experiment 1, described in chapter 3 represents is a continuation of work originally conducted by Parsons and Wales (2004), the first half of the (4 participants) data being collected by the fore mentioned persons. The remaining data was collected jointly by the author and Mr. M.Harnett. The author was responsible for assisting with the supervision of M.Harnett during this, his BSc dissertation work.

The study described in chapter 4 represents work conducted by the author during their own undergraduate dissertation. The data from this study was re-analysed and supplemented with addition thermal manikin data.

Chapter 5 is representative of work conducted jointly by the author and Prof. Ken Parsons of Loughborough University. Data from ten participants was collected by Prof Parsons, with data from the remaining six participants and thermal manikin being collected by the author. The author re-analysed the raw data obtained in this study for inclusion in this thesis.

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1 General Introduction

1.1 Chapter Summary

In this chapter the aims and objectives of this thesis are presented and explained. It investigates the factors that effect human thermal comfort, with particular reference to vehicle environments and environmental factors. It provides a basis for the laboratory experiments and field trials that follow, by highlighting the need for research and further understanding of how people interpret and react to their thermal environment.

1.2 Introduction

The aim of the research presented in this thesis was to investigate factors that may affect passenger comfort in train carriages, and produce a predictive model to assess passengers' 'local' thermal comfort by incorporating factors that influence them individually.

Passenger comfort is becoming increasingly important in the design of modern vehicles. The wide choice for consumers and increasingly competitive markets mean that simply getting from A to B is no longer enough. Customers are demand more from their mode of transport, creating an interest within the industry in improving vehicle comfort.

Thermal environments have been studied for over a hundred years. Faraday provided evidence as early as 1835 to a House of Commons committee, on the inadequacy of using air temperature alone in determining optimum conditions. As might be expected, the majority of research has focussed on thermal comfort in buildings and there is a great amount of literature available in this area. When compared with buildings however, human thermal environments in vehicles typically have much greater variation in space and time (Parsons, 2003) which can lead to a much more dynamic and rapidly changing internal thermal environment.

O'Neill and Whyte (1985) concluded that internal vehicle environments can often be greatly influenced by outdoor conditions, in particular solar radiation. Hodder and Parsons (2002) investigated the effects of direct solar radiation on participants in an otherwise neutral environment, deemed as PMV = 0 ± 0.5 (ISO 7730, 1994), concluding that thermal comfort was significantly affected in proportion to the intensity of the solar radiation (measured in Wm-2).

These findings not only provide a valuable tool in assessing thermal comfort where direct solar radiation is present, but also demonstrate the possible inadequacy of thermally assessing individuals in mass transit vehicles as one and the same. It has been argued that large closed vehicle environments such as can be found in ships, railway carriages and buses, environments can be assessed as for rooms (Parsons, 2003). It is perfectly feasible however, for one individual to be sat in direct solar radiation on one side of a bus, whilst another is completely shielded from it on the other. The fact that these two individuals will experience very different local thermal environments, presents an argument against evaluating the internal environment as a whole.

The aim of this thesis is to investigate conditions that are known to cause thermal discomfort that may need to be considered when evaluating vehicle environments for individuals; specific reference is paid to solar radiation (Rohles and Wallis 1979; Nielsen et al, 1988), radiant asymmetry (Olesen, 1985; McIntyre, 1980) and draught (Nevins 1971; Fanger and Pederson, 1977). A specific aim is to re-evaluate the predictive model given in ISO 7730 and adapted by Hodder and Parsons, by testing its effectiveness in different conditions, and extend it to incorporate some of the effects of the conditions outlined above.

1.3 Thermal Environments

The four basic environmental and two personal parameters that effect the physiological perception of thermal comfort are defined below.

1.3.1 Air Temperature (t_a)

Air temperature can be defined as 'the temperature of the air around a person', EN27726; 1993. Clothing acts as an insulative barrier between ambient air temperature and the body, which means the temperature of the air next to the skin is usually different from that of the environment as a whole.

1.3.2 Air Velocity (v_a)

This is often defined as the movement of air across or against the body. 'Mean' air velocity is often used as air movement is not constant in time, direction or space.

1.3.3 Humidity

The absolute humidity of air, describes the actual amount of water vapour contained in any given quantity. Relative humidity (Ø) is often used as an alternative measure and can be expressed as the ratio of the partial vapour pressure of water vapour to the saturated vapour pressure. It is often given as the percentage of water vapour contained in the air, to the maximum amount of water vapour it could contain at a given temperature.

1.3.4 Radiant Temperature

Heat is exchanged by radiation between all bodies. There is a net heat flow from a hot to a cold body by an amount related to the difference between the fourth powers of the absolute temperatures of the two bodies.

1.3.4.1 Plane Radiant Temperature (t_{pr})

Plane radiant temperature is defined as 'the uniform temperature of an enclosure where the radiance on one side of a small plane element is the same as the non uniform actual environment', ISO 7726 (1998). The effects of directional radiation are influenced by orientation and therefore the adequacy of a single measurement of t_{pr} is limited when attempting to accurately assess the radiant temperature of a given environment. Plane radiant temperature can be used to derive mean radiant temperature using the following equation.

$$t_r = \frac{0.08(t_{up} + t_{down}) + 0.23(t_{right} + t_{left}) + 0.35(t_{front} + t_{back})}{2(0.08 + 0.23 + 0.35)}$$

1.3.4.2 Mean Radiant Temperature (t_r)

This is defined as 'the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body is equal to the radiant transfer in the actual non uniform enclosure', EN27726, 1993. Radiant temperature can be derived by a number of methods, one of which is to obtain globe temperature (t_g), air temperature and air velocity and enter them in the following equation for natural convection:

$$t_r = \left[\left(t_g + 273\right)^4 + \frac{0.25x10^8}{\varepsilon} \left(\frac{\left|t_g - t_a\right|}{d} \right)^{\frac{1}{4}} x\left(t_g - t_a\right) \right]^{0.25} - 273$$

Or the following equation for forced convection (i.e. > 0.15m/s):

$$t_r = \left(\left(t_g + 273\right)^4 + \frac{1.1x10^8 v^{0.6}}{\epsilon d^{0.4}} x\left(t_g - t_a\right) \right)^{0.25} - 273$$

where,

ε = Emissivity of the globe
d = Diameter of the globe

1.3.5 Metabolic Heat Production

Metabolism is the process by which the body creates energy by converting food and oxygen. The energy produced is used for muscle contraction, blood circulation, breathing and building body tissues and so the more work the body does, the higher the metabolic rate. Due to the Human body's relative inefficiency when converting food and oxygen in metabolism, only some of the energy produced is used for work, the remaining energy is transformed into heat.

Metabolic rate depends on age, gender and body dimensions, but for all people regardless of this; the greater the level of activity, the greater the amount of metabolic heat production. There are a number of ways by which metabolic rate can be measured or estimated, however it is acceptable to use reference tables of estimates of metabolic rate for a number of activities (e.g. ISO 8996, 2004).

Table 1.1, Estimates of metabolic rates for various occupations (ISO 8996, 2004)

Occupation	**Metabolic rate (Wm^{-2})**
Clerical work	55 to 70
Janitor	80 to 115
Bricklayer	110 to 160
Butcher	105 to 140
Welder	75 to 125
Bus driver	75 to 125
Blast Furness worker	170 to 220

1.3.6 Clothing

Clothing helps humans sustain an acceptable thermal state by providing a resistant thermal barrier between the body and the environment, reducing evaporative and convective heat loss and heat loss through radiation. Because it reduces heat loss from the body, clothing is classified according to it's insulative properties.

The Clo unit was developed by Gagge et al (1941) and is still used today. 1 Clo is defined as being equal to the insulation provided by a standard business suit. A more technical unit by which to measure the insulative value of clothing is $m^2{}^\circ C/W$, where 1 Clo = $0.155 m^2{}^\circ C/W$. ISO 9920 (2003) provides tables of Clo values for individual garments, which can be added together to give a Clo value for a clothing ensemble. Table 2.2 gives examples of clothing items and their respective Clo values.

Table 2.2, Summary of clothing insulation values(ISO 9920, 2003)

Clothing Item	Thermal Insulation Clo (I_{clu})
T-Shirt	0.09
Short sleeved shirt	0.15
Normal long sleeved shirt	0.25
Shorts	0.06
Light-weight trousers	0.20
Normal trousers	0.25
Sweater	0.28
Coat	0.60

1.4 Heat Balance and Thermoregulation

People need to maintain an internal core temperature of around 37°C. Deviations from this will lead to physical problems and , if not rectified, eventually death. The heat produced from metabolism needs to be balanced by heat exchange with the surrounding environment to regulate the internal temperature. As the body's temperature is dynamic (kept between acceptable limits) and the level of metabolic heat production and surrounding environment are unique for a given point in time and space, humans have physiological and behavioural forms of thermoregulation to keep it in heat balance.

1.4.1 Vasoconstriction and vasodilation

The surface of the body, unlike the core, has a comparably large range of 'allowable' temperature fluctuation. Vasoconstriction and vasodilation are mechanisms that occur in the blood vessels near the surface to facilitate heat loss (vasodilation) or retention (vasoconstriction). When the body is too hot, blood flow is directed to the skin where capillaries dilate, increasing heat loss to the surrounding environment increases (vasodilation). If the body is too cold, blood flow is directed away from the skin to the vital organs to reduce heat loss to the environment (vasoconstriction).

1.4.2 Piloerection

Piloerection is an Integumentary System response to the cooling of the skin. The hairs on the surface of the skin stand on end to reduce convective heat loss by maintaining a layer of still air between the body and the environment. It's contribution to thermoregulation is questionable due to the relatively small amount of body hair that humans have and the fact that they are usually covered by clothing.

1.4.3 Shivering

Shivering has been described as an 'activity producing heat with no net external muscular work' (Parsons 2003). It can be both voluntary and involuntary (i.e. consciously controlled or not) and is controlled by the primary motor centre of the brain. Muscle groups contract and relax vigorously in response to a drop in core body temperature, increasing metabolic heat production in an attempt to restore it to an acceptable level. A bye product of shivering is an increase in blood flow which can make the mechanism counterproductive by increasing heat loss to the environment. It is thought that piloerection may be important to the effectiveness of shivering by reducing this heat loss.

1.4.4 Sweating

Sweating is a thermoregulatory response to an increase in body temperature, facilitating an increase in evaporative heat loss through the secretion of sweat by eccrine glands onto the external surface of the skin. It is complementary to vasodilation as the increase in skin temperature that this causes is transferred to the sweat, which then evaporates resulting in heat loss. Sweating is controlled by the autonomic nervous system and can happen as a response to thermal and non-thermal stimuli.

1.4.5 Behavioural thermoregulation

Arguably the most powerful form of thermoregulation is a person's behavioural response to their thermal environment. De Dear et al (1998) describe humans as 'playing an instrumental role in creating their own thermal preferences'. Any action that changes our thermal environment and/or our interaction with it could be deemed as behavioural thermoregulation. Examples of this could be changing posture to conserve heat (i.e. folding arms or curling into a ball), putting on or taking off clothes or moving out of wind or into shade. Nicol and Humphreys (2002) state that the fundamental assumption of this adaptive school of thought is the principle that 'if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort'. Technical regulation (Hensel, 1981) refers to a extension of this as more complex behavioural responses and involves designing an environment for human occupancy (i.e. building a shelter). All behavioural thermoregulation in voluntary and can reduce the burden on, or even remove the need for, physiological thermoregulatory mechanisms.

1.5 Thermal Comfort

Thermal comfort can be defined as 'That condition of mind which expresses satisfaction with the thermal environment' (ISO 7730, 1994). Whether a person is thermally comfortable or not is a subjective assessment, derived from the effect that the thermal environment has on the body and it's physiological responses to this. It is however a state of mind that reflects our individual feelings about our thermal state, and so cannot be solely attributed to these. Thermal comfort is often wrongly thought of, as being solely attributable to the surrounding air temperature (ta). Although this is an important factor, it is ultimately the interaction of this and several other parameters that makes the evaluation of thermal comfort so difficult. Indices can aid us in doing this.

1.5.1 Effective Temperature

Effective temperature (ET) is an index devised over a series of studies in the 1920's (Houghton and Yagloglou, 1923, 1924; Yagloglou and Miller, 1925). ET can be calculated using psychrometric charts, from the air temperature, air velocity and humidity are known. Parsons (2003) defines ET as 'the temperature of a standard environment that contains still, saturated air that would provide the same sensation of warmth as in the actual environment'. He also cites the limitations of the index when considering steady state environments, due to it overestimating the effects of humidity. Effective temperature did not initially consider the effects of radiation, but has since been corrected to amend this. The new index was aptly named Corrected Effective temperature (CET; Vernon and Warner, 1932).

1.5.2 Equivalent temperature

The Eupatheoscope was developed by Dufton (1929) to mimic the thermal interaction of the human body with the environment. This was an internally heated black copper cylinder that could maintain a set temperature, in spite of fluctuations in air temperature, radiant temperature and humidity. It was in essence one of the earliest forms of thermal manikin that simulated a humans dry heat loss, from which equivalent (T_{eq}) temperature was derived.

$$teq = 0.55t_a + 0.45t_r + \frac{0.24-0.75\sqrt{v}}{1+Icl}(36.5 - t_a)$$

Icl = Insulation index of clothing (1clo. = 0.155 m^2°C/W)

A heated dry manikin, Voltman, was used by Wyon (1982, 1985) to assess thermal environments in cars. The manikin was heated and the heat loss to the surrounding environment was calculated over a range of operational conditions. The results were integrated into equivalent temperature. The advancement of thermal manikins over the years, and the fact that they more accurately mimic the human form, has resulted in the existence of several rational indexes for it's calculation.

1.5.3 Operative Temperature

Operative temperature is defined as 'the temperature of a uniform black enclosure in which a human occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment. It is derived using the following equation:

$$t_o = \frac{h_r \, \bar{t}_r + h_c \, t_a}{h_r + h_c}$$

h_c = convective heat transfer coefficient, W/(m^2·°C)

h_r = linearized radiative heat transfer coefficient, W/(m^2·°C)

1.5.4 Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD)

In order to predict thermal comfort, we must first understand the conditions necessary to achieve it. These conditions were highlighted by Fanger (1970), in his highly influential text '*Thermal Comfort*'. Fanger's methods for analysing thermal environments in relation to thermal comfort are now the most commonly used and recommended. In his text, Fanger outlined the parameters (physical factors) which when combined, would ultimately determine human thermal comfort. These parameters (Air temperature, Mean radiant temperature, Air velocity, Relative humidity, Metabolic rate and the thermal resistance of clothing) have been detailed earlier in this chapter.

Fanger's comfort model was created from the results of studies conducted in a thermal chamber, with American students giving thermal sensation votes on a range of environmental conditions. The model takes into account the six basic parameters to give a PMV (ISO 7730, 1994) output on a seven point bi-polar scale and is derived from the following heat balance equation.

$$H - E_{dif} - E_{sw} - E_{res} - L = K = R + C$$

Where,

H = Internal heat production

E_{dif} = Heat loss by water vapour diffusion through the skin

E_{sw} = Heat loss by evaporation of sweat from the surface of the skin

E_{res} = Latent respiration heat loss

L = Dry respiration heat loss

K = Heat transfer from the skin to the outer surface of the clothed body (conduction through the clothing)

R = Heat loss by radiation from the outer surface of the clothed body

C = Heat loss by convection from the outer surface of the clothed body

PMV Scale:

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

Fanger's model can also be used to obtain the Predicted Percentage Dissatisfied (PPD), which is directly related to the PMV and predicts the percentage of people that will be dissatisfied with a given thermal environment. Fanger defined dissatisfaction as being above 2 or below –2 on the sensation scale, but as thermal comfort is a completely subjective interpretation of the environment, he suggests that even in neutral conditions (PMV = 0) there will be a minimum PPD of 5%.

1.5.5 Adaptive modelling

The PMV is the most widely used and recognised index for assessing thermal environments but despite this is not devoid of criticism with some people questioning it's validity and reliability. Oleson and Parsons (2002) question the sensitivity of the model and the fact that it has not been developed to correspond with improvements in the heat balance equation. They also question it's accuracy when used in field studies and the fact that it does not take into account cultural and ethnic diversity.

The general criticism of the PMV and other models is that they do not consider other factors, outside the six basic parameters, that are contributory to determining a person's thermal state. In essence they are 'static' and view humans as passive, when in fact our behavioural response to our thermal environment is often the most effective in altering our thermal state.

The American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) funded a wide scale survey of buildings throughout the world. The results of the survey were later developed into a global database. From this deDear and Brager (1998) proposed a thermal comfort standard that would take into account the effects of thermal adaptation. In doing this they made the distinction between buildings with centralized (i.e. centrally controlled) HVAC (heating, ventilation and air-conditioning), and buildings with natural ventilation. In HVAC buildings the PMV index was found to make accurate predictions, whereas in naturally ventilated buildings it was found to overestimate the effects of high and low air temperatures.

The hypothesis of adaptive thermal comfort predicts that contextual factors and past thermal history modify the occupant's thermal expectations and preferences.

People in warm climate zones would prefer higher indoor temperatures than people living in cold climate zones, which is in contrast to the assumptions underlying comfort standards based on the comfort model by Fanger. Adaptation is defined as the gradual lessening of the human response to repeated environmental stimulation, and can be both behavioural, physiological as well as psychological (deDear et al, 1997; cited in Hoof and Hensen).

Nicol and Humphreys (2002) state that the fundamental assumption of the adaptive approach is expressed by the adaptive principle: if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort. They go on to conclude that the options for people to react will reflect their situation: those with more opportunities to adapt themselves to the environment or the environment to their own requirements will be less likely to suffer discomfort. The authors make specific reference to PMV and ISO 7730, stating that it should note the limitations of PMV for use in buildings, and give a range of applicability in line with the empirical findings, but concluding additionally that PMV is capable of modification greatly to improve the validity of its predictions (Humphreys and Nicol 2002a).

The general conclusion of those supporting an adaptive approach is that 'rational indices are difficult to use in real situations and are poor indicators of comfortable conditions in buildings' (Nicol and Humphreys, 2002). Predicting thermal comfort in vehicles is different, due to the more limited opportunity of the occupants to adapt behaviourally as stated above. Because of this, it is thought that PMV will provide an adequate measure of internal vehicle environments on which to base the investigations in this thesis.

1.5.6 Local thermal discomfort

Fanger (1970) outlined three conditions required in order for a person to be in whole body thermal comfort.

1. The body is in heat balance
2. The sweat rate is within comfort limits
3. Mean skin temperature is within comfort limits

A fourth condition was later added, this being that there was an absence of any local thermal discomfort. Fanger stated that for the body to be in thermal comfort, all of the conditions highlighted above had to be met. This means that for at any give time although the body as a whole is thermally neutral and within comfort limits, if any local area experiences thermal discomfort, whole-body thermal comfort will not be achieved.

1.5.7 Draught

Draught is defined as unwanted local cooling of the body caused by air movement (ISO 7730, 1994). A major factor in a person's perception of a draught is their thermal state. It is possible that people who are already cold will feel draught more severely, however this has not yet been demonstrated (Parsons, 2003). Fanger et al (1988) investigated the effect of air turbulence intensity on the sensation of draught. Fifty subjects took part in three experiments with low medium and high turbulence intensities. In each experiment, subjects were exposed to six different mean air velocities in otherwise neutral conditions. Turbulence intensity was found to have a significant impact on the occurrence of draught sensation.

ISO 7730 (1994) proposes a draught rating index that predicts the effects of draught on a persons level of thermal comfort, by generating an prediction of the percentage of people that will be dissatisfied with the environment.

$$\mathbf{DR = (34 - t_a)(v - 0.05)^{0.62}\,(0.37vT_u + 3.14)}$$

Where,

DR	=	Draught rating (percentage of people dissatisfied due to draught)
T_a	=	Local air temperature (°C)
v	=	Local mean air velocity (ms^{-1})
T_u	=	Local air turbulence (%) defined as the ratio of the standard deviation of the local air velocity to the local mean air velocity.

1.5.8 Asymmetric thermal radiation

There is a constant radiation exchange between two bodies, with a net flow from the warmer body to the cooler one. This considered, a person has a dynamic radiation exchange with every object in their immediate environment. If one of these is sufficiently hotter or cooler than another then discomfort may be experienced due to radiation asymmetry, although this will be reduced if the thermal environment is otherwise thermally neutral (McIntyre, 1980). Radiant temperature asymmetry (Δt_{pr}) is the difference between the plane radiant temperature of the two opposite sides of a small plane element (Parsons, 2003). 'The concept of radiant temperature asymmetry is used when the mean radiant temperature does not completely describe the radiative environment' (ISO 7726, 1998). Olesen (1985) carried out experiments that investigated the relationship between radiant temperature asymmetry and thermal discomfort. Subjects were exposed to either a warm or cold, ceiling or wall, recording the percentage of participants dissatisfied at varying degrees of radiant asymmetry for each condition. ISO 7730 provides a means of estimation of the percentage of people dissatisfied as a function of the degree and type of asymmetric radiation (Figure 1.1)

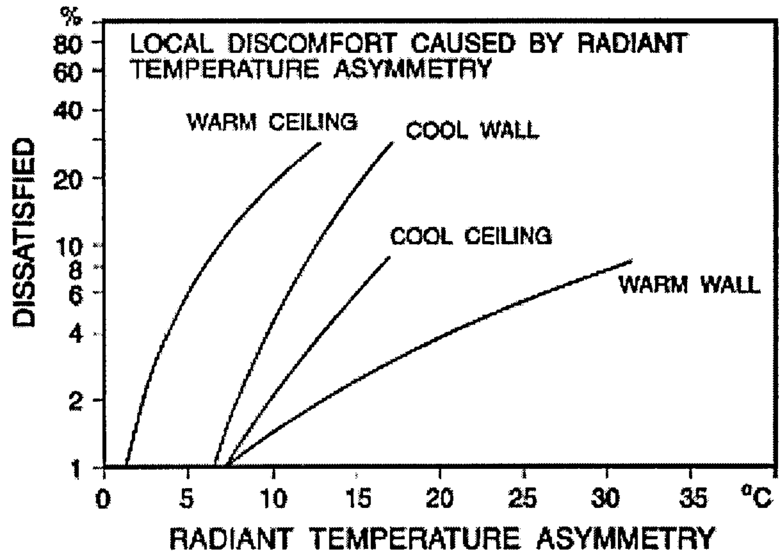


Figure 1.1, percentage of people dissatisfied as a function of the degree and type of asymmetric radiation

1.6 Experiments with solar radiation

A number of studies have investigated the effects of solar radiation on thermoregulation and thermal comfort.

Nielsen (1990) investigated the effects of artificial radiation on clothed subjects, each exercising for 60 minutes in four different clothing ensembles; these being black and white polyester and black and white cotton sports clothing. There was found to be little difference between the black and white materials in terms of solar radiation gains. Black clothing ensembles were found to have a significant effect on heart rate and sweat loss, when compared to white.

Mezrhab and Bouzidi (2006) describe a numerical model to study the behaviour of thermal comfort inside the passenger car compartment, according to climatic conditions and materials that compose the vehicle. To accomplish this, the compartment was subdivided into several solid nodes (materials constituting the compartment) and fluid nodes (volumes of air inside the compartment), with the establishment of the heat balance for each node giving the evolution of its temperature. The study produced the following conclusions:

- For a car parked facing the sun, the air and the materials reach considerable temperatures, such as about 100 °C for the dashboard.
- A considerable reduction of the temperature inside the compartment is caused by the use of a reflecting glazing and a white colour of the bodywork of the car.
- When the car runs with the air-conditioning on, the temperatures of solid nodes directly exposed to the cold blasts from the aerator decrease significantly.

Hodder and Parsons conducted a series of experiments to investigate the effects of different levels of solar radiation on thermal comfort when in an otherwise neutral environment; thermally neutral being defined as PMV = 0 $\pm$ 0.5. Participants were exposed to four different levels of simulated solar radiation (0, 200, 400 and 600Wm^2) for a period of 30 minutes, with subjective and objective responses being measured and recorded throughout. From this an adaptation of the PMV model was derived to take into account the effects of direct solar radiation . The model was named PMV_{Solar}

$$\mathbf{PMV_{Solar} = PMV + Actual\ Solar\ Radiation / 200Wm^{-2}}$$

1.7 Thermal comfort in vehicles

One of the main ways in which assessing thermal comfort differs when considering vehicles as oppose to buildings is the relative inability of occupants to thermo regulate behaviourally. For this reason static models, namely PMV, provide a solid assessment of vehicle environments. In recent years it has also been reported that thermal comfort in vehicles is much more complex than in buildings, a major factor being the intensive and non-uniform influence from solar radiation (Madson et al, 1992). The car for example is eminently sensitive to climatic conditions. The compartment is a place where often thermal discomfort is obvious. In winter, at least about ten minutes is often needed before obtaining an acceptable temperature in the car if it has been parked a long moment outside. In the same way in summer, it is difficult to settle into a car having been exposed several hours to solar radiation (Mezrhab and Bouzidi, 2005).

ISO 14505 part 3 (2006) adds weight to this argument by stating that although mathematical and physical models and thermal indices can provide repeatable, reliable methods of assessment, vehicle environments are often complex, dynamic and influenced by many factors. Models and indices are therefore often limited in validity. The standard also states that because comfort is a psychological phenomenon, thermal comfort is most effectively carried out using subjective methods that provide a direct and quantifiable method.

The acceptance that solar radiation could potentially be the largest cause of discomfort has resulted in it becoming a major topic of research in the area of vehicle thermal comfort. Parsons (1992), and more recently Hodder and Parsons (2002), have conducted research on this subject, which will be discussed in more detail later in this chapter.

Far less work has been conducted however, on discomfort caused by sources of cold when inside a vehicle and, as is argued below, there is good reason to investigate the effects of a cold window on thermal comfort. In application, passengers travelling in a vehicle at night may be exposed to such conditions regularly. The absence of solar radiation coupled with a low external air temperature and the movement of air across the external surface of the vehicle's windows, will cool them to the same equivalent temperature. These conditions are neither dependant on time of day, direction of travel (which may be the case when investigating solar radiation), nor speed. It therefore follows, that findings could have potential for application to several forms of mass transit vehicles.

1.7.1 Thermal comfort and trains

The British rail network is a multi-billion pound industry, relied upon by millions of people on a daily basis. Furthermore congestion charges, taxes on emissions and the heavy duty payable on fuel seem to be aimed at deterring the motorist whilst encouraging the use alternative forms of transport. It is widely accepted that the UK is several years behind some of our European counterparts in terms of the standard of our rail network and research is currently being funded through Rail Research United Kingdom (RRUK) into all aspects of train travel; thermal comfort and the thermal environments of train carriages being one of them. Thermal discomfort is a major factor limiting the use of public transport in London, consequently keeping car use levels high in urban areas (Maidment and Missenden, 2002).

The dynamic thermal environment makes it extremely difficult to assess thermal comfort in train carriages. The level of solar radiation may be a highly influential parameter, which will in turn be affected by several other factors, such as time of day, direction of travel and cloud cover. Another problem is the non uniform conditions, created by doors that are constantly being opened and closed. Persons in and around these areas may even be considered to be in a transitional space, depending on the frequency and duration of door openings. Chun et al (2004) define transitional spaces, as locations where the physical environment bridges between the interior and exterior environment—a modified climate characterized by highly variable physical conditions. Furthermore, they argue that PMV should not be used for transitional space thermal comfort predictions because of its unstable and dynamic nature. The main area of a train carriage, although affected by this, should not fall into that category.

1.8 Thesis Layout

The aim of the thesis is to produce a predictive tool, that will take into account 'local' and personal factors, to evaluate human thermal comfort in rail carriages. The initial laboratory experiments will investigate the affects on thermal comfort of conditions regularly found on trains, i.e sitting next to a cold window or in direct solar radiation. For the latter of these, a model (PMV_{Solar}; Hodder and Parsons, 2002) already exists and this will be validated in cooler environmental conditions. A laboratory experiment will also be conducted to investigate the effects of the colour and fit of clothing on thermal comfort when in direct solar radiation. The results of the experiments will be collated and used to derive a predictive tool that will be tested and validated in field experiments.

2 Experimental Methodologies

2.1 Chapter summary

This Chapter provides an introduction to the experimental research methods that were used to investigate the issues within this thesis. It offers an explanation of the techniques and outlines their suitability when evaluating the environments that were investigated. It also describes the experimental facilities that were used and details the experimental protocol and procedures for the laboratory experiments and field trials.

2.2 Methods of Investigation

Thermal comfort has been investigated in three manners:

1. Laboratory experiments with human subjects
2. Field Experiments with Human subjects
3. Experiments with a thermal manikin

2.2.1 Laboratory experiments with human subjects

Using experimental laboratory studies allows close control over environmental and personal parameters and easy manipulation of the independent variable. The ability of the experimental facility to closely replicate solar radiation is paramount to producing valid and meaningful results.

2.2.2 Field Experiments with Human subjects

Field trials provide a 'real world' environment resulting in a high 'face validity' of the results obtained. However, there is little or no control over weather conditions and the experimenter often has to investigate the thermal environment presented to them. The United Kingdom is well suited to field trials as it offers a range of different weather conditions and thermal environments to investigate. This however, also poses a problem in that it may not be possible to investigate specific conditions on a specific day. Field trials will therefore have to be repeated until the desired range of has been attained.

2.2.3 Experiments with a thermal manikin

The manikin studies can be conducted in both the laboratory and the field. The use of a thermal manikin is a lot more flexible than that of human subjects and is also devoid of potentially large differences in the subjective opinion of people assessing an environment. However, there is a large issue presented when using a thermal manikin to replicate a human when investigating the effects of solar radiation. The manikin primarily works by determining heat loss in a thermal environment, by calculating the required amount of energy needed to maintain a fixed body temperature. Solar radiation can cause significant heat gain to a body and, because manikins do not possess an active cooling system as humans do, they will not accurately simulate a human subject in the same conditions. The manikin therefore is not suitable to use as a substitute for human subjects, but can be used to provide accurate information into the heat gained by a body in different intensities of solar radiation.

2.3 Experimental Methods

A generic protocol was used in the laboratory experiments undertaken as part of this thesis. The generic facility, methods and procedures are described in detail in this chapter and the individual experimental design for each lab study is explained in their relevant chapters.

2.3.1 Test Facility

The parameters that affect a person's thermal comfort were outlined in the previous chapter. The laboratory experiments required a test facility that was able control these parameters and maintain 'thermally neutral' conditions whilst subjects were exposed to a stimulus. A purpose built solar simulation chamber had previously been designed by Hodder and Parsons at Loughborough University and been used in a number of similar experiments to investigate the effects of solar radiation on human thermal comfort. The ability of the chamber to control environmental parameters was demonstrated during these experiments and so the chamber was chosen for use in the laboratory experiments within this thesis.

The chamber is constructed from insulated box panels of 18mm plywood skins with a 50mm timer inner frame. This is insulated with Rockwool with a K value of 0.036 $Wm^{-2}K^{-1}$. The chamber is fitted with an air conditioning unit that can be set to provide a thermally neutral environment, PMV = 0 $\pm$ 0.5, (ISO 7730: 1994). The chamber is fitted with a specially designed end panel that includes a vertical and a 45° angled frame. Glazing can be placed in both of these frames which allows for the simulation of different vehicles, such as the front seat of a car (angled frame) or a window seat in a train (vertical frame).

The lamps used to simulate solar radiation are positioned outside the chamber to prevent excessive heating of the air inside the chamber, as the housing of each lamp can reach temperatures in excess of 150 °C when in use (Hodder, 2002).

The glazing is cooled externally with fans that produce an airflow over its external surface at a velocity of approximately 3 ms^{-1}. This prevents any notable temperature increase in the glazing and ensures that any re-radiation from it is minimal and insignificant.

The cold box used to simulate cold external environments is positioned externally around the window frame to cool the outer surface of the window .

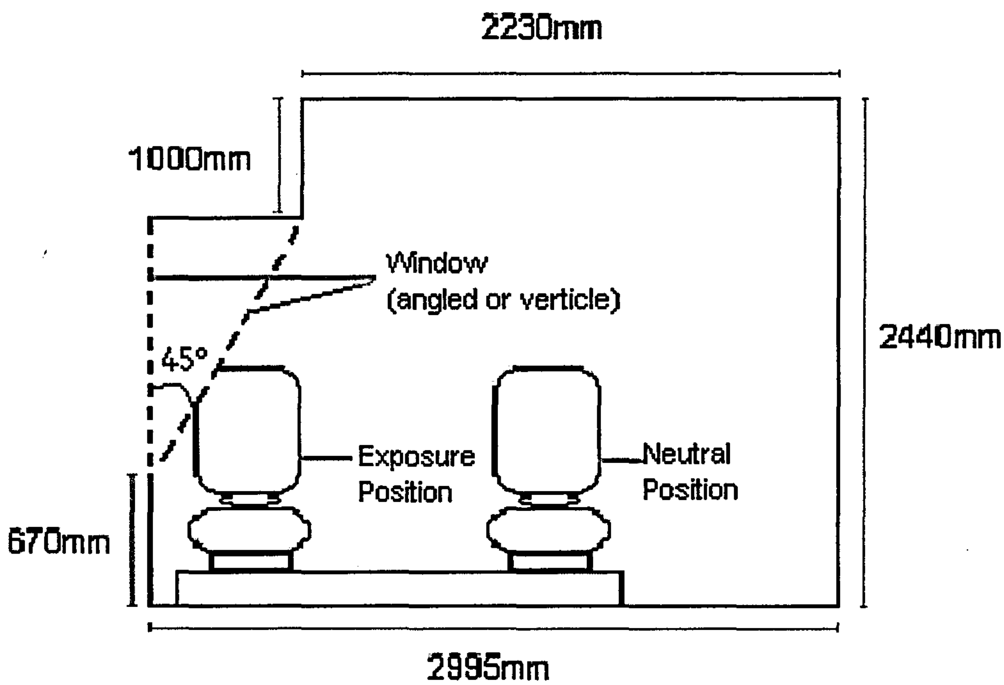


Figure 2.2, Schematic of the solar simulation chamber showing its dimensions and the angled and vertical frames at one end.(not to scale)

The chamber contains two Fiat Punto car seats that are fitted to movable bases. The base is fitted with wheeled tracking that allows the seat to be moved back and forth in one directional plane. The base fits into track on the floor of the chamber which allow it to be moved in to, or away from, the stimulus at the window. One seat is fixed perpendicular to the tracking on the base, and one parallel to it. This allows subjects to be exposed both side-on to a stimulus or facing it. The chamber is shown in Figure 2.2 and Figure 3.2

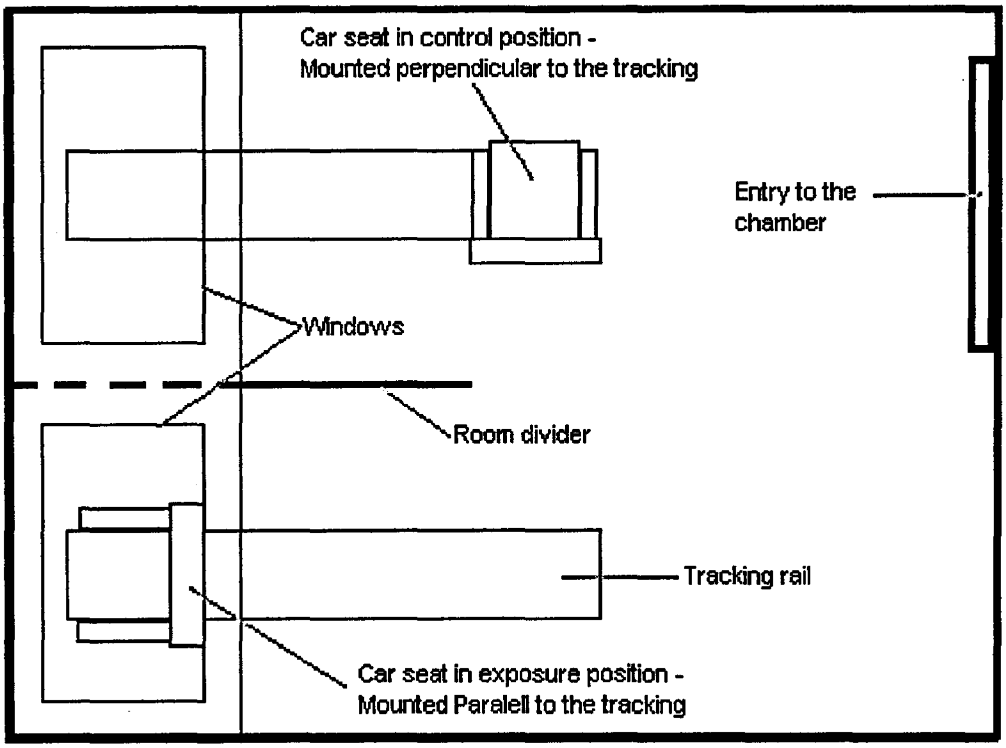


Figure 3.2, Plan view of the test chamber showing the car seats and rails into which they fit

2.3.2 Simulating Solar Radiation

The solar lamps used to simulate solar radiation are 1000 Watt metal halide CSI lamps, manufactured by GE lighting. The lamps use housings, igniters and ballast units manufactured by Thorn Lighting and produce light that has a spectrum similar to that of sunlight.

The lamps are fitted on runners and mounted on a steel rig positioned in front of the windows of the test chamber. The lamps can be moved up and down the rig at an angle of 45°, thus increasing or decreasing their distance from the window and the subject. The intensity of solar radiation falling on the subject was manipulated by moving the lamps in this way, (Figure 2.4)

Figure 2.4,Solar simulation chamber with external lamp rig

2.3.3 Cooling the Window

In order to simulate cold external environmental conditions, the external surface of the window needs to be cooled. This was achieved by creating a cold microclimate next to the window outside the chamber, by means of an insulated box around the window, in which ice containers can be stacked (Figure 2.5). The box has a wooden frame with three shelves and an outer layer of blue modelling foam for insulation. The dimensions of the frame are identical to those of the window. The blue foam fits securely around the window frame and is held in place using duck tape.

The insulated frame has a removable back, constructed of blue foam, that fits into it to create an insulated space on the outside of the window. Ice containers were pre-frozen to around –20°C and placed in the frame along with a small electric fan. The fan circulated air inside the box to evenly distribute the cooling effect on the outer surface of the window.

Figure 2.5, The insulated box used to simulate cold external environmental conditions. view from inside and outside

In pilot studies it was found that the effect of the box, was to reduce the internal surface temperature of the window to around 6°C or below, for a period of up to 50 minutes (Figure 2.6).

Further details and descriptions of the cold-box can be found in the appendices, along with details of the pilot studies conducted to test different methods of cooling the window.

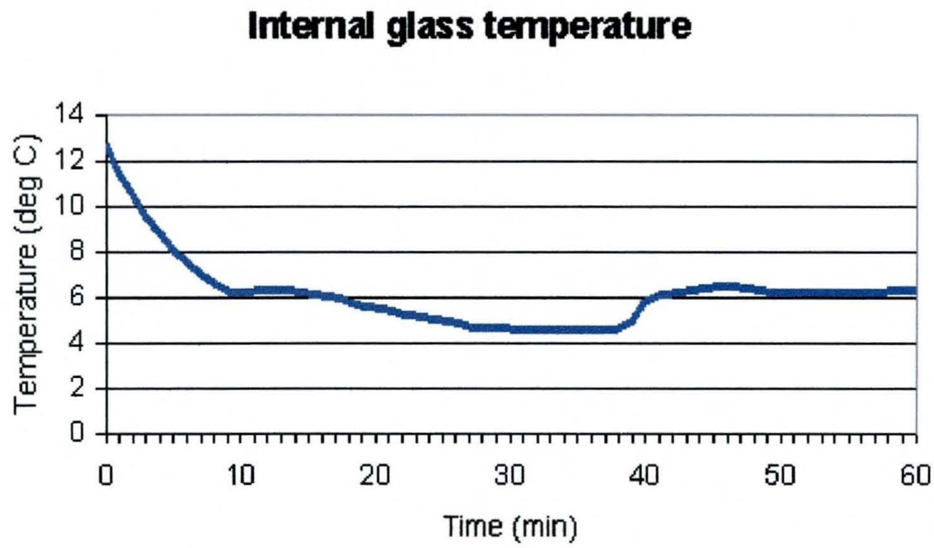


Figure 2.6, Graph showing the internal surface temperature of the window during a pilot study using the cold-box.

2.3.4 Environmental Measurements

Environmental conditions were measured throughout the chamber during lab experiments

- t_a – At various points around the chamber using thermistors. The thermistors were wrapped with aluminium foil to minimise the effects of radiation.
- t_r - Using 150mm diameter black globes
- Air velocity using a hot wire anemometer and kata thermometer
- Relative Humidity using a Solax hygrometer

Environmental conditions were recorded every thirty seconds, unless otherwise stated, using Eltek / Grant squirrel data loggers. Direct radiation was measured with a Skye pyronometer SP1110. Measurements of direct solar radiation were taken relative to the subjects' chest or upper arm when the car seats were fully inserted into the radiation.

2.3.5 Objective measurements

A series of physiological measurements were taken on each subject, during each experiment.

2.3.5.1 Mean skin temperature

The skin acts as an interface for thermal sensations (Hodder, 2002), with heat exchanges between body core and the external environment. Mean skin temperature is a good predictor of sensation and discomfort (McIntyre 1980). Other physiological responses, such as sweat rate, pulse rate and rectal temperature, respond only slightly or do not respond at all to variations in the external temperature (Givoni 1976). A measurement of mean skin temperature will therefore provide a reasonably responsive and accurate objective measure, by which to assess Participants' reactions to their thermal environment. Skin temperature is usually measured in the following ways

- Radiometric Methods
- Contact techniques

2.3.5.2 Radiometric Methods

The technique utilises infra red thermal imaging to produce an accurate measure of skin temperature. The temperature of a surface is measured by detecting the thermal radiation that it emits (McIntyre 1980). The main advantage of this technique is that it is non contact, however it only measures the temperature of the first surface it comes into contact with. If the subjects being measured are wearing clothes, as is the case in this thesis, the temperature measurement will be of the clothing surface as oppose to the skin. The equipment tends to be sensitive and expensive; it tends to be impractical in real world situations, as well as in areas where space is limited (Hodder, 2002). For these reasons it is thought that the use of remote methods to measure skin temperature would be impractical for the experiments in this thesis.

2.3.5.3 Contact techniques

This method uses thermistors or thermocouples attached to the skin to measure surface temperature. This provides a more practical method than the use of radiometric techniques, but due consideration must be given to errors that are present with the use of thermistors. In most cases, the presence of a thermocouple, or any alternative transducer, will cause a perturbation of the temperature distribution at the point of attachment (Hoersch et al 1993). McIntyre (1980) also highlights also highlights the problem of the sensor acting as an insulator over the point of contact, but that error can be minimised by the use of a small thermistor or thermocouple wire. The use of small thermistors will therefore be used to provide an objective measure of mean skin temperature during the lab experiments.

2.3.5.4 Weighting techniques

When measuring mean skin temperature, it is important to recognise the inadequacy of measuring at only one point. In contrast with the consistency of the internal body temperature, the temperature of the peripheral tissues may vary greatly within the range 15-40° C (Givoni 1976). The four-point Ramanathan (1964) technique for weighting skin temperature is widely used today. It incorporates all of the major body areas, requiring measurements at the Chest, upper arm, thigh and shin in the following formula:

$$\mathbf{t}_{sk} = (\mathbf{t}_{skchest} * 0.3) + (\mathbf{t}_{skupperarm} * 0.3) + (\mathbf{t}_{skthigh} * 0.2) + (\mathbf{t}_{skshin} * 0.2)$$

Although it could be thought that weighting techniques that use a large number of thermistors, such as the Hardy/Dubois 12-point method or QREC 10-point method, should provide a more accurate portrayal of mean skin temperature, the Ramanathan method has been found to correlate well with optimal skin temperature and be less dependant than most on the temperature range it is measuring Mitchell and Wyndham (1969). Parsons (2003) highlights the practical considerations of the time required to prepare a person for measurement and the interference caused by the associated wires and equipment. With this in mind, the Ramanathan formula will be used to weight thermistor measurements.

Figure 2.7, Example of the standard clothing ensemble

2.3.6 Subjective Measurements

Subjects' Psychological reactions to the thermal environments were assessed by means of a generic questionnaire (Figure 2.8).

2.3.6.1 Generic Questionnaire

The questionnaire was derived from a similar one, that had previously been used by Hodder and Parsons (2002) in a series of experiments to investigate subjective responses to simulated solar radiation. Amendments were made to it to allow accurate assessment of the thermal environments created in this thesis. The questionnaire required subjects to rate themselves both in terms of overall feeling and in specific sections of their body.

Date:__________ Time:__________ Experimental time:__________ Subject:__________

1. Thermal Environment. Please rate how YOU feel NOW:

	Overall	Head	Trunk Left	Trunk Right	Arms Left	Arms Right	Upper legs Left	Upper legs Right	Lower legs/Feet Left	Lower legs/Feet Right
3 hot										
2 warm										
1 slightly warm										
0 neutral										
-1 slightly cool										
-2 cool										
-3 cold										

	Overall	Head	Trunk Left	Trunk Right	Arms Left	Arms Right	Upper legs Left	Upper legs Right	Lower legs/Feet Left	Lower legs/Feet Right
4 very uncomfortable										
3 uncomfortable										
2 slightly uncomfortable										
1 not uncomfortable										

	Overall	Head	Trunk Left	Trunk Right	Arms Left	Arms Right	Upper legs Left	Upper legs Right	Lower legs/Feet Left	Lower legs/Feet Right
4 very sticky										
3 sticky										
2 slightly sticky										
1 not sticky										

	Overall	Head	Trunk Left	Trunk Right	Arms Left	Arms Right	Upper legs Left	Upper legs Right	Lower legs/Feet Left	Lower legs/Feet Right
4 very draughty										
3 draughty										
2 slightly draughty										
1 not draughty										

2. Please rate on the scale how YOU would like to be NOW:

Much warmer | Warmer | Slightly warmer | No change | Slightly cooler | Cooler | Much cooler

3. Please Rate on the scale how YOU feel NOW in this thermal environment:

Very pleasant | Pleasant | Slightly pleasant | Neither pleasant nor unpleasant | Slightly unpleasant | Unpleasant | Very unpleasant

4. Please indicate how acceptable YOU find this thermal environment NOW:

acceptable ☐ unacceptable ☐

5. Please indicate how satisfied YOU are with this thermal environment NOW:

satisfied ☐ dissatisfied ☐

Comments, (Main source of discomfort):____________________

Figure 2.8, Field trial questionnaire containing all scales

2.3.6.2 Thermal Sensation

The scale used by Hodder to measure thermal sensation evolved from the ISO scale used to evaluate thermal comfort (ISO 7730). The ISO scale ranges form –3 (Cold) to +3 (hot) with 0 being neutral, and allows a persons thermal sensation to be quantified by means of a numeric value.

ISO 7730:	+3	Hot
	+2	Warm
	+1	Slightly Warm
	0	Neutral
	-1	Slightly Cool
	-2	Cool
	-3	Cold

Whist the ISO scale is adequate and widely used to measure thermal comfort, Hodder thought that a 7 point bi-polar scale may not be sensitive enough to allow participants to accurately express the effects of solar radiation. With this in mind, he extended the scale by a further two points at the positive end, based on a wider scale outlined by Givoni (1976 and ISO 10551)

Givoni Scale:	0 – Unbearably cold	5 – Slightly warm
	1 – Very cold	6 – Warm
	2 – Cold	7 – Hot
	3 – Cool	8 – Very hot
	4 – Comfortable	9 – Unbearably hot

Hodder Scale:	+5	Extremely Hot
	+4	Very Hot
	+3	Hot
	+2	Warm
	+1	Slightly Warm
	0	Neutral
	-1	Slightly Cool

Although Hodder only utilised part of the scale, due to the investigation of conditions expected to be warm, essentially the full version of this adapted ISO scale is an 11 point bi-polar scale, ideal for evaluating the wide range of thermal environments presented in this thesis. The rating scales used were continuous Likert ones that subjects could mark at exactly the point that represented the thermal sensation they experienced. These were preferred to discreet point scales as they allowed participants to more precisely record how they felt.

i.e. They could rate themselves as +2.5 (between warm and hot) or 3.1 (just above hot) etc.

Fully extended version of the ISO scale:	+5	Extremely Hot
	+4	Very Hot
	+3	Hot
	+2	Warm
	+1	Slightly Warm
	0	Neutral
	-1	Slightly Cool
	-2	Cool
	-3	Cold
	-4	Very Cold
	-5	Extremely Cold

2.3.6.3 Thermal Comfort, Stickiness and Draughtiness

The questionnaire also uses the same scales as Hodder's to evaluate thermal comfort and stickiness. Parsons (2003) states that thermal sensation is a bipolar phenomenon; i.e. it ranges form uncomfortably cold to uncomfortably hot with comfort or neutral sensations being somewhere around the middle. As a persons perception of comfort is open to interpretation and subject to wide variation, Hodder used a 4 point discomfort scale to assess thermal comfort where not uncomfortable/no discomfort would be viewed as a state of thermal neutrality.

Thermal Comfort Scale:	4	Very Uncomfortable
	3	Uncomfortable
	2	Slightly Uncomfortable
	1	Not Uncomfortable

A continuous Likert scale was again used and as the level of discomfort increased from not uncomfortable, it was associated with deviation from neutrality in subjects' thermal sensation. The scale is in keeping with the view that Comfort is an absence of discomfort and it was observed by Hodder that it could provide valuable information about how far from neutrality a person can be before it starts to become an issue in their thermal comfort.

A similar scale was used to assess Stickiness, a term used to incorporate the experience of sweating and skin wettedness. Hodder proclaimed that perceptions of stickiness can provide information about a subject's source of thermal discomfort, increases in stickiness being associated with an increase in sweating, and that ratings of thermal sensation, comfort and stickiness were highly correlated with each other.

Stickiness scale:	4	Very sticky
	3	Sticky
	2	Slightly sticky
	1	Not sticky

As some of the conditions in this thesis will expose participants to a cold stimulus rather than radiation, a draughtiness scale will also be used on the questionnaire on relevant occasions. The scale is again based on the four point thermal comfort scale. A draught is defined as unwanted local cooling of the body caused by air movement (ISO 7730, 1994), and Parsons (2003) states that the human body can perceive relatively low air movements. It is thought that the cold surface of the stimulant will cause convection currents that could result in local discomfort to areas of participants' bodies. A draught scale will provide useful information into how closely the perception of draught is linked to thermal discomfort.

Draught scale:	4	Very draughty
	3	Draughty
	2	Slightly Draughty
	1	Not Draughty

2.3.6.4 Thermal preference, satisfaction and environmental acceptability

In the final sections subjects are asked to rate the environment in terms of their thermal preference, and indicate whether they find it acceptable and satisfactory. The preference scale is a bipolar scale ranging from much warmer to much cooler with no change in the centre and is based on recommendations made by McIntyre (1980).

Preference scale:

Much Warmer	Warmer	Slightly Warmer	No Change	Slightly Cooler	Cooler	Much Cooler

Participants were asked to indicate whether they found the environment acceptable and satisfactory using simple yes/no tick boxes. This provides a crude but useful indication of the PPD which can then be compared with the actual PPD calculated for that environment.

2.3.7 Participant clothing

To standardise the experiments and ensure validity, each participant will wear a standard clothing ensemble (Figure 2.7). The one chosen has previously been used by Hodder and Parsons (2002) and has been selected as an appropriate representation of what the average person might wear from day to day. The ensemble consists of a long sleeved white shirt, with the sleeves rolled up to the elbow and top button unfastened, and beige trousers. Both the trousers and the shirt are 65%/35% cotton/polyester mix, and several different sizes will be available, to accommodate participants' individual anthropometric dimensions. Participants will wear their own undergarments and shoes. The clothing ensemble, coupled with the insulation provided by the chair in the test facility, has an estimated insulation value of 0.72 Clo. Variations of the clothing ensembles were used in one of the laboratory experiments to include black and white, loose and tight fitting shirts (Figure 2.9)

Figure 2.9, Example of variations of the standard clothing ensemble

2.4 Procedure

The generic procedure used for the laboratory experiments is outlined below. In some cases there were changes made to the environmental conditions, stimulus and preparation conditions and these are outlined in the relevant chapters.

Subjects arrived at the laboratory approximately 30 minutes before the experiment, at which point the solar simulation lamps were turned on if they had not already been previously. They were asked not to engage in any exercise or strenuous physical activity for 2 hours prior to the experiment, which helped ensure that they reached a state of thermal neutrality relatively quickly once they arrived at the lab. Upon arrival they were taken to a thermally neutral preparation room, where they completed medical consent forms, had their temperature taken orally and were briefed on experimental procedure and withdrawal criteria. After the consent forms were completed and the subject had been briefed and deemed fit to participate they were fitted with thermistors and dressed in the standard clothing ensemble. They then remained in the thermally neutral room for a total period of around 30 minutes, at which point they were asked to fill out a questionnaire to assess their thermal state. If they rated themselves as 0 (thermally neutral) $\pm$ 0.5 they were deemed ready for participation. If they were not thermally neutral, they were left in the room until they reached thermal neutrality, which was ascertained by the completion of further questionnaires. The last questionnaire completed prior to leaving the room was deemed the 'neutral' questionnaire.

The subjects' were taken into the solar simulation chamber and seated in the car seat. At this point the seat was in the neutral position and the stimuli shield was in place, so that they were totally shielded from the stimulus. They were left in this position for 5 minutes to ensure that they were still thermally neutral and allow them to assess the thermal environment without the presence of the stimulus. At the end of this period they completed a questionnaire – the 'pre' questionnaire. The subjects seat was then pushed into the stimulus, the shield removed and they were given another questionnaire to complete. Questionnaires were then administered every five minutes for a 30 minute period. Subjects were asked to remain a still as possible during this time. After competition of the '30' minute questionnaire, the seat was withdrawn from the stimulus to the neutral position and the shield repositioned. The subjects remained in this position for 5 minutes at which point the 'post' questionnaire was administered.

The subjects were then taken back to the thermally neutral room where they changed back into their own clothes and had their oral temperature taken. When female participants were used, a female lab technician was present to assist in dressing/undressing and the fitting of thermistors.

2.5 Calibration of Equipment

2.5.1 Aim

Calibration is the determination of the correct value of each reading on a measuring instrument. The aim of the calibration process is to ensure that data collected from experiments using this equipment will give an appropriate representation of actual real-world values. This is done by comparing an instrument's outputs to known, accurate values.

2.5.2 Thermistors

Thermistors were used extensively in lab experiments and field trials to measure mean skin temperature, air temperature and globe temperature. They were calibrated throughout the ranges at which they were required to operate using a water bath. The temperature of the water bath was measured using an independently calibrated and certified mercury in glass thermometer. Thermistors were stirred in the water bath and their output temperatures compared to the thermometer. Thermistors were accepted for use if they were within $\pm$ 0.1°C. Thermistors were calibrated prior to each laboratory experiment or field trial.

2.5.3 Thermal manikin

The thermal manikin was calibrated immediately prior to the manikin lab experiments, all three of these being conducted in close proximity. A thermal chamber that was designed to maintain a set temperature and humidity was used as the facility for calibration. To ensure accuracy, the manikin required calibration at two temperatures, these being at either end of the range in which it was expected to operate (around 15°C and 35°C).

All the manikins clothes were removed and it was hung from a rig in the chamber, by means of a rope attached to the top of it's head, so that the entire body was free from contact with other surfaces. This ensured that the manikin had no form of material insulation and that there would be no insulative effects attributable to posture. Four pieces of string; on in front one behind and one at either side of the manikin; were also suspended from the rig and secured to the floor using duck tape. Calibrated thermistors (see section 5.3.2) were attached to the string at different heights around the manikin, including one above the head and one below the feet.

This enabled the measurement of local air temperature around the manikin. Four fans were positioned at different points around the manikin and blew air directly at it to remove any vertical air temperature gradients.

The manikin was set to a 'No Heat' setting which restricted power input and the manikin was left to reach equilibrium with the surrounding environmental conditions. At this point readings from the manikin were essentially measuring it's temperature – which should have been equal to air temperature. The chamber temperature was monitored using the 8 thermistors and once the manikin had reached steady state it was calibrated in accordance with thermistor readings.

Calibrations were conducted with the manikin at steady state at 14.8°C and at 34.85°C, the results of which are shown below:

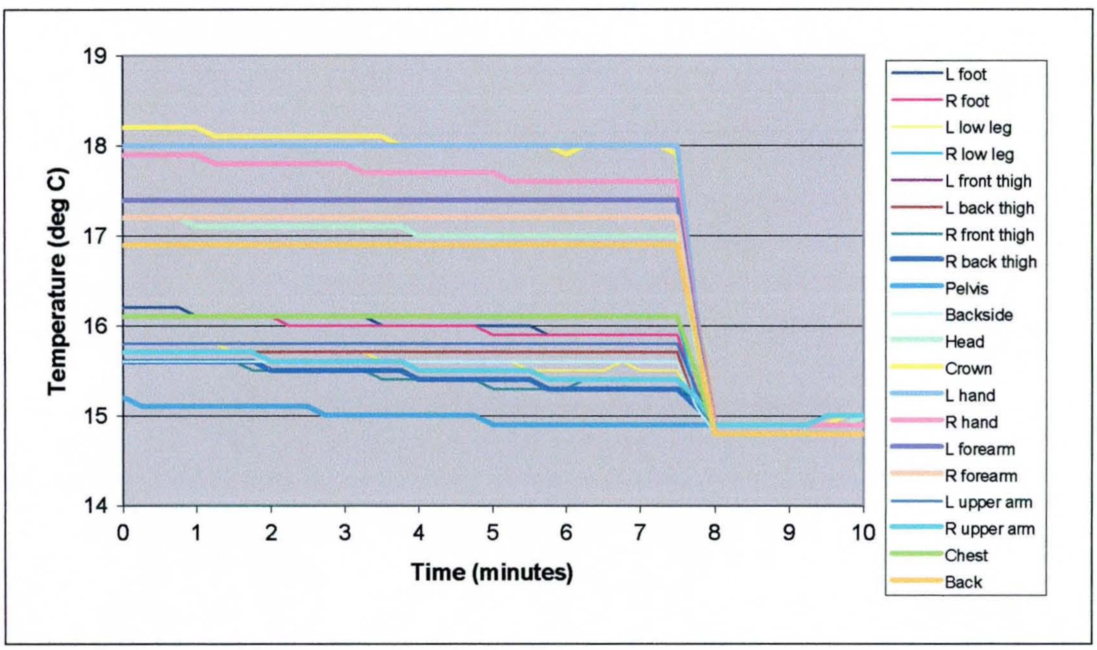


Figure 2.10, Manikin Calibration at 14.8°C

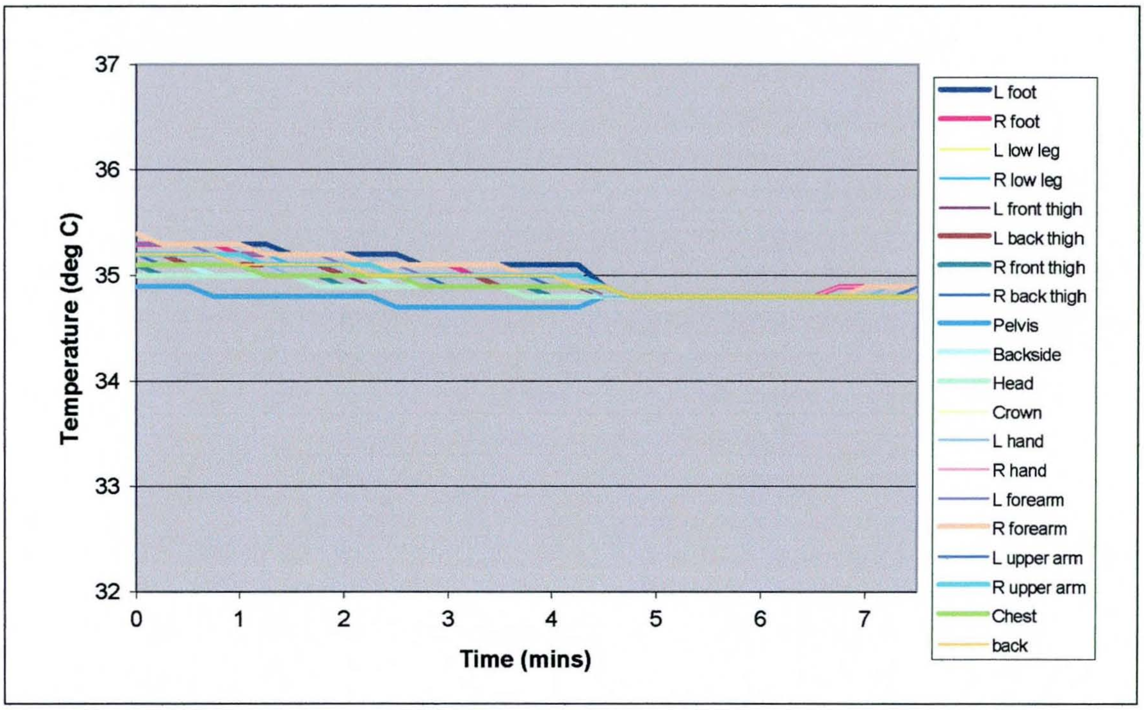


Figure 2.11, Manikin calibration at 34.85°C

It can be seen from Figure 2.10 that on the initial calibration, the spread of temperature readings from different body segments was quite large, over 3°C. At this pint all temperature readings were constant (i.e the manikin was in steady state), but measuring temperatures across a wide range of values, which indicated that there were large pre-calibration inaccuracies.

In contrast, on the second calibration at 34.85°C, the pre-calibration range of temperature readings was much smaller; less than 0.5°C (Figure 2.11). A summary of calibration temperature data is given by Table 2.3.

Table 2.3, Thermistor data (air temp) and manikin calibration data

Th1	Th2	Th3	Th4	Th5	Th6	Th7	Th8	Mean	**Manikin Calibration at**
14.85	14.75	14.70	14.70	14.80	14.85	14.90	14.75	14.79	**14.8°C**
34.90	34.85	34.75	34.75	34.90	34.95	34.95	34.75	34.85	**34.85°C**

It is concluded that the manikin was calibrated successfully and accurately at two levels and can validly be used to assess and quantify thermal environments.

3 The effect of colour and fit of clothing on thermal comfort in simulated solar radiation

3.1 Chapter Summary

This chapter investigates the effect of colour and fit of clothing on human thermal comfort. The experiment had previously been carried out on a smaller scale by Wales et al (2005), using four male participants. The laboratory experiments conducted for this chapter are a repeat of the ones conducted by Wales and provide data for a further four male participants. The experimental facility and protocol are exactly the same as those used by Wales. The subjects were exposed on four separate occasions to simulated solar radiation with an intensity of 500 Wm^{-2}. On each occasion subjects wore a different one of the following shirts: Black loose fitting, black tight fitting, white loose fitting or white tight fitting. There was found to be a significant increase in thermal discomfort when a black shirt was worn as oppose to a white one. There was found to be no significant differences due to clothing fit. Analysis of data taken from a thermal manikin supported these findings.

3.2 Introduction

Without wearing clothing humans can only live comfortably in a very narrow thermal environment from 26 to 30 °C. With clothing human beings can live and perform various physical activities in a wide range of thermal environments from −40 to 40°C and beyond. Clothing creates a portable thermal microclimate so that we can survive and live in the thermal environments in which our body cannot cope alone. Therefore, thermal functional design of clothing is critically important for human health and comfort, and in extreme cases, it can be a matter of life and death (Yi et al, 2006).

Shkolnik et al (1979) investigated why black robes were worn by people who reside and work in a hot desert. Subjects stood in a desert environment during mid day, exposing them to both a high radiant temperature and air temperature. The subjects wore a variety of different coloured clothing including a black robe. The black robes were found to have the greatest net heat gain of all the clothing however, in this case, the findings showed that there was no differences in the rate of net heat gain by subjects, regardless of the colour of clothing. This was accredited to the 'chimney effect'; this being described as the movement of cooler air from beneath the robes upwards, passing through the heated fabric thus cooling it, and the wearer, down.

It is widely thought that the heat exchange between the body and the environment may be affected significantly by the dynamic response of clothing (Huang, 2006). Nielsen (1990) examined the efficiency of different types of clothing colour and material on the thermal strain of exercising subjects. A black or white, cotton or polyester garment was worn whilst simulated solar radiation was directed onto their backs. The results show that there was little differences between black and white clothing in terms of the short wave radiation gains for each. There were however, found to be large increases in heart rate (10 beats per minute) and sweat loss (100g/hour) due to black clothing being worn as oppose to white. It was also found that thin clothing, regardless of how reflective it was, allowed greater levels of solar radiation to pass through and contact the body. This finding is supported by Roller and Goldman (1968), who conducted studies to investigate the effects of solar heat load on man. One of their findings was that thicker clothing helped to reduce solar radiation levels on the body.

Experiments conducted by Blazejczyk et al (1997) resulted in the conclusion that skin temperatures are higher under clothing that is black as oppose to white. It seems to be apparent that there is an affect on a peoples physiological responses when black clothing is worn as oppose to white, but this has not yet been quantified in terms of a measurable change in thermal comfort or sensation. A study by Wales et al (2004) investigated the affect of colour and fit of clothing on thermal comfort when exposed to 500Wm^{-2} of simulated solar radiation. Subjects were exposed in four conditions: wearing black and white and tight and loose fitting shirts, but due to the small sample size (4 participants) and questionable analytical techniques, results were inconclusive. The data from this experiment will be used and a further four participants added to this using the same experimental procedure. The data will be reanalysed with the aim of drawing stronger, more valid findings as to the effect of colour and fit of clothing on thermal comfort when exposed to solar radiation.

3.3 Experimental Method

The experimental protocol used was the same as the one detailed in chapter 2 with the exception of the variables detailed below.

3.3.1 Design

A repeated measures, within subject design was used. The subjects were exposed in four conditions (Figure 3.12), wearing a:

1 Black loose fitting shirt

2 Black tight fitting shirt

3 White loose fitting shirt

4 White tight fitting shirt

Environmental conditions were recorded along with physiological and psychological responses.

Figure 3.12, Examples of the four shirt types used in the experiment

A 4 x 4 Latin Square was used to ensure that order effects were minimised

Table 3.4, Latin square used to counter act order effects

Subject	Session 1	Session 2	Session 3	Session 4
E	BT	BL	WT	WL
F	BL	WT	WL	BT
G	WL	BT	BL	WT
H	WT	WL	BT	BL

3.3.2 Subjects

Eight healthy male participants were used in the experiments. All participants were students from the Loughborough area, aged between 18 –25. The subjects wore the four shirts listed above, with the top button unfastened. All of the shirts used were cotton/polyester (65%/35%) long sleeved. With this they wore beige cotton/polyester (65%/35%) trousers and their own under garments and shoes.

3.3.3 Apparatus

The facility and equipment used is exactly the same as is detailed in chapter 2, with participants exposed front on to radiation through plane monolithic glass at a 45 degree angle.

3.3.4 Environmental Conditions

The environmental chamber was controlled throughout the experiment to maintain a constant neutral condition, deemed as PMV = 0 $\pm$ 0.5 (ISO 7730) without the consideration of the direct simulated solar radiation. Air temperature, mean radiant temperature, relative humidity and air velocity were all taken as outlined in chapter 2, while subjects work rate and clothing (Clo value = 0.72Clo) remained constant throughout.

3.3.5 Objective measurements

Mean and local skin temperatures were taken throughout the experiments by means of thermistors positioned at the following points on the body:

- Left Chest
- Right chest
- Left Upper Arm
- Left Lower Arm
- Left Anterior Thigh
- Left Shin

A 4 Point Ramanathan technique for weighting skin temperatures was used to calculate a mean whole body skin temperature, whilst the additional thermistors on the chest and lower arm provided local skin temperatures for these areas.

3.3.6 Subjective Measurements

A copy of the subjective questionnaire completed by subjects in this experiment can be found in the appendix, and further details of each of the scales used can be found in chapter 2. Subjects gave ratings of Thermal comfort, sensation, stickiness, preference and satisfaction in local areas and for the whole body. The draughtiness scale was not used as it was expected that there would be no draught created that was significantly different from normal levels.

3.3.7 Procedure

The procedure followed for each session was exactly as illustrated in chapter 2, and is described in more detail in that section. Subjects arrived approximately 30 minutes before exposure, which allowed them to be medically screened, fitted with thermistors and gain a thermally neutral state, PMV = 0 ± 0.5 (ISO 7730). The completion of a subjective questionnaire ensured neutrality.

Subjects were then taken into the chamber and seated in the car seat, facing forward towards the solar lamps but still in the shade. After five minutes they completed a questionnaire in the control/pre-rad condition to ensure that they were still thermally neutral. They were then exposed to the simulated solar radiation for 30 minutes, completing a form immediately and then every five minutes throughout exposure. After completion of the 30 minute questionnaire, they were withdrawn from the radiation into the neutral position and the 'post' experimental questionnaire was completed.

3.4 Results

3.4.1 Environmental conditions

Table 3.5, A summary of environmental conditions for each experimental condition

	BL	BT	WL	WT
Shirt type				
$\mathbf{t_a}$ (°C)	25.16	25.53	25.5	25.3
$\mathbf{t_r}$ (°C) derived from exposed $\mathbf{t_g}$	41.1	41.6	41.5	41.3
$\mathbf{t_r}$ (°C) derived control $\mathbf{t_g}$	26.1	26.8	26.6	25.9
Air velocity (m/s)	0.1	0.09	0.08	0.1
Relative Humidity (%)	45.3	46.3	46.1	48.4
PMV derived from exposed $\mathbf{t_r}$	2.6	2.7	2.7	2.6
PPD derived from exposed $\mathbf{t_r}$	94.7%	97%	96.7%	96
PMV derived from control $\mathbf{t_r}$	0.3	0.5	0.4	0.3
PPD derived from control $\mathbf{t_r}$	6.5%	9.7%	9.2%	7.3
AMV	2.8	3.1	2.3	2.5
APD	50	37.5	25	25

Table 3.5 shows environmental conditions at during the experiments. PMV (ISO 7730) is calculated for each conditions using t_r derived form an exposed and shielded globe. It can be seen that PMV increases by over 2 scale units when t_r from an exposed globe is used as oppose to a shielded one. This highlights the extreme differences in thermal sensation that could potentially be experienced by two participants travelling in the same train carriage, should one of them be in direct solar radiation.

3.4.2 Objective Results – Mean Skin Temperature

This section contains data obtained from skin thermistors, as skin temperature data.

3.4.2.1 Presentation of results

Table 3.6, Mean skin temperatures for each participant, wearing each shirt, after 30 min exposure

Subject	Mean skin temperature exposed to 500W/m^2			
	Black Loose	**Black Tight**	**White Tight**	**White Loose**
Subject A	34.09	36.14	35.77	35.42
Subject B	36.17	35.29	35.78	35.29
Subject C	37.44	36.49	35.13	35.56
Subject D	35.47	36.96	35.98	36.18
Subject E	36.53	38.36	36.16	34.63
Subject F	37.85	37.34	37.59	35.92
Subject G	37.17	37.01	36.59	35.33
Subject H	37.86	36.99	36.62	36.84
Mean	36.57	36.82	36.20	35.65

The mean whole-body skin temperature after 30 minutes exposure can be seen for each shirt in Table 3.6. This also shows the 30-minute mean skin temperature of each participant individually.

Figure 3.2 shows mean skin temperatures for all participants in the four different shirts, over the course of exposure.

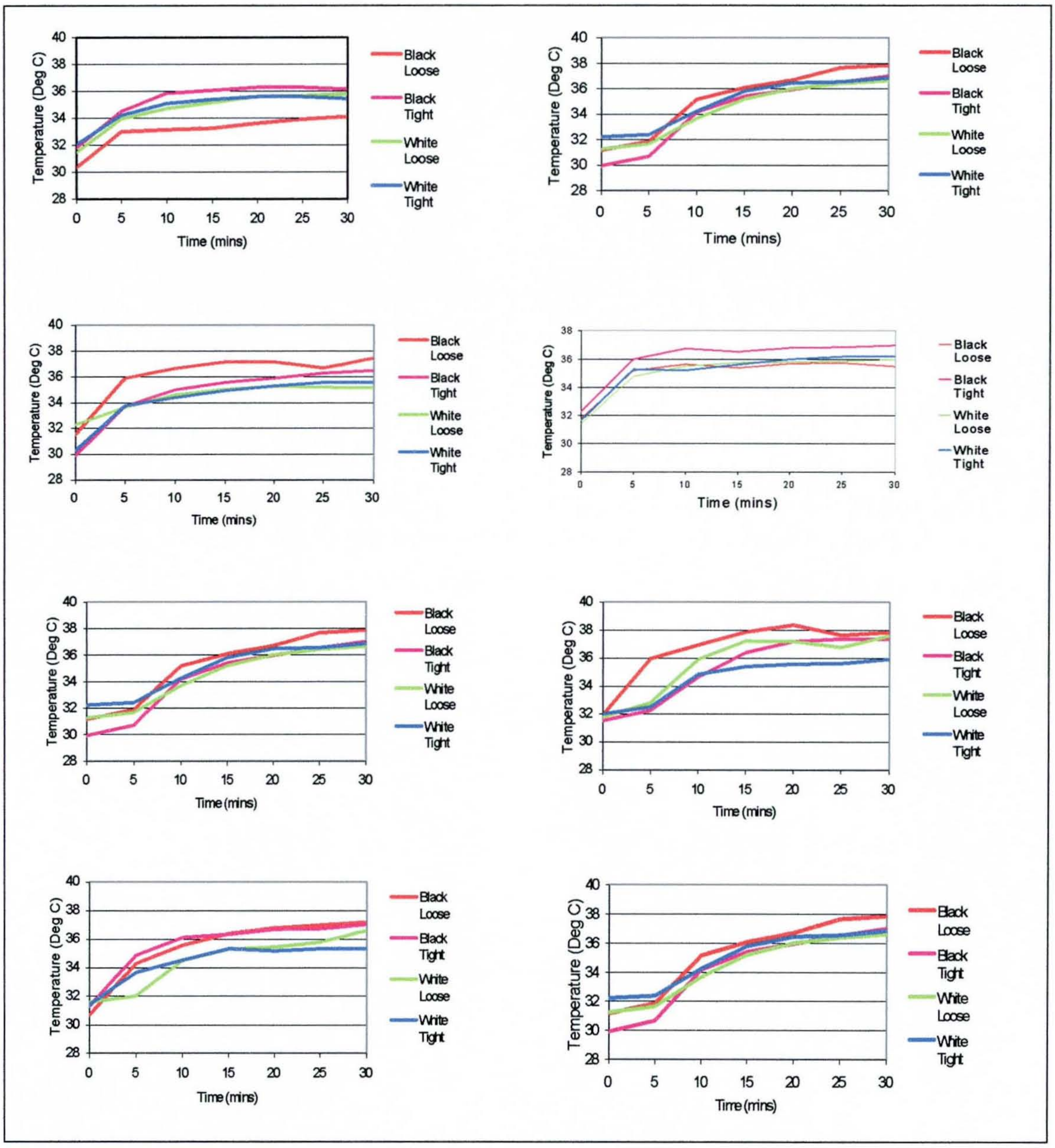


Figure 3.13, Comparison of mean skin temperatures for each participant wearing the four shirts

Figure 3.14 shows the mean skin temperature calculated for all subjects, when wearing each of the shirts. The change in mean skin temperature from the initial point of exposure (0 mins) to the end of exposure (30 mins) is shown.

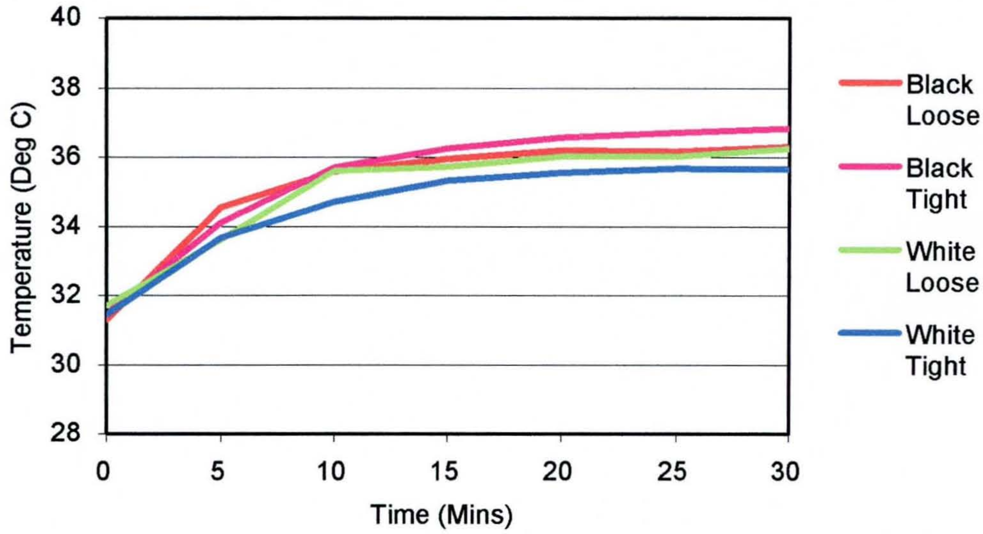


Figure 3.14, Mean skin temperature for all subjects wearing the four shirts

Statistical analysis of the 30 minute mean skin temperature was conducted using a two-way within subjects ANOVA (Table 3.7). From this it can be seen that there is no significant difference in mean skin temperature between black and white clothing, P = 0.147; tight and loose clothing, P = 0.961; or between variables, P = 0.187.

Table 3.7, Two-way, within subjects ANOVA for whole-body skin temperature after 30 min exposure

Source	F	Sig.
Colour	2.663	.147
Fit	.003	.961
Colour * Fit	2.142	.187

Graphical and statistical analysis was also made for mean chest temperatures, when wearing each of the shirts. Figure 3.15 shows mean chest temperature over the course of exposure for the four clothing types.

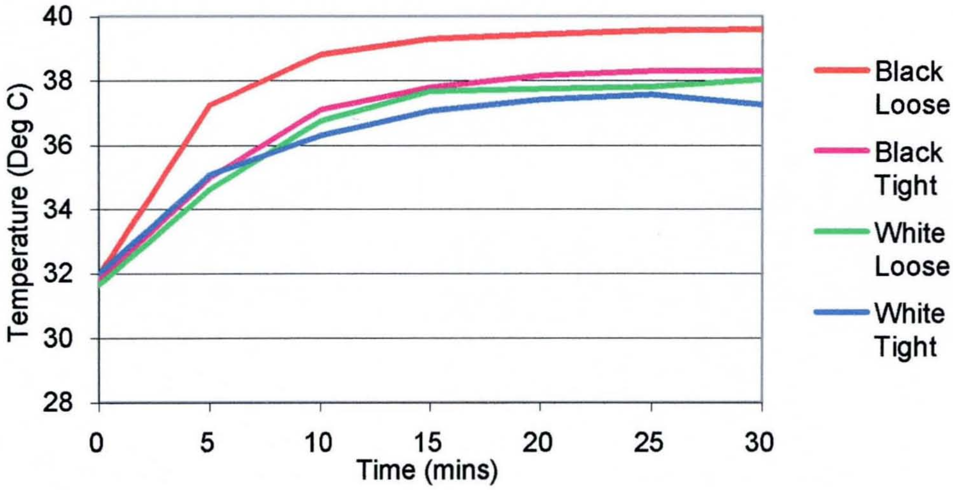


Figure 3.15, Mean chest temperature for the clothing types during exposure

From the statistical analysis in Table 3.8 it can be seen that there is a significant difference in chest temperature due to clothing fit, P = 0.002; and clothing colour, P = 0.015. There was no significant difference found between variables.

Table 3.8, Mean chest temperature for the clothing types during exposure

Source	F	Sig.
Colour	10.152	.015
Fit	24.262	.002
Colour * Fit	.977	.356

3.4.2.2 Interpretation of results

As was expected, mean skin temperature increased from a comfortable level of around 33°C (Gagge et al, 1967), to a significantly higher one, for all conditions. It can be seen that there are minimal differences in mean skin temperature between the four conditions at the 30-minute exposure point, the greatest difference being between black tight and white loose (Table 3.6 and Figure 3.14). This is supported by statistical analysis showing no significant differences within and between variables for mean skin temperature (Table 3.7).

When the data was reanalysed, an analysis of mean chest skin temperature at the 30-minute point was found to have more significant results. The differences between each condition at the end of exposure were visibly were noticeably greater than for mean whole-body skin temperature (Figure 3.15 and Figure 3.14) and there was found to be significant differences due to colour and fit (Table 3.8). There was not found to be a significant difference between variables for mean chest skin temperature.

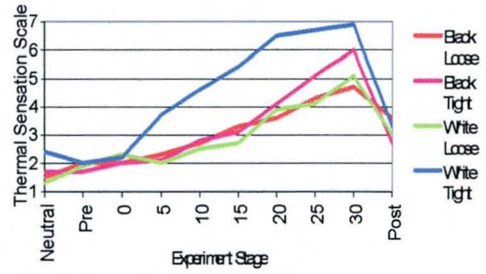
3.4.3 Subjective Results – Thermal sensation

3.4.3.1 Presentation of results

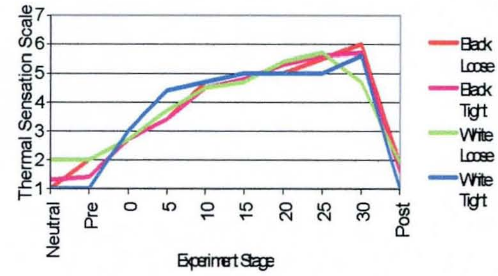
Table 3.9, Comparison of each participants Thermal sensation vote for each shirt type, at the 'pre' and '30min' stages of experimentation (

Participan t	Black Loose "Pre"	Black Loose "30"	Black Tight "Pre"	Black Tight "30"	White Loose "Pre"	White Loose "30"	White Tight "pre"	White Tight "30"
A	1.5	4.7	1.7	6	1.3	5.1	2.4	6.9
B	1	6	1.3	5.7	2	4.7	1	5.6
C	2.1	3	2	2.8	2	2.4	2	2.4
D	2	4.5	3.3	5.2	2	4.5	2	4.4
E	2.1	3.9	1.6	4.4	2	2.5	2.2	2.7
F	2	6.4	2	6.6	2	6.2	2	5.6
G	2	5.4	2	6	2	5.2	2	4.1
H	2	4.5	2	4.3	2	3.9	2.5	4.3
Mean	**1.8**	**4.8**	**2**	**5.1**	**1.9**	**4.3**	**2**	**4.5**

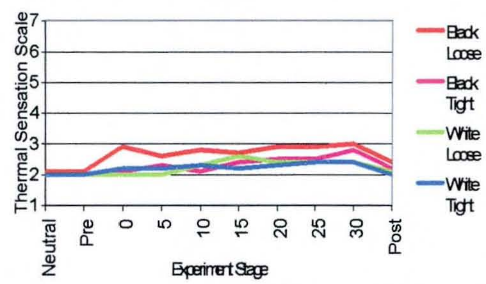
Figure 3.16 shows subjects' individual thermal sensation results for the four clothing conditions, recorded every five minutes throughout exposure. Table 3.9 displays numerical values for each participants thermal sensation vote at the 'pre' and '30min' stages of experimentation, for each shirt type.



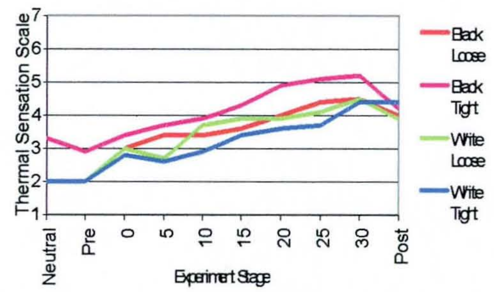
Participant A



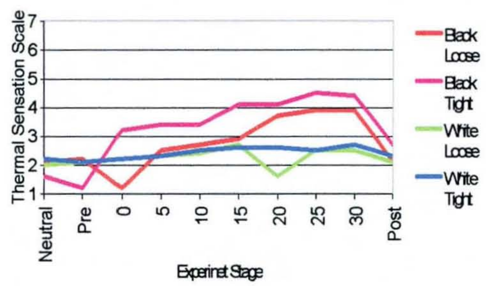
Participant B



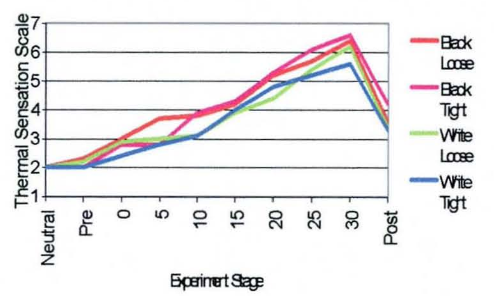
Participant C



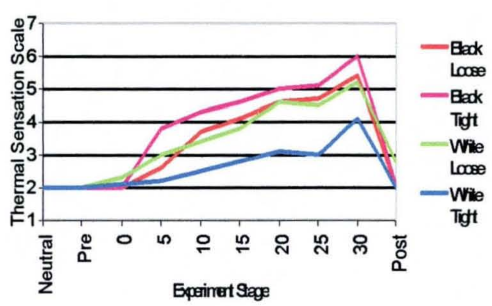
Participant D



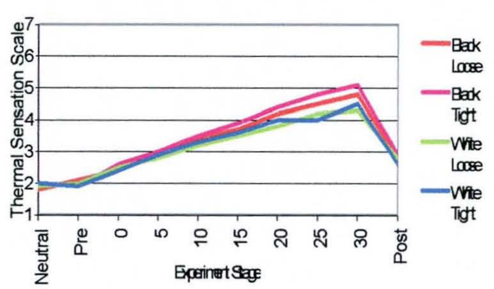
Participant E



Participant F



Participant G



Participant H

Figure 3.16, Comparison of thermal sensation for each subject in the four clothing conditions

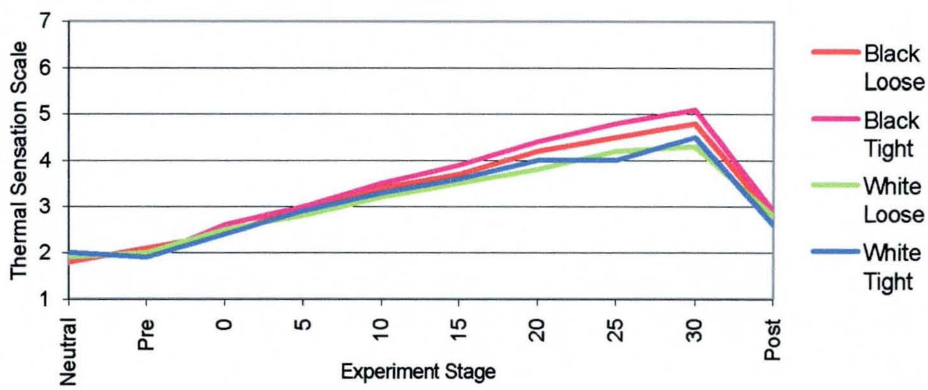


Figure 3.17, Mean thermal sensation votes for the four clothing conditions during the experiment

The mean thermal sensation during the course of the experiment is illustrated for each clothing condition by Figure 3.17.

Table 3.10, Wilcoxon signed rank test for thermal sensation scoress after 30 min exposure

	Black loose-Black tight	White loose-White tight	Black tight – White tight	Black loose-white loose
Z	-1.404(a)	-.210(a)	-.491(b)	-.772(a)
Asymp. Sig. (2-tailed)	.160	.833	.623	.440

a Based on positive ranks.
b Based on negative ranks

Statistical analysis of the 30-minute mean thermal sensation vote for each clothing condition is shown in Table 3.10. There was found to be no significant difference in thermal sensation vote due to clothing type: For Black loose - Black tight, P = 0.16; for white loose – white tight, P = 0.833: for black tight white tight, P = 0.623 and for black loose – white loose, P = 0.44 (all 2 tailed).

3.4.3.2 Interpretation of results

For all clothing conditions is can be seen that mean thermal sensation is around neutral at the beginning of the experiment and gradually increases during exposure to the simulated radiation, for each of the clothing types (Figure 3.17). There are visible but slight differences between the sensation votes for the four conditions at 30-minutes exposure. These differences were found to be insignificant by the statistical analysis in Table 3.10.

3.4.4 Subjective results – Thermal Comfort

3.4.4.1 Presentation of results

Thermal comfort votes for individual participants at the 'pre' and '30min' stages of experimentation are shown by Table 3.11. Mean thermal comfort vote is shown for each shirt type over the course of the experiment by Figure 3.18.

Table 3.11, Comparison of each participants Thermal comfort vote for each shirt type, at the 'pre' and '30min' stages of experimentation (1 = Not uncomfortable, 2 = Slightly uncomfortable, 3 = uncomfortable, 4 = Very Uncomfortable)

Participant	Black Loose "Pre"	Black Loose "30"	Black Tight "Pre"	Black Tight "30"	White Loose "Pre"	White Loose "30"	White Tight "pre"	White Tight "30"
A	1	2.9	1	3.5	1	2.7	1.2	3.9
B	1	3.7	1	3.7	1	2.6	1	3
C	1	1.8	1	1.8	1	1.5	1	1.4
D	1	3	2.5	3.1	1	3.2	1	3
E	1.2	2.4	1.1	2.6	1.1	1.3	1.2	1.7
F	1	3.6	1	3.5	1	3.4	1	2.8
G	1	3.2	1	3.2	1	3.1	1	2.1
H	1	2.7	1	2.7	1	2.4	1.3	2.7
Mean	**1**	**2.9**	**1.2**	**3**	**1**	**2.5**	**1.1**	**2.6**

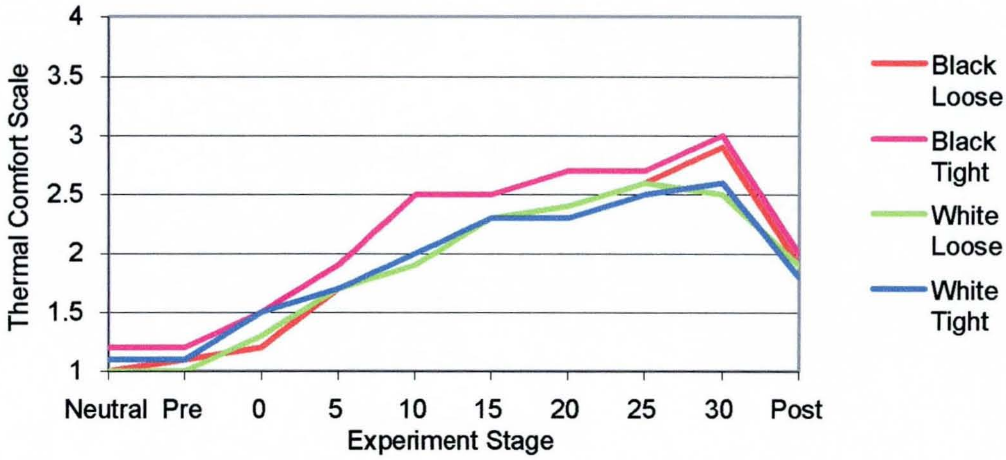


Figure 3.18, Mean thermal comfort vote during the experiment for all shirt types (1 = Not uncomfortable, 2 = Slightly uncomfortable, 3 = uncomfortable, 4 = Very Uncomfortable)

Table 3.12 displays a Wilcoxon signed rank test for thermal comfort, with data taken at 30-minutes exposure for each shirt type. There was found to be significant differences in thermal comfort between White loose – Black loose, P = 0.034 (2 tailed). . Differences between White loose – White tight, P = 1 (2 tailed), White tight - Black tight, P = 0.059 (2 tailed) and Black loose – Black tight (2 tailed), P = 03.17 were all found to be insignificant at the P < 0.05 level.

Table 3.12, Wilcoxon signed rank test for shirt types at30-minutes exposure and ratings of thermal comfort

	Black loose-Black tight	**White loose-White tight**	**White tight-Black tight**	**White loose-Black loose**
Z	-1.000(b)	.000(c)	-1.890(a)	-2.121(a)
Asymp. Sig. (2-tailed)	.317	1.000	.059	.034

a Based on positive ranks
b Based on negative ranks
c The sum of negative ranks equals the sum of positive ranks

3.4.4.2 Interpretation of results

The addition of simulated solar radiation to the participants' environment caused an increase in discomfort for all participants in all shirt types (Figure 3.19 and Table 3.11). Discomfort steadily increased from the point of exposure (experimental stage = 0) to the end of exposure (experimental stage = 30), with black tight causing most discomfort (3 scale units) and white loose causing the least (2.5 scale units), at this point. It can also been seen that both black shirts have a similar 30-minute comfort score, with a notable difference between the two white shirts, which also have a similar score. This difference due to colour is supported statistically by Table 3.12, which shows a significant difference between the Black and White loose shirts. All other differences between shirt types were found to be insignificant.

3.4.5 Subjective results – Stickiness

3.4.5.1 Presentation of results

Table 3.13 shows each participant's stickiness score at the 'pre and 30 minute stages of the experiment for all shirt types. The mean stickiness score for each shirt over the course of the experiment is illustrated by Figure 3.19.

Table 3.13, Comparison of each participants stickiness score, for all shirt types, at the 'pre' and 30 minute stages of experimentation (1 = Not sticky, 2 = slightly sticky, 3 = sticky, 4 = Very sticky)

Participant	Black Loose "Pre"	Black Loose "30"	Black Tight "Pre"	Black Tight "30"	White Loose "Pre"	White Loose "30"	White Tight "pre"	White Tight "30"
A	1	2.8	1	3.4	1	2.8	1.2	3.9
B	1	4	1	3.6	1	2.6	1	3
C	1	1.8	1	1.8	1	1.5	1	1.1
D	1	3.1	1.5	3.2	1	3.2	1	2.7
E	1.2	2.4	1.2	2.5	1.2	1.3	1.2	1.4
F	1	3.6	1	3.4	1	3.2	1	2.1
G	1	3	1	3	1	3	1	1
H	1	2.6	1.1	2.7	1	1.7	1	1.3
Mean	**1**	**2.9**	**1.1**	**3**	**1**	**2.4**	**1.1**	**2.1**

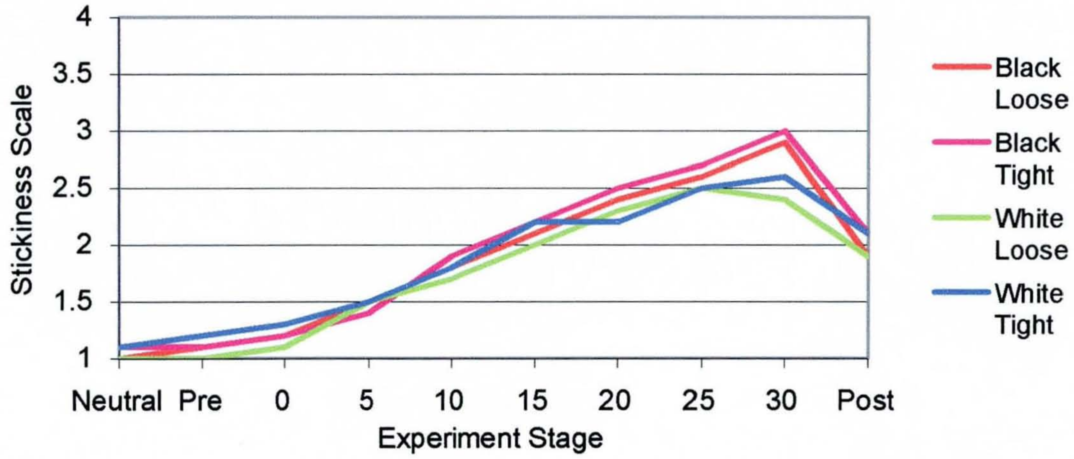


Figure 3.19, Mean Stickiness scores for all shirt types, during the experiment (1 = Not sticky, 2 = slightly sticky, 3 = sticky, 4 = Very sticky)

Table 3.14 shows a Wilcoxen signed rank test for differences in stickiness score due to shirt type, at the 30-minute point of exposure. There were found to be significant differences at the $P < 0.05$ level between White loose – Black loose, P = 0.046 (2 tailed) and White tight – Black tight, P = 0.069 (2 tailed). There were found to be no significant differences between Black loose – Black tight, P = 0.750 and White loose – White tight, P = 0.497, (both 2 tailed).

Table 3.14, Wilcoxon signed rank test for stickiness, at 30-minutes exposure, between shirt types

	Black loose-Black tight	**White loose-White tight**	**White tight-Black tight**	**White loose-Black loose**
Z	-.318(b)	-.679(b)	-1.820(a)	-1.992(a)
Asymp. Sig. (2-tailed)	.750	.497	.069	.046

3.4.5.2 Interpretation of results

Table 3.13 and Figure 3.19 both show that exposure to simulated solar radiation increased subjects' individual and mean stickiness scores for each shirt type. Stickiness rating for Black loose and tight shirts appears to be notably higher than for white loose and tight shirts, with the largest difference at the 30-minute point being between Black tight (3 scale units) and white loose (2.4 scale units). A difference in stickiness due to shirt colour is supported by the statistical data in Table 3.14, with significance identified between White – Black tight and White loose – Black loose.

3.4.6 Subjective results – Thermal preference

Data in this section was obtained from questionnaires that were administered throughout exposure to simulated solar radiation.

3.4.6.1 Presentation of results

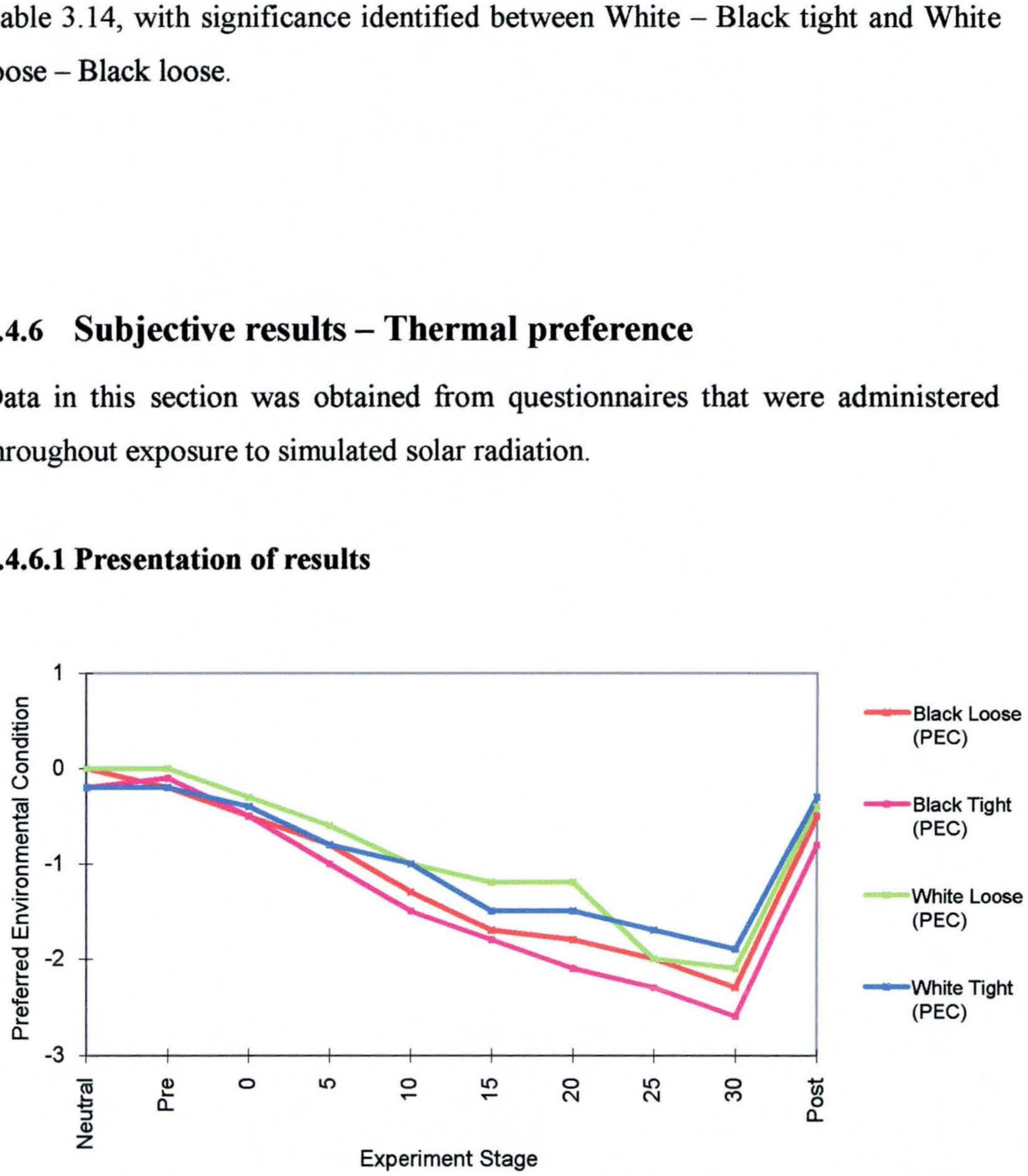


Figure 3.20, Mean thermal preference scores for all shirt types, over the course of the experiment (-3 = Much cooler, -2 = Cooler, -1 = slightly cooler, 0 = cooler, 1 = slightly warmer)

Figure 3.20 shows the mean thermal preference vote for each shirt type over the course of the experiment. Only part of the preferred environmental condition scale in displayed, with –3 = much cooler, -2 = Cooler, -1 = slightly cooler, 0 = no change and 1 = slightly warmer.

3.4.6.2 Interpretation of results

From the start of exposure (experimental stage = 0) the extent of preferred change to the environment increases, will all clothing conditions producing a preference for a cooler environment. The greatest required change was induced by wearing a black tight shirt, and the smallest by wearing a white tight shirt. There again appears to be a difference due to colour, but not due to fit.

3.4.7 Subjective results – Acceptance and satisfaction

Data in this section was obtained from questionnaires that were administered throughout exposure to simulated solar radiation.

3.4.7.1 Presentation of results

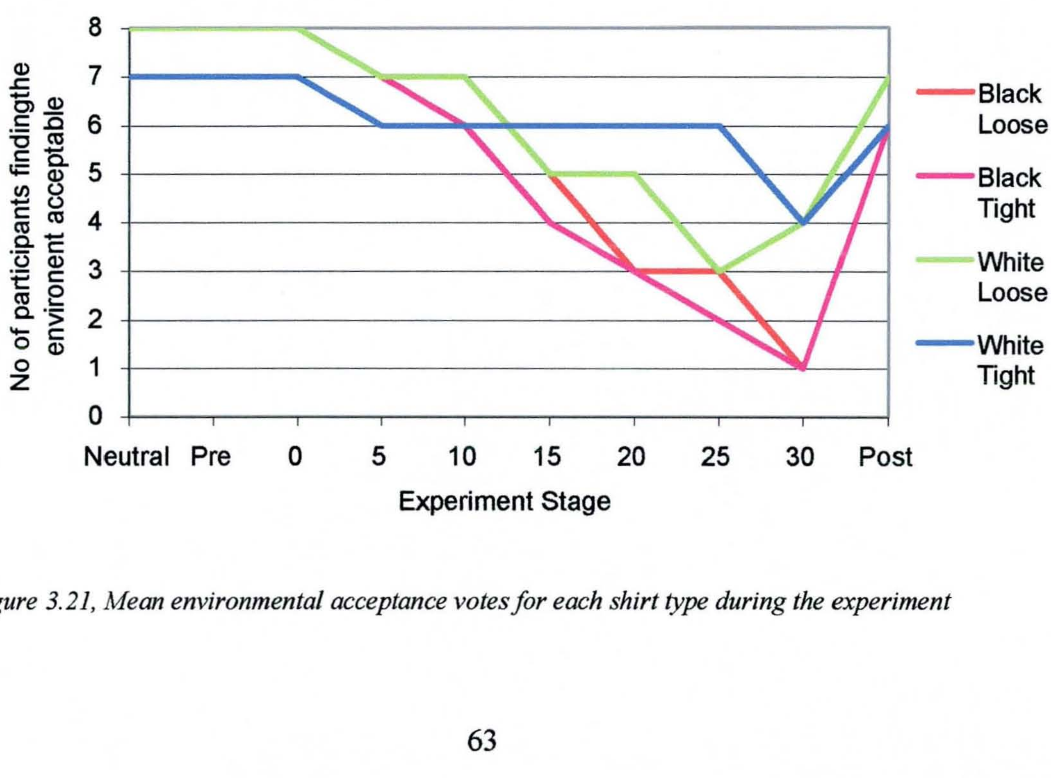


Figure 3.21, Mean environmental acceptance votes for each shirt type during the experiment

Mean environmental acceptance for each shirt type during the experiment is shown by Figure 3.21, in terms of the number of participants finding the environment acceptable at each experimental stage. Mean environmental satisfaction is shown in the same way by Figure 3.22.

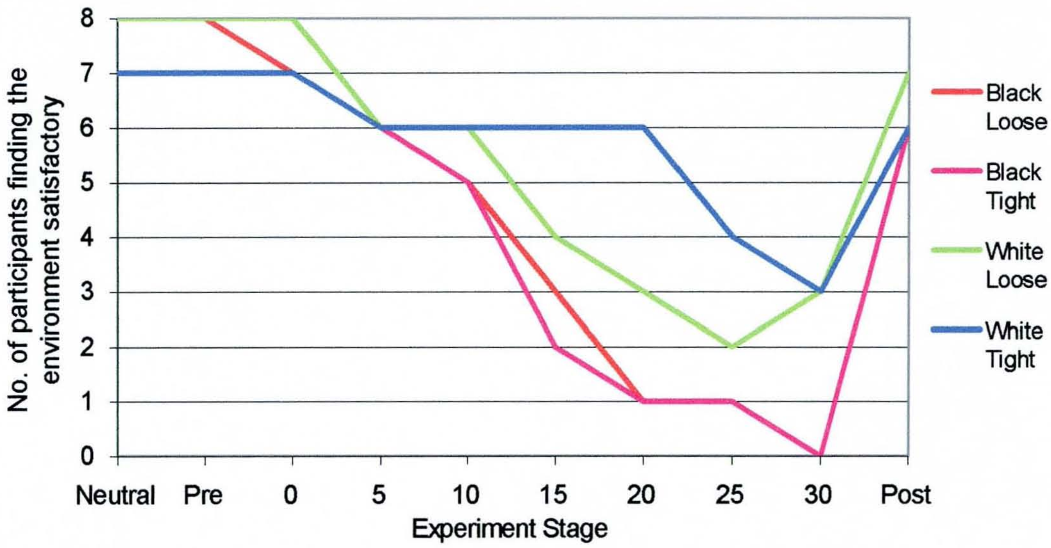


Figure 3.22, Mean environmental satisfaction votes for each shirt type during the experiment

3.4.7.2 Interpretation of results

It can be seen from Figure 3.21, that at the end point of exposure (experimental stage = 30) there is no difference in acceptance scores for Black tight and loose (acceptance number = 1) or White tight and loose (acceptance number = 4). The fact that these scores are the same indicates that there is no difference in environmental acceptance due to fit. The difference of 3 scale units between Black and white shirts, shows that environmental acceptance decreases due to wearing a white shirt as oppose to black.

There is also no difference shown by Figure 3.22 between the satisfaction scores of Black shirts (acceptance number = 0) or White shirts (acceptance number = 3). There is a difference of 3 scale units between different coloured shirts.

3.5 Thermal Manikin

3.5.1 Aim

The aim of the manikin experiment was to further validate findings from subjective and mean skin temperature data and provide a more comprehensive view into the effects of each shirt type on thermal comfort when in solar radiation. The manikin is a 20 compartment female form thermal manikin and was set to control all body segment temperatures to remain constant at 34°C. The power input therefore reports heat loss and is a measure of the insulative effect of the clothing type.

3.5.2 Method

3.5.2.1 Facility and set-up

The experimental facility and environmental conditions were almost exactly as specified for participants (see chapter 2). The only difference being the intensity of radiation to which the manikin was exposed, this being 200Wm-2. The experiment was previously attempted at higher intensities which resulted in the manikin overheating, due to it not having an active cooler mechanism.

3.5.2.2 Procedure

Prior to each experiment, the air conditioning system and lights were turned on to get the chamber to the required environment. The manikin was dressed in the standard clothing ensemble of a cotton/Polyester (65/35%) long sleeved shirt with sleeves rolled up to the elbow, and beige cotton/Polyester (65/35%) trousers. The manikin was then placed in the chamber in the exposure position (next to the window) and set to maintain a constant temperature of 34°C. the power input required to maintain this temperature was recorded at fifteen second intervals throughout the experiment. At this point squirrel data loggers were also started to record environmental conditions along with the manikins file log. The manikin remained in the exposure position until it reached steady state; this was deemed to be achieved when the power input overall and for all segments remained at a similar level for a period of 5 minutes. At this point the squirrels and manikin file log were stopped and the manikin was removed from the radiation and changed into one of the other shirt types. The experiment was then repeated until all four conditions (shirt types) has been tested.

3.5.3 Results

3.5.3.1 Presentation of results

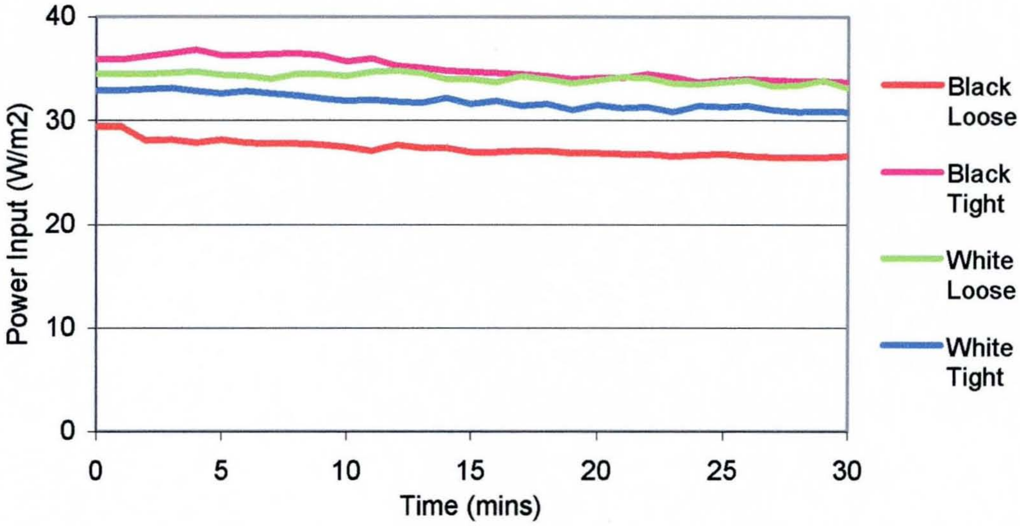


Figure 3.23, Mean Power input over all body segments to maintain 34°C, in each clothing condition, for the 30 minutes prior to the end of exposure (steady state reached)

Figure 3.23 Shows the mean power input to all body segments, in each of the shirt types, for the 30 minutes prior to the end of the experiment. Mean power input to the chest is shown for all shirt types during the same period by Figure 3.24.

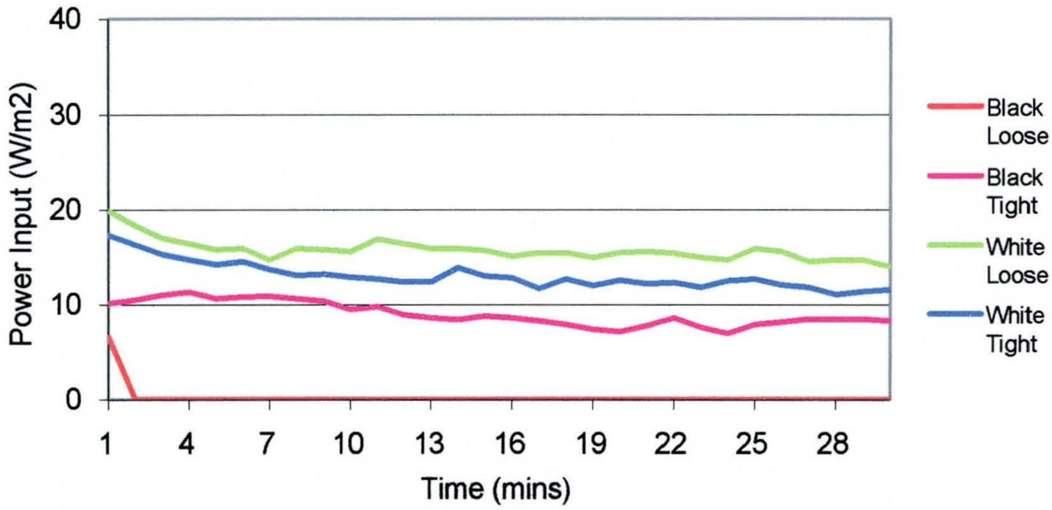


Figure 3.24, Mean power input for chest segments, in each clothing condition, for the 30 minutes prior to the end of exposure (steady state reached) and all segments maintained at 34°C

3.5.3.2 Interpretation of results

With the manikin at steady state there were some noticeable differences between the mean power input to all body segments, in each of the clothing conditions (Figure 3.23). The shirt type resulting in the lowest power input was black loose (26.6Wm-2), next was white tight (30.8Wm-2). White loose and Black tight has similar power requirements at steady state of 33.1Wm-2 and 33.7Wm-2 respectively.

There were noticeable differences between all clothing conditions, for mean chest power input, at steady state (Figure 3.24). Black loose required no power, Black tight 8.3Wm-2 and White tight 11.6Wm-2. White loose required the greatest power input of 14Wm-2.

3.6 Discussion

3.6.1 Environmental conditions

Analysis of environmental data shows that the required conditions of neutral (PMV = 0 $\pm$ 0.5) were achieved for all conditions. This implies that discomfort experienced by participants can be attributed to the effects of their exposure to direct solar radiation.

3.6.2 Mean skin temperature

On first impressions clothing colour and fit did not seem to have a great influence skin temperature, with graphical data for mean 30-minute skin temperature indicating very small differences due to clothing type, that were found to be insignificant by statistical testing. Reanalysis using only chest temperature revealed a significant difference within the colour variable, indicating that black shirts produce a significantly greater increase in temperature than white. Neither whole body or chest temperature analysis showed a significant difference due to fit.

The fact that no significance was found between conditions in mean skin temperature analysis could be attributed to the generic clothing ensemble. Data from two of the four thermistors used to calculate mean skin temperature, positioned anterior thigh and shin, were covered by the same trousers in each condition, and diluted any differences found in the other areas. Data from the thermistors positioned at the chest was unique for each condition, allowing clear comparisons to be made between variables.

3.6.3 Thermal sensation

Analysis of subjective data showed no significant differences due to clothing colour (P = 0.44 for BL-WL and P = 0.623 for BT-WT, both 2 tailed) for participants' mean sensation rating. Although the data followed a similar trend to objective data, with both black shirts inducing a 'hotter' mean sensation score than white, it was apparent that on the whole, participants could not easily or unquestionably identify a difference in sensation due to clothing colour. Clothing fit was found to have an insignificant influence on sensation ($P = 0.16$ for BL-BT and $P = 0.833$ for WL-WT), again supporting findings from objective data analysis.

3.6.4 Thermal comfort

The mean thermal comfort votes followed a similar trend to thermal sensation and objective data. Both black shirts produced greater mean discomfort scores than white at the 30-minute point and there were found to be significant differences between white tight and black tight ($P = 0.059$, 2 tailed), and white loose and black loose ($P = 0.034$). The implication from these findings is that participants' have interpreted the significant differences found in chest skin temperature analysis subjectively as increases in discomfort. There was again found to be no significant differences in comfort due to clothing fit.

3.6.5 Stickiness

Stickiness data supports previous findings that the colour of clothing has a significant influence on a person's thermal state and that fit does not. Significant differences were found between white tight and black tight ($P = 0.069$, 2 tailed), and white loose and black loose ($P = 0.046$, 2 tailed). The data indicates that the increased chest temperature, attributed to wearing black shirts, induced thermoregulatory response in the form of increased sweating.

3.6.6 Thermal preference

As was expected, exposure to simulated solar radiation resulted in a desire for a cooler environment for all shirt types. There is a clear difference in preference rating due to shirt colour, with black shirts creating a desire for a cooler environment than white. There are again no differences due to fit.

3.6.7 Acceptance and satisfaction

The fact that both black shirts produced the same 30-minute acceptance and satisfaction score (1 and 0 scale units) and both white shirts also produced the same scores (4 and 3 scale units) shows that clothing fit has no influence on participants' ratings. The difference of 3 scale units in both categories indicates that there is a effect due to clothing colour.

3.6.8 Manikin data

The thermal manikin was used to provide an additional source of objective data to support skin temperature data. Analysis of the manikin data showed it to be complimentary to findings from skin temperature analysis. Initially manikin data seemed to contradict findings from subjective and skin temperature, that clothing colour is a significant factor in influencing thermal state. There was no relationship found between clothing colour and the mean power requirement of all body segments.

When mean power requirement for the chest was analysed, it was clear that black shirts required less power input at steady state than white shirts, implying that black shirts make the body surface hotter than white. As was the case with skin temperature, analysis of the whole body is ineffective, as it dilutes significant differences found in local affected with data from the rest of the body. There was found to be no effect on chest power requirement, due to clothing fit.

It seems that, for the conditions tested, the level of the radiation had the greatest effect on participant responses and that subjects in black clothes were warmer than those in white. Clothing fit was not found to have an effect however in different conditions, for example, where there is significant air movement or subject activity then fit may become a factor.

3.7 Conclusions

Relationships between clothing colour and fit, and objective and subjective data have been established.

1 Clothing colour was found to have a significant influence on mean chest skin temperature.

2 Clothing colour was found to have a significant effect on thermal sensation, with black shirts making participants feel hotter than white

3 Clothing colour was found to have a clear effect on thermal comfort, stickiness and preference, with black shirts creating an increase in discomfort and associated thermoregulatory responses.

4 Both objective and subjective analysis showed that clothing fit had no effect on thermal state.

5 Manikin data supports the findings of objective and subjective data.

4 The effect of exposure to a cold window on Human thermal comfort

4.1 Chapter summary

This chapter investigates the effect of exposure to a cold window on thermal comfort, when in an otherwise neutral environment, PMV = 0 $\pm$ 0.5 (ISO 7730). Eight Male subjects were exposed side-on to a cold vertical window ($\leq$ 6°C) for a single period of 30 minutes. Weighted mean skin temperature was recorded by use of body thermistors, and subjective responses measured every five minutes by means of questionnaire. All participants wore a standard clothing ensemble with an insulation value of 0.72clo. It was established that exposure to the window caused a thermal sensation shift of one negative scale unit, as well as significantly decreasing mean skin temperature and causing radiant asymmetry across the body (Olesen 1985; ISO 7730 1994).

4.2 Introduction

Windows provide a visual link between an enclosure and the outside world. In the case of a driver of a vehicle they are a necessity and , due to a desire for natural light, they are highly desirable for passengers in vehicles and the occupants of buildings. Windows often have lesser insulation properties when compared the other materials of which a structures shell is composed. They are crucial for people's experience of the indoor climate and can provide a thermal bridge between the external and internal environment. (Larsson & Moshfegh, 1999).

Khalifa and Marshall (1990) investigated the heat transfer coefficients on interior building surfaces (such as walls ceilings and glazing). They conducted 124 tests, each one lasting 24 hours, using a real sized indoor test cell of dimensions 2.95m x 2.35m x 2.08m (length x width x height). They found that the heat transfer coefficient on a single glazed window of an enclosure was at least three times higher than those which occur on other opaque elements, such as vertical walls and ceiling. The heat transfer coefficient on the window was also found to be far less temperature difference dependant compared with that of the walls.

What is less clear is how this will affect the thermal comfort of persons inside an enclosure, and by what mechanisms. Cold windows have always caused drafts and asymmetrical radiation. This is especially true when the glazing is high, and in this case even radiators positioned on the floor cannot stop the formation of drafts. (Kumitski et al, 2004).

Berglund and Fobelets (1987) investigated the subjective responses of 50 subjects wearing winter clothing (0. 86 Clo) to low level air currents and asymmetric radiation. Participants undertook two-hour-long exposures of various kinds of winter indoor conditions that included air speeds between 0. 05 and 0. 5 m/s and asymmetric radiation to a cold wall, that produced radiant temperature asymmetries ranging from 0 to 20 K (0 to 36 F). The study was conducted at neutral temperatures and at conditions 3° C lower (cool). Discomfort due to draught increased with the air velocity ($P<0.05$), but was independent of radiant asymmetry ($P>0.05$). Subjective responses to air velocity and radiant asymmetry were also found to be independent with the interaction between air velocity and radiant temperature asymmetry being non-significant. The percent of subjects experiencing a draught approximately doubled in the cool environment as compared to the neutral environment.

4.3 Experimental method

The experimental protocol used was the same as the one detailed in chapter 2 with the exception of the variables detailed below.

4.3.1 Design

A single measures design was used. Subjects were exposed side-on to a cold vertical window for 30 minutes. The window was kept cool with a surface temperature of 4 -6°C, achieved by using the insulated box and pre-frozen ice discussed in chapter 2. Physiological and psychological measurements were taken throughout.

4.3.2 Subjects

Eight healthy male subjects were used in the experiment. All were from the Loughborough area and aged between 18 – 24 years. Subjects wore the specified clothing ensemble of white cotton/Polyester (65/35%) long sleeved shirt with sleeves rolled up to the elbow, and beige cotton/Polyester (65/35%) trousers, with their own undergarments and shoes. The estimated insulation value for the ensemble and car seat was 0.72 Clo (ISO 7730).

4.3.3 Apparatus

The facility and equipment used is exactly the same as is detailed in chapter 2. The insulated box was placed around the window frame, stacked with pre-frozen ice containers and sealed to create a cold micro-climate around the external surface of the window (Figure 4.25). This ensured that the internal surface temperature of the window was between 4-6°C during experimentation.

Figure 4.25, The insulated box used to simulate cold external environmental conditions., viewed from inside and outside the chamber

4.3.4 Environmental Chamber

The environmental chamber was controlled throughout the experiment to maintain a constant neutral condition, deemed as PMV = 0 $\pm$ 0.5 (ISO 7730) without consideration of the cold window. Air temperature, mean radiant temperature, relative humidity and air velocity were all taken as outlined in chapter 2; while subjects work rate and clothing (Clo value) remained constant throughout.

4.3.5 Objective Measures

Mean and local skin temperatures were taken throughout the experiments by means of thermistors positioned at the following points on the body:

- Left Chest
- Right chest
- Left Upper Arm
- Right Upper Arm
- Left Anterior Thigh
- Right Anterior Thigh
- Left Shin
- Right shin

A 4-Point Ramanathan technique for weighting skin temperatures was used to calculate a mean whole body skin temperature, and individual mean skin temperatures for the left and right side of the body.

4.3.6 Subjective Measurements

A copy of the subjective questionnaire completed by subjects in this experiment can be found in the appendix, and further details of each of the scales used can be found in chapter 2. Subjects gave ratings of Thermal comfort, sensation, draughtiness, preference and satisfaction in local areas and for the whole body. The stickiness scale was not used as it was expected subjects body temperatures would not increase during exposure and sweating was therefore not expected.

4.3.7 Procedure

Subjects arrived approximately 30 minutes before exposure, which allowed them to be medically screened, fitted with thermistors and gain a thermally neutral state, PMV = 0 ± 0.5 (ISO 7730). The completion of a subjective questionnaire ensured neutrality.

Subjects were then taken into the chamber and seated in the car seat where after five minutes they completed a questionnaire in the control/neutral condition, to ensure that they were still thermally neutral. They were then exposed side-on to the cold window for 30 minutes, completing a questionnaire immediately upon exposure, and then every five minutes throughout. After completion of the '30-minute' questionnaire, subjects were withdrawn from the exposure position into the neutral position and the 'post' experimental questionnaire was completed.

4.4 Results

4.4.1 Environmental results

Environmental data were taken during the experiment, to ensure that the conditions experienced by each subject were consistent.

Table 4.15 displays environmental conditions at the 'pre' and 30 minute stages. The PMV and PPD (ISO 7730) are displayed for the environmental conditions measured at each of these stages. Mean Radiant temperature was calculated at the control position and at the window to allow comparative PMV's to be calculated. It can be seen that PMV calculated at the control position stays at a similar level through the exposure period. PMV calculated at the exposure position decreases as a result of exposure, giving a subsequent increase in PPD. It should also be noted that there is an increase in relative humidity of almost 10% during the experiment.

Table 4.15, Environmental measurements at the 'PRE' and '30 minute' stages

Experimental stage	'PRE'/Control	At 30min exposure
t_a (°C)	22.15	21.9
t_r (°C) derived from exposed t_g	21.89	19.68
t_r (°C) derived control t_g	21.89	21.53
Air velocity (m/s)	0.09	0.31
Relative Humidity (%)	41.49	50.26
PMV derived from exposed t_r	-0.3	-1
PPD derived from exposed t_r	7.5	25.8
PMV derived from control t_r	-0.3	-0.4
PPD derived from control t_r	7.5	8.8
AMV	0	-1
APD	0	25

PMV – Predicted Mean Vote
PPD – Predicted Percentage Dissatisfied
AMD – Actual Mean Vote
APD – Actual Percentage Dissatisfied

4.5 Objective results: Mean Skin temperature

4.5.1 Presentation of results

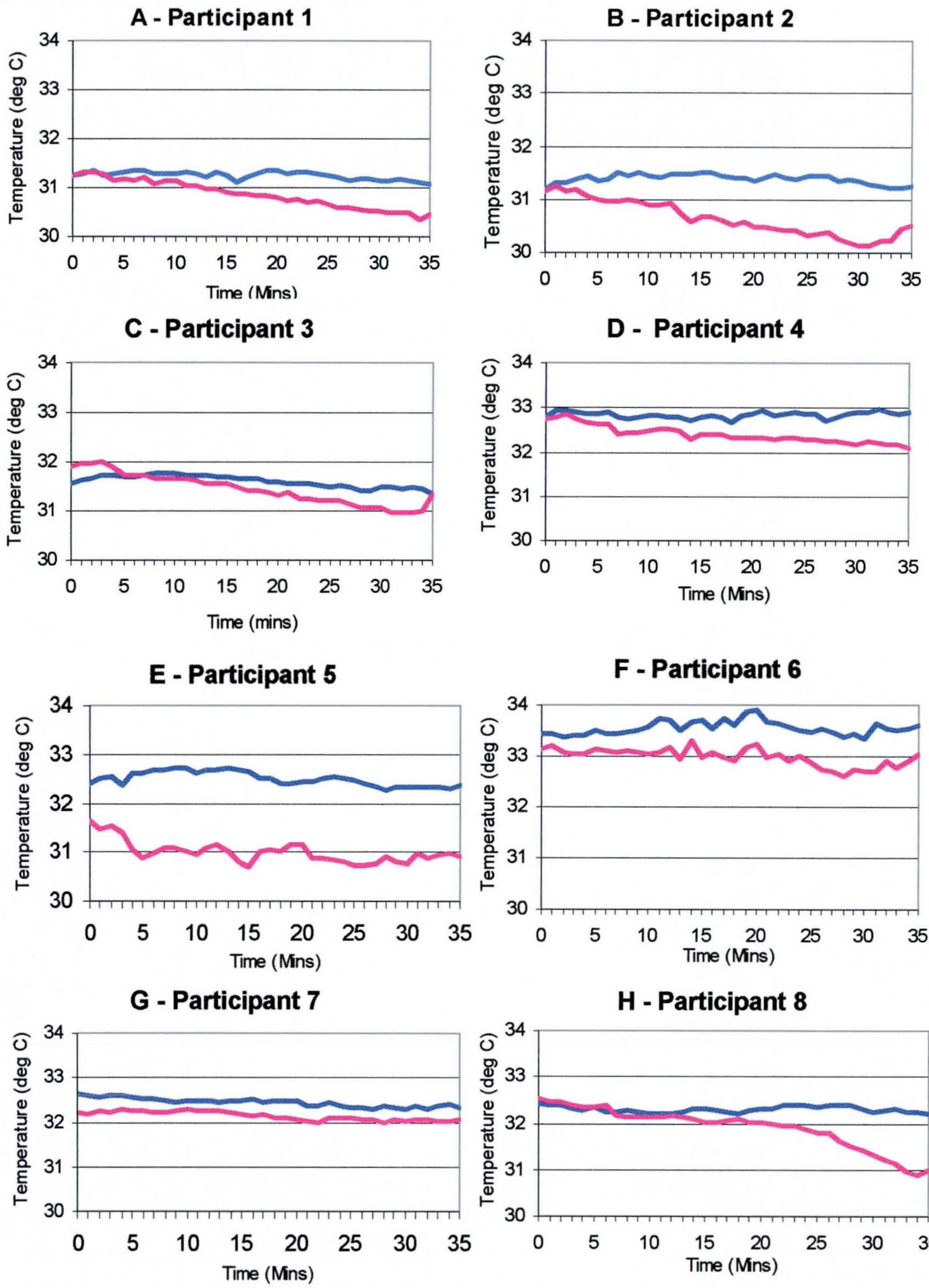


Figure 4.26, Comparison of left and right sided mean skin temperature during exposure – **Left side**, – **Right side**

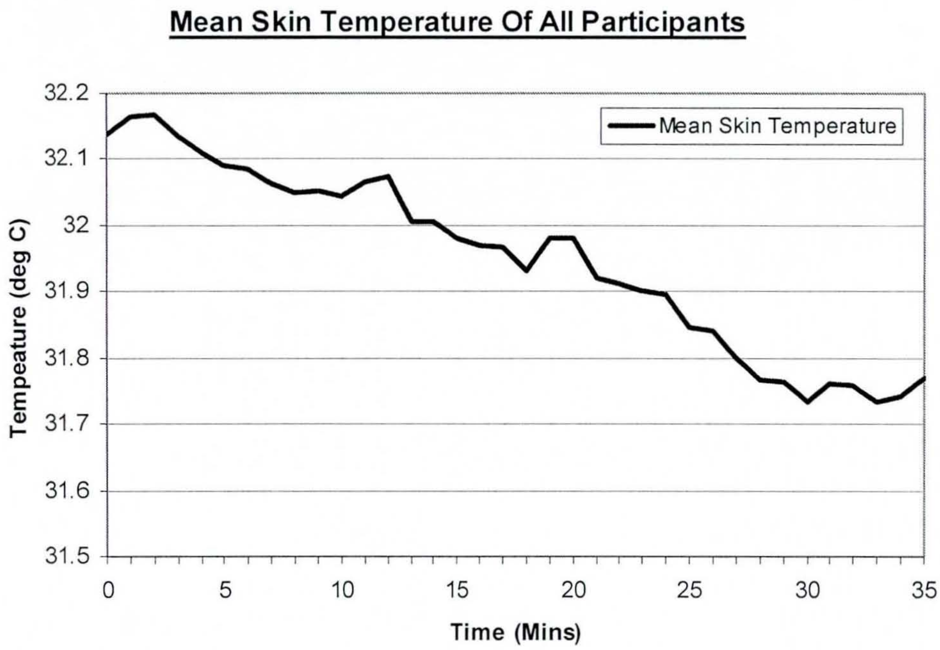


Figure 4.27, Mean skin temperature of participants during exposure

Figure 4.26 shows a comparison of each participant's left and right sided skin temperature during exposure to the cold window. Figure 4.27 shows mean skin temperature for all participants during exposure. Table 4.16 shows a paired sample t-test between mean skin temperature values at the 'pre' and 30 minute stages of the experiment. The test proved to be significant, P = 0.001 (2 tailed).

Table 4.16, Paired sample t-test between mean skin temperature values at the 'pre' and 30 minute stages

		t	df	Sig. (2-tailed)
Pair 1	Mean skin temp prior to exposure - Mean skin temp at the end of exposure	5.759	7	.001

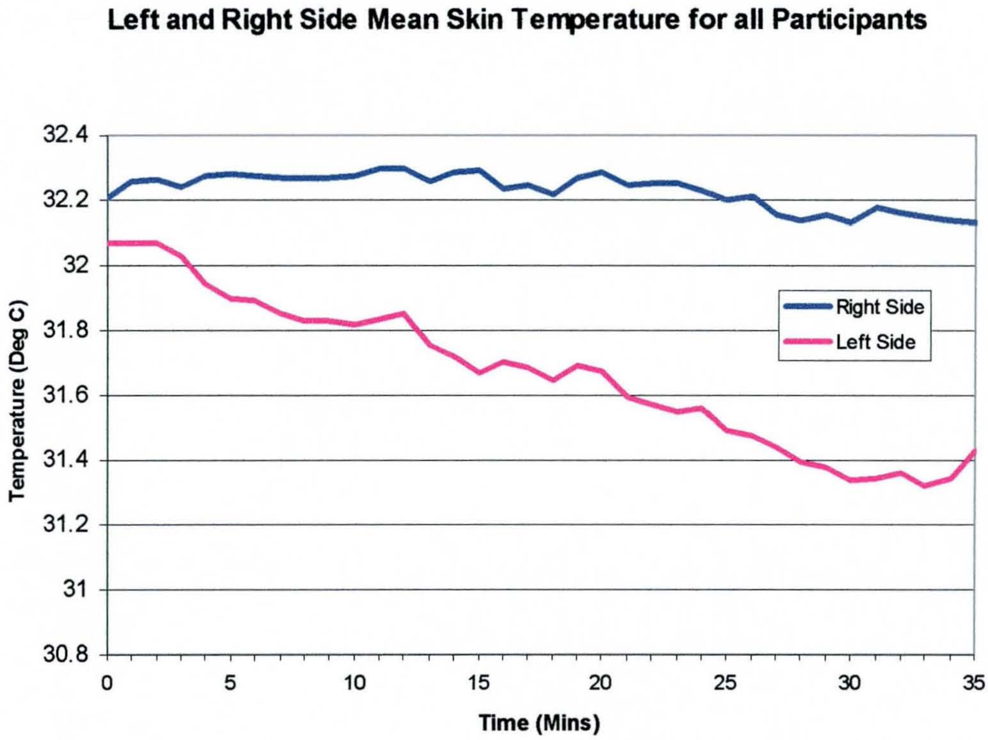


Figure 4.28, Mean left and right sided skin temperature during exposure

Figure 4.28 shows participants' mean left and right sided skin temperature during exposure. Table 4.17 displays a paired sample t-test between left and right sided skin temperature at the 30 minute point of exposure.

Table 4.17, Paired sample t-test between left and right sided mean skin temperature at the end of exposure.

		t	df	Sig. (2-tailed)
Pair 1	Mean skin temp for right side of the body at the end of exposure - Mean skin temp for left side of the bost at the end of exposure	5.646	7	.001

Table 4.18 displays mean left and right sided skin temperatures for each participant at the 'PRE' and '30-minute' stages of experimentation.

Table 4.18, Participants' mean left and right sided skin temperature at 'PRE' and '30 Minute' stages

	'PRE'		'30 MINUTES'	
Participant	**Right**	**Left**	**Right**	**Left**
1	31.2	31.2	31	30.2
2	31.2	31.2	31.2	30.3
3	31.6	31.9	31.4	31.3
4	32.8	32.8	32.9	32.1
5	32.4	31.7	32.4	30.8
6	33.4	33.1	33.6	32.9
7	32.6	32.3	32.3	32
8	32.5	32.6	32.3	30.9
Mean	32.2	32.1	32.1	31.3

4.5.2 Interpretation of results

Figure 4.27 shows a clear, steady decrease in mean skin temperature during exposure to the cold window. The statistical data in Table 4.16 shows that this decrease is significant, P = 0.001 (2 tailed), between the start and end of exposure.

There is also a clear difference between left and right sided skin temperatures at the end of exposure. It can be seen that the difference between the 2 steadily increases during exposure and is in excess of 0.7 °C at the end of exposure (Figure 4.28). This was supported by statistical data in Table 4.17, which showed that there was a significant difference between the temperatures of opposing body sides due to exposure to the cold window.

4.6 Subjective results – Sensation

4.6.1 Presentation of results

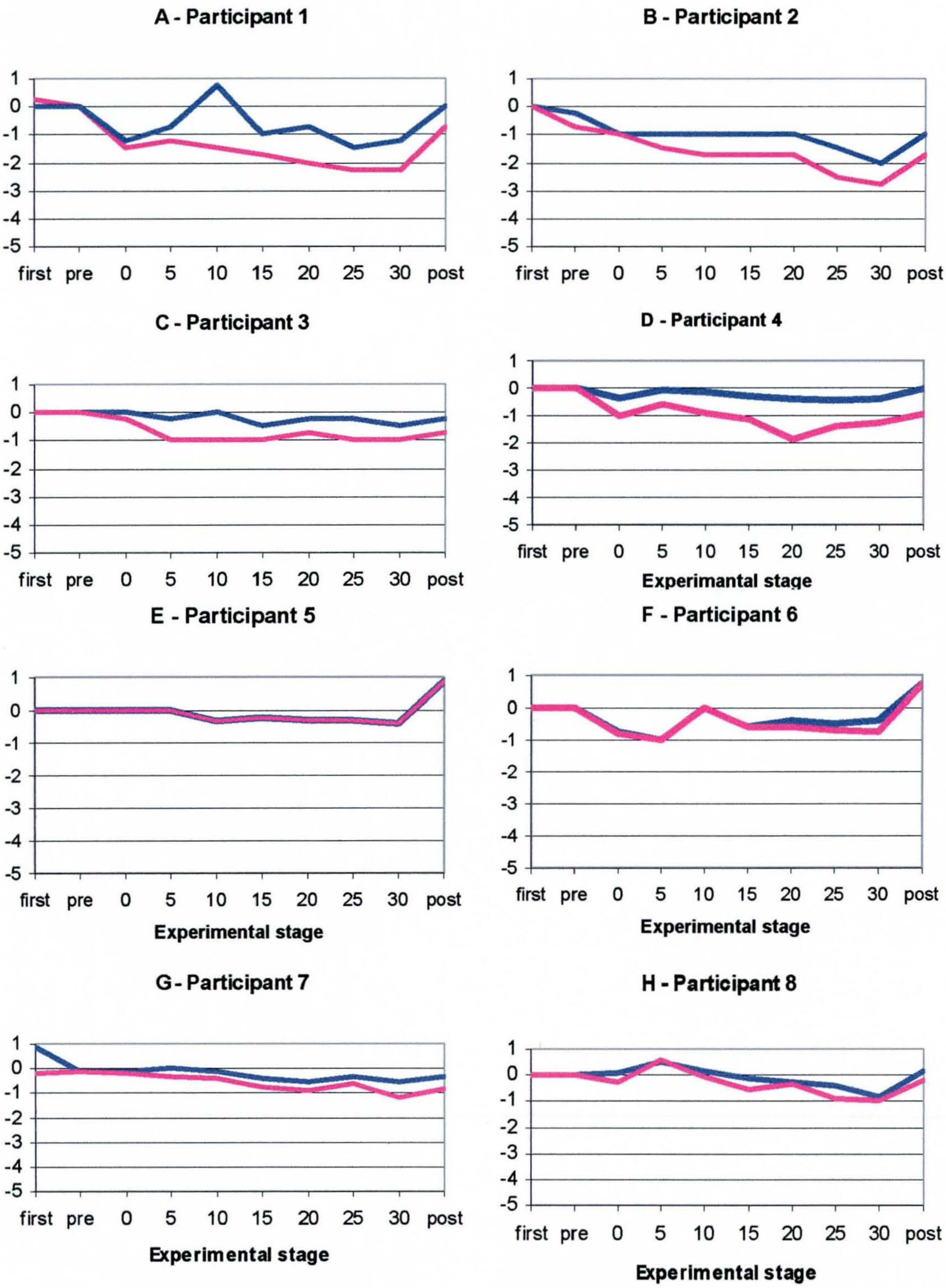


Figure 4.29, Comparison of each participant's left and right sided sensation vote (1=slightly warm, 0=Neutral, -1=Slightly cool, -2=Cool, -3=Cold, -4=Very cold, -5=Extremely cold) – **Left side**, – **Right side**

Figure 4.29 shows a comparison of each participants mean sensation vote for their left and right side, during exposure to the cold window. Figure 4.30 shows the mean sensation vote of all participants, at each experimental stage.

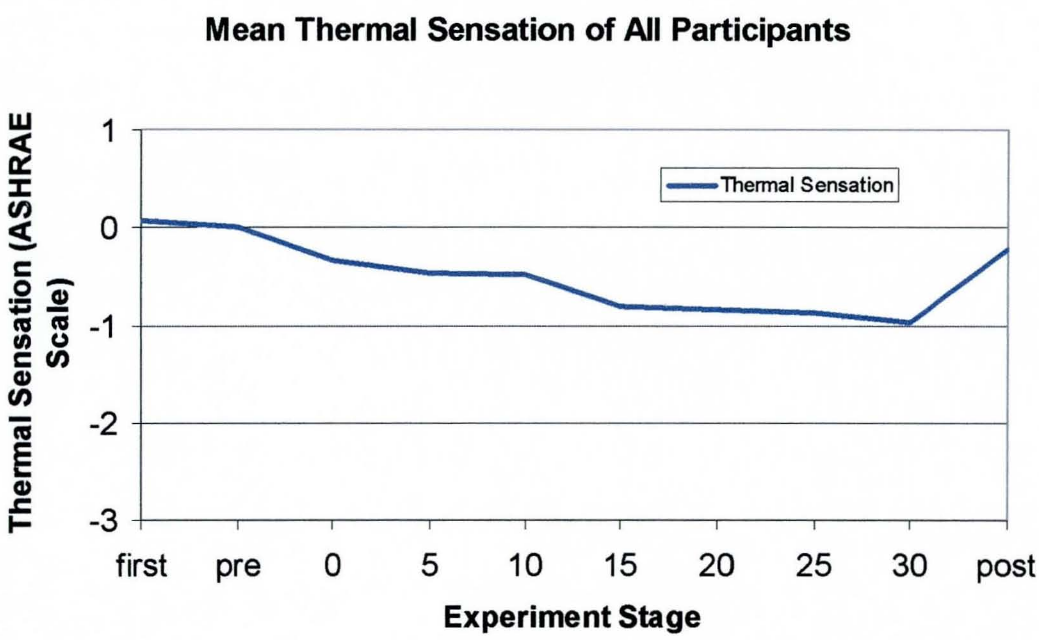


Figure 4.30, Participants' mean overall sensation vote during exposure (1=slightly warm, 0=Neutral, -1=Slightly cool, -2=Cool, -3=Cold)

Table 4.19 shows a wilcoxon signed ranks test between the sensation vote prior to exposure (pre) and the sensation vote at the 30-minute exposure point. There was a significant difference between these points, $P = 0.028$ (2 tailed).

Table 4.19, , Wilcoxon signed ranks test between the 'pre' and '30-minute' sensation votes

Wilcoxon Test Statistics between thermal sensation at the 'PRE' and '30min' stages[b]

	Z	Asymp. Sig. (2-tailed)
Thermal sensation at end of exposure - Thermal sensation before exposure	-2.197[a]	.028

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

Figure 4.31 displays participants' mean sensation vote for their left and right sides during the experiment.

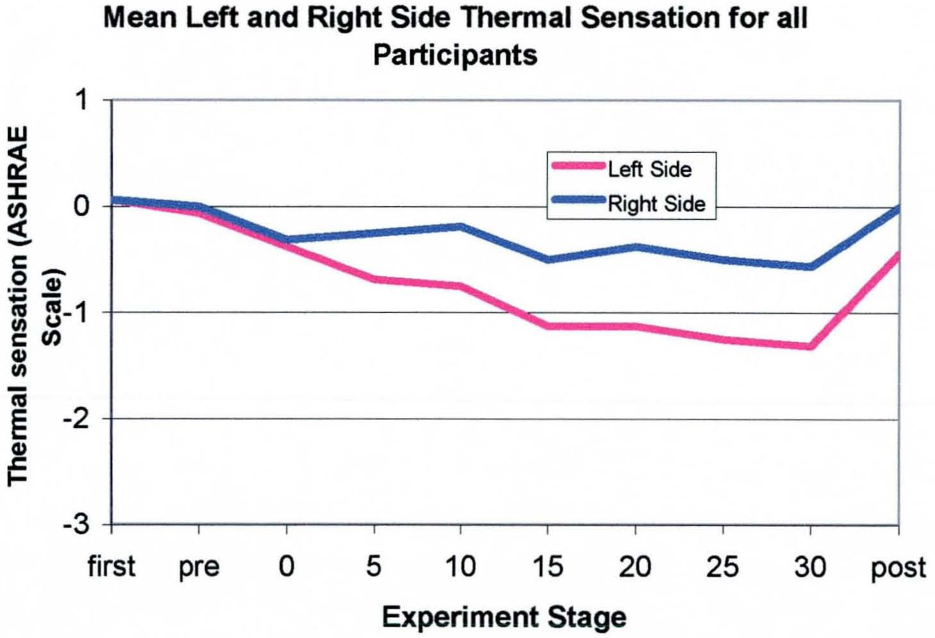


Figure 4.31, Participants' mean left and right sided sensation vote during exposure (1=slightly warm, 0=Neutral, -1=Slightly cool, -2=Cool, -3=Cold) – **Left side**, – **Right side**

Table 4.20, A Wilcoxon signed rank test between the mean' 30-minute' left and right sided sensation vote

Wilcoxon Test Statistics between the end mean thermal sensation, of the left and right sides of the body[b]

	Z	Asymp. Sig. (2-tailed)
end thermal sensation left side - end thermal sensation right side	-2.366[a]	.018

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

Table 4.20 contains statistical data from a Wilcoxon signed ranks test between the mean sensation vote for the left and right sides of the body, at the '30-minute' point of exposure. The difference was found to be significant, P = 0.018 (2 tailed). The data can be seen in raw form in Table 4.21.

Table 4.21, Participants' mean left and right sided sensation vote at 'PRE' and '30 Minute' stages

Participant	'PRE' Left	'PRE' Right	'30 MINUTES' Left	'30 MINUTES' Right
1	0.0	0.0	-2.2	-1.2
2	-0.8	-0.2	-2.8	-1.8
3	0.0	0.0	-1	-0.4
4	0	0	-1.3	-0.2
5	0	0	-0.3	-0.2
6	0	0	-0.9	-0.3
7	-0.1	-0.1	-1.2	-0.4
8	0	0	-1.0	0.9
Mean	-0.1	-0.04	-1.35	-0.65

4.6.2 Interpretation of results

The mean thermal sensation vote for participants steadily decreases throughout exposure to the window (Figure 4.30). It falls by just over one scale unit from around 0 (neutral) to -1 (slightly cool). This difference in sensation vote was found to be significant by statistical testing (Table 4.19).

At the end point of exposure there was a clear difference between the sensation votes for the left and right sides of the body, illustrated in Figure 4.31. This difference steadily increased from the start of the experiment, where the sensation votes were equal for opposing body sides. The difference at the end of exposure was found to be significant by statistical testing (

Table 4.20), P = 0.18 (2 tailed).

4.7 Subjective results – Thermal comfort

4.7.1 Presentation of results

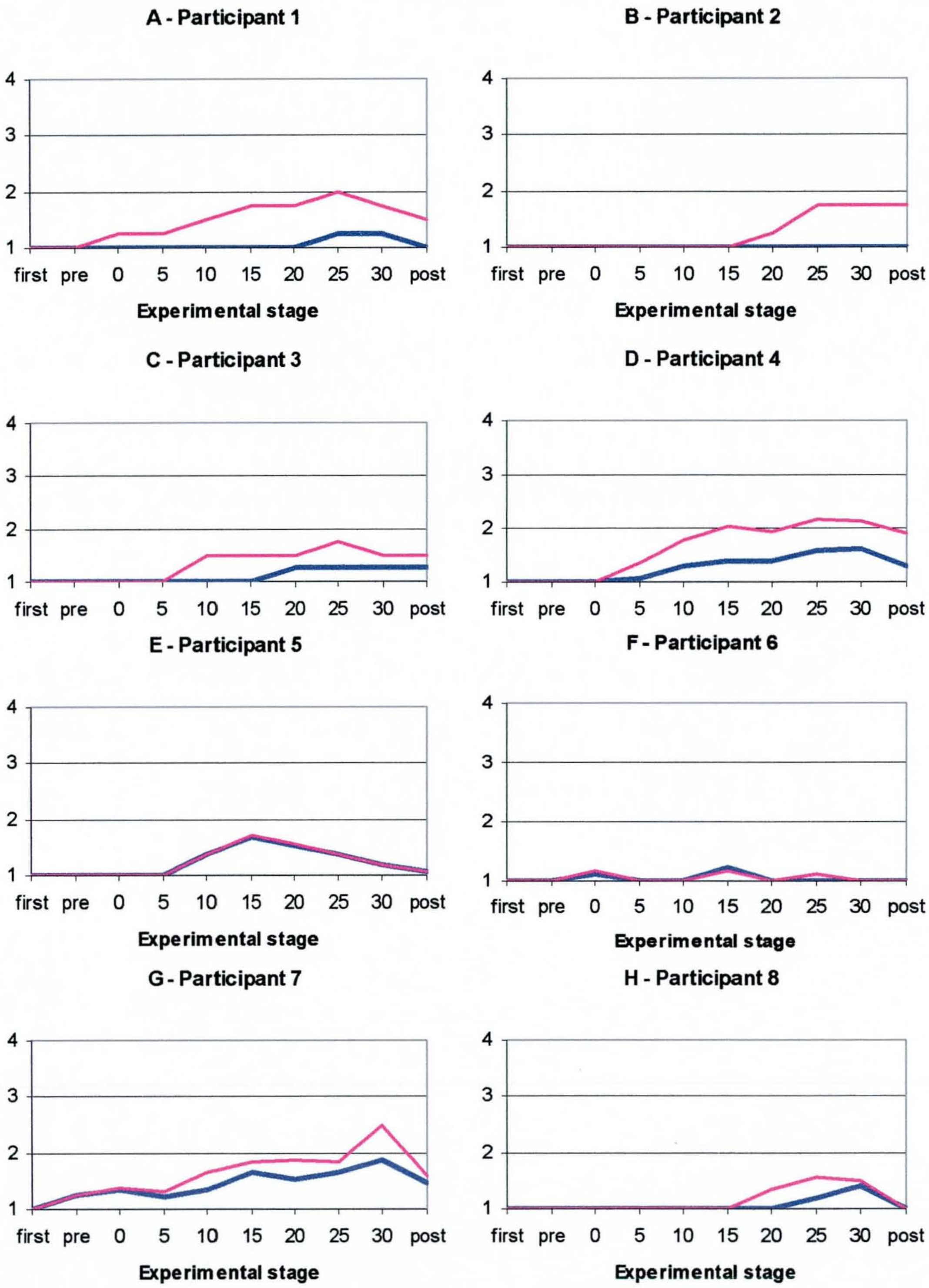


Figure 4.32, Comparison of participants mean left and right sided thermal comfort vote (1=Not uncomfortable, 2=Slightly uncomfortable, 3Uncomfortable, 4=Very uncomfortable) – **Left side**, – **Right side**

Wilcoxon Test Statistics between the mean thermal comfort vote at the 'PRE' and '30min' stages [b]

	Z	Asymp. Sig. (2-tailed)
Thermal comfort at end of exposure - Thermal comfort before exposure	-2.521 [a]	.012

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

Statistical analysis was conducted between the mean thermal comfort vote at the 'pre' and '30-minute' points of exposure. This is illustrated by Table 4.22, in the form of Wilcoxon signed ranks test, that shows a significant decrease in comfort vote, P = 0.12 (2 tailed).

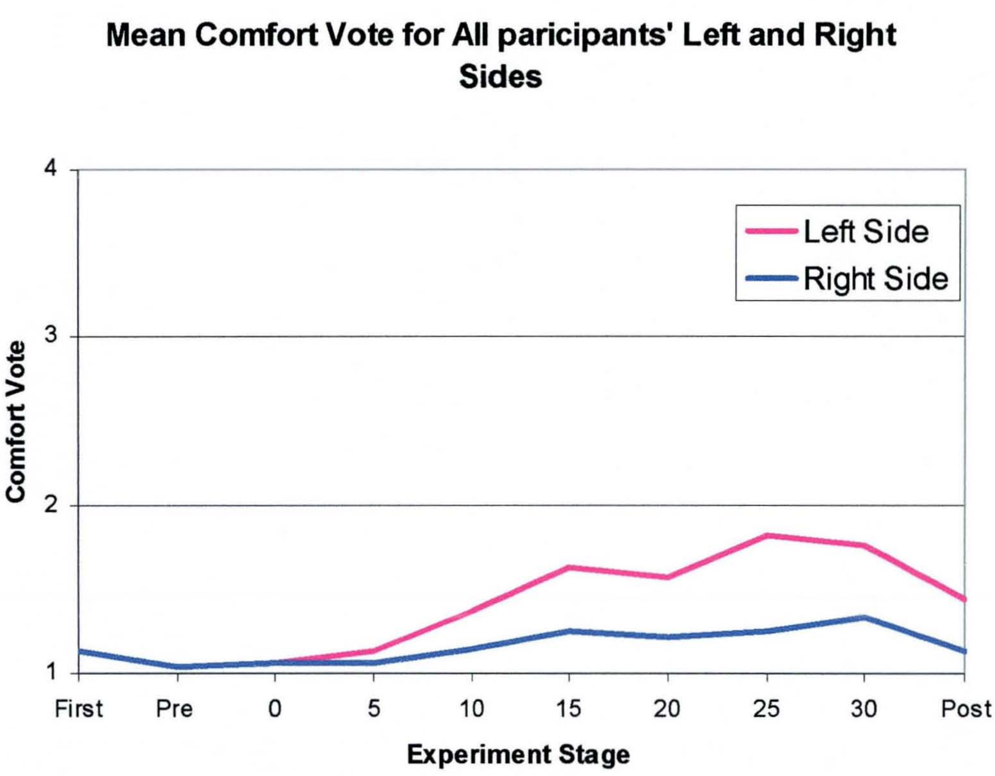


Figure 4.34, Mean comfort votes for the left and right sides of the body during the experiment (1=Not uncomfortable, 2=Slightly uncomfortable, 3Uncomfortable, 4=Very uncomfortable)

Figure 4.34 shows the mean left and right sided thermal comfort votes at each experimental stage. A wilcoxon signed ranks test was used to analyse differences between the comfort votes of opposing body sides at the '30-minute' point. The difference was found to be significant and the statistical data is shown in Table 4.23. Table 4.24 displays each participants left and right sided comfort vote at the 'pre' and 30-minute' stages of experimentation.

Table 4.23, Wilcoxon Signed rank test between the '30-minute' mean comfort votes of the left and right sides of the body

Wilcoxon Test Statistics between the end mean thermal comfort vote, for both sides of the body[b]

	Z	Asymp. Sig. (2-tailed)
End thermal comfort of left side - End thermal comfort of right side	-2.207[a]	.027

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

Table 4.24, Participants' mean left and right sided comfort vote at 'PRE' and '30 Minute' stages

	'PRE'		'30 MINUTES'	
Participant	**Left**	**Right**	**Left**	**Right**
1	1.1	1.1	1.7	1.3
2	1.1	1.1	1.8	1.1
3	1	1	1.6	1.3
4	1.1	1.1	2.2	1.6
5	1.1	1.1	1.3	1.3
6	1	1	1	1
7	1.3	1.3	2.5	1.9
8	1.1	1.1	1.6	1.4
Mean	1.1	1.1	1.7	1.3

4.7.2 Interpretation of results

Statistical data shows that the mean thermal discomfort vote significantly increases due to exposure to the window (Table 4.22). This difference is displayed clearly in Figure 4.33, where a steady increase in comfort can be seen from the start of the experiment to the end point of exposure at 30-minutes. The difference in the thermal comfort vote of opposing body sides gradually increased from the start of exposure to the end at 30-minutes (Figure 4.34). There was a significant difference between the left and right sides at the 30-minute point, due to exposure to the window (Table 4.23).

4.8 Subjective results – Draughtiness

4.8.1 Presentation of results

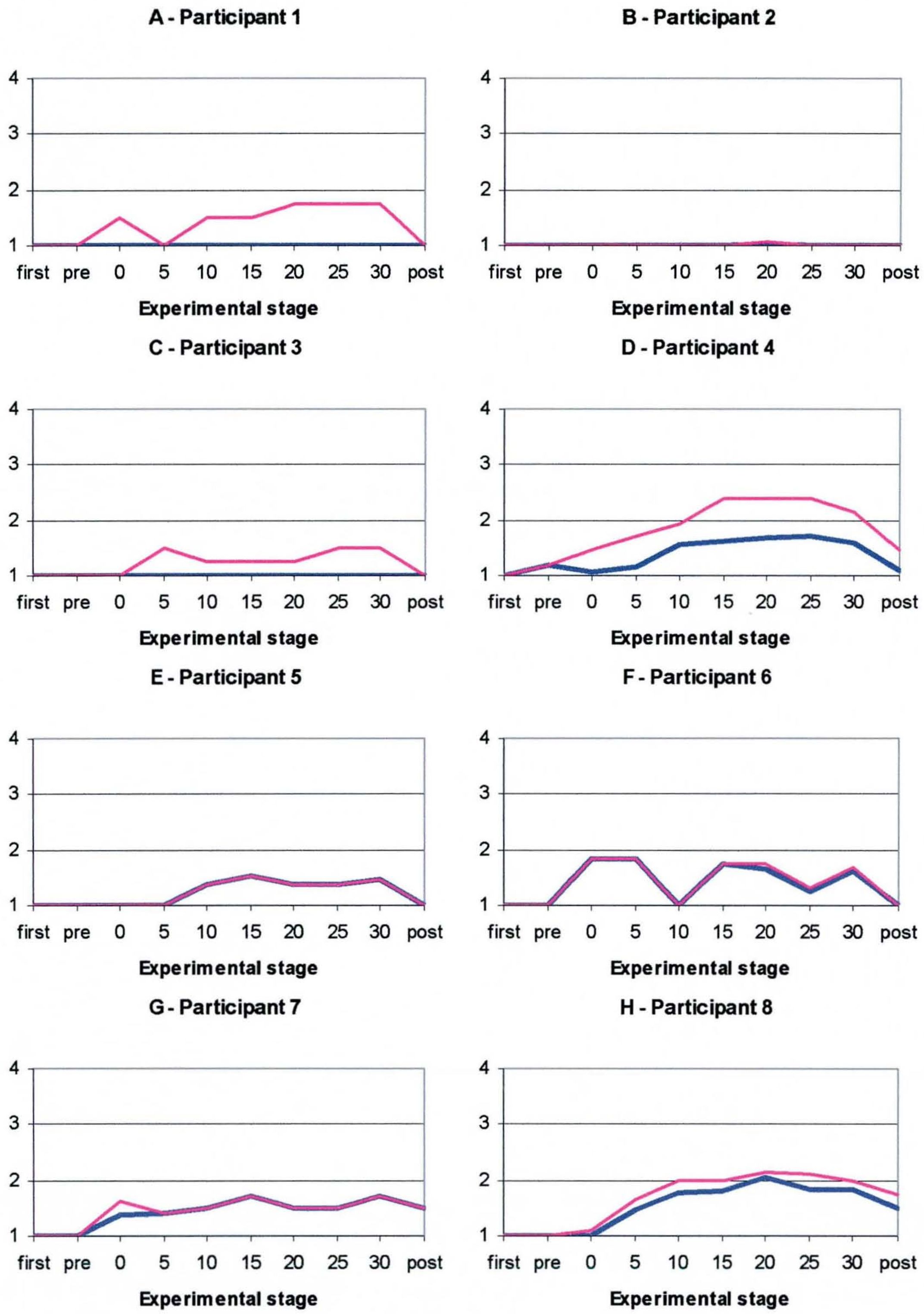


Figure 4.35, Comparison of participants' left and right sided draughtiness vote (1=Not draughty, 2=Slightly draughty, 3=Draughty, 4=Very draughty) – **Left side**, – **Right side**

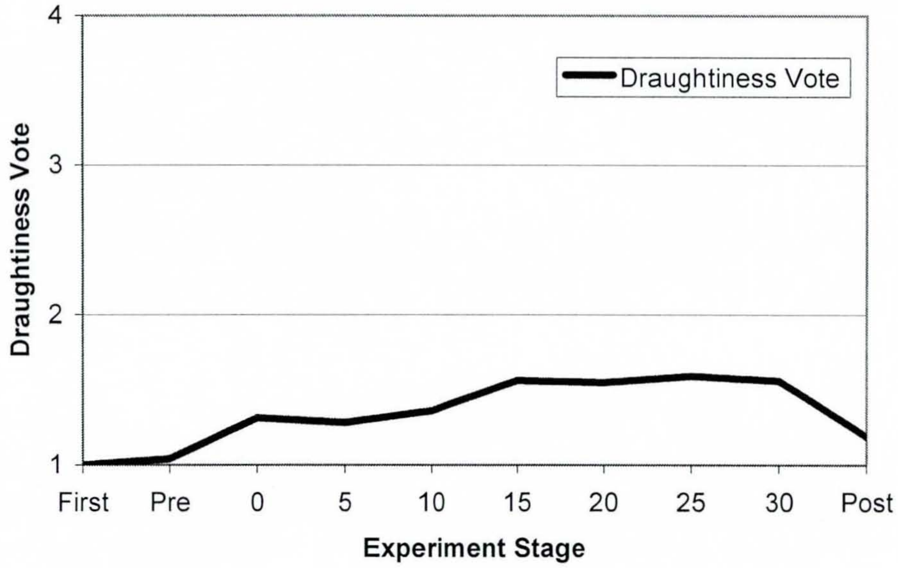


Figure 4.36, Mean draughtiness vote for all participants during the experiment. (1=Not draughty, 2=Slightly draughty, 3=Draughty, 4=Very draughty)

Figure 4.35 shows each participant's left and right sided draughtiness vote at each experimental stage. The mean draughtiness vote during the experiment is illustrated by Figure 4.36.

A wilcoxon signed ranks test was used to test for significance between the draughtiness vote at 'pre' and '30-minutes'. Table 4.25 shows a significant difference between the two values.

Table 4.25, Wilcoxon signed rank test between the mean draughtiness vote at the start and the end of exposure.

Wilcoxon Test Statistics between the mean draughtiness vote at the 'PRE' and '30min' stages [b]

	Z	Asymp. Sig. (2-tailed)
Draft sensation at end of exposure - Draft sensation at start of exposure	-2.366[a]	.018

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

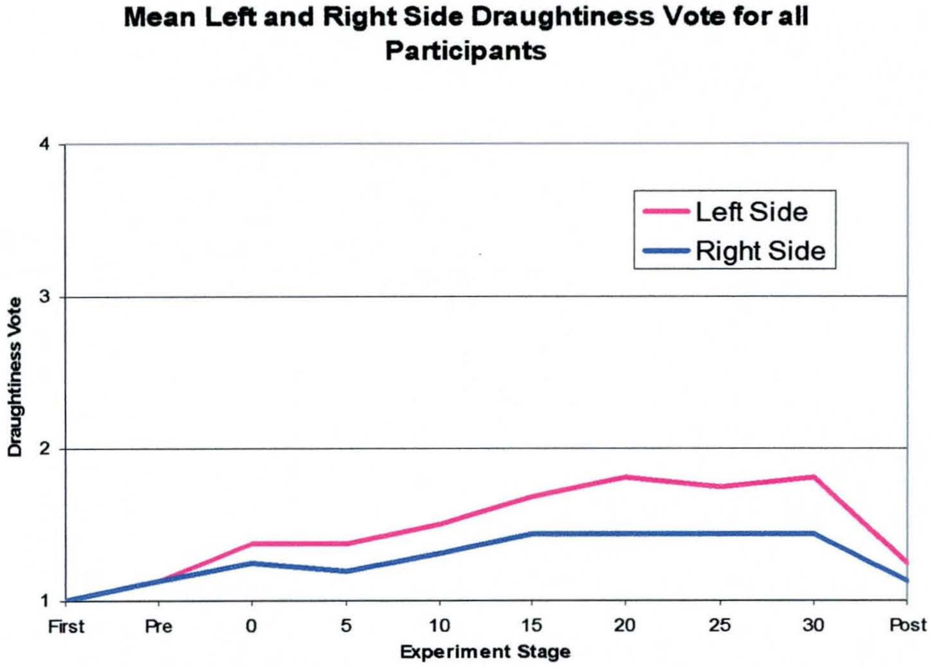


Figure 4.37, Left and Right sided mean draughtiness vote during the experiment (1=Not draughty, 2=Slightly draughty, 3=Draughty, 4=Very draughty) – **Left side**, – **Right side**

Table 4.26, Wilcoxon signed rank test between the mean end draughtiness votes for participants' left and right sides

Wilcoxon Test Statistics between the mean end draftiness vote, for the left and right sides of the body[b]

	Z	Asymp. Sig. (2-tailed)
End draught sensation for the left side - End Draught sensation for the right side	-2.201[a]	.028

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

Figure 4.37 shows the mean left and right sided draughtiness vote at each experimental stage. Individual participants' draughtiness vote at the 'pre' and '30-minute' stages is displayed by Table 4.27. Statistical data from a wilcoxon signed ranks test can be seen in Table 4.26. This shows a significant difference between the '30-minute' draughtiness votes for the left and right sides, P = 0.028 (2 tailed).

Table 4.27, Participants' mean left and right sided draughtiness vote at 'PRE' and '30 Minute' stages

Participant	'PRE'		'30 MINUTES'	
	Left	Right	Left	Right
1	1.1	1.1	1.8	1.1
2	1.1	1.1	1.1	1.1
3	1.1	1.1	1.5	1.1
4	1.3	1.3	2.2	1.7
5	1.1	1.1	1.5	1
6	1.1	1.1	1.7	1.6
7	1.1	1.1	1.8	1.8
8	1.1	1.1	2	1.8
Mean	1.13	1.13	1.7	1.4

4.8.2 Interpretation of results

There is shown to be a significant increase in the perception of draught as a result of exposure to the window (Table 4.25). This increase is gradual, increasing from the point of exposure, to the end of exposure at 30-minutes (Figure 4.36). During exposure, a difference between the draughtiness votes of the left and right sides becomes more apparent. The difference gradually increases from the start of the experiment to the end of exposure at 30-minutes (Figure 4.37). At the end of exposure, participants were found to perceive draught significantly more on their left side than their right (Table 4.26).

4.9 Subjective results – Thermal preference and environmental satisfaction

4.9.1 Presentation of results

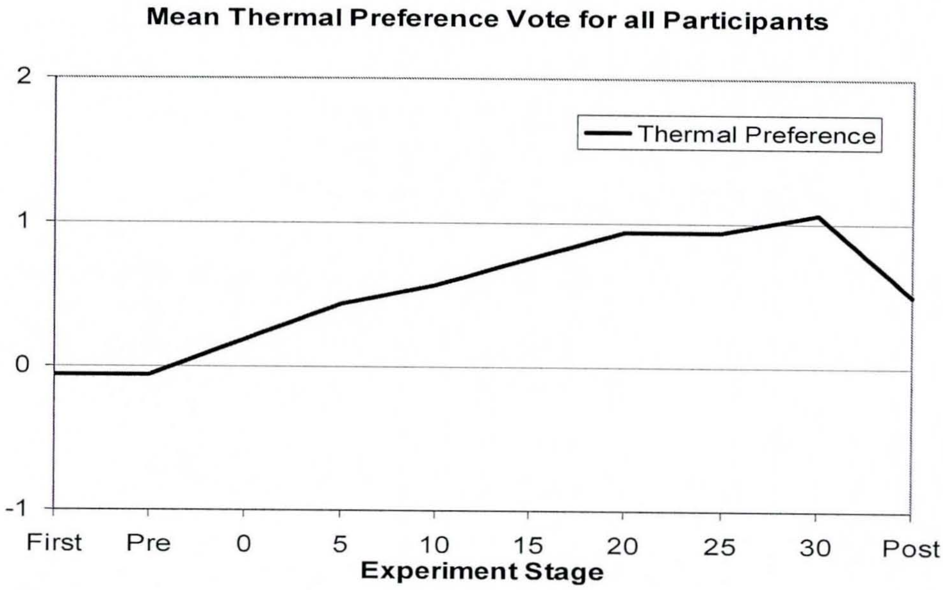


Figure 4.38, Mean thermal preference vote during the experiment. (-1=slightly cooler, 0=No change, 1=Slightly warmer, 2=Warmer)

Figure 4.38 shows the mean thermal preference vote of all participants during the course of the experiment, in terms of how they would like to be thermally in the environment at that point. Figure 4.39 shows the environmental satisfaction votes of participants, in terms of the number of participants voting the environment to be satisfactory.

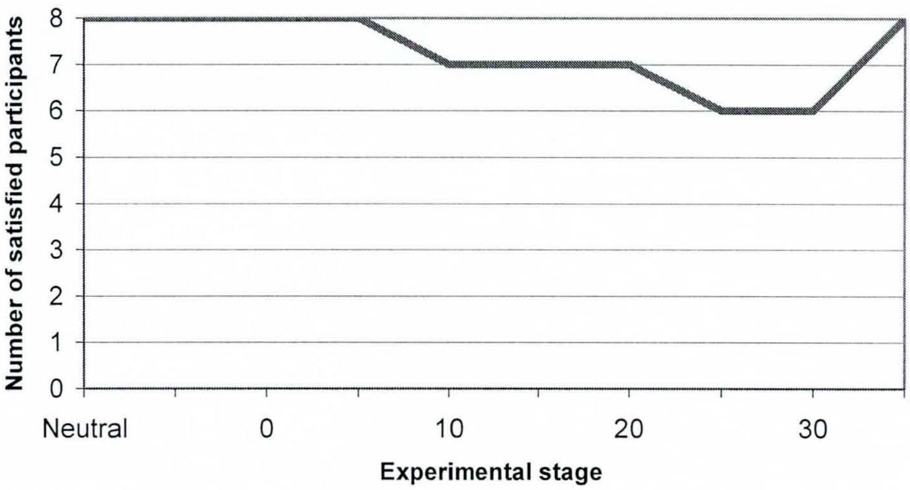


Figure 4.39, The sum of satisfaction vote, during the course of the experiment. (8=All participants satisfied, 0=No participants satisfied)

4.9.2 Interpretation of results

Thermal preference results show that there was a change of just over one scale unit due to exposure to the window. After being 0 (neutral) prior to exposure, the mean thermal preference changed to 1 (desire to be slightly warmer) by the end of exposure (Figure 4.38). Participants also voted the environment to be less satisfactory at the end of exposure compared to the start. All participants voted the environment to be satisfactory at the start of exposure (0 minutes) and only 6 voted it to be satisfactory at the end, giving an APD of 25% (Figure 4.39).

4.10 Thermal manikin

After completing the experiment using human subjects, it was repeated using a thermal manikin.

4.10.1 Aim

The aim of the experiment was to provide a more comprehensive view of the effects of the cold window by supplementing mean skin temperature data and data obtained subjectively from questionnaires; with data from the thermal manikin.

4.10.2 Method

4.10.2.1 Facility and set-up

The experimental facility and environmental conditions were identical to those used with participants (see section 4.3.3).

4.10.2.2 Procedure

The manikin was dressed in the standard clothing ensemble of white cotton/Polyester (65/35%) long sleeved shirt with sleeves rolled up to the elbow, and beige cotton/Polyester (65/35%) trousers. The manikin was placed in the chamber in the exposure position (next to the window), with the cardboard shield in place to ensure that it was not exposed to the window. It was then set to maintain a constant temperature of 34°C and the power input required to maintain this temperature was recorded at fifteen second intervals throughout the experiment. At this point squirrel data loggers were also started to record environmental conditions. The insulated box on the outside of the window was then stacked with ice and sealed. One the window had cooled the shield was removed and the manikin was exposed to the cold window until it reached steady state; this was deemed to be achieved when the power input remained at a similar level for a period of 5 minutes. At this point the shield was replaced and the chair moved out to the 'pre'/neutral position until steady state was again reached.

4.10.3 Results

4.10.3.1 Presentation of results

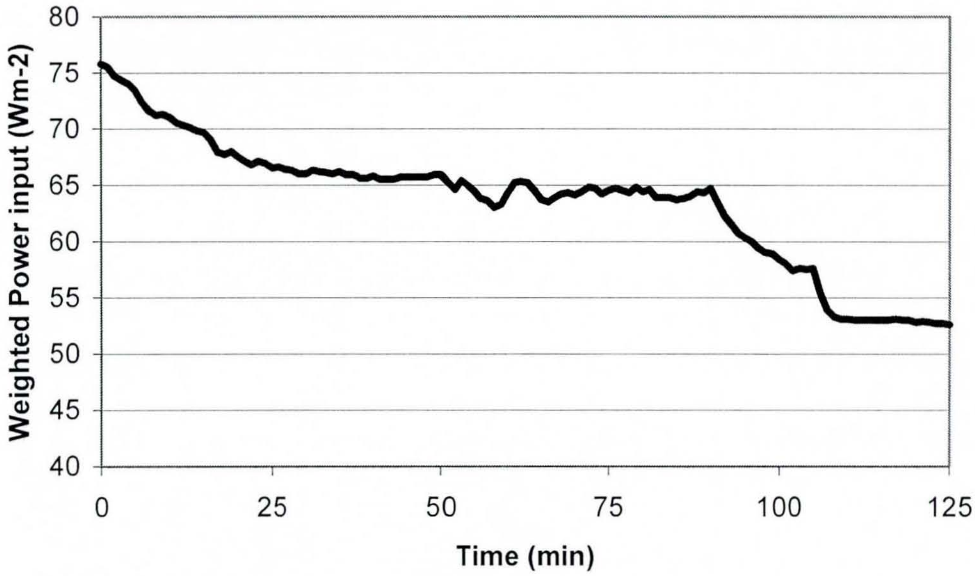


Figure 4.40, Mean weighted power input for the manikin during the experiment

Table 4.28, Mean power input required to achieve equilibrium during exposure and when in the neutral position

	At Exposure	At neutral position	Difference
Mean Power input at equilibrium (Wm-2)	64.7	52.7	12

Figure 4.40 displays the mean power input required to keep the manikin at 34°C during exposure. Table 4.28 displays values for the mean power input at exposure and in the control position, and the difference between them.

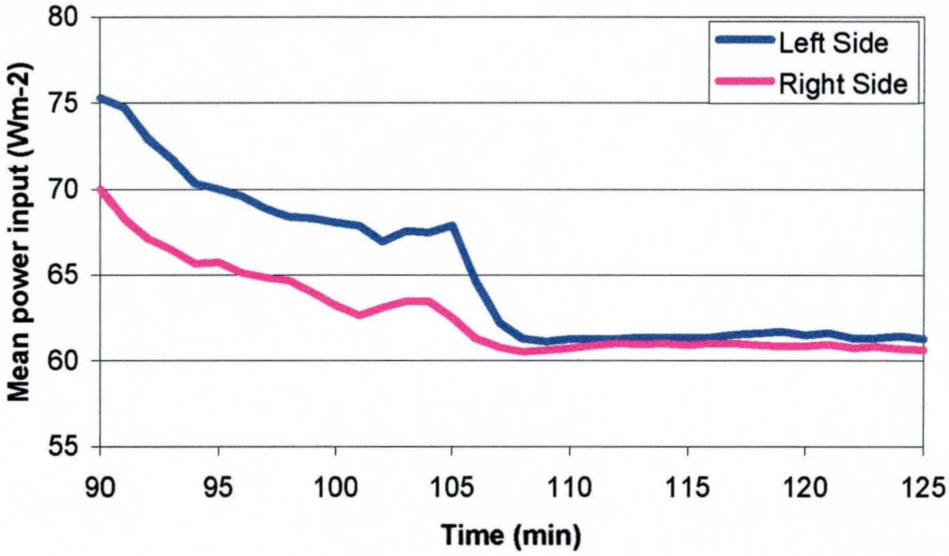


Figure 4.41, Mean power input for the left and right sides of the manikin during experimentation

Figure 4.41 displays the mean power input, for the left and right sides of the manikin, during exposure. As the manikin software does not have a weighting calculation for left and right body sides, the mean of the respective left and right sided segments was calculated. Table 4.29 displays values for the mean left and right sided power input, at exposure and neutral equilibriums, and the differences between them.

Table 4.29, Total power input required for left and right sides to reach equilibrium during exposure, and when in the neutral position

Mean Power input at equilibrium (Wm-2)	**Left**	**Right**	**Difference**
At 90min (When exposed to the window)	75.28	70	5.28
At 125min (In the neutral/pre position)	61.26	60.63	0.63
Difference	14.02	9.37	**4.65**

4.10.3.2 Interpretation of results

There is a clear difference in the amount of power needed to keep the manikin at steady state in each of the conditions (Figure 4.40). For equilibrium to be achieved during exposure to the window the power input required was 64.7Wm-2, and 52.7Wm-2 in the neutral position (Table 4.28). The manikin therefore required 12Wm-2 more power to achieve equilibrium when placed next to the cold window, which can be attributed to exposure.

Figure 4.41 shows that there is a clear difference in the amount of power required by the left and right sides of the manikin during exposure. When equilibrium was achieved in the exposure position, the exposed left side required 5.28Wm-2 more power than the right. For equilibrium in the neutral position the left side required only 0.63Wm-2 more than the right. The difference between the mean power requirement of the left and right sides when exposed and unexposed was 4.65Wm-2 (Table 4.29).

4.11 Discussion

4.11.1 Environmental results

Environmental conditions in the chamber were adequately controlled so that PMV = 0 $\pm$ 0.5 (ISO7730) was achieved for all experimental sessions. Outputs for three environmental predictive models, outlined in ISO 7730, are shown in Table 4.30, along with a summary of environmental conditions and the actual percentage dissatisfied (APD) derived from subjective analysis. The Table compares APD with the predicted percentage dissatisfied output from the models, at the 'pre'/control and '30-minute' stages of the experiment.

Table 4.30, Summary of environmental data and predictive model outputs at the 'pre' and '30-minute' stages

Experimental stage	'PRE'/Control	At 30min exposure
t_a (°C)	22.15	21.9
t_r (°C) derived from exposed t_g	21.89	19.68
t_r (°C) derived control t_g	21.89	21.53
Air velocity (m/s)	0.09	0.31
Relative Humidity (%)	41.49	50.26
PMV derived from exposed t_r	-0.3	-1
PPD derived from exposed t_r	7.5	25.8
PMV derived from control t_r	-0.3	-0.4
PPD derived from control t_r	7.5	8.8
AMV	0	-1
APD	0	25
Draught Rating (% dissatisfied)	9.2	16.7
Radiant asymmetry (% dissatisfied)	1	40

PMV – Predicted Mean Vote
PPD – Predicted Percentage Dissatisfied
AMD – Actual Mean Vote
APD – Actual Percentage

At the 30 min exposure point the 'local' calculated PMV of –1 was able to account for the effects of the cold window on thermal comfort, this matching exactly the AMV of –1. The 'local' predicted percentage dissatisfied of 25.8% also compared well with an APD of 25%. The locally calculated Draught rating and radiant asymmetry models were not as accurate, giving percentage dissatisfied outputs of 16.7% and 40% respectively and seem limited in their ability to assess the effects of the environment in general.

It can be concluded therefore that for people with sitting side on next to a cold window, current thermal comfort models (i.e. the PMV, ISO 7730) will provide a reasonable assessment of thermal comfort and satisfaction, when mean radiant temperature is measured locally to the window.

4.11.2 Mean skin temperature

Mean skin temperature was clearly affected by exposure to the cold window, decreasing by almost 0.4°C (Table 4.18, Figure 4.27). The decrease in skin temperature between the start and end of exposure was found to be significant, P = 0.001, 2 tailed (Table 4.16). However, the effect on the exposed left side of the body was expected to be even greater, and data were re-analysed to compare the temperatures of both body sides. The difference between the temperatures of opposing body sides gradually increased during exposure (Figure 4.28), and at the end of exposure the exposed left side was significantly cooler than the right (Table 4.17). The results show that exposure to the window not only significantly decreases mean skin temperature, but also creates a significant skin temperature gradient across the body.

4.11.3 Sensation

Thermal sensation was affected by exposure to the window, with the mean participant vote decreasing from neutral to slightly cool on the sensation scale (Figure 4.30). The decrease in mean sensation vote was found to be significant by statistical testing (Table 4.19). Participants' also experienced a significant sensation gradient across the body, which steadily increased from start of exposure to the end (Figure 4.31,
Table 4.20). The results support findings from mean skin temperature analysis and indicate that participants were able to subjectively interpret their decrease in mean skin temperature and the temperature gradient present across their bodies.

4.11.4 Thermal comfort

The mean discomfort vote also increased as a result of exposure to the window (Figure 4.33). By the end of exposure it increased by 0.7 scale units from 0 (no discomfort) at the start of the experiment. This increase was found to be significant by statistical testing (Table 4.22). At the end of exposure there was also a difference in the mean thermal comfort vote for opposing sides of the body, with the exposed left side being more uncomfortable than the right (Figure 4.34). Although the difference does not appear to be as large as the one found for thermal sensation, it was also found to be significant (Table 4.23). Thermal comfort results therefore support findings from previous results and show that exposure to the window creates whole body discomfort and local discomfort to the exposed side.

4.11.5 Draughtiness

Subjective analysis indicates that participants experienced a steady increase in draught due to exposure (Figure 4.36). This increase was found to be significant by statistical analysis (Table 4.25). As expected, draught was experienced to a significantly greater extent on the exposed left side of the body (Figure 4.37, Table 4.26). This supports the theory that the cold window would cause convection currents, coming down from the window, experienced on the participants left side.

4.11.6 Thermal preference and environmental satisfaction

Thermal preference results show that exposure to the window had a noticeable effect on participants' desire for change in the thermal environment. The desired change is shown by Figure 4.38 to be one positive unit on the preference scale, from 'no change' to 'slightly warmer'. This corresponds well with the previously reported, one scale unit, change in thermal sensation from 'neutral' to 'slightly cool'.

Environmental satisfaction data has previously been mentioned in the environmental results section of the discussion, in terms of the actual percentage of participants dissatisfied with the thermal environment (APD). This changed from all (8/8) participants being satisfied at the start of the experiment, APD=0%; to 6/8 at the end of exposure, APD = 25% (Figure 4.39). Results show that exposure had a detrimental effect on participants' opinion of the thermal environment.

4.11.7 Manikin data

Exposure to the window visibly increased the amount of power required to keep the manikin at a steady state of 34°C, indicating that exposure to the window cools the body (Figure 4.40). This supports the previous findings from mean skin temperature analysis. Although the exposed left side of the manikin required more power to achieve equilibrium in both the neutral and exposure positions, The difference in mean power requirement between the left and right sides of the manikin increased by 4.65Wm-2 when in the exposure position compared to the neutral position (Table 4.29). This finding also supports mean skin temperature analysis, indicating that exposure to the window creates a temperature gradient across the body.

4.12 Conclusions

1 A significant decrease in mean skin temperature occurred as a result of exposure to the window

2 Subjective analysis shows a general increase in discomfort caused by the window

3 There was a significant temperature gradient created across the body, as a result of exposure to the window.

4 Subjective results indicate that participants interpreted the temperature gradient as discomfort.

4 There was significant perception of draught local to the left side of the body.

5 Existing environmental assessment models (i.e. the PMV, ISO 7730) appear valid provided mean radiant temperature is measured at the locally to the window.

6 As an alternative, a correction factor of -1 can be added to the PMV derived from the ambient environment (i.e. t_r shielded)

7 It can be concluded that for the conditions tested, if a person were exposed side on to a cold window then, when compared with a person in identical conditions but without the effects of the window, they would be 'cool' instead of 'neutral'

5 A test of PMV_{Solar} in 'cold' environmental conditions

5.1 Chapter Summary

Hodder and Parsons (2000) proposed a revised model of the PMV (Fanger, 1970; ISO 7730) to incorporate the effects of different intensities of direct solar radiation, calling it PMV_{Solar}.

Where;

$$PMV_{Solar} = PMV + \frac{\text{Radiation Intensity (Wm-2)}}{200}$$

In this experiment the standard PMV scale of +3 to -3 was extended by two points at either end, making an eleven point bi-polar scale. The above formula was concluded to work, but only tested in neutral environmental conditions (PMV = 0 $\pm$ 0.5).

In this chapter PMV_{Solar} is re-evaluated to determine it's accuracy at a different starting point on the revised eleven point PMV scale. Eight male and Eight female participants were exposed for thirty minutes to 600 Wm-2 of simulated solar radiation, in an environment of 17° C. Prior to exposure, participants had an acclimatisation period of thirty minutes in an environmental chamber, also at 17° C. All participants wore a standard clothing ensemble. PMV_{Solar} was found to work well in cool environmental conditions.

5.2 Introduction

Many studies have been conducted to investigate the effects of solar radiation on human thermal comfort and thermoregulation; Nielson (1990) and McNeill (1999) to name but a couple. All studies have concluded that solar radiation has a significant effect on thermal comfort and that existing standards for assessing hot environments (ISO 7933) did not predict well in conditions with solar radiation. This was supported by findings from Hodder (2002) who found that the existing standards for assessing moderate environments (the PMV, ISO 7730) did not accurately take into account the effects of direct solar radiation on thermal comfort, with these being greatly underestimated.

Direct solar radiation has been identified as a factor that could affect some individuals travelling on a train carriage. A model for assessing the effects of varying levels of direct solar radiation, PMV_{Solar} was proposed by Hodder (2002) for participants exposed front-on to a radiation source. This was validated by Vaugan and Parsons (2004) for participants with side on exposure to direct solar radiation. The model seems to be a reasonable tool for assessing such environments, but so far has only been tested in neutral conditions (PMV = 0 $\pm$ 0.5). If the model is to be fully validated, it must work across the range of sensation on the scale. In this chapter PMV_{Solar} will be tested and validated in cool conditions (PMV = -1.5 $\pm$ 0.1) and for a solar radiation intensity of 600Wm-2, that may be present on train carriages for persons seated near to an air conditioning system. According to the model this should correspond to an increase in AMV of +3 scale units form the original starting point on the scale.

5.3 Experimental Method

The experimental protocol used was similar to the generic one described in chapter 2. Alterations and additions to this protocol are detailed below.

5.3.1 Design

A single measures deign was used. Each subject had a 30 minute pre-cooling period, in an environmental chamber, at 17° C. They were then moved to a solar chamber and exposed to simulated solar radiation of 600Wm-2 for a further 30 minutes, again at an air temperature of 17° C. Environmental, physiological and psychological measurements were all recorded.

5.3.2 Subjects

Sixteen healthy participants were used, eight male and eight female. All participants were students at Loughborough University and aged between 19 and 23. The subjects wore the standard clothing ensemble of White cotton/Polyester (65/35%) long sleeved shirt, neck unfastened and sleeves rolled up to the elbow, and beige cotton/Polyester (65/35%) trousers. Participants wore their own undergarments and shoes. The estimated insulation value for the ensemble and car seat was 0.72 clo (ISO 7730).

5.3.3 Apparatus

The facility and equipment used in this experiment was exactly the same as is detailed in chapter 2. In addition to this a thermal chamber was used, in which air temperature could be accurately set to remain at a specific humidity and temperature ($\pm$ 0.5° C). The thermal chamber was located adjacent to the solar chamber and participants could be moved from one to the other in under 30 seconds (Figure 5.42).

Figure 5.42, Picture of 2 test chambers

5.3.4 Environmental Conditions

Environmental conditions were controlled throughout the experiment to be cool, deemed as PMV = -2 $\pm$ 0.5 (ISO 7730) without the consideration of the simulated solar radiation. Air temperature, mean radiant temperature, relative humidity and air velocity were all measured as outlined in chapter 2. Participant's metabolic rate and clothing insulation (Clo) remained constant throughout exposure.

5.3.5 Objective Measurements

Mean and local skin temperatures were taken throughout the experiment by means of thermistors positioned at the following points on the body.

- Right forehead
- Left forehead
- Right thigh
- Left thigh
- Left forearm
- Right forearm
- Left upper arm
- Right upper arm
- Left shin
- Right shin
- Chest

A modified Ramanathan weighting technique was used to calculate mean skin temperature.

5.3.6 Subjective Measurements

Subjects gave ratings of thermal comfort, thermal sensation, stickiness, preference and satisfaction with the environment in local areas and for the 'whole body' at 5 minute intervals throughout the experiment.

5.3.7 Procedure

Upon arrival at the test facility, participants completed medical screening questionnaires, to assess their ability to participate. They were then taken to the thermal chamber for a period of thirty minutes. Participants completed a questionnaire upon entering the chamber and were then fitted with thermistors and dressed in the standard clothing ensemble. Questionnaires were completed when appropriate throughout this period. A further questionnaire was completed prior to leaving the chamber after 30 minutes. For female participants a female lab technician fitted thermistors and aided changing.

Participants were then taken to the solar chamber seated on the car seat in the 'pre-rad' position where, after five minutes, they completed another questionnaire. The seat was then moved in to the exposure position and they immediately completed a further questionnaire. Participants remained in the exposure position for thirty minutes, completing questionnaires every five minutes throughout this period. They were than withdrawn from the radiation into the neutral position and completed a final questionnaire after five minutes.

5.4 Results

5.4.1 Environmental Results

Table 5.31, Summary of environmental conditions at the PRE and '30min' stages

Experimental stage	'PRE'/Control	At 30min exposure
t_a (°C)	16.65	16.85
t_r (°C) derived from exposed t_g	26.9	26.7
t_r (°C) derived control t_g	17.86	17.91
Air velocity (m/s)	0.09	0.08
Relative Humidity (%)	42	45.6
PMV derived from exposed t_r	-0.6	-0.5
PPD derived from exposed t_r	11.8%	11.12%
PMV derived from control t_r	-1.5	-1.5
PPD derived from control t_r	53.2%	50.4%
AMV	-1.82	1.28
APD	31.25%	12.5%

Table 5.31 displays a summary of environmental conditions at the 'pre/control' and '30minutes exposure' stage of experiments. Also displayed is the related PMV and PPD outputs, with t_r calculated with both a shielded and exposed globe. It can be seen from this that environmental conditions in the chamber give a PMV output of -1.5 (between 'slightly cool' and 'cool') when there is no exposure to direct solar radiation, but around --0.5 (between neutral and 'slightly cool') when exposed t_r is used in calculations. When participants are in the control position (i.e. not in radiation), PMV output compares well with an AMV of -1.82. For exposed subjects however, the PMV output of -0.5 largely underestimates the effect of the radiation when compared to an AMV of 1.28.

5.4.2 Objective Results – Mean Skin Temperature

Mean skin temperature data was not available from the previous experiment (Wales 2004), but was taken for the six participants in this study. The data is presented below.

The mean skin temperature of each participant during experimentation is displayed in Figure 5.43 and Table 5.32. The mean skin temperature of all participants is presented graphically in Figure 5.44.

5.4.2.1 Presentation of results

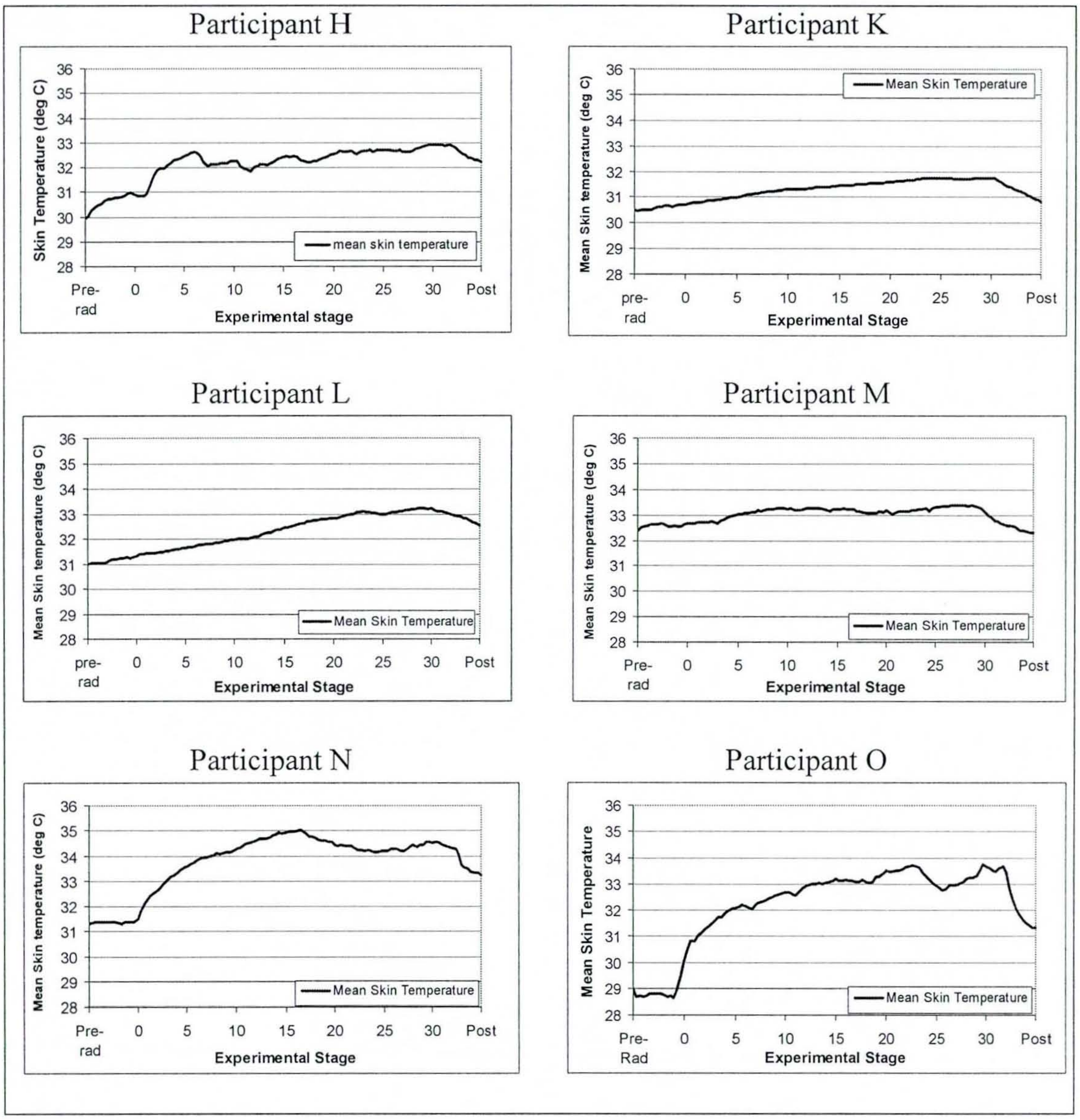


Figure 5.43, Participants' mean skin temperature during experimentation

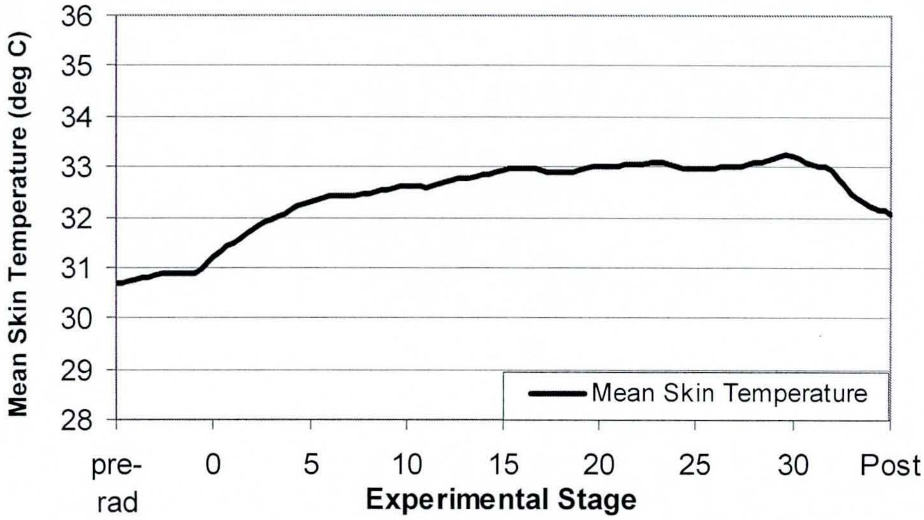


Figure 5.44, Mean skin temperature of all participants during experimental sessions

Table 5.32, Each participants mean skin temperature at the PRE and '30min' stages of experimentation

	Pre/Neutral	30 min exposure
Participant H	29.95	32.9
Participant K	30.5	31.76
Participant L	31	33.21
Participant M	32.38	33.1
Participant N	31.32	34.53
Participant O	29	33.6
Mean	30.69	33.19

Table 5.33 displays the results of a paired sample t-test between mean skin temperature in the environment prior to radiation exposure (pre-rad) and after 30 minutes radiation exposure (30 min).

Table 5.33, paired sample t-test between mean skin temperature prior to exposure and after 30 minutes exposure

Paired Samples Test

		t	df	Sig. (2-tailed)
Pair 1	Mean Skin temperature at Pre-Rad - Mean Skin Temperature after 30 mins radiation exposure	-4.336	5	.007

5.4.2.2 Interpretation of results

It can be seen that exposure to the cold window increases has an effect on all participants, increasing their mean skin temperature over the course of exposure (Figure 5.43 Table 5.32). When the mean of subjects' measurements is taken, mean skin temperature increases by 2.5°C (Figure 5.44 and Table 5.32). This difference was found to be significant when a paried sample t-test was conducted between mean skin temperature prior to exposure and after 30 minutes of exposure; P = 0.007 2-tailed (Table 5.33).

5.4.3 Subjective Results - Thermal Sensation

5.4.3.1 Presentation of Results

Figure 5.45 Shows thermal sensation curves for each male participant (A to H) during the experiment. Curves for female participants (I to P) and shown in Figure 5.46.

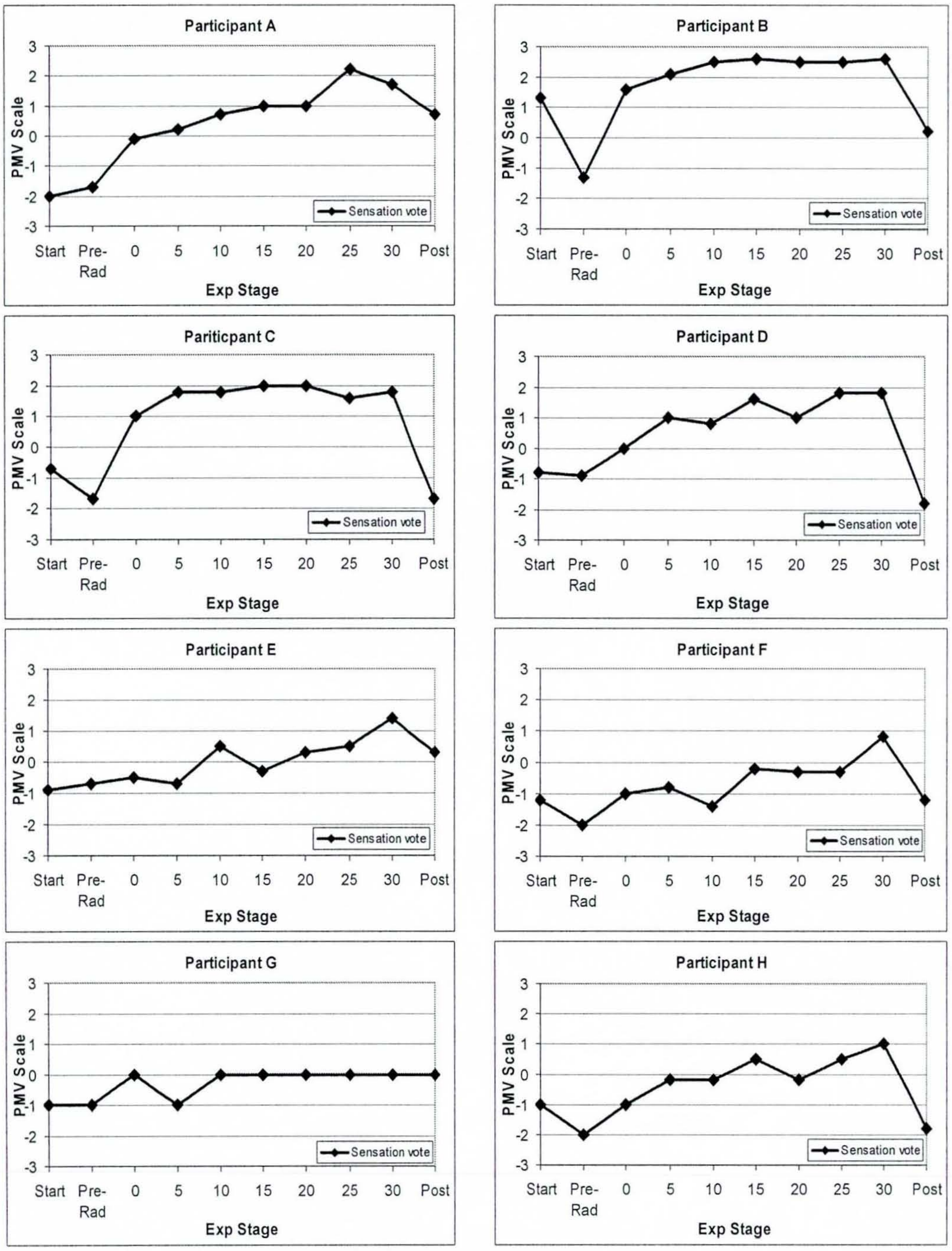


Figure 5.45, Thermal sensation votes for male participants (A – H)

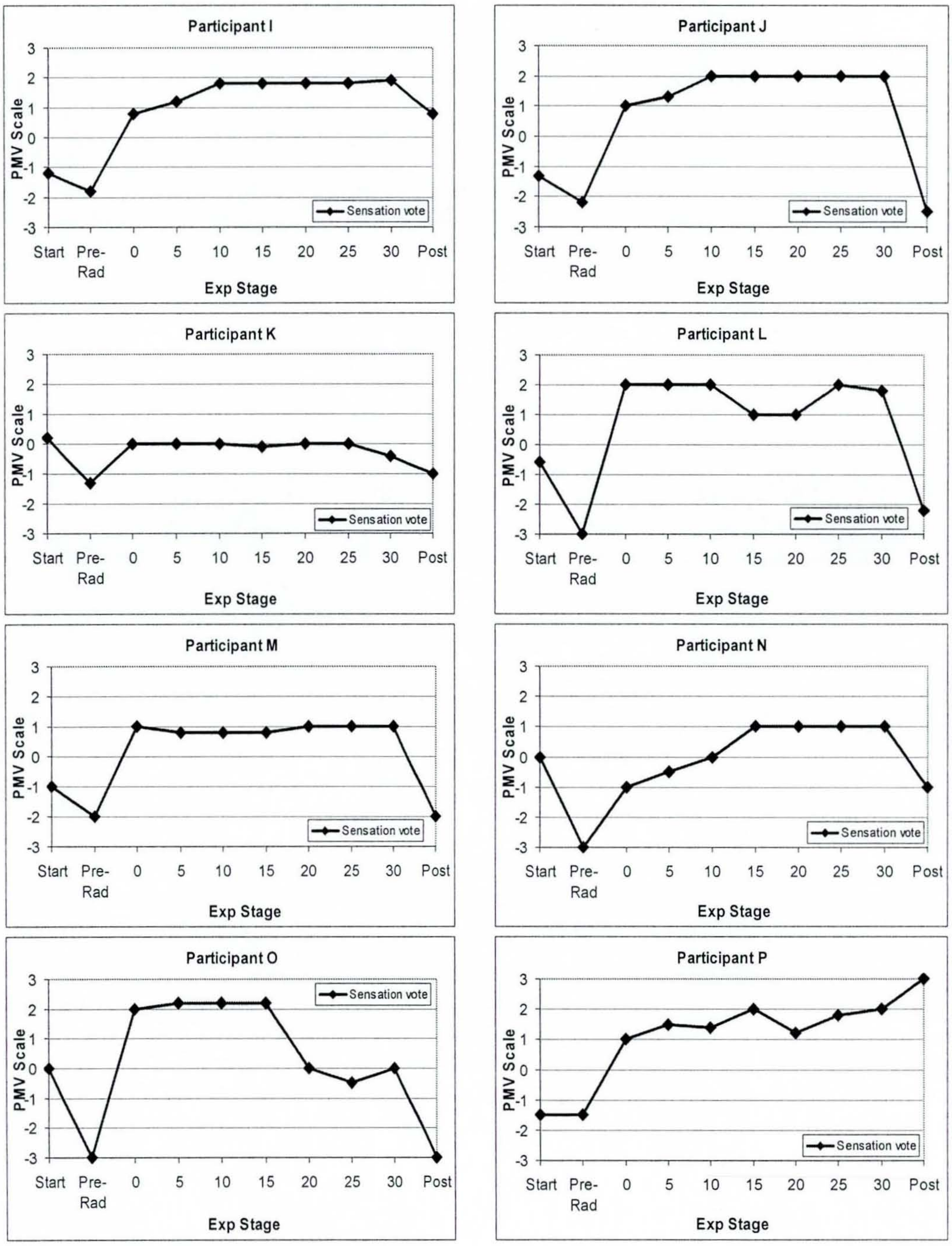


Figure 5.46, Thermal sensation votes for female participants (I – P)

The mean sensation vote during experimentation for males, females and all participants is shown by Figure 5.47.

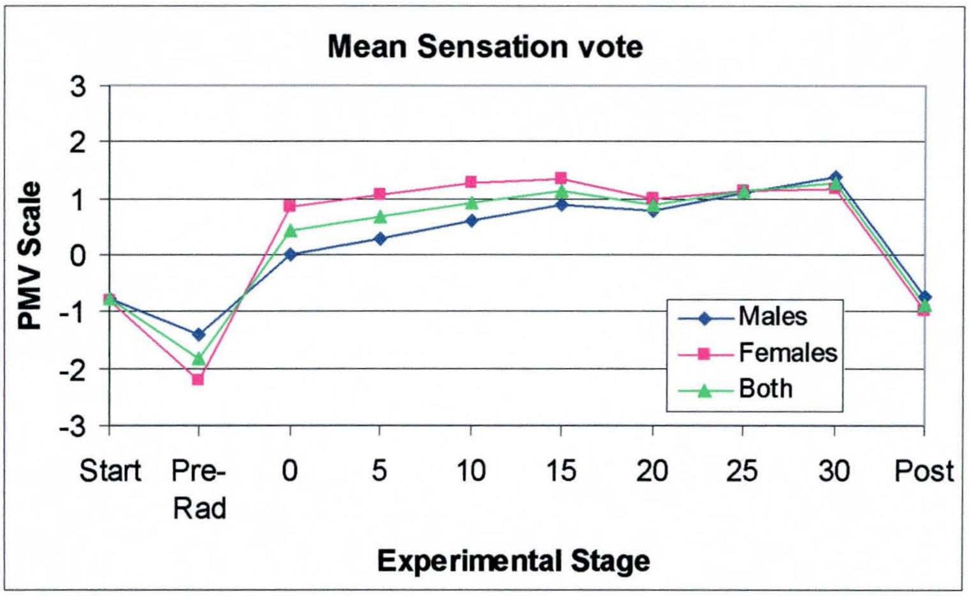


Figure 5.47, Mean sensation vote for males (participants A–H), females (participants I-P) and all participants (A-P)

Numeric values of sensation votes at different stages of the experiment are displayed in Table 5.34. Table 5.35 displays a wilcoxon signed ranks test, used to test for significance between the 'pre-rad' and 30-min comfort scores. The test shows significant (2 tailed) differences between the scores for males ($P = 0.012$), females ($P = 0.012$) and all participants ($P = 0.00$).

Table 5.34, Each particvipants sensation vote a the 'start', 'pre-rad' and '30min' stages of experimentation

Participant	Start (thermal chamber – questionnaire 1)	Pre-Rad	30-min
A	-2	-1.7	1.7
B	1.3	-1.3	2.6
C	-0.7	-1.7	1.8
D	-0.8	-0.9	1.8
E	-0.9	-0.7	1.4
F	-1.2	-2	0.8
G	-1	-1	0
H	-1	-2	1
I	-1.2	-1.8	1.9
J	-1.3	-2.2	2
K	0.2	-1.3	-0.4
L	-0.6	-3	1.8
M	-1	-2	1
N	0	-3	1
O	0	-3	0
P	-1.5	-1.5	2
Males (mean)	-0.76	-1.41	1.39
Females (mean)	-0.8	-2.23	1.16
All subjects (mean)	-0.78	-1.82	1.28

Table 5.35, Wilcoxon signed ranks test between the pre-rad and 30min stages for male, female and all participants

Test Statistics[b]

	Z	Asymp. Sig. (2-tailed)
All Subjects end sensation scores - All Subjects Pre-rad sensation scores	-3.519[a]	.000
Male Subjects end sensation score - Male Subjects Pre-rad sensation score	-2.521[a]	.012
Female Subjects end sensation score - Female Subjects Pre-rad sensation score	-2.524[a]	.012

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

5.4.3.2 Interpretation of Results

It can be seen from Figure 5.45, Figure 5.46 and Table 5.34 that all participants have a 'below neutral' (PMV < 0) sensation score immediately prior to radiation exposure; in the pre-rad position. The mean sensation vote in the pre-rad position was –1.82 for all participants, -1.41 for males and –2.23 for females; indicating that females interpreted the environmental conditions to be colder than males. Mean sensation vote increases greatly upon exposure to radiation and gradually increased between the start and end of exposure (Figure 5.47, Table 5.34). The mean increase in sensation score for all participants was 3.1, with a slightly greater for increase for females (3.4) and lower for males (2.8). Each of the increases was found to be significant (Table 5.35); P = 0.00, P = 0.12 and P = 0.12 respectively, all 2 tailed.

5.4.4 Subjective Results – Thermal Comfort

5.4.4.1 Presentation of Results

Thermal Comfort curves during experimentation are shown for each male participant (A to H) in Figure 5.48

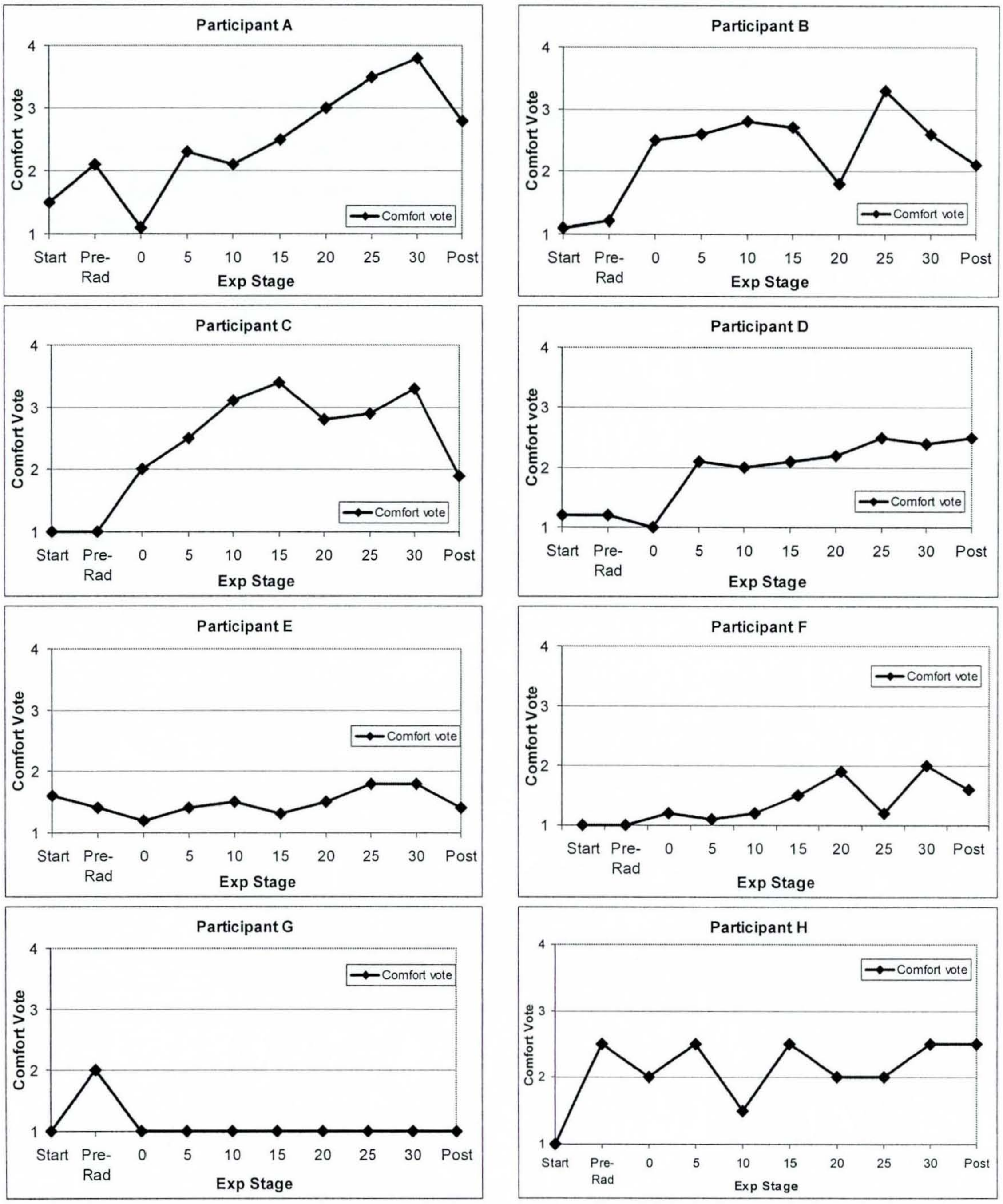


Figure 5.48, Thermal comfort curves for male participants (A – H) 1 = Not uncomfortable, 2=slightly uncomfortable, 3=uncomfortable, 4=Very uncomfortable

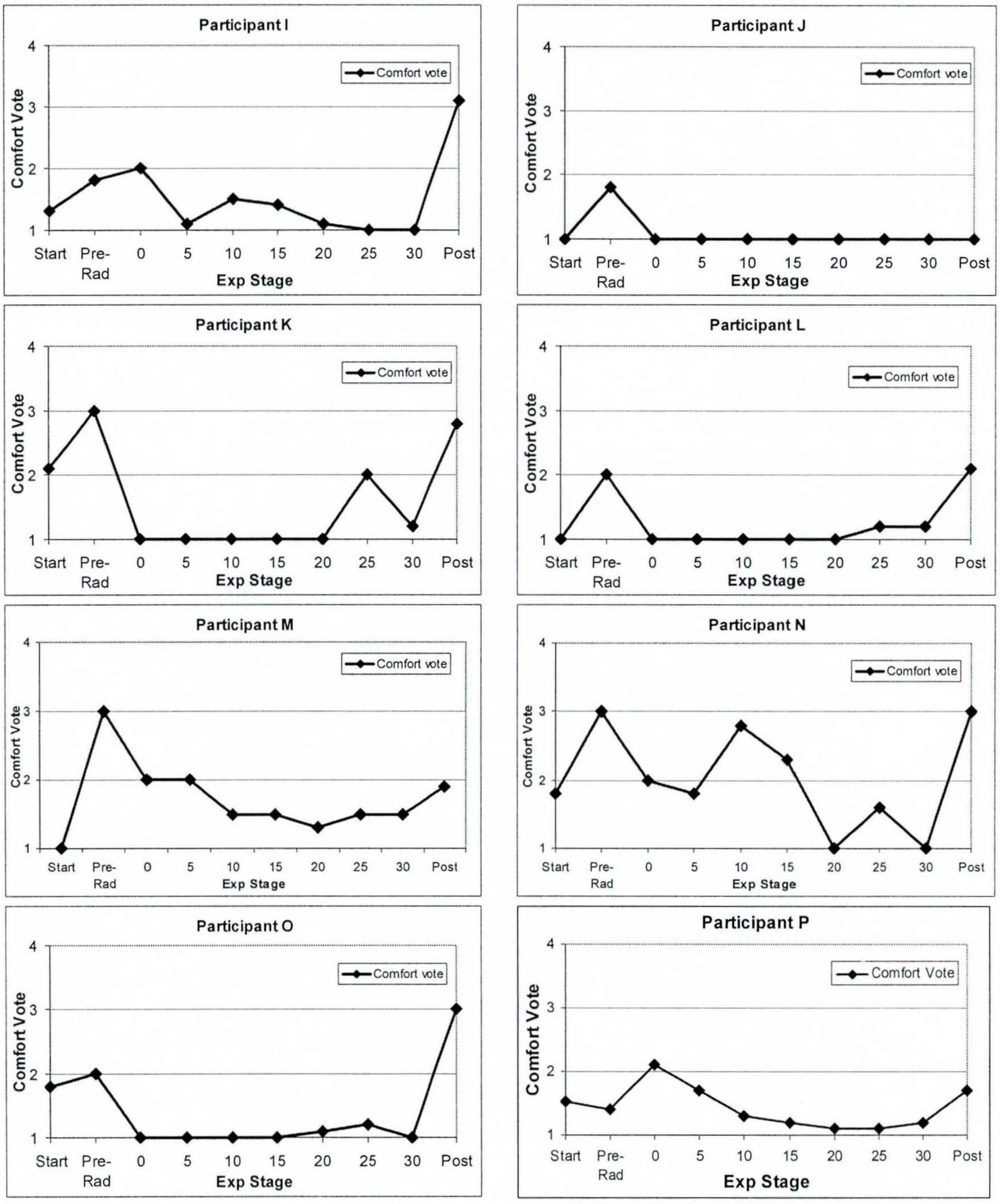


Figure 5.49, Thermal comfort curves for female participants (I – P) 1 = Not uncomfortable, 2=slightly uncomfortable, 3=uncomfortable, 4=Very uncomfortable

Figure 5.49 displays thermal comfort curves for female participants (I – P) during experimentation. The mean comfort scores for males, females and all participants are displayed graphically in Figure 5.50.

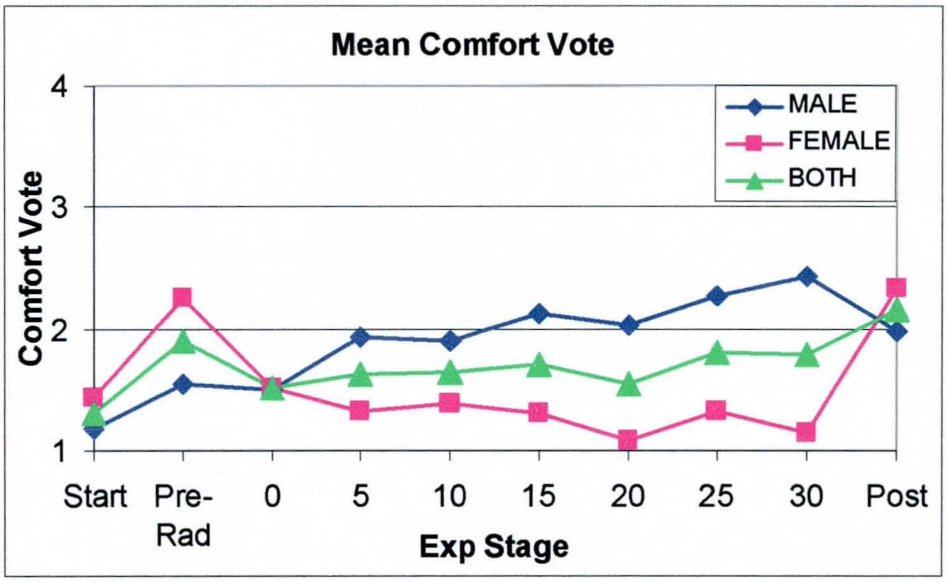


Figure 5.50, Mean thermal comfort curves for male (A – H), female (I – P) and all (A – P) participants 1 = Not uncomfortable, 2=slightly uncomfortable, 3=uncomfortable, 4=Very uncomfortable

Table 5.36, Thermal Comfort scores for each participant at the 'start', 'pre-rad' and 30min points of experimentation 1 = Not uncomfortable, 2=slightly uncomfortable, 3=uncomfortable, 4=Very uncomfortable

Participant	Start	Pre-rad	30-min
A	1.5	2.1	3.8
B	1.1	1.2	2.6
C	1	1	3.3
D	1.2	1.2	2.4
E	1.6	1.4	1.8
F	1	1	2
G	1	2	1
H	1	2.5	2.5
I	1.3	1.8	1
J	1	1.8	1
K	2.1	3	1.2
L	1	2	1.2
M	1	3	1.5
N	1.8	3	1
O	1.8	2	1
P	1.5	1.4	1.2
Males (mean)	1.18	1.55	2.42
Females (mean)	1.44	2.25	1.14
All Participants (mean)	1.31	1.9	1.78

Table 5.36 displays thermal comfort scores at the 'start', 'pre-rad' stages and after 30 minutes of radiation exposure. Table 5.37 gives statistics from a Wilcoxon signed ranks test between participants comfort scores at the 'pre-rad' and 30-minute stages of experimentation. There were found to be significant differences between values for Males (P = 0.051, 2 tailed) and Females (P = 0.011, 2 tailed) but tests for all participants were found to be insignificant (P = 0.776, 2 tailed).

Table 5.37, A wilcoxon signed ranks test between mean thermal comfort vote at the pre-rad and 30min stages of experimentation

Test Statistics[c]

	Z	Asymp. Sig. (2-tailed)
All Subjects end comfort scores - All Subjects Pre-rad comfortscores	-.284[a]	.776
Male Subjects end comfort score - Male Subjects Pre-rad comfort score	-1.947[b]	.051
Female Subjects end comfort score - Female Subjects Pre-rad comfortscore	-2.533[a]	.011

a. Based on positive ranks.

b. Based on negative ranks.

c. Wilcoxon Signed Ranks Test

5.4.4.2 Interpretation of results

Figure 5.48 and Figure 5.49 show that subjects comfort votes varied greatly at each stage of the experiment. Some subjects reported high 'pre-rad' discomfort levels in the sub-neutral environment (PMV < 0) prior to radiation exposure; participants H, K M and N being examples of this. In these cases radiation exposure was, initially at least, reported to decrease discomfort. Others reported comparatively low 'pre-rad' discomfort (participants B, C, D and F). In these cases, radiation exposure was found to increase discomfort. Figure 5.50, Table 5.36 and Table 5.37 show that the mean discomfort vote between 'pre-rad' and 30-min (the end of exposure) significantly decreased for females (2.55 to 1.14; P = 0.011, 2 tailed) and significantly increased for males (1.55 to 2.42; P = 0.051, 2 tailed), resulting in a an insignificant change for all participants' mean discomfort vote (1.9 to 1.78; P = 0.776, 2 tailed).

5.4.5 Subjective Results – Stickiness

5.4.5.1 Presentation of results

Stickiness vote during experimentation is shown for each male participant (A to H) in Figure 5.51.

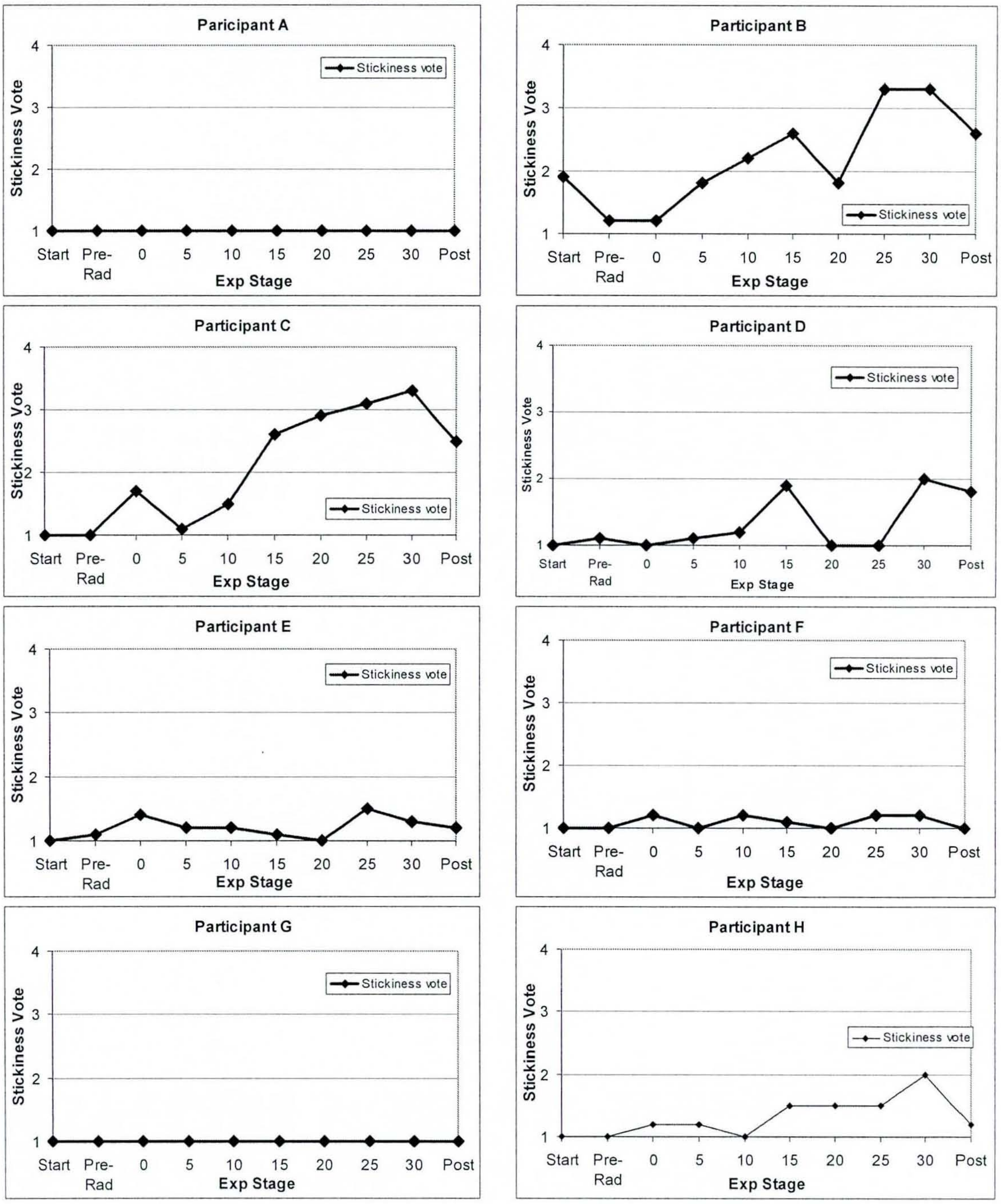


Figure 5.51, Stickiness curves for male participants (A – H) 1=Not Sticky, 2=slightly sticky, 3=sticky, 4=Very sticky

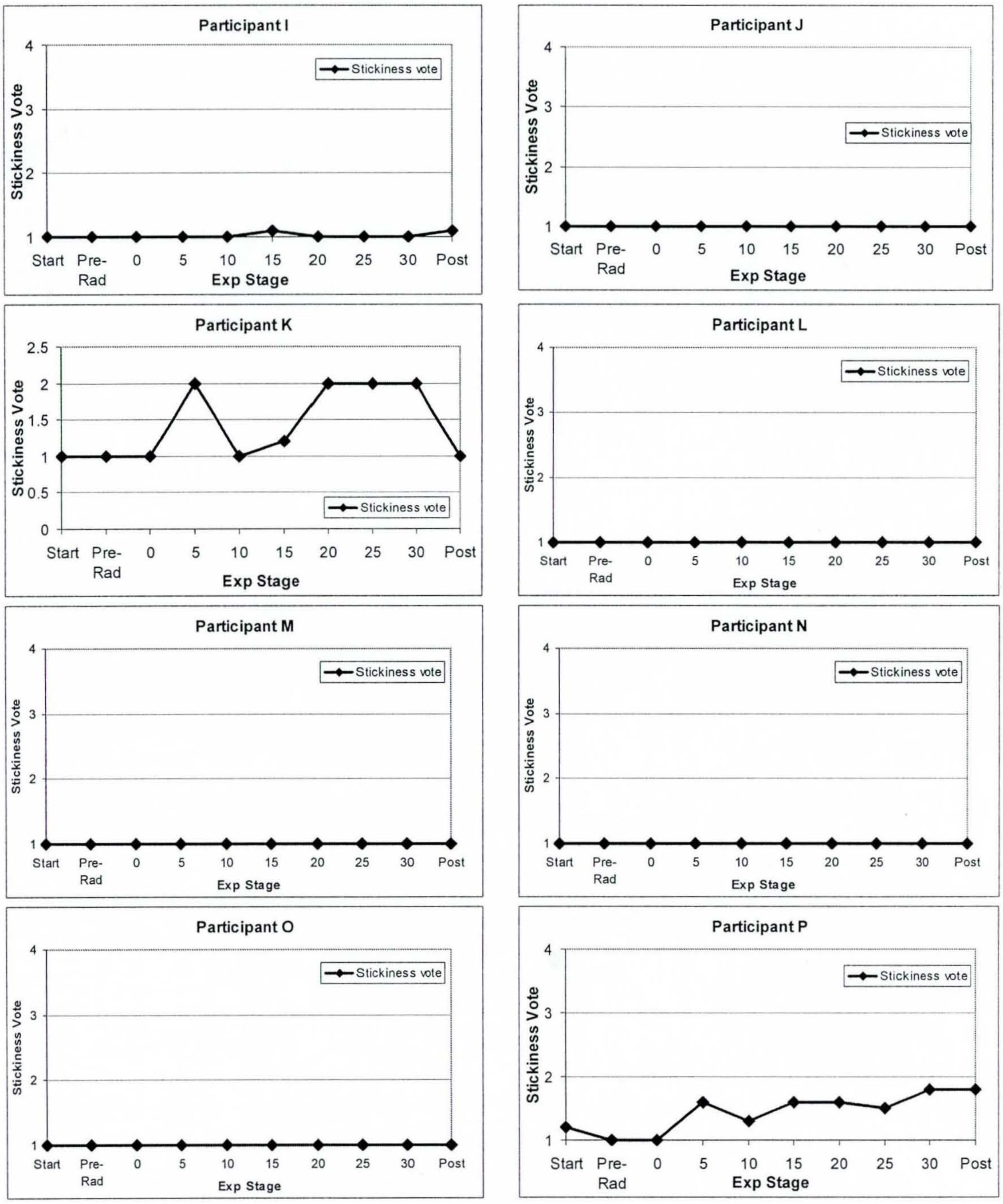


Figure 5.52, Stickiness curves for female participants (I – P) 1=Not Sticky, 2=slightly sticky, 3=sticky, 4=Very sticky

Figure 5.52 displays stickiness curves for female participants (I – P) during experimentation. The mean stickiness scores for males, females and all participants are shown by Figure 5.53.

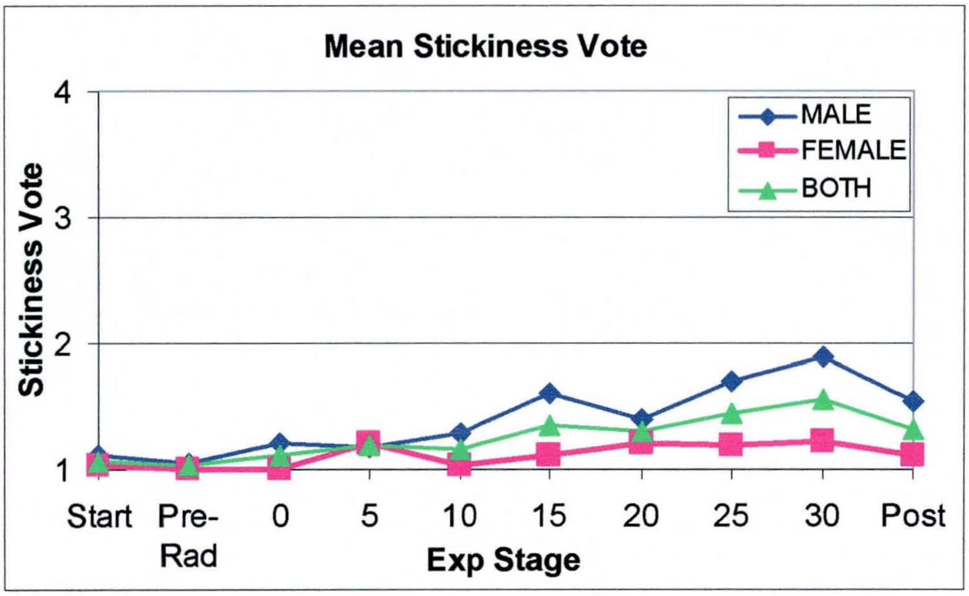


Figure 5.53, Mean stickiness curves for male (A – H), female (I – P) and all participants1=Not Sticky, 2=slightly sticky, 3=sticky, 4=Very sticky

Table 5.38, Stickiness vote for each participant at the 'start', 'pre-rad' and 30min 1=Not Sticky, 2=slightly sticky, 3=sticky, 4=Very sticky

Participant	Start	Pre-rad	30-min
A	1	1	1
B	1.9	1.2	3.3
C	1	1	3.3
D	1	1.1	2
E	1	1.1	1.3
F	1	1	1.2
G	1	1	1
H	1	1	2
I	1	1	1
J	1	1	1
K	1	1	2
L	1	1	1
M	1	1	1
N	1	1	1
O	1	1	1
P	1.2	1	1.8
Males (mean)	1.11	1.05	1.89
Females (mean)	1.03	1	1.23
All Participants (mean)	1.07	1.03	1.56

Stickiness ratings at the 'start', 'pre-rad' stages and after 30 minutes of radiation exposure are shown by Table 5.38. A wilcoxon signed ranks test was conducted between the 'pre-rad' and 30-min values (Table 5.39). The differences are significant when all participants (P = 0.012) and male participants only (P = 0.027, 2 tailed) were tested. The results for female participants were found to be insignificant (P = 0.18, 2 tailed).

Table 5.39, A wilcoxon signed ranks test between mean stickiness vote at the pre-rad and 30min stages of experimentation

Test Statistics[b]

	Z	Asymp. Sig. (2-tailed)
All Subjects end stickiness scores - All Subjects Pre-rad stickiness scores	-2.527[a]	.012
Male Subjects end stickiness score - Male Subjects Pre-rad stickness score	-2.207[a]	.027
Female Subjects end stickiness score - Female Subjects Pre-rad stickiness score	-1.342[a]	.180

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

5.4.5.2 Interpretation of results

As would be expected all participants had a low stickiness vote in the ambient environment at the 'pre-rad' stage (Figure 5.51 snd Figure 5.52). For some participants (A, G and J being examples) this remained low during radiation exposure. Other participants reported a notable increase in stickiness with radiation exposure; Examples include participants B, C and K. Mean stickiness vote (Figure 5.53,, Table 5.38) increased most greatly in male participants, from 1.05 (pre-rad) to 1.89 (30-min). Female participants stickiness vote increased form 1 to 1.23; giving a resultant 'all participant' increase of 0.53, from 1.03 (pre-rad) to 1.56 (30-min). The change in stickiness vote (Table 5.39) was found to be significant for 'all subjects' and male subjects (P = 0.027 and P = 0.012 respectively; both 2 tailed), but insignificant for female subjects; P = 0.180, 2 tailed.

5.4.6 Subjective results – Thermal Preference

5.4.6.1 Presentation of results

Male participants' (A to H) thermal preference vote during experimentation is shown in Figure 5.54.

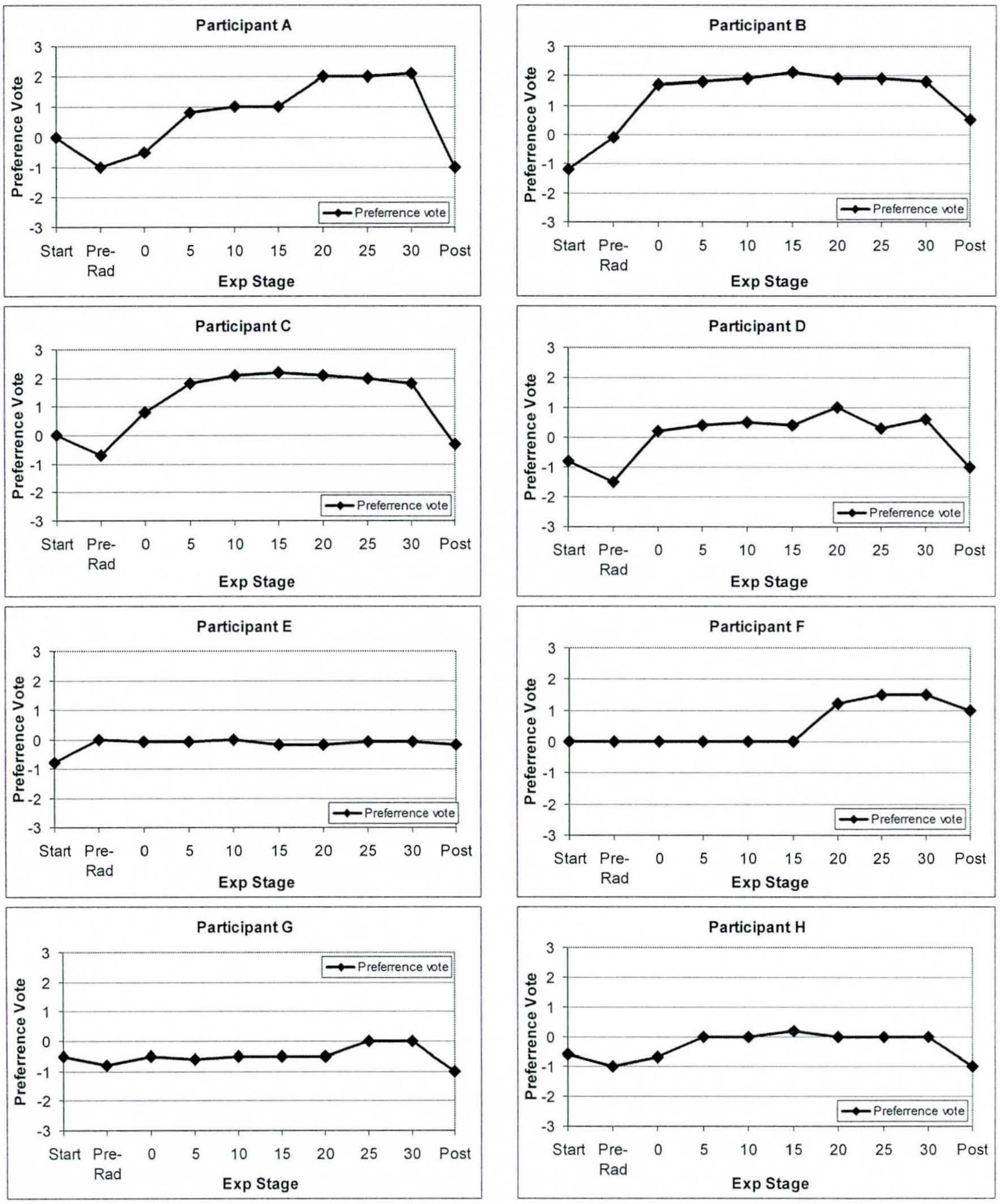


Figure 5.54, Thermal preference curves for male participants (A – H) -3=Much warmer, -2=Warmer, -1=Slightly warmer, 0=No Change, 1=Slightly cooler, 2=Cooler, 3=Much cooler

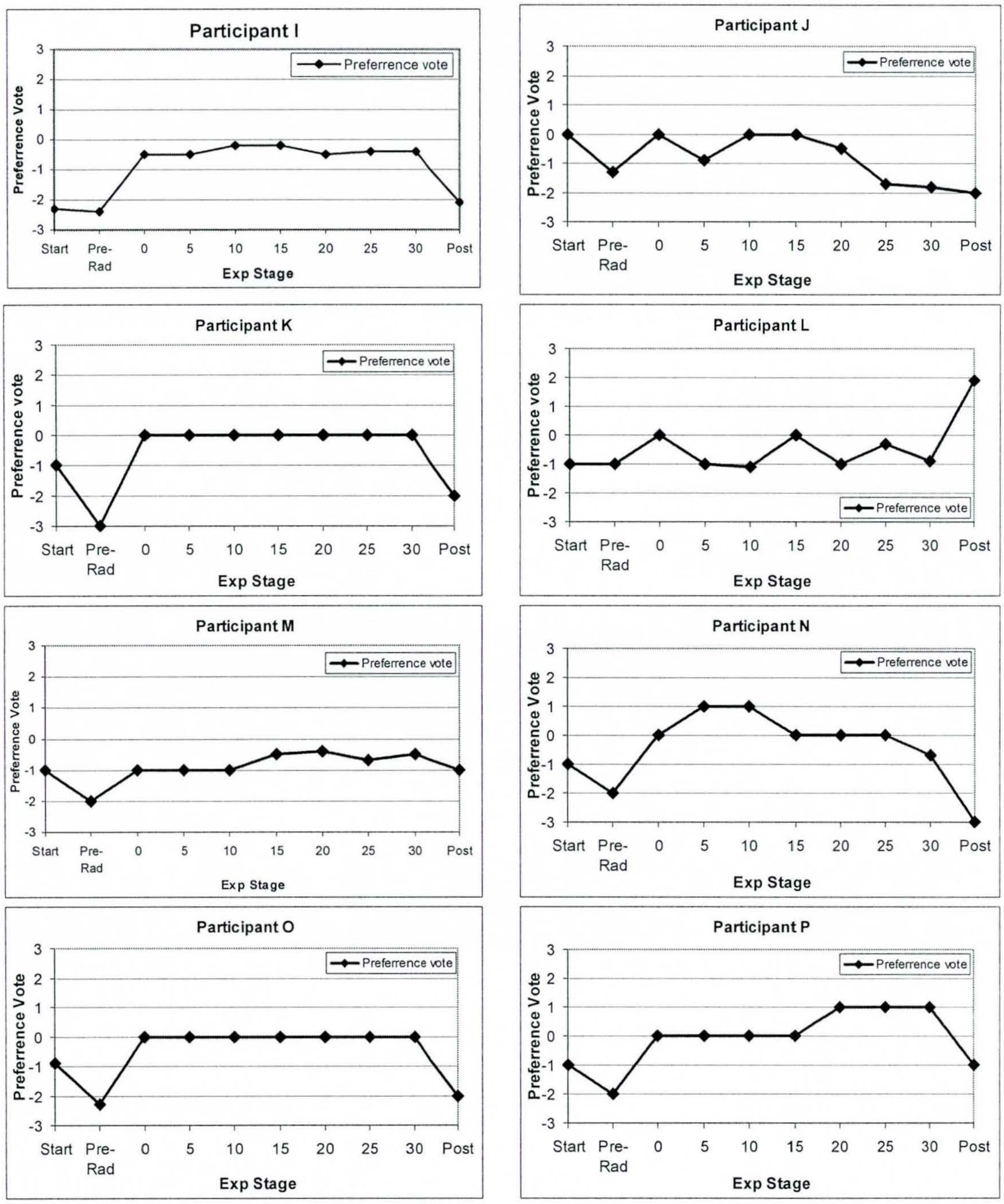


Figure 5.55, Thermal preference curves for female participants (I - P) 3=Much warmer, -2=Warmer, -1=Slightly warmer, 0=No Change, 1=Slightly cooler, 2=Cooler, 3=Much cooler

Figure 5.55 displays thermal preference curves for female participants (I – P) during experimentation. The mean Thermal preference vote for males, females and all participants are shown by Figure 5.56.

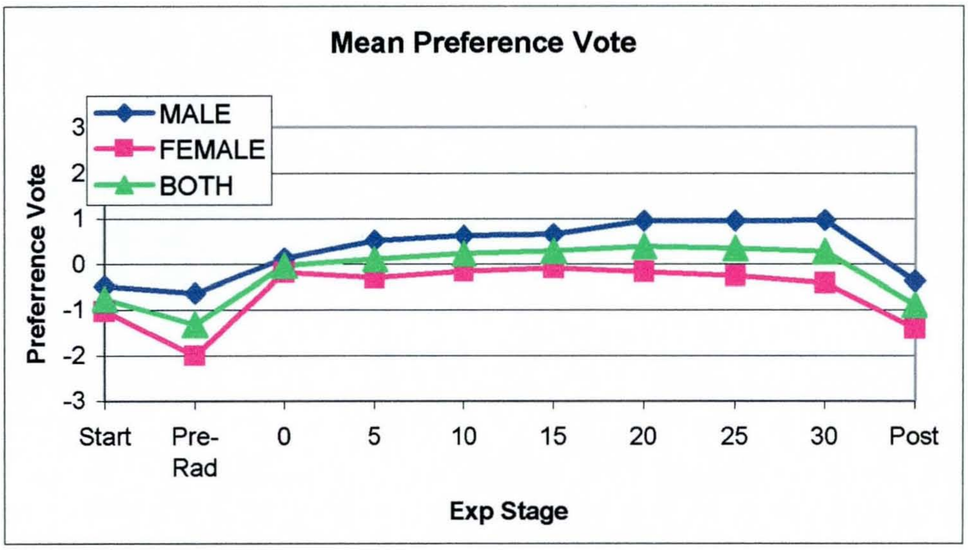


Figure 5.56, Mean thermal preference vote for male (A – H), female (I – P) and all Participants (A – P) 3=Much warmer, -2=Warmer, -1=Slightly warmer, 0=No Change, 1=Slightly cooler, 2=Cooler, 3=Much cooler

Table 5.40, Thermal preference scores for each participant at the 'start', 'pre-rad' and 30min 3=Much warmer, -2=Warmer, -1=Slightly warmer, 0=No Change, 1=Slightly cooler, 2=Cooler, 3=Much cooler

Participant	Start	Pre-rad	30-min
A	0	-1	2.1
B	-1.2	-0.1	1.8
C	0	-0.7	1.8
D	-0.8	-1.5	0.6
E	-0.8	0	-0.1
F	0	0	1.5
G	-0.5	-0.8	0
H	-0.6	-1	0
I	-2.3	-2.4	-0.4
J	0	-1.3	-1.8
K	-1	-3	0
L	-1	-1	-0.9
M	-1	-2	-0.5
N	-1	-2	-0.7
O	-0.9	-2.3	0
P	-1	-2	1
Males (mean)	-0.49	-0.64	0.96
Females (mean)	-1.03	-2	-0.41
All Participant (mean)	-0.76	-1.32	0.28

Thermal preference vote at the 'start' and 'pre-rad' stages and after 30 minutes of radiation exposure are shown by Figure 4.40. Table 5.41 displays results from a wilcoxon signed ranks test for significance between the 'pre-rad' and 30-min values. Test for 'all participants' and 'male only' participants were found to be significant; P = 0.009 and P = 0.17 respectively (2 tailed). A test for female participants was found to be insignificant (P = 0.161)

Table 5.41, A wilcoxon signed ranks test between preference vote at the pre-rad and 30min stages of experimentation

Test Statistics[b]

	Z	Asymp. Sig. (2-tailed)
All Subjects end preference scores - All Subjects Pre-rad preference scores	-3.29[a]	.001
Male Subjects end preference score - Male Subjects Pre-rad preference score	-2.38[a]	.017
Female Subjects end preference score - Female Subjects Pre-rad preference score	-2.24[a]	.025

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

5.4.6.2 Interpretation of results

It can be seen from Figure 5.54 and Figure 5.55 that each participants pre-rad thermal preference vote was below 0, meaning all participants required the environment to be warmer. The only exceptions to this were participants E and F who both required 'no change'. The mean preference vote at the pre-rad stage was –1.32 (between 'slightly warmer' and 'warmer') with females at -2 (warmer) and males –0.64 (between 'no change' and 'slightly warmer). All preference votes changed as a result of radiation exposure (Figure 5.56, Table 5.40). These changes were to be significant for male (P = 0.017, 2 tailed), female (P = 0.025) and 'all participants' (P = 0.001, 2 tailed). At the end of exposure (30-min) preference votes were 0.96 (slightly cooler) for male participants, -0.41 (

between 'no change' and 'slightly warmer') for female participants and 0.28 (between 'no change' and 'slightly cooler) for all participants.

5.5 Thermal Manikin

5.5.1 Aim

The thermal manikin mimics the human form and will experience a similar radiative heat exchange with the environment, due to its shape and surface area. The aim of using the manikin is to provide an objective measure of heat loss to the environment, by measuring the power input required to keep it at a constant temperature in different conditions. This will supplement subjective data to provide a more comprehensive view of the effects of solar radiation in a 'cool' environment.

5.5.2 Method

5.5.2.1 Facility and Set-up

The experimental facility used was the solar simulation chamber, which was set to have the same environmental conditions as in the experiments with participants. The thermal chamber that was used to dress subjects prior to them entering the solar chamber was not needed, as the manikin outputs are objective and are therefore not dependant upon a habituation period.

5.5.2.2 Procedure

Prior to exposure, the lamps were turned on and the air-conditioning set to provide the required environmental conditions. The manikin was dressed in the standard clothing ensemble of white cotton/Polyester (65/35%) long sleeved shirt with sleeves rolled up to the elbow, and beige cotton/Polyester (65/35%) trousers. It was seated in the forward facing car seat, moved into the exposure position and set to maintain a temperature of 36°C. The experiment had previously been attempted with the manikin set to maintain 34°C, but some body parts had overheated and so an adjustment was made in accordance with this. The data loggers and manikin file log were set to start recording every 30 seconds and the manikin was left to reach steady state; this was deemed to be achieved when the manikins power input remained at similar levels for a period of 5 minutes or more. Once steady state had been achieved the manikin was moved out to the control position, with the curtain in place to shield it from radiation exposure. It was then left to reach steady state again. Once this had been achieved in the 'control' position, the manikin file log and squirrel data loggers were stopped and the data downloaded for analysis.

5.5.3 Results

5.5.3.1 Presentation of results

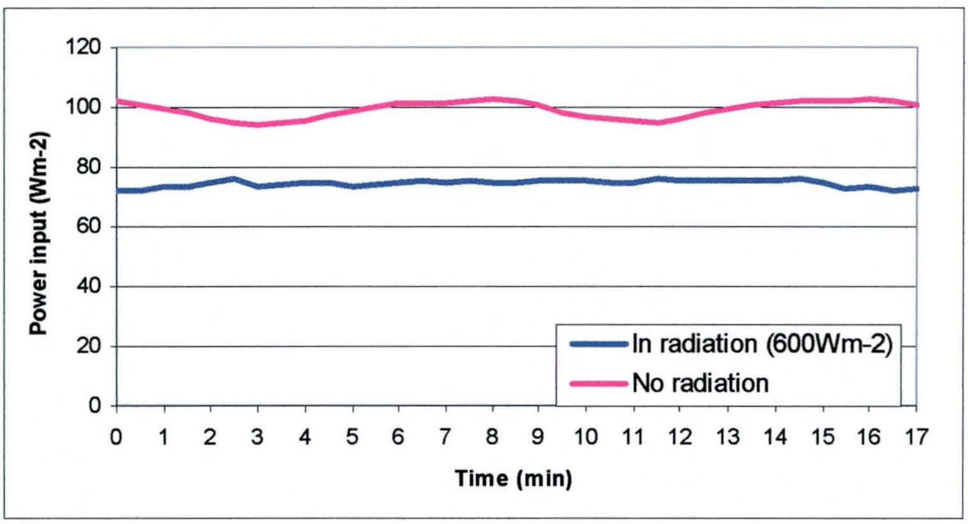


Figure 5.57, Mean weighted power requirement for the thermal manikin in the environment, exposed and not exposed to radiation

Figure 5.57 displays the mean power input required by the manikin to maintain a temperature of 36°C, with and without exposure to radiation. The mean power input during 'steady state' at the 2 conditions is displayed by Table 5.42.

Table 5.42, Displaying the power requirement of the manikin during the 'steady state period, with and without radiation exposure (600Wm-2)

	Highest value	Lowest value	Mean value
In radiation	102.7	94.3	74.44
No radiation	76.2	72.1	99.13
Difference	26.5	22.2	24.69

5.5.3.2 Interpretation of results

It can be seen from Figure 5.57 that there is a clear difference in manikin power requirement to maintain a constant temperature (36°C) in both conditions (exposed and unexposed to radiation). The manikin reached a steady state for power input levels in both conditions, however, power input fluctuated during the steady state period and for this reason the mean of all recorded values during this period was taken for a means of comparison. The difference in mean values was 24.69Wm^2 (Table 5.42); the mean value in radiation exposure being 74.44Wm^2 and 99.13 Wm^2 when not exposed.

5.6 Discussion

5.6.1 Environmental conditions

Environmental conditions were controlled to be between 'cool' and 'slightly cool' (PMV = -1.5 $\pm$ 0.5) for experimental sessions. This was in subjective measures to a reasonable degree of accuracy, with participants voting the environment to be -1.82 when they were not exposed to radiation. After 30 minutes of radiation exposure, participants' mean sensation score was 1.28 (between 'slightly warm' and 'warm'), which was not accurately represented by a PMV of -0.5 when t_r was calculated using an exposed globe. The implication is that PMV does not accurately account for high levels of direct solar radiation, a finding in keeping with Hodder (2002).

5.6.2 Mean skin temperature

Mean skin temperature increase for all participants as a result of exposure to simulated solar radiation of 500Wm^{-2} in a cool environment (PMV = -1.5 $\pm$ 0.5). The overall mean increase in mean skin temperature as a result of exposure was 2.5°C and was found to be significant when a t-test was performed (P = 0.007, Table 5.33) This is in keeping with findings by Hodder (2002), although the effect is less extreme in this experiment compared with an increase of .over 3 °C for participants exposed to 400Wm^{-2} in Hodder's experiment.

5.6.3 Thermal sensation

The pre-cooling period in the thermal chamber resulted in participants having a below neutral mean sensation vote of –1.82 on the sensation scale immediately prior to radiation exposure (Figure 5.47, Table 5.34). The ambient environment was reported to be cooler by female participants (mean sensation vote = -2.23) than male (mean sensation vote = -1.41). Radiation exposure had a significant effect on thermal sensation ($P < 0.05$, Table 5.35), causing a sharp increase upon initial exposure and then a more gradual one throughout the remaining exposure period. The mean sensation vote increase was 3.1 scale units, which is in accordance with the expected increase of 3 scale units, derived from PMV_{Solar} (Hodder and Parsons, 2002). The increase was larger in females (3.4 scale units) than in males (2.8 scale units), indicating that female participants perceived changes in environmental stimuli more strongly.

5.6.4 Thermal comfort

Thermal comfort vote varied greatly for individual participants (Figure 5.48 and Figure 5.49) with a clear gender specific difference apparent. The ambient environmental conditions were in general reported to cause discomfort in female participants; the mean female comfort vote being 2.55 (between 'slightly uncomfortable' and 'uncomfortable') immediately prior to radiation exposure. This resulted in solar radiation exposure leading to a significant decrease in discomfort levels (P < 0.05, Table 5.37), which corresponds well with a move from –2 (cool) towards 1 (slightly warm) in mean female sensation vote at this point. Essentially, exposure to the radiation had a warming effect in a cool environment and hence resulted in a decrease in discomfort.

In contrast, male participants did not report the ambient environment to cause as much discomfort, with a mean comfort vote of 1.55 (between 'not uncomfortable' and 'slightly uncomfortable'). Radiation exposure caused a significant increase in discomfort levels for males (P < 0.05, Table 5.37), which counteracted the corresponding decrease in female discomfort vote. The result is that the mean comfort vote of all participants changed only slightly and insignificantly (Figure 5.50, Table 5.36).

5.6.5 Stickiness

As expected, participants did not report to be sticky in the ambient environment; stickiness votes being around 1 on the scale (not sticky) for all participants (Table 5.38). Mean stickiness vote increased significantly (P < 0.05) by around half a scale unit as a result of radiation exposure (Figure 5.53 Table 5.39). The increase in stickiness was greatest and most significant in male participants (0.84 scale units) which relates well to the greater reported discomfort levels for males.

5.6.6 Thermal preference

The mean preference vote in the ambient environment was –1.32 (between 'slightly warmer' and 'warmer'), as would be expected in a sub-neutral environment (PMV < 0). Female preference vote deviated further than this to -2 (warmer), corresponding with their lower mean sensation vote in these conditions (Figure 5.54 and Figure 5.55). Radiation exposure caused a significant change in mean preference vote of approximately 1.6 scale units to between 'no change and 'slightly warmer'. At this point the greatest required change was by male participants (1 = slightly cooler), corresponding with their higher stickiness and discomfort votes at this point.

5.6.7 Thermal Manikin

Data from the thermal manikin quantifies subjective findings by determining the heat loss to the environment in different conditions. In the ambient environment, with no solar radiation, the manikin required 74.44Wm^2 to maintain a constant temperature of 36 °C compared with 99.13Wm^2 when it was exposed to solar radiation. The difference of 24.69 Wm^2 (Table 5.42 Figure 5.57) can be attributed to heat gained from solar radiation. The assumption that subjects will have experienced a similar heat gain supports the changes in thermal sensation, stickiness and thermal preference observed from subjective data.

5.7 Conclusions

1. Mean skin temperature increased significantly as a result of exposure to direct solar radiation
2. Thermal sensation increased approximately 3 scale units as a result of exposure to solar radiation.
3. Thermal comfort, stickiness and preference votes indicate that discomfort was caused initially by the cool environmental conditions and then by solar radiation, after 30 minutes exposure to this.
4. Thermal manikin data showed that there was a net heat gain of 24.69Wm^2 as a result of radiation exposure.
5. There were some effects of gender, with females generally reporting conditions more extremely than males. i.e. Warm conditions as warmer and cool conditions as cooler than males.
6. The results imply that PMV_{Solar} can be used across the range of the sensation scale and not just for people in neutrality
7. PMV_{Solar} was accurate in predicting the effects of solar radiation in this study and is adequate tool for assessing cool environments with direct solar radiation.

6. Development of predictive model

6.1 Chapter summary

This chapter reviews the results from laboratory experiments (chapters 3 – 5), previous studies and relevant literature with the aim of developing a practical thermal comfort model. The model will integrate 'local' factors and their effects on thermal comfort to provide a tool for the assessment of thermal comfort in train carriages. A number of models are developed and are validated in field trials and data from laboratory experiments (chapters 7 and 8).

6.2 Aim

The aim of this chapter is to collate the results from laboratory experiments in order to develop a predictive model which can integrate the effects of local environmental and personal factors into methods for the assessment of thermal comfort in trains.

6.3 Introduction

The laboratory experiments in chapters three to five were designed to provide a greater understanding into variables that might effect an individual's thermal comfort on a train. This is mainly focused on people sat next to windows as these provide a gateway through which external environmental factors can influence internal thermal comfort. The chapters primarily focus on the effects of direct solar radiation and those of exposure to a cold window as these are thought to be conditions that could regularly occur and feasibly affect thermal comfort. For people not sat next to windows and not directly influenced by external conditions, it may be reasonable to assume that existing methods for assessing thermal comfort may apply (e.g. PMV/PPD, ISO 7730)

Predictive models are widely used to assess internal environments. Subjects physiological and psychological responses to an environment can be predicted using a rational heat balance model, provided the environmental conditions of the space are known. Models such as the PMV (ISO 7730) have been extensively used to assess buildings and are thought to provide a solid assessment of some vehicle spaces, because of the relative inability of the occupants to thermo-regulate behaviourally and the relative stability of the environment. A model that could provide a general assessment of the environment, but also easily incorporate local environmental effects on individuals within that environment, would be beneficial in evaluating thermal comfort in large vehicle spaces (In a train carriage). That is , if the PMV model is satisfactory for, for example,. built environments, then a modified version of that model to take into account the effects of a cold window or prolonged exposure to direct solar radiation, provides a basis for a thermal; comfort model for rail carriages.

6.4 Model Development

6.4.1 Basis for Model

The basis of the model will be the Predicted Mean Vote (Fanger, 1970; ISO 7730). Over the last 30 years this comfort index has been the dominant model for assessing human thermal comfort. It's ease of use and provision of a single figure output that can be easily related to subjective responses to an environment make it an obvious choice as the foundation for environmental assessment.

6.4.2 Correction for Solar radiation

A number of studies have been conducted to investigate the effects of solar radiation on thermal comfort, most of them concurring that it may have a significant effect on a persons perception of their thermal environment. As discussed in pervious chapters, Hodder (2002) proposed a model; based essentially on the PMV but incorporating a correction factor; to allow an environmental assessments to be made for different intensities of solar radiation (Figure 6.58)

$$\mathbf{PMV_{Solar} = PMV + Actual\ Solar\ Radiation\ (Wm^{-2})/\ 200Wm^{-2}}$$

The model was found to accurately assess the effects of a given intensity of solar radiation, comparative to the subjective responses of subjects exposed to it.

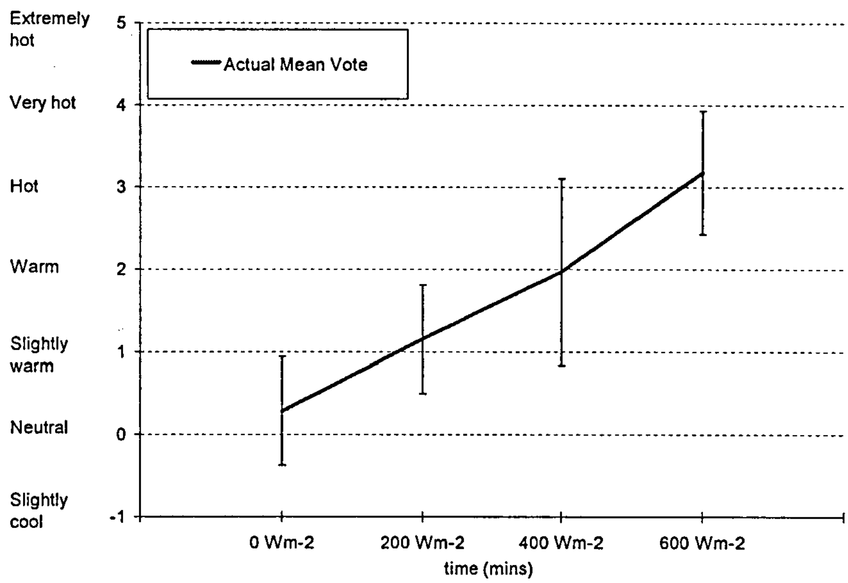


Figure 6.58, Sensation curve for different levels of solar radiation - the basis for PMV_{Solar} (Hodder and Parsons 2002)

The model was tested and validated in field trials and laboratory experiments and Vaughn and Parsons (2004) later found that the model also worked to a reasonable degree of accuracy for subjects with side on exposure to solar radiation (Figure 6.59). PMV_{Solar} is therefore considered to be an acceptable tool for evaluating solar radiation effects on individuals in a train environment.

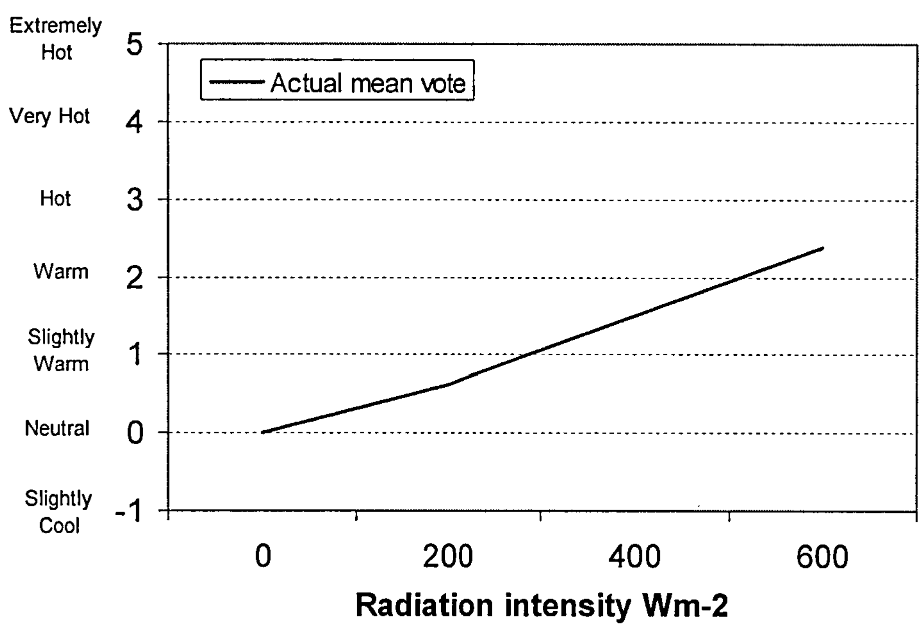


Figure 6.59, Mean sensation curve for side-on exposure to different levels of solar radiation

In Hodder's and Vaughn's laboratory experiments and field trials, the environmental conditions were engineered to be thermally neutral (PMV = 0 ± 0.5) and so it was not known if the model would be accurate in environments that were dissimilar to this. Chapter 3 of this thesis aimed to investigate whether the model would work accurately for a given intensity of solar radiation ($600Wm^{-2}$) in cooler environmental conditions.

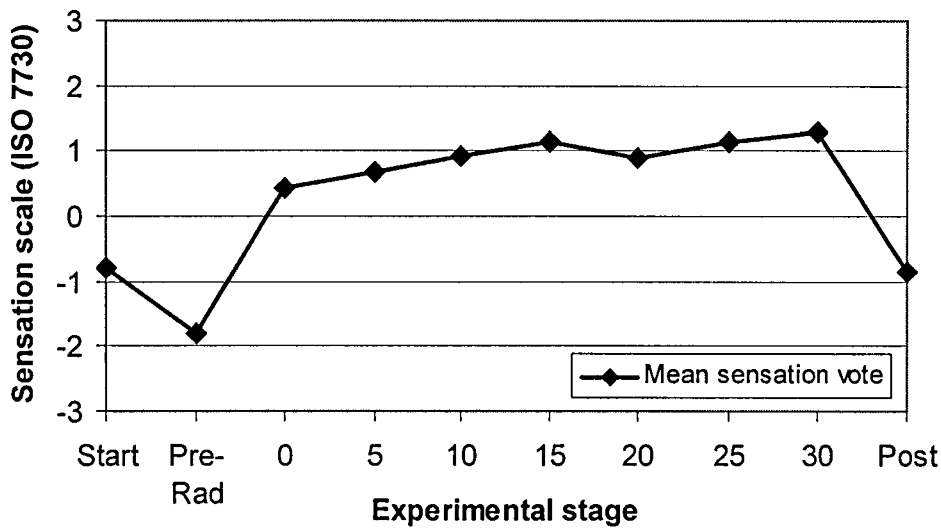


Figure 6.60, Mean sensation vote during exposure to solar radiation in a 'cool' environment

Using PMV_{Solar} , the estimated increase in subjective sensation vote was calculated to be 3 scale units. This was found to be accurate when compared to the average increase of subjects' Actual Mean Vote (AMV) of 3.1 scale units. This can be seen in Figure 6.60 with an approximate increase of 3 scale units from pre-radiation to the 30 minute exposure point. It is therefore concluded that the model will provide a means of assessing the effects of solar radiation in cooler environments to an acceptable degree of accuracy. This supports it's inclusion in a model for evaluating these effects on train carriages. It also implies that the model may apply across the range of the thermal sensation scale.

6.4.3 Correction for the effects of cold windows

The effects of exposure to a cold window on a persons thermal comfort are not fully understood. In contrast to solar radiation exposure, where the affect on thermal comfort is solely attributable to a single definable factor, exposure to a cold window may cause thermal discomfort through a number of different mechanisms, the 2 primary ones being the generation of draught and through radiant asymmetry.

A number of studies have been conducted to investigate the effects of radiant asymmetry on thermal comfort; McIntyre (1980), Olesen (1985) and Langkilde et al (1985) to name but a few; most of which conclude that radiant asymmetry can have a significant affect. A means of predicting the percentage of those dissatisfied as a function of the degree and type of radiant temperature asymmetry is given by ISO 7730 (Figure 6.61).

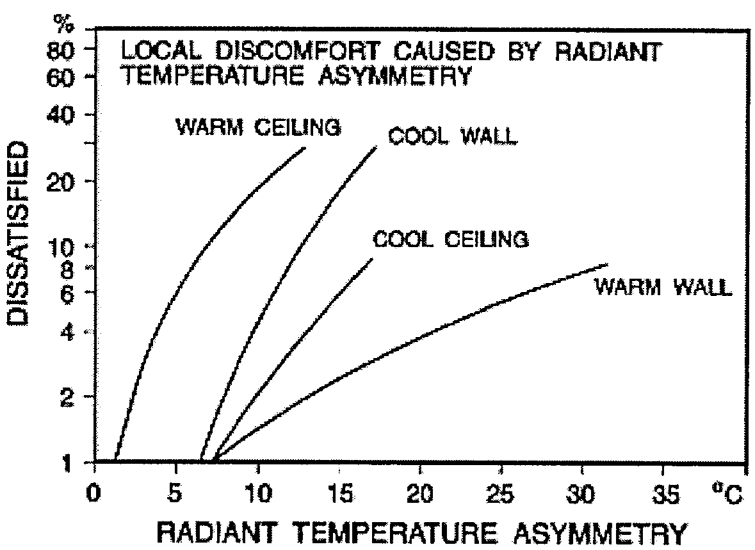


Figure 6.61, Percentage of people dissatisfied as a function of the degree and type of asymmetric radiation (ISO 7730)

Cold windows are also a known to create draught, something that has been shown to cause local discomfort in people exposed to it. As has been discussed in previous chapters, a draught rating (DR) model is presented by ISO 7730 and provides a method by which to assess the effects of draught on thermal comfort by means of predicting the percentage of people that will be dissatisfied due to it. Details of the model are given below:

$$DR=[(34-t_a)(v-0.05)^{0.62}]\ [0.37\times v\times(Tu+3.14)]$$

However, studies conducted by Griefhahn (1999) and Toftum et al (2000) suggest that predictions derived from the model are inaccurate, leading to Olesen and Parsons (2002) to conclude that further studies are needed to evaluate whether amendments are needed.

Chapter 4 of this thesis aimed to investigate the affects of exposure to a cold window on thermal comfort and provide further insight into the mechanisms through which this might be facilitated. Thirty minutes exposure to a cold window was found to significantly affect subjects' mean thermal sensation vote, decreasing it by 1 scale unit.

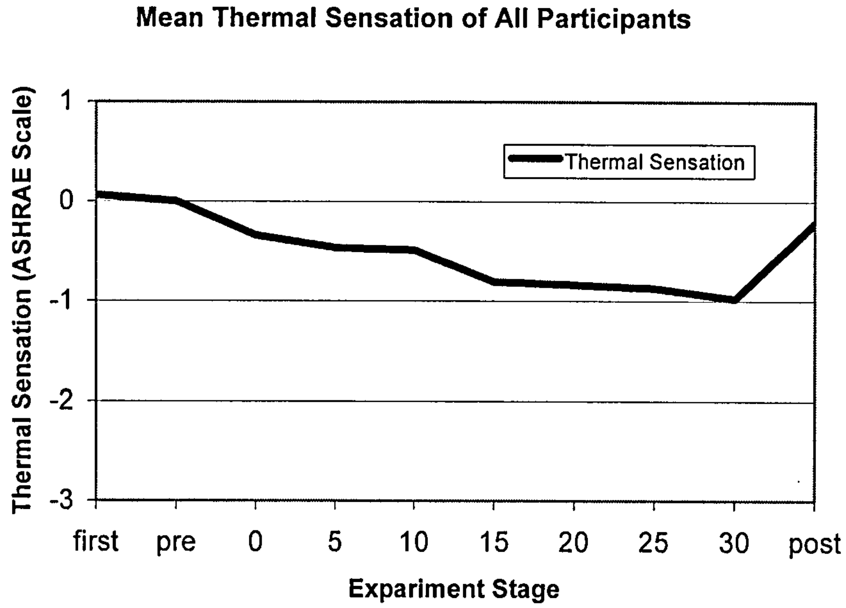


Figure 6.62, Mean thermal sensation vote during exposure to a cold window-3=Cold, -2=Cool, -1=Slightly cool, 0=Neutral, 1=Slightly warm

Predictions were also made using the Draught Rating (DR) and Radiant Asymmetry models, and compared with the Actual Mean Vote (AMV) and Actual Percentage Dissatisfied (APD) obtained through subjective measurements.

Table 6.43, Environmental data, outputs from predictive models and comparative subjective data

Experimental stage	'PRE'/Control	At 30min exposure
t_a (°C)	22.15	21.9
t_r (°C) derived from exposed t_g	21.89	19.68
t_r (°C) derived control t_g	21.89	21.53
Air velocity (m/s)	0.09	0.31
Relative Humidity (%)	41.49	50.26
PMV derived from exposed t_r	-0.3	-1
PPD derived from exposed t_r	7.5	25.8
PMV derived from control t_r	-0.3	-0.4
PPD derived from control t_r	7.5	8.8
AMV	0	-1
APD	0	25
Draught Rating (% dissatisfied)	9.2	16.7
Radiant asymmetry (% dissatisfied)	1	40

It can be seen from Table 6.43 that predictions from these models were inaccurate and they will therefore not be considered for incorporation into a model for predicting the effects of the window. In this situation the PMV does appear to give an accurate environmental assessment, provided the relevant local environmental factors value is used in it's calculation. However, having a generic model with correction factors applied where necessary does have advantages.

As it cannot be accurately determined which factors are attributable to causing thermal discomfort, and to what extent they contribute to the overall effect, the following practical model is proposed to assess the effects of exposure to a cold window on thermal comfort.

$$PMV_{Window} = PMV - 1$$

This can be used to assess a persons 'local' PMV when they are sat next to a cold window (5°C $\pm$ 1°C).

6.4.4 Correction for clothing factors

Chapter 5 investigated the effect of colour and fit of clothing on thermal comfort when exposed to simulated solar radiation. The results of the study were inconclusive and whilst in some cases, there looked to be an associated effect on comfort in relation to subjective responses, no significant differences were found between conditions.

It is feasible to conclude from the literature reviewed in chapter one that there is a difference in radiation exchange that black clothing has with the environment when compared with white. However, this effect is not quantifiable in a sense that it could be incorporated into a model to assess the effects of clothing colour on thermal comfort. For this reason, an adaptation of the model will not be made for clothing colour, although it is accepted that this may well be a personal factor that effects thermal comfort. The effects of black clothing over white clothing were significant, but were relatively small when compared to the effects of radiation intensity, therefore a correction for clothing will not be included

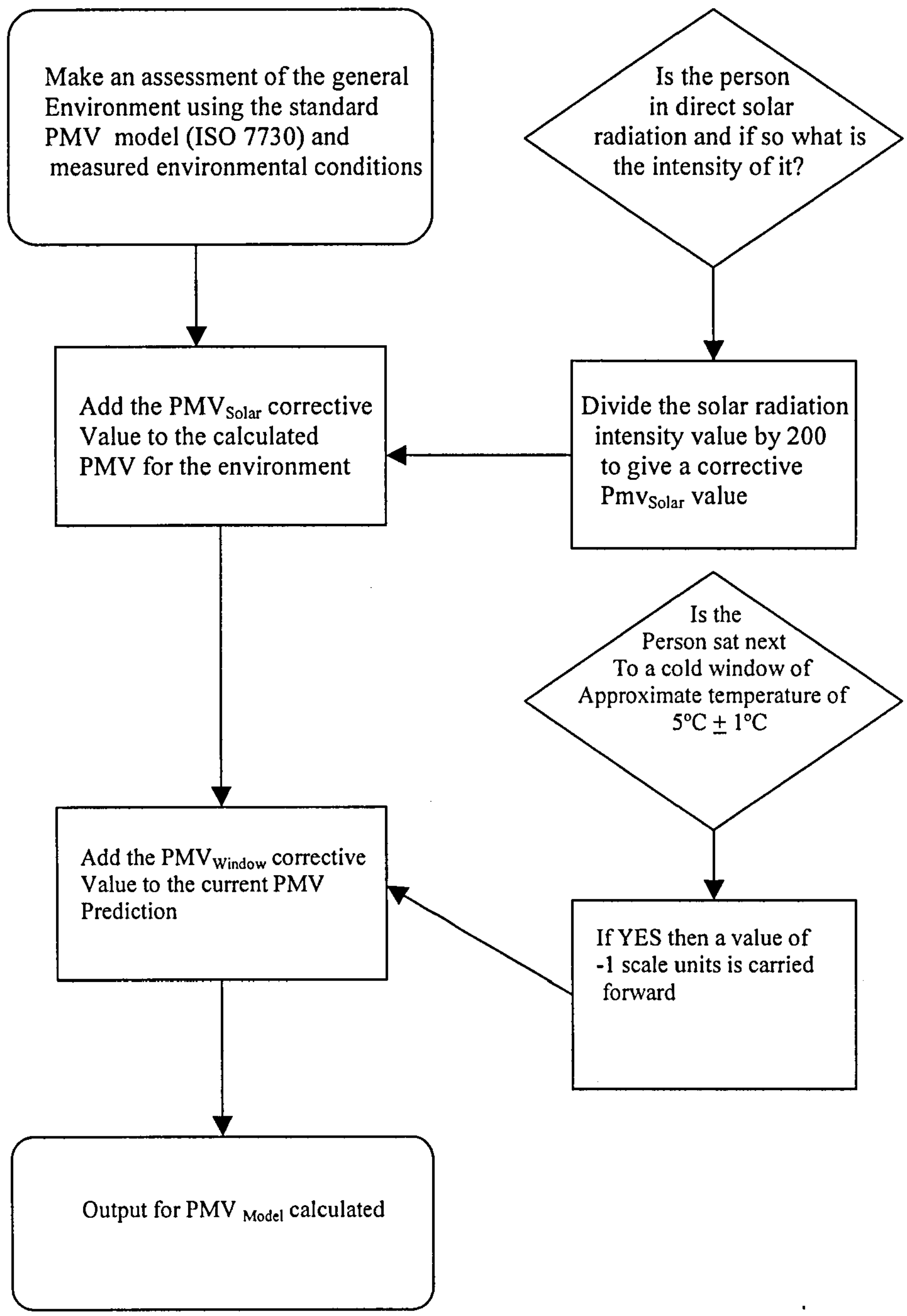
6.4.5 PMV_{Model}

A review of laboratory experiments and relevant literature has determined PMV_{Solar} and PMV_{Window} as acceptable methods for incorporating feasibly occurring 'local' factors into an assessment of thermal comfort in a train carriage. The following method Is proposed to incorporate them in one model: i.e. PMV_{Model}

$$\mathbf{PMV_{Model} = PMV + [Solar\ radiation\ (Wm^{-2}) / 200(Wm^{-2})]}\ \mathit{-1}^{*}$$

**Only applicable if person is sat next to a cold window (5°C ± 1°C)*

Below is a flow chart showing the process of the practical application fo the model



6.5 Conclusions

A model to assess individuals' thermal comfort in rail carriages has been derived. The model is based on PMV (ISO 7730) but makes adjustments for people sat next to a cold window or in direct solar radiation. It will now be tested and validated in field studies.

7 Field trials in trains: Validation of the thermal comfort model

7.1 Background

The field trials were conducted on Midland mainline meridian train services between Loughborough and London St.Pancras stations. Two sets of data were generated by each outing, one from the outward journey and one from the return. During the journey thermal comfort responses were recorded along with environmental conditions. A comparison of comfort responses with those predicted from the thermal comfort model developed in the laboratory allowed a validation of the model. Between experiments, participants were taken to a near by café, where they were allowed one caffeinated drink and a sandwich. There was usually a gap of between one and two hours between the end of the outward and the start of the return journeys. One or two experimenters accompanied four participants on each journey.

Two field trials were conducted, the first on 21st June 2005 and the second 20th July 2005. A brief summary of the details of each journey is listed below. The times stated are the start and end points of data recording.

Table 7.44, Field trials: Dates and durations

FT Date	Outward journey time	Return journey time
21/06/05	09:51 – 11:11	13:55 – 15:16
20/07/05	09:50 – 11:15	12:04 – 13:37

7.1.1 Aim

The aim of the field trials was to validate the thermal comfort model that had been devised from laboratory experiments.

7.2 Experimental route

The experimental route ran from Loughborough station to London St.Pancras station and is illustrated in Figure 7.63.

The route ran south east on the outward journey and north west on the return. The chosen services on this route gave a relatively uninterrupted journey, with trains stopping just once at Leicester station on both outbound and return journeys.

Figure 7.63, A Map of the experimental route used in all field trials

7.3 Method

7.3.1 Design

Each participant completed both an outward and return journey contributing two runs/sets of data for analysis. As participants were seated in different areas of the train and environmental conditions were dynamic and uncontrolled, a validation was not made by aggregating data sets over individuals. This is the routine of field trials, each data set for individuals being unique. Data for individuals were therefore collated and analysed separately and the results integrated at a later stage to provide the validation. Correlations were used to assess how appropriately different models predicted participants' evaluations of the dynamic thermal environment.

7.3.2 Subjects

Eight healthy Caucasian male volunteers, all students in the Loughborough area, took part in the field trials. The subjects were paid upon completion of both journeys. Each subject wore a standard clothing ensemble of white cotton/polyester (65%/35%) long sleeved shirt (open neck with sleeved rolled up to the elbow), beige cotton/polyester (65%/35%) trousers and their own undergarments and shoes. This gave an estimated clo value of 0.72 including the train seat.

7.3.3 Experimental vehicles

Midland mainline Meridian trains were used to conduct field trials. Each test took place in standard class, in which there is a centre isle, with two rows of seats on each side. Participants were positioned in seating bays on opposite sides of the train, two next to the windows on either side and two facing them in the isle seats (Figure 7.64).

Figure 7.64, Participants on the train

7.3.4 Environmental Measurements

Two rigs were devised to measure air and radiant temperature, which allowed a quick and easy set up once the train was boarded. The rigs consisted of a clamp stand, with a metal pole attached horizontally across the centre. At either end of the pole was a black globe. Four thermistors were positioned on the stand to measure air temperature. A further thermistor was taped to the window to measure window temperature. The 2 rigs were placed in the centre of the tables with one globe next to the window and one towards the isle. The isle globes were shielded and used to calculate mean radiant temperature for either side of the train. The other globes were exposed to any direct solar radiation coming through the windows on either side of the train. Relative humidity and air velocity were also measured..

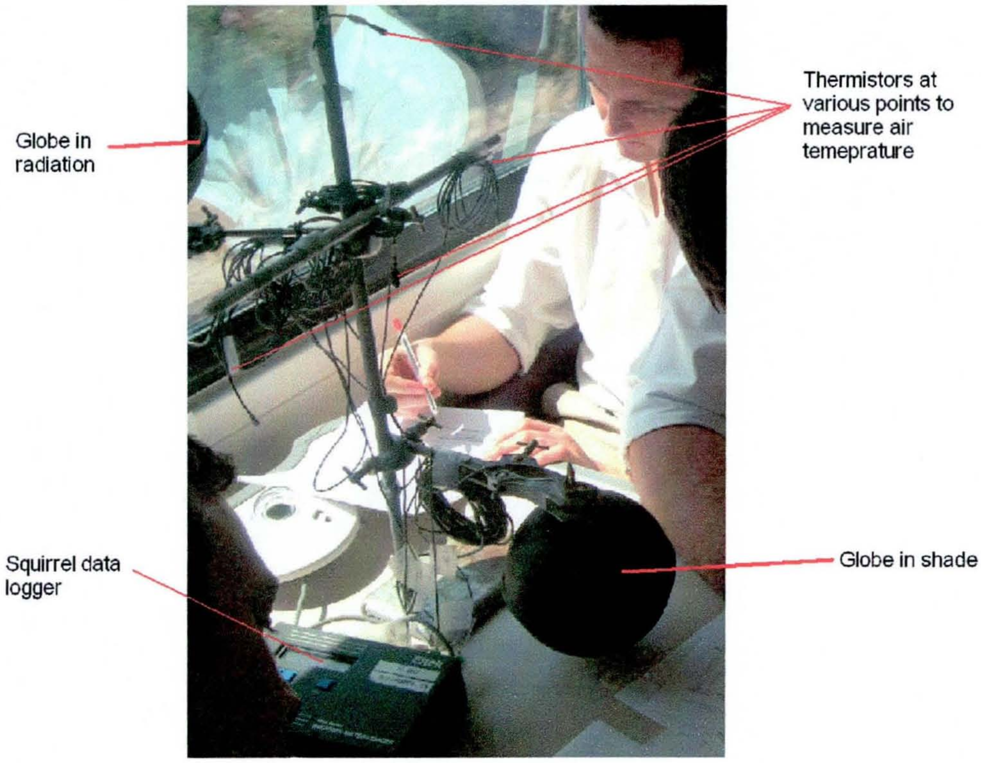


Figure 7.65, Experimental rig to measure environmental details

A prediction of the amount of direct solar radiation falling on each participant was also made at each data point (at the same time as the questionnaires were filled out). The method used gave a prediction of either 0, 200, 400 or 600W/m-2 based on the following criteria.

Table 7.45, Description of estimations of solar radiation intensities

Estimated Level (Wm^2)	Description
0	Completely overcast
200	Some sun coming through a predominantly cloudy sky
400	A lot of sunlight coming through sparse cloud
600	Unobstructed sunlight, no cloud

PMV (Predicated Mean Vote; Fanger 1970; ISO 7730, 2005) for all participants at all data points was calculated using mean radiant temperature, obtained from shielded globe temperature on their respective side of the train. PMV_{Solar} could then be calculated using the estimations of direct solar radiation for each participant at each data point, in the PMV_{Solar} equation:

$$\mathbf{PMV_{Solar} = PMV + \frac{estimation\ of\ solar\ radiation\ (Wm^{-2})}{200\ (Wm^{-2})}}$$

7.3.5 Subjective Measurements

Questionnaires were used to attain subjective data. Participants gave ratings of thermal sensation, comfort, stickiness, draughtiness, preference and pleasantness, in terms of overall body sensation and localised body parts. Questionnaires were completed every 15 minutes throughout each journey.

7.4 Procedure

Field trails were conducted between Loughborough and London St.Pancras stations, with 1 stop on the journey at Leicester. A return consisted of 2 runs conducted at different times of day, to acquire different environmental conditions for each one. Equipment was prepared and calibrated and participants were briefed on the experimental procedure the day before the experiment. At this time they also completed medical screening questionnaires, were fitted with a standard clothing ensemble and completed practise subjective questionnaires to familiarise themselves with them. Participants were asked to refrain from drinking alcohol for 24 hours prior to the trial. On the day of each trial, subjects were picked up and transported to the station by car approximately 30 minutes before the trains departure from Loughborough station. On boarding the train, participants sat in their allocated seats and were given a questionnaire. The environmental measurement stands were placed in the centre of the tables and the window thermistors was fastened to the centre of the windows with transpore tape. Participants were then asked to complete the questionnaires, the data loggers were started (recording at one minute intervals throughout the journey) and then air velocity and humidity were measured and recorded. At this point subjective estimations of the amount of additional direct solar radiation falling on each participant were recorded by experimenters. Questionnaires were then administered every 15 minutes for the remainder of the journey. Air velocity, humidity, and subjective environmental assessments were recorded in unison with this. Data loggers were switched off a few minutes prior to the journeys end so that the equipment could be packed away ready to disembark.

The return journey's were scheduled with at least one hours break between them and the journey down to St.Pancras. In this time participants were allowed a snack, water and a maximum of one caffeinated drink.

On the return journey, the train was boarded ten minutes prior to departure (the maximum allowed by the train operator). The equipment was set up as it was for the outward journey and participants were given a questionnaire to complete. The data loggers were started as the train started to move. Questionnaires were then administered every 15 minutes for the duration of the journey, in unison with environmental observations and air velocity and humidity measurements. Data loggers were switched off a few minutes prior to the journeys end, just after departure from Leicester station.

Journeys lasted for between one hour twenty and one hour and forty minutes which resulted in six or seven questionnaires being completed. On arrival at Loughborough station participants were taken by car back to the lab where they changed back into their own clothes.

7.5 Results

During the field trials the environment was not controlled and was therefore the 'actual' conditions as would be experienced by passengers. Subjects responded subjectively to the conditions to which they were exposed at each stage of the journey. Due to the variable weather conditions, the trains alternating orientation to the sun and the uncontrolled (by us) air conditioning system on the train, each subjective response was treated as an individual data point rather than an accumulation over time. There were 100 data points in total collected from the four journeys. Thermal sensation was chosen as the main factor with which to compare other variables to, as it is linked directly to the PMV and relates well to how a subject interprets their environment.

7.5.1 Environmental Results

7.5.1.1 Presentation of results

A summary of environmental recordings at each data point is presented in Table 7.46 and Table 7.47, A summary of environmental data and PMV outputs for participants' five to eight Sensation score has been included for comparison with PMV values.

It can be seen from these tables that initial air temperatures on boarding the train are noticeably low for participants 5-6. With the exception of these values, air temperature varied by a maximum of 3°C, for any of participants, on an individual journey. Mean radiant temperature varied slightly throughout individual journeys. Air velocity fluctuated constantly throughout each experimental run, between values of 0.08m/s^{-1} and 0.26m/s^{-1}. Relative humidity also fluctuated between 40.5% and 56.3%. The minimum recorded window temperature was 18.6°C.

Table 7.46, A summary of environmental data and PMV outputs for participants' one to four

	Outward Journey						**Inward Journey**					
	0	15	30	45	60	75	0i	15i	30i	45i	60i	75i
Participant 1												
ta	24.15	24.7	24.3	26.1	24.15	25	25.4	23.55	24.55	23.9	23.6	23.6
tr	24.2	24.9	24.75	24.9	25.05	25.2	25.9	25.7	25.6	25.45	25.25	24.8
Vchest	0.13	0.17	0.17	0.12	0.19	0.22	0.21	0.25	0.13	0.14	0.15	0.12
rh	54.7	56.3	47	46.2	45.4	43	41.6	40.5	41.1	41.6	42.5	43.4
twindow	25.7	27.6	26.65	26.95	27.25	26.8	28.2	27.5	27.2	26.7	25.85	25.1
Solar radiation	0	0	0	0	0	0	0	0	0	0	0	0
PMV	0.2	0.3	0.1	0.5	0.1	0.2	0.3	-0.1	0.3	0.1	0	0.1
PPD	5.6	6.5	5.3	10.2	5.2	5.7	7.4	5.1	6.8	5.3	5	5.1
PMVsolar	0.2	0.3	0.1	0.5	0.1	0.2	0.3	-0.1	0.3	0.1	0	0.1
PPDsolar	5.6	6.5	5.3	10.2	5.2	5.7	7.4	5.1	6.8	5.3	5	5.1
PMVwindow	0.2	0.3	0.1	0.5	0.1	0.2	0.3	-0.1	0.3	0.1	0	0.1
PMVmodel	0.2	0.3	0.1	0.5	0.1	0.2	0.3	-0.1	0.3	0.1	0	0.1
Sensation vote	0.5	1.5	1.9	1.9	1.7	1.9	0	0.5	0.5	1	2.1	1.8
Participant 2												
ta	24.4	23.05	23.15	23.8	23.25	24.1	26.1	24.3	24.85	23.7	23.1	23.1
tr	23.7	24.15	24.5	24.65	24.75	24.65	26.4	26.15	26.05	25.25	24.65	24.35
Vchest	0.14	0.19	0.16	0.18	0.24	0.12	0.12	0.09	0.14	0.13	0.17	0.20
rh	54.7	56.3	47	46.2	45.4	43	41.6	40.5	41.1	41.6	42.5	43.4
twindow	23.7	23.7	24.15	24.25	24.2	24.7	32.2	30.75	29.85	27.55	25.8	25.15
Solar radiation	0	0	0	0	0	0	0	0	0	0	0	0
PMV	0.1	-0.1	-0.1	0	-0.2	0.2	0.6	0.4	0.4	0.1	-0.1	-0.2
PPD	5.3	5.3	5.1	5	5.7	5.5	13.8	9	8	5.4	5.2	5.8
PMVsolar	0.1	-0.1	-0.1	0	-0.2	0.2	0.6	0.4	0.4	0.1	-0.1	-0.2
PPDsolar	5.3	5.3	5.1	5	5.7	5.5	13.8	9	8	5.4	5.2	5.8
PMVwindow	0.1	-0.1	-0.1	0	-0.2	0.2	0.6	0.4	0.4	0.1	-0.1	-0.2
PMVmodel	0.1	-0.1	-0.1	0	-0.2	0.2	0.6	0.4	0.4	0.1	-0.1	-0.2
Sensation vote	2.0	0.9	1.0	0.5	0	-1.9	2.3	1.0	0	0	0	-1.0
Participant 3												
ta	24.45	24.6	24.35	24.75	24.5	24.8	25.5	23.8	24.4	23.75	23.1	23.5
tr	24.2	24.9	24.75	24.9	25.05	25.2	25.9	25.7	25.6	25.45	25.25	24.8
Vchest	0.16	0.21	0.19	0.11	0.08	0.17	0.11	0.15	0.10	0.18	0.18	0.14
rh	54.7	56.3	47	46.2	45.4	43	41.6	40.5	41.1	41.6	42.5	43.4
twindow	25.7	27.6	26.65	26.95	27.25	26.8	28.2	27.5	27.2	26.7	25.85	25.1
Solar radiation	200	400	200	200	400	200	0	0	0	0	0	0
PMV	0.2	0.2	0.1	0.2	0.4	0.2	0.5	0.2	0.4	0.1	-0.1	0
PPD	5.5	5.8	5.2	5.6	7.9	6.1	10.7	5.5	7.6	5.1	5.1	5
PMVsolar	1.2	2.2	1.1	1.2	2.4	1.2	0.5	0.2	0.4	0.1	-0.1	0
PPDsolar							10.7	5.5	7.6	5.1	5.1	5
PMVwindow	0.2	0.2	0.1	0.2	0.4	0.2	0.5	0.2	0.4	0.1	-0.1	0
PMVmodel	1.2	2.2	1.1	1.2	2.4	1.2	0.5	0.2	0.4	0.1	-0.1	0
Sensation vote	1.6	1.6	2	2.5	2.8	3.0	1.4	1.2	0.8	1.8	1.7	1
Participant 4												
ta	23.9	22.3	22.5	23.6	23.15	23.9	26	24.4	24.7	24.15	23.55	24.05
tr	23.7	24.15	24.5	24.65	24.75	24.65	26.4	26.15	26.05	25.25	24.65	24.35
Vchest	0.17	0.12	0.15	0.11	0.24	0.16	0.18	0.11	0.09	0.14	0.08	0.16
rh	54.7	56.3	47	46.2	45.4	43	41.6	40.5	41.1	41.6	42.5	43.4
twindow	23.7	23.7	24.15	24.25	24.2	24.7	32.2	30.75	29.85	27.55	25.8	25.15
Solar radiation	0	0	0	0	0	0	600	400	400	200	200	200
PMV	0	-0.1	-0.1	0.1	-0.2	0	0.5	0.4	0.5	0.2	0.2	0
PPD	5	5.1	5.4	5.4	5.8	5	11	7.6	9.8	5.7	5.6	5
PMVsolar	0	-0.1	-0.1	0.1	-0.2	0	3.5	2.4	2.5	1.2	1.2	1
PPDsolar	5	5.1	5.4	5.4	5.8	5						
PMVwindow	0	-0.1	-0.1	0.1	-0.2	0	0.5	0.4	0.5	0.2	0.2	0
PMVmodel	0	-0.1	-0.1	0.1	-0.2	0	3.5	2.4	2.5	1.2	1.2	1
Sensation vote	1.0	-0.1	-0.2	0.6	-0.1	-0.5	2.6	3.0	3.0	2.0	0.5	0

Table 7.47, A summary of environmental data and PMV outputs for participants' five to eight

	Outward Journey						**Inward Journey**						
	0	15	30	45	60	75	0i	15i	30i	45i	60i	75i	90i
Participant 5													
ta	19.5	21.65	22.65	23.2	22.75	22.9	21.2	22.45	22.8	22.55	22.8	23.25	23.6
tr	17.4	21.85	23	24	23.55	23.7	22.4	23.2	23.6	23.7	24.1	23.9	23.45
Vchest	0.10	0.23	0.20	0.23	0.10	0.19	0.23	0.21	0.20	0.25	0.12	0.16	0.19
rh	48.8	49.7	50.4	48.4	48.4	48.4	46.3	47.4	44.3	47	43.3	43.2	42.7
twindow	18.6	20.45	21.65	22.5	23.1	24.55	21.85	22.95	23.65	23.7	24.35	24.15	23.65
Solar radiation	0	0	0	0	0	0	0	0	0	0	0	0	0
PMV	-1.2	-0.7	-0.4	-0.2	-0.1	-0.2	-0.8	-0.4	-0.3	-0.4	-0.1	-0.1	-0.2
PPD	36.4	16.2	7.9	6.2	5.1	6.3	17.4	8.8	7.2	8.9	5.2	5.4	5.8
PMVsolar	-1.2	-0.7	-0.4	-0.2	-0.1	-0.2	-0.8	-0.4	-0.3	-0.4	-0.1	-0.1	-0.2
PPDsolar	36.4	16.2	7.9	6.2	5.1	6.3	17.4	8.8	7.2	8.9	5.2	5.4	5.8
PMVwindow	-1.2	-0.7	-0.4	-0.2	-0.1	-0.2	-0.8	-0.4	-0.3	-0.4	-0.1	-0.1	-0.2
PMVmodel	-1.2	-0.7	-0.4	-0.2	-0.1	-0.2	-0.8	-0.4	-0.3	-0.4	-0.1	-0.1	-0.2
Sensation vote	1.0	1.0	1.0	0.9	1.0	1.0	-1.0	0	0	0	0	-1.0	1.0
Participant 6													
ta	18.9	21.85	22.85	23.45	22.8	21.95	21.1	21.9	22.4	22.35	22.9	22.95	23.4
tr	17.25	21.65	23	23.95	23.4	23.1	22.4	23.2	23.6	23.7	24.1	23.9	23.45
Vchest	0.12	0.24	0.20	0.23	0.16	0.19	0.22	0.18	0.21	0.18	0.14	0.15	0.20
rh	48.8	49.7	50.4	48.4	48.4	48.4	46.3	47.4	44.3	47	43.3	43.2	42.7
twindow	18.7	19.8	21.1	22.05	22.45	22.95	21.85	22.95	23.65	23.7	24.35	24.15	23.65
Solar radiation	0	0	200	200	0	0	0	200	200	200	200	0	0
PMV	-1.6	-0.7	-0.3	-0.2	-0.2	-0.5	-0.8	-0.5	-0.4	-0.3	-0.1	-0.2	-0.2
PPD	56.6	16.3	7.4	5.8	6.2	9.7	17.3	9.3	8.5	7.2	5.3	5.6	6.3
PMVsolar	-1.6	-0.7	0.7	0.8	-0.2	-0.5	-0.8	0.5	0.6	0.7	0.9	-0.2	-0.2
PPDsolar	56.6	16.3			6.2	9.7	17.3					5.6	6.3
PMVwindow	-1.6	-0.7	-0.3	-0.2	-0.2	-0.5	-0.8	-0.5	-0.4	-0.3	-0.1	-0.2	-0.2
PMVmodel	-1.6	-0.7	0.7	0.8	-0.2	-0.5	-0.8	0.5	0.6	0.7	0.9	-0.2	-0.2
Sensation vote	0	0.6	1.0	1.0	1.0	-0.4	-1.4	-0.1	-1.0	-1.0	0.3	0	0.6
Participant 7													
ta	19.8	21.85	22.9	23.5	23.2	23.1	21.05	21.9	21.85	21.7	22.05	22.45	22.45
tr	17.4	21.85	23	24	23.55	23.7	22.7	23.2	23.6	23.5	23.85	23.65	23.25
Vchest	0.09	0.21	0.21	0.24	0.12	0.23	0.17	0.25	0.26	0.20	0.20	0.17	0.21
rh	48.8	49.7	50.4	48.4	48.4	48.4	46.3	47.4	44.3	47	43.3	43.2	42.7
twindow	18.6	20.45	21.65	22.5	23.1	24.55	22.05	22.95	23.45	23.45	23.75	23.3	23.35
Solar radiation	0	0	0	0	0	400	200	0	0	0	0	0	0
PMV	-1.2	-0.7	-0.4	-0.2	-0.1	-0.3	-0.6	-0.6	-0.6	-0.5	-0.4	-0.3	-0.4
PPD	34.2	14.1	7.6	5.8	5.1	6.7	13.2	12.3	12.4	10.2	8.7	7.1	9.2
PMVsolar	-1.2	-0.7	-0.4	-0.2	-0.1	1.7	0.4	-0.6	-0.6	-0.5	-0.4	-0.3	-0.4
PPDsolar	34.2	14.1	7.6	5.8	5.1			12.3	12.4	10.2	8.7	7.1	9.2
PMVwindow	-1.2	-0.7	-0.4	-0.2	-0.1	-0.3	-0.6	-0.6	-0.6	-0.5	-0.4	-0.3	-0.4
PMVmodel	-1.2	-0.7	-0.4	-0.2	-0.1	1.7	0.4	-0.6	-0.6	-0.5	-0.4	-0.3	-0.4
Sensation vote	0	0	1.0	1.0	1.0	1.4	0	1.3	-1.0	-1.0	0	-1.0	0
Participant 8													
ta	19.65	22.5	22.9	23.25	22.6	21.55	20.85	21.9	21.65	21.85	22.1	22.7	22.35
tr	17.25	21.65	23	23.95	23.4	23.1	22.7	23.2	23.6	23.5	23.85	23.65	23.25
Vchest	0.09	0.21	0.18	0.22	0.17	0.23	0.23	0.21	0.21	0.21	0.17	0.18	0.23
rh	48.8	49.7	50.4	48.4	48.4	48.4	46.3	47.4	44.3	47	43.3	43.2	42.7
twindow	18.7	19.8	21.1	22.05	22.45	22.95	22.05	22.95	23.45	23.45	23.75	23.3	23.35
Solar radiation	0	0	0	0	0	0	0	0	0	0	0	0	0
PMV	-1.2	-0.6	-0.3	-0.2	-0.3	-0.6	-0.8	-0.5	-0.5	-0.5	-0.3	-0.3	-0.5
PPD	36.1	11.8	6.8	6	6.8	12.2	18.4	10.6	10.9	10.1	7.5	6.9	10.2
PMVsolar	-1.2	-0.6	-0.3	-0.2	-0.3	-0.6	-0.8	-0.5	-0.5	-0.5	-0.3	-0.3	-0.5
PPDsolar	36.1	11.8	6.8	6	6.8	12.2	18.4	10.6	10.9	10.1	7.5	6.9	10.2
PMVwindow	-1.2	-0.6	-0.3	-0.2	-0.3	-0.6	-0.8	-0.5	-0.5	-0.5	-0.3	-0.3	-0.5
PMVmodel	-1.2	-0.6	-0.3	-0.2	-0.3	-0.6	-0.8	-0.5	-0.5	-0.5	-0.3	-0.3	-0.5
Sensation vote	-0.4	0	0.8	0.4	0.3	0	0	0.1	-1.0	-0.4	-0.1	-0.6	0

7.5.1.2 Interpretation of Results

It can be seen from Table 7.46 and Table 7.47 that environmental conditions varied for all participants throughout each journey. Initially low air temperature values upon boarding the train can be explained by a low external air temperature whilst waiting to board the train. Fluctuations in air velocity may be due to passenger movement through the isles and the air conditioning system turning on and off. Fluctuations in humidity can also be attributed to the air conditioning system. As window temperature was never lower than 18.6°C no correction to PMV for a low window temperature was made:

$$\mathbf{PMV_{window} = PMV}$$

As there are no correction for cold window temperatures, the only correction made to PMV values were due to direct solar radiation by the PMV_{solar} model. PMV_{solar} and PMV_{window} are the only two corrective factors in PMV_{model} and as PMV_{window} contributes no corrective factor in these results:

$$\mathbf{PMV_{solar} = PMV_{model}}$$

For participant data's where there is no additional solar radiation:

$$\mathbf{PMV_{model} = PMV_{solar} = PMV_{window} = PMV}$$

7.5.2 Subjective Results

Table 7.48, Summary of all participants' subjective data

	Outward Journey						**Inward Journey**						
	0	15	30	45	60	75	0i	15i	30i	45i	60i	75i	90i
Participant 1													
Sensation	0.5	1.5	1.9	1.9	1.7	1.9	0	0.5	0.5	1.0	2.1	1.8	
Comfort	1.4	1.4	1.8	1.8	1.3	1.7	1.0	1.2	1.2	1.2	2.1	2.0	
Draughtiness	1.0	1.2	1.3	1.2	1.6	1.5	1.0	1.0	1.2	1.2	1.5	1.3	
Stickiness	1.4	1.8	2.3	2.4	2.3	2.2	1.4	1.2	1.3	2.0	2.5	2.4	
Preference	0.7	0.9	1.1	1.2	1.3	1.0	0.2	0.2	0.8	1.4	2.1	0.9	
Acceptability	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0	1.0	
Satisfaction	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0	0	0	
Participant 2													
Sensation	2.0	0.9	1.0	0.5	0	-1.9	2.3	1.0	0	0	0	-1.0	
Comfort	3.2	2.1	1.9	1.8	1.4	1.0	3.0	1.8	1.2	1.0	1.0	1.1	
Draughtiness	1.9	1.5	2.0	1.8	2.8	2.0	1.0	2.4	2.5	2.0	1.5	1.0	
Stickiness	2.0	2.8	2.6	2.5	1.4	1.0	2.8	2.0	1.6	1.0	2.1	1.0	
Preference	1.0	0.5	0.3	0.3	0	-0.1	2.0	0.3	0	-0.2	-0.2	-0.4	
Acceptability	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
Satisfaction	1.0	0	0	0	1.0	1.0	1.0	0	1.0	1.0	1.0	1.0	
Participant 3													
Sensation	1.6	1.6	2.0	2.5	2.8	3.0	1.4	1.2	0.8	1.8	1.7	1.0	
Comfort	2.4	3.0	3.0	3.3	3.7	3.9	2.0	2.0	2.2	2.3	1.8	1.7	
Draughtiness	1.0	1.0	1.0	1.0	1.0	1.1	1.2	1.0	1.2	1.1	1.2	1.1	
Stickiness	1.0	1.0	1.0	1.0	1.3	1.0	1.9	1.3	1.2	1.8	1.7	1.2	
Preference	2.1	2.2	2.3	2.4	2.6	2.6	1.8	1.3	1.1	1.5	0.9	0.4	
Acceptability	0	0	0	0	0	0	1.0	1.0	1.0	1.0	1.0	1.0	
Satisfaction	0	0	0	0	0	0	1.0	0	1.0	0	0	1.0	
Participant 4													
Sensation	1.0	-0.1	-0.2	0.6	-0.1	-0.5	2.6	3.0	3.0	2.0	0.5	0	
Comfort	2.8	1.5	1.2	2.0	1.0	1.0	3.0	4.0	4.0	2.8	1.6	1.0	
Draughtiness	1.5	1.4	1.3	1.0	2.0	0.5	1.0	1.0	1.0	1.0	1.0	1.6	
Stickiness	1.6	1.3	1.0	1.0	1.3	1.0	3.2	3.2	4.0	3.3	2.1	1.0	
Preference	1.0	0.8	0.9	0.8	0.4	0.6	2.5	3.0	3.0	1.9	1.9	0.9	
Acceptability	1.0	1.0	0	1.0	1.0	1.0	0	0	0	1.0	1.0	1.0	
Satisfaction	1.0	1.0	1.0	0	1.0	1.0	0	0	0	0	0	1.0	
Participant 5													
Sensation	1.0	1.0	1.0	0.9	1.0	1.0	-1.0	0	0	0	0	-1.0	1.0
Comfort	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.2	1.0	1.0	1.0	1.0
Draughtiness	1.0	2.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0	1.0	1.0	2.0	1.0
Stickiness	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Preference	0.5	-0.5	0.5	0	0	0	-1.0	0	-0.5	0	0	-0.5	1.0
Acceptability	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Satisfaction	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Participant 6													
Sensation	0	0.6	1.0	1.0	1.0	-0.4	-1.4	-0.1	-1.0	-1.0	0.3	0	0.6
Comfort	1.1	1.1	1.2	1.6	1.5	1.5	1.0	1.6	1.5	1.4	1.9	2.0	1.8
Draughtiness	1.0	1.5	1.5	1.9	1.7	2.0	2.0	1.6	1.9	2.0	2.0	1.8	1.5
Stickiness	1.2	1.4	1.5	1.5	1.9	1.6	1.4	1.6	1.5	1.6	1.9	2.0	1.9
Preference	0	0	0	0	0.4	0	-0.1	0.1	-0.1	-0.2	0	-0.2	0.3
Acceptability	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Satisfaction	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Participant 7													
Sensation	0	0	1.0	1.0	1.0	1.4	0	1.3	-1.0	-1.0	0	-1.0	0
Comfort	1.0	1.0	1.0	1.0	1.1	1.0	1.0	1.0	1.5	1.5	1.0	1.5	1.0
Draughtiness	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.7	2.1	2.0	2.5	1.0
Stickiness	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Preference	-1.0	-0.5	-0.4	-0.4	-0.4	-0.4	-0.5	0	-1.5	-1.0	-0.4	-1.0	-0.4
Acceptability	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Satisfaction	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Participant 8													
Sensation	-0.4	0	0.8	0.4	0.3	0	0	0.1	-1.0	-0.4	-0.1	-0.6	0
Comfort	1.0	1.0	1.2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.3	1.0
Draughtiness	1.0	1.0	1.0	1.2	1.0	1.7	1.0	1.0	1.6	1.0	1.6	2.0	1.6
Stickiness	1.0	1.0	1.2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Preference	-0.3	0	0	0.2	0	-0.1	0	-1.0	-0.5	0	-0.5	-0.7	-0.3
Acceptability	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Satisfaction	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 7.48 presents a summary of subjective responses at each data point.

7.6 A comparison of thermal sensation data with PMV, PMV_{Window} PMV_{Solar} and PMV_{Model}

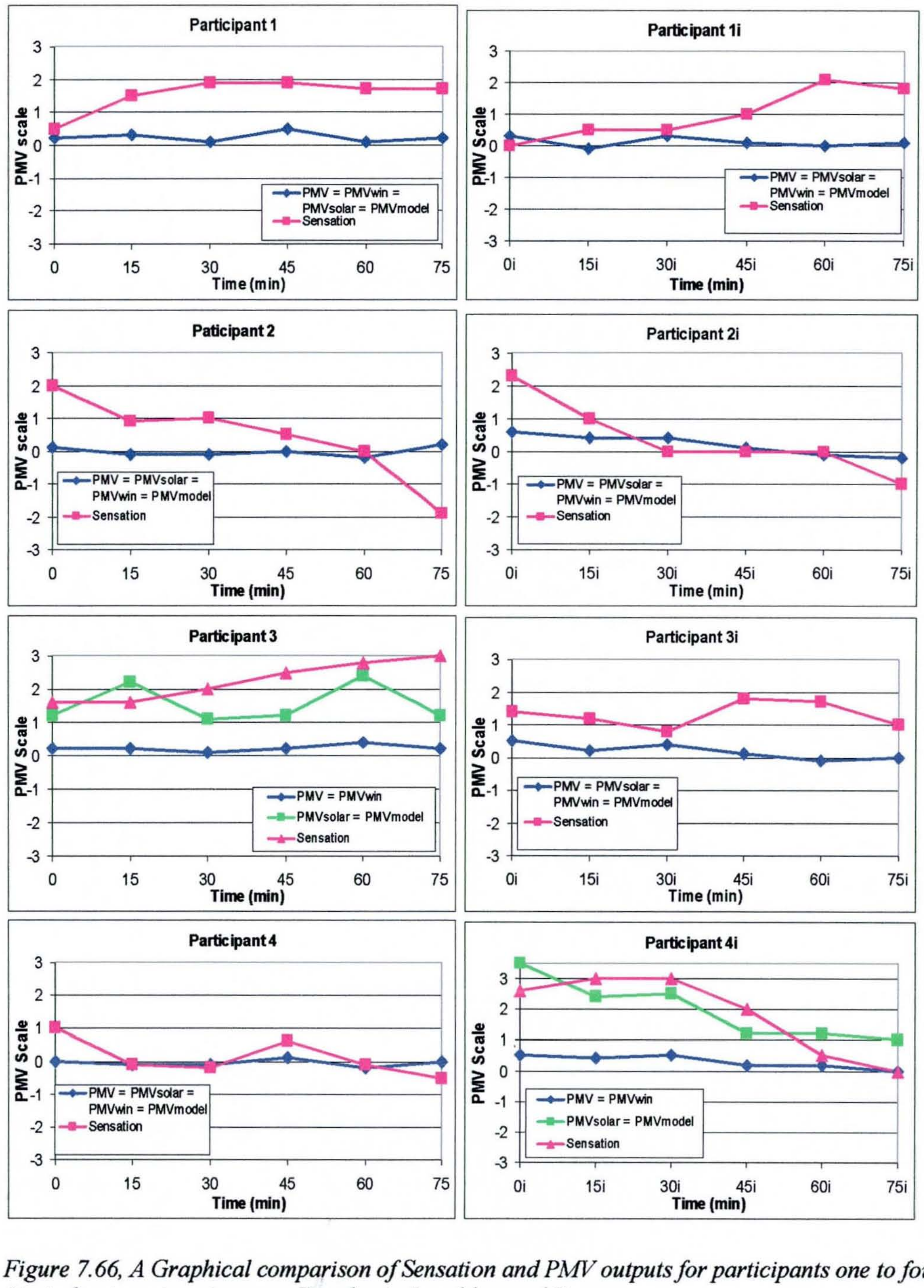


Figure 7.66, A Graphical comparison of Sensation and PMV outputs for participants one to four (i - indicates return journeys [London to Loughborough]),

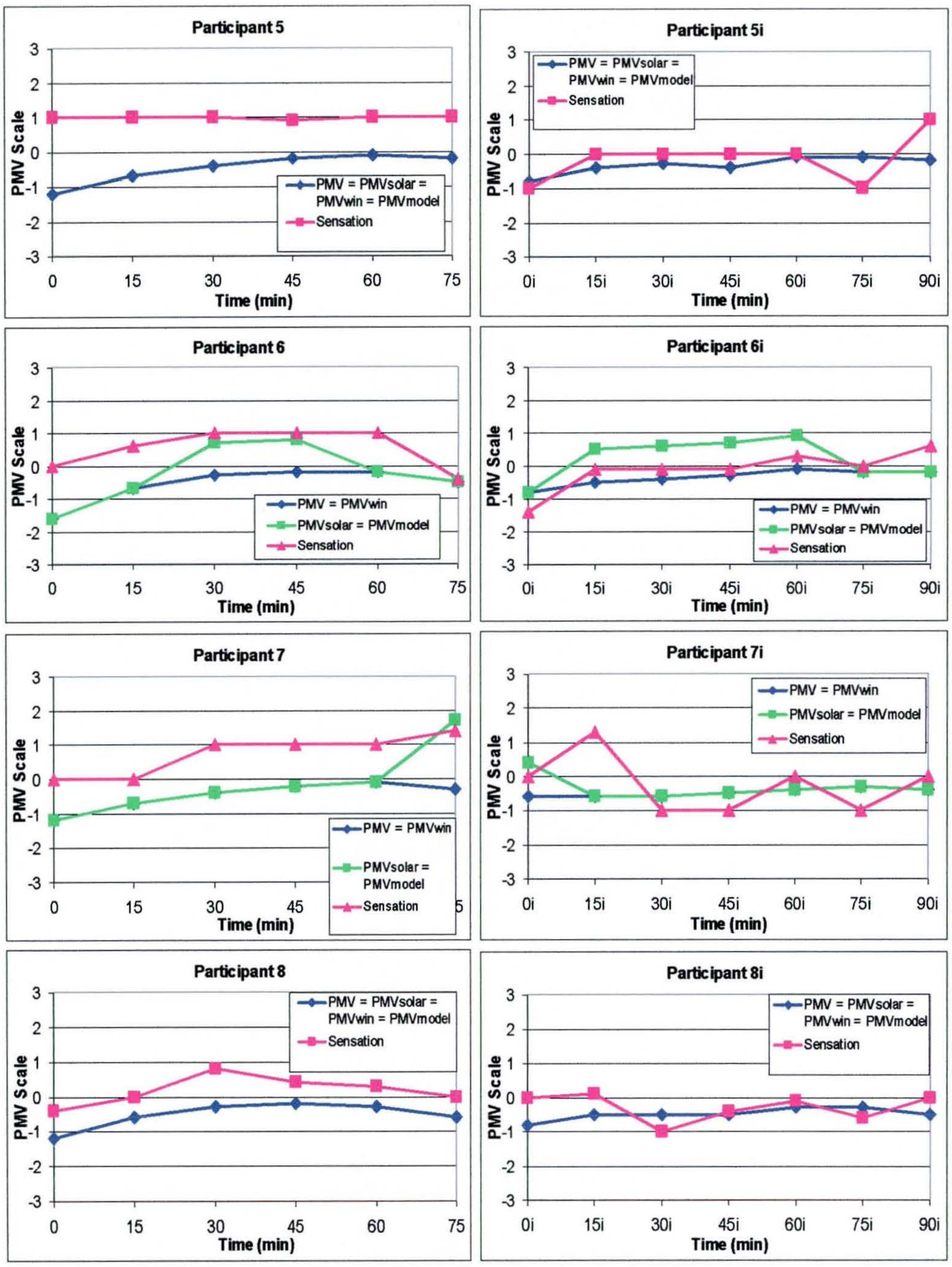


Figure 7.67, A Graphical comparison of Sensation and PMV outputs for participants five to eight (i - indicates return journeys [London to Loughborough])

Figure 7.66 and Figure 7.67 show comparisons of Participants' sensation votes and outputs for PMV, PMV_{Window}, PMV_{Solar} and PMV_{Model}. In most cases all of these variations produce the same output/prediction and this only changes when a subject is in direct solar radiation, in which case PMV = PMV_{Window} and PMV_{Solar} = PMV_{Model}.

It can be seen from Participants 3, 4i and 6 that PMV_{Model} seems to more closely match objective sensation data than PMV. The exception to this trend is participant 6i, where for the majority of the journey, standard PMV produces a closer match to sensation scores.

In both outward and return journeys for Participant 7 (and 7i), there is only a single point where a subject is in direct solar radiation. At both of these points PMV_{Model} gives a more accurate prediction of sensation vote than PMV.

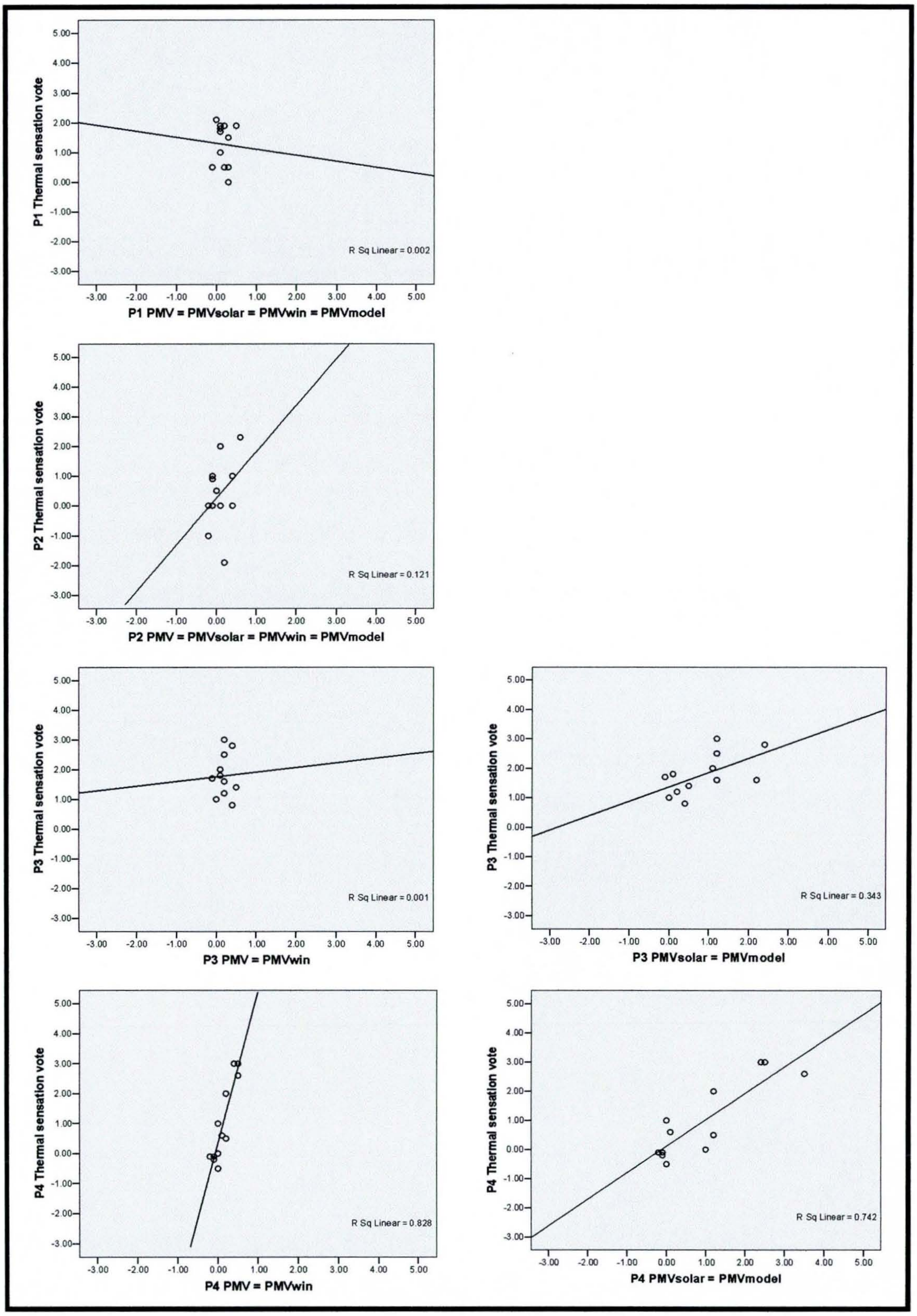


Figure 7.68, Correlations between sensation vote and PMV outputs for participants one to four

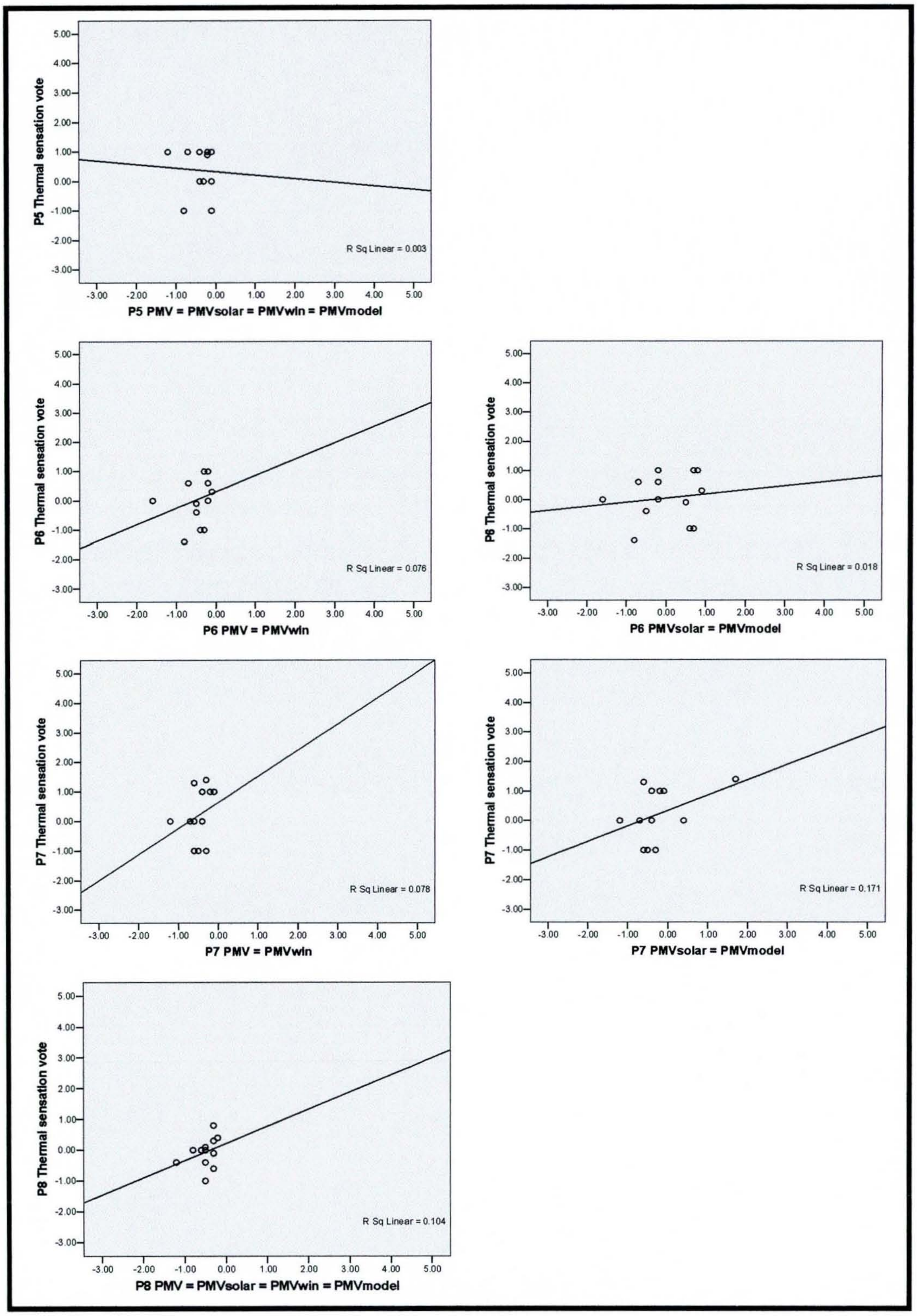


Figure 7.69, Correlations between sensation vote and PMV outputs for participants five to eight

Figure 7.68 and Figure 7.69 show correlations between each Participants' sensation votes and:

1. PMV (= PMV_{window})
2. PMV_{solar} (= PMV_{train})

Participants 1,2,5 and 8 were at no stage in direct solar radiation during the experiments and so for these participants all correlations are the same

i.e. $PMV_{train} = PMV_{solar} = PMV_{window} = PMV$,

and therefore only one graph is shown. For participants where there is a difference between correlations the, new model has varying degrees of success. For participant 3 the new model produces a much stronger correlation with sensation vote than PMV alone, R sq = 0.343 and 0.001 respectively. There was also an stronger correlation for participant 7 when the new model was used, R sq increasing from 0.078 to 0.171. However for participants 4 and 6 there is are slightly weaker correlations when the new model is used, R sq = 0.828 to 0.742 and 0.076 to 0.018.

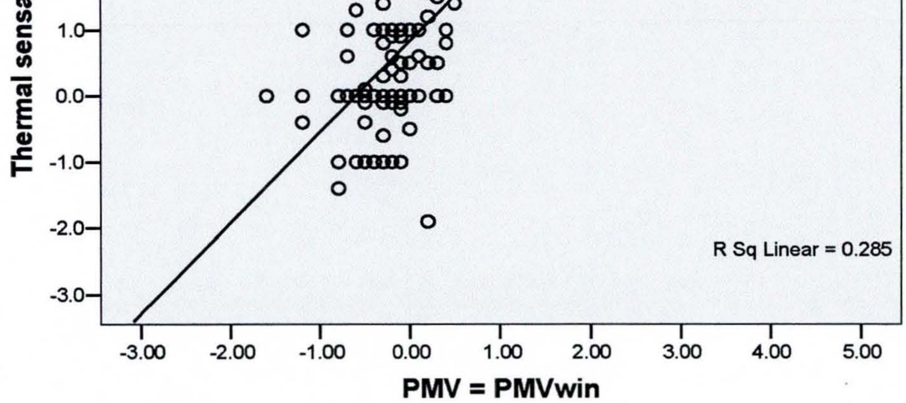


Figure 7.70, A correlation between all Participants' sensation scores and corresponding calculated PMV (=PMVWindow) outputs.

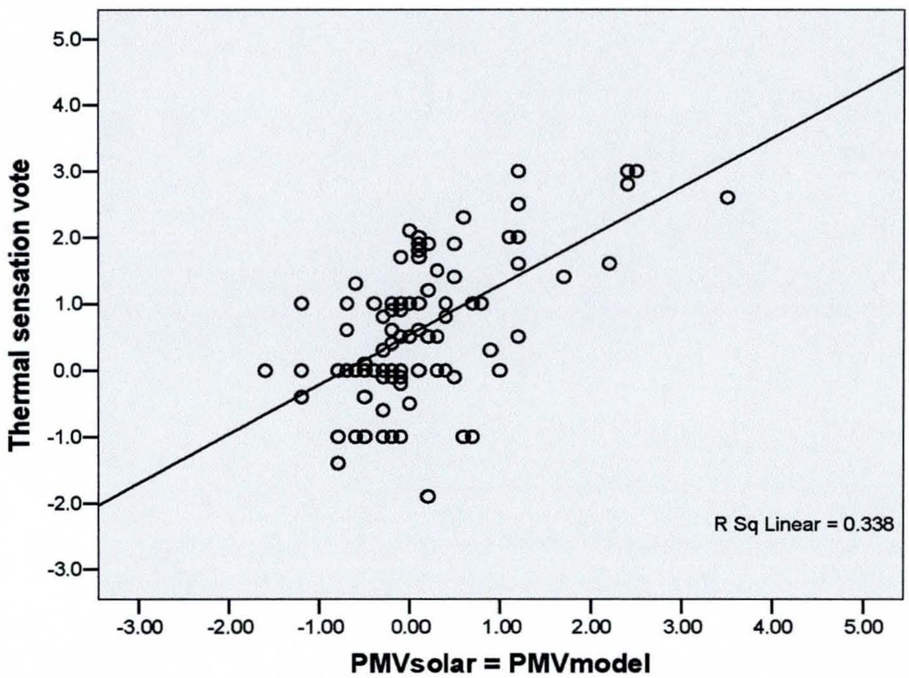


Figure 7.71, A correlation between all Participants' sensation scores and corresponding calculated PMVModel (=PMVSolar) outputs.

Figure 7.70 and Figure 7.71 show correlations between sensation vote and PMV (=PMV_{window}), and sensation vote and PMV_{Model} (=PMV_{solar}) respectively, for all participant data. It can be seen that there is an increase in correlation strength from Rsq = 0.285 to Rsq = 0.338 when the PMV_{Model} is used instead of PMV.

7.7 Validation of the thermal comfort model

The aim of this section was to validate the developed thermal comfort model by comparing outputs generated by it in a dynamic environment, against PMV outputs and subjective responses. When data generated by the model were correlated with the corresponding subjective data (i.e. data relating to the same point in time and space), it was found that it more closely matched participants' evaluation of the environment (Rsq = 0.338, Figure 7.70) than data derived from the PMV (Rsq = 0.285, and Figure 7.71).

i.e. The data points were nearer to forming a straight line of uniform gradient (Rsq = 1).

7.8 Conclusions

Field trails were undertaken in which external weather conditions continually changed. As a result of this the environmental conditions for each participant were unique in a given point in time and space.

1 Estimated levels of solar radiation experienced varied between participants and throughout experimental sessions
2 Environmental conditions within the train changed throughout the experimental sessions, exposing participants to a variety of thermal conditions.
3 PMV_{Model} correlated more strongly with sensation votes than standard PMV.

8. Validation of Model

8.1 Chapter summary

This chapter collates all data from laboratory experiments and field trials to evaluate the predictive thermal comfort models developed in chapter 6. The models mostly include empirically derived correction factors for Fanger's PMV model and are validated in this chapter by means of correlation with the Actual Mean Sensation Vote (AMV) of subjects.

8.2 Aim

The aim of this chapter is to validate PMV_{Model}, and other developed models, by means of correlating outputs from them with the subjective responses of participants at the same point in time and space.

8.3 Introduction

The PMV_{Model} to evaluate local thermal comfort for passengers on train carriages was developed in chapter 6 and is based on the PMV (Fanger, 1970; ISO 7730) with correction factors for solar radiation and exposure to a cold window. The model was tested in field trials (Chapter 7) and found to correlate well with subjective thermal sensation responses. Other thermal comfort models, PMV_{Solar} and PMV_{Window}, (from which PMV_{Model} was principally derived), were also tested but, due to the warm environmental conditions at the time of the experiment, the study did not investigate thermal comfort in conditions where PMV_{Window} would become relevant and contribute a corrective factor. In essence, because of this, $PMV_{Model} = PMV_{Solar}$ and $PMV_{Window} = PMV$. Therefore to fully evaluate the model, the data from experiments 3 – 6 where the effects of both solar radiation and a cold window have been investigated, will be collated and re-analysed. It is thought that PMV_{Model} will out perform both PMV_{Solar} PMV_{Window} and PMV in terms of model outputs correlating with subjective sensation responses.

8.4 Models for validation

The models discussed in chapter 6 and evaluated in chapter seven are presented below and described in detail in Table 8.49.

1. **PMV** (Fanger, 1970; ISO 7730)

2. $\mathbf{PMV_{Solar} = PMV + [Radiation\ intensity\ (Wm^{-2}) / 200]}$

   (Hodder and Parsons 2002)

3. $\mathbf{PMV_{Window} = PMV - 1}$ *(For exposure to a window of 5°C ± 0.5°C)*

4. $\mathbf{PMV_{Model} = PMV: + [Radiation\ intensity\ (Wm^{-2}) / 200]}$

   $\mathbf{- 1}$ *(For exposure to a window of 5°C ± 0.5°C)*

Table 8.49, Description of thermal comfort models

Model	Description
PMV	ISO 7730 thermal comfort model derived from Fanger (1970). A single output is generated, giving an estimation of peoples sensation vote in a given environment, from which PPD (Predicted Percentage Dissatisfied) can be calculated. Four environmental factors (air temperature, Mean radiant temperature, Relative Humidity and air velocity) are combined with 2 personal factors (insulative value of clothing and metabolic rate) and put into a heat balance equation to calculate a PMV output. In these experiments environmental conditions were measured around subjects, estimated Clo value was 0.72 and estimated metabolic rate was 70 Wm^{-2}
PMV_{Solar}	An empirically developed model based on PMV but including a correction factor for exposure to direct solar radiation. Calculated from environmental measurements taken from around the subject, an estimated Clo value of 0.72 and an estimated metabolic rate of 70 Wm^{-2}. Solar radiation intensity (Wm^{-2}) was set in laboratory experiments and estimated in field trials. This value was then divided by 200 to give a corrective factor which was added to PMV.
PMV_{Window}	An model developed empirically to evaluate the effect of exposure to a cold window on thermal comfort. It is based on the PMV but includes a correction factor of - 1 for people exposed to a cold window of 5 $\pm$ 1°C, which was measured by thermistors. Calculated from environmental measurements taken from around the subject, an estimated Clo value of 0.72 and an estimated metabolic rate of 70 Wm^{-2}.
PMV_{Model}	Developed to evaluate the local thermal environment of passengers on a train carriage. It is based on the PMV but includes the individual corrective factors of PMV_{Solar} and PMV_{Window}. Calculated from environmental measurements taken from around the subject, an estimated Clo value of 0.72 and an estimated metabolic rate of 70 Wm^{-2}.

Environmental data will be taken from the end points of each individual exposure in laboratory studies (after 30 minutes exposure to the relevant stimuli) and used with each of the above models to create predictive outputs (4 for each data point – one for each model evaluated). Each of these outputs will be correlated with the associated subjective sensation vote for the same point in time and space.

8.4.1 Results

8.4.1.1 Presentation of results

A Pearson's product moment correlation analysis was conducted between the actual sensation votes of the subjects and the predictive PMV outputs for all thermal comfort models, for all laboratory experiments and fields trials. The results are summarised in Table 8.50. Results are displayed for all experimental sessions and for all experimental sessions with the exception of those with black shirts in the clothing ensemble.

Table 8.50, Pearson's product moment correlations for all comfort models against actual sensation votes (AV)

	n	Pearson's Correlation, r	Significance (2 tailed)
Actual Vote	156	1.00	-
PMV_{Model}	156	0.741	0.000
PMV_{Solar}	156	0.719	0.000
PMV_{Model}*	140	0.694	0.000
PMV_{Solar}*	140	0.662	0.000
PMV_{Window}	156	0.441	0.000
PMV_{Window}*	140	0.387	0.000
PMV	156	0.348	0.000
PMV*	140	0.274	0.001

**Excludes data from participants wearing black shirts*
Note 1 – Assumes all points are independent

8.4.1.2 Interpretation of results

The correlation of all predictive models against actual sensation votes showed that PMV_{Model} gave the highest correlation of 0.741 (Table 8.50), which can be described as large/strong (Cohen 1988). This was just ahead of PMV_{Solar}, this being due to the relatively high number of cases involving a solar radiation correction. The cold window corrective factor, with which PMV_{Model} correlates better than PMV_{Solar}, is only required in a small percentage of the overall sample and so PMV_{Model}'s out performance of PMV_{Solar} is somewhat diluted.

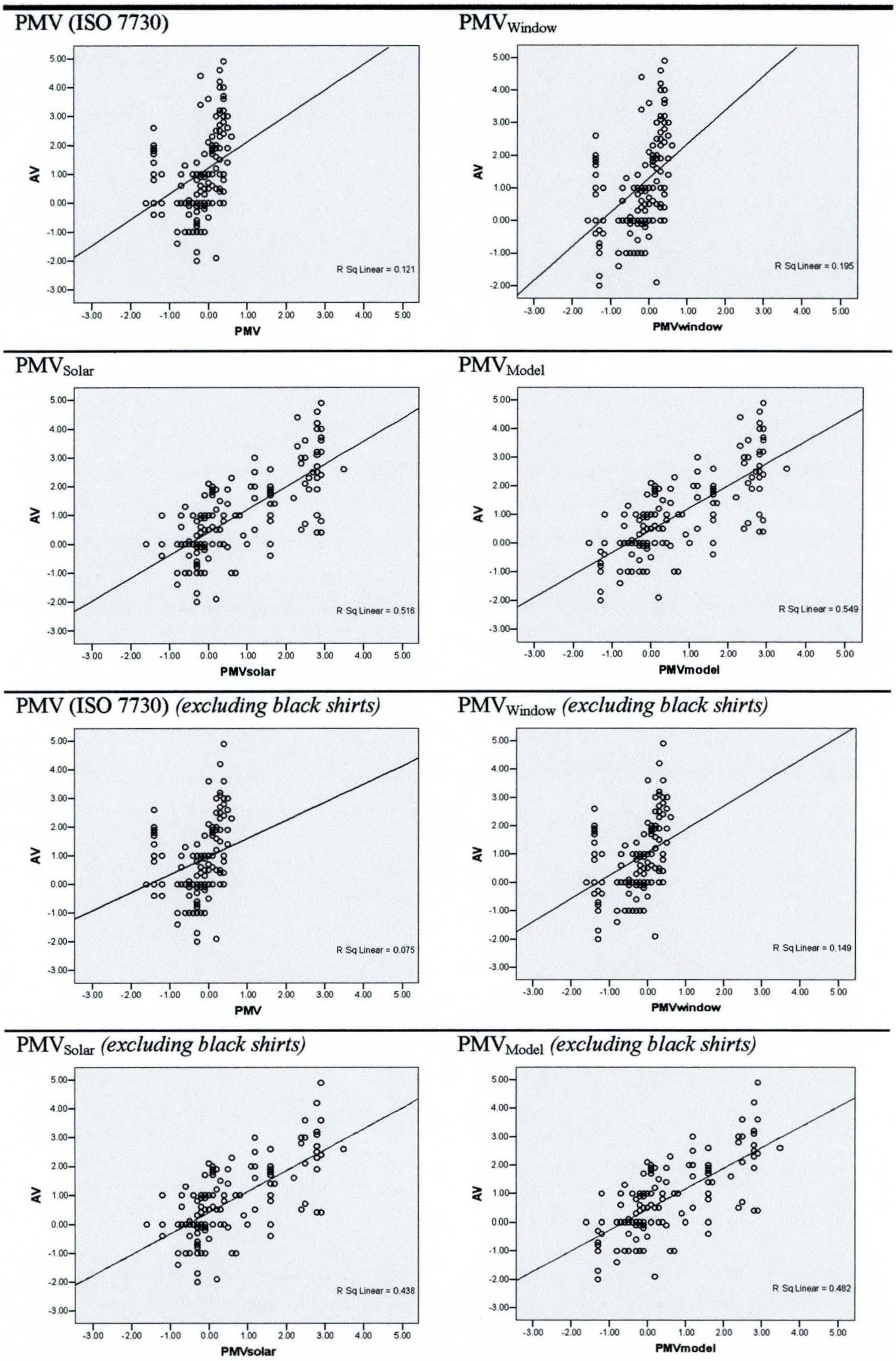


Figure 8.72, Scatter plots for all predictive models with Actual sensation Votes (AV) -3=Cold, -2=cool, -1=slightly cool, 0=neutral, 1=slightly warm, 2=warm, 3=hot, 4=very hot, 5=extremely hot.

PMV, calculated from shaded t_r, is the least accurate with a correlation value of 0.274 (weak), when sessions involving participants wearing black shirts were excluded. The correlation between PMV and sensation votes is 0.348 (medium strength) when calculated for all experimental sessions.

Figure 8.72 displays scatter plots with regression lines for all predictive model outputs with Actual sensation Votes (AV). From these the relationship between each model and subjective responses can be viewed graphically, with the superior correlations of PMV_{Model} and PMV_{Solar} clearly visible.

8.5 Discussion

The ISO 7730 model for predicting thermal comfort in given environments may be inadequate when assessing individual passengers' thermal comfort in a large dynamic environment, such as a train carriage. In these cases, 'local' environmental and personal factors may have a large and significant affect on an individuals perception of thermal sensation and therefore their comfort.

Hodder (2002) concluded that the PMV model was inaccurate when estimating human thermal comfort in environments in which people were exposed to direct solar radiation; under predicting the subjective thermal sensation responses of those exposed. He presented a model (PMV_{Solar}) with a corrective factor to account for exposure to varying levels of direct solar radiation. PMV_{Solar} has been further tested, validated and then added to in this thesis, to create a thermal comfort model that can easily integrate numerous 'local' factors into a predictive output for individuals to whom they may be affecting (PMV_{Model}).

The additional corrective factor in this model is for exposure to a cold window, a circumstance that may occur regularly for passengers on a train. The PMV was found to accurately account for effects of cold window exposure when calculated using actual t_r, derived form a globe local to the window. Calculating PMV for every occupant in a large dynamic environment (i.e. a train carriage) is impractical and would require environmental measurements to be taken at every seating point in the area. A corrective factor of – 1 sensation scale unit, for persons sat next to a cold window (3 - 6°C), was found to work well in predicting subjective responses when combined with PMV calculated from t_r in the centre of the room (not local to the window). It should be noted however that, for cold window conditions, the model was validated using the data from which it was derived and so further testing may be required in such conditions.

PMV_{Model} has been tested for accuracy by means of correlation with actual sensation votes in a range of environmental conditions, incorporating both solar radiation and cold window exposure, and compared with other predictive thermal comfort models. The results show that PMV_{Model} had the strongest correlation with subjective responses, outperforming PMV_{Solar} largely due to it's ability to take into account the effects of cold windows on thermal sensation vote (Table 8.50).

Findings from chapter 3 of this thesis indicate that there was no significant effect on thermal sensation caused by the colour and/or fit of clothing when exposed to direct solar radiation and so data from subjects wearing black shirts was included in the initial correlations. Previous studies however (Nielsen, 1990; Blazejczyk et al, 1997) indicate that there are physiological responses, associated with wearing black clothing in solar radiation, that may have an affect on a persons thermal comfort. Whilst these effects are not yet quantifiable in terms of the derivation of a corrective factor, they should be considered and so correlations were also performed with the exclusion of data from experiments with black shirts. This made little difference to the results and whilst the PMV_{Model}'s correlation was slightly weaker (r = 0.694), it was still stronger than that of PMV_{Solar} (r = 0.662). Other predictive models gave weak or medium strength r values when correlated with subjective sensation responses.

8.6 Conclusions

1 A predictive model PMV_{Model} was developed from experimental data and a review of previous studies, which provides a means of assessing thermal comfort on train carriages.

2 The model incorporates allowances for the effects of local stimuli that affect passengers travelling in a train carriage. These are

a. Exposure to direct solar radiation

b. Exposure to a cold window

3 When calculating the PMV component of PMV_{Model}, radiant temperature should be calculated without the influence of the stimuli in question:

i.e. Shielded from direct solar radiation and away from, or shielded from, cold windows.

4 The model has been validated using data from laboratory experiments and field trial data and was found to correlate strongly with associated subjective thermal sensation responses, outperforming PMV_{Solar} and other thermal comfort models.

9 Discussion

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The aim of this thesis was to produce a predictive tool for assessing thermal environments in rail carriages. Specifically, the tool would be able to take into account the affects of individuals' environmental factors to give a 'local' environmental assessment for specific persons. Conditions that may often be found on a rail carriage and have a large affect were identified, these being prolonged exposure to direct solar radiation and exposure to a cold window. The idea for the model was that it would provide a general assessment of the thermal environment with corrective factors for the presence of the fore mentioned conditions. The use for such a model is demonstrated in Figure 9.73, where two participants sat next to each other are experiencing differing thermal environments due to one being in direct solar radiation. The participant could also be next to a cold window, for example in winter where, due to air (train) movement, the outside surface window temperature will be similar to the air temperature.

Figure 9.73, Participants on a train with differing environmental conditions

9.1 Current models and standards

The debate goes on as to whether an adaptive approach to thermal comfort modelling would be more suitable than the more static methods given in current standards. It was thought that the opportunities for people to adapt to their environment that are the basis for the pro-adaptive argument would be less in vehicles than in buildings, the latter being the environments on which the majority of the pro-adaptive studies have been based; Examples include de Dear et al (1997), de Dear and Brager (1998), Humphreys and Nicol (2002) and Parsons (2003). This argument carries even greater weight when assessing rail carriages, as occupants often have no personal control over means of ventilation such as air conditioning systems and the ability to open and close windows.

In such environments, it was thought that the current method for assessing moderate thermal environments given in ISO 7730, the PMV, would be suitable and provide a solid base for a predictive tool. The environmental and subjective data taken in lab experiments in control conditions (with the absence of a stimuli of solar radiation or a cold window) support this claim, with PMV out puts derived from environmental measurements providing reasonably accurate predictions of the Actual Mean Vote of participants in the ambient environment. Examples of this are PMV = -0.3, AMV = 0 (table 4.15, chapter 4) and PMV = -1.5, AMV = -1.82 (table 5.31, chapter 5). These results imply that the PMV was appropriate for the assessment of the ambient environment.

9.2 The effects of solar radiation

A review of previous literature revealed that solar radiation has a significant affect on a persons thermal comfort. Whilst the nature of these studies differed slightly, some using active subjects (Nielsen et al, 1990; Blazejezyk 1994) others using sedentary (Hodder, 2002), the general implication is that an ability to quantify the effects of exposure to solar radiation would enhance the ability to predict human thermal comfort in such conditions.

Current thermal comfort standards and models for assessing thermal environments do not adequately take into account the effects of direct solar radiation on thermal comfort. Hodder (2002) on PMV (ISO 7730 for the assessment of moderate thermal environments) and McNeill (1999) on ISO 7933 (standard for assessing hot environments) both reported the inadequacy of these standards when predicting in solar conditions. Data from this thesis supports this stance with PMV outputs calculated using an exposed globe greatly under predicting thermal sensation when compared with the AMV of participants (PMV = -0.5, AMV = 1.28; Table 5.31, chapter 5). Whilst PMV has been shown to provide a solid assessment 'in normal' conditions (with the absence of an extreme stimuli), the argument for the addition of a corrective factor for use in solar conditions remains strong.

PMV_{Solar} (Hodder and Parsons 2002) was used as the basis for the assessment of solar conditions in rail carriages. The linear proposed linear relationship between thermal sensation and the intensity of solar radiation (Wm^{-2}) worked well when tested in cool conditions (PMV = -1.5 $\pm$ 1) as oppose to neutral (PMV = 0 $\pm$ 0.1) in which it had previously been validated, with an increase of 3.1 scale units in thermal sensation when compared with a predicted PMV_{Solar} increase of 3 scale units for exposure to 600 Wm^{-2} of solar radiation (figure 5.47, table 5.34, chapter 5) This AMV increase for male participants, this being the gender of participants from which the model was derived and validated, was slightly less at -2.8 scale units but still compared well with the PMV_{Solar} prediction. The finding that PMV_{Solar} is also accurate for a lower range on the sensation scale further supports the consideration for it's inclusion in future standards to assess thermal comfort in solar conditions.

9.3 The effects of exposure to a cold window

Exposure to cold vertical cold surfaces (i.e. windows) ahs been shown in several studies to cause some degree of thermal discomfort. The overall affect of exposure to a window of temperature 5 $\pm$ 1°C was found to be a reduction of 1 sensation scale unit. Although some mechanisms by which this is facilitated (draught and radiant asymmetry) have been identified to cause thermal discomfort, the extent to which they contribute individually to the overall affect of exposure to a cold window is still not known. Models to predict discomfort caused due to radiant asymmetry and draught (ISO 7730) were found to be inaccurate when compared with the Actual Percentage Dissatisfied (APD) obtained through subjective measures. Whilst an ability to quantify the effects from such conditions would be useful, the quantification of the overall effect of exposure to a cold window on thermal comfort is the main thing required when assessing such environments and it is this that has been identified.

9.4 The affects of the colour and fit of clothing

Although there was found to be an affect on thermal comfort attributable to clothing colour, it is difficult to quantify this in terms of a corrective factor for the PMV model due to the differences being relatively small and easily mistakable for variations in individuals perception for the thermal environment. These conditions have also only been investigated for one level of radiations intensity, this being relatively high (500 Wm^{-2}), and so smaller, less significant affects could be expected for lower intensities. Due to the continually fluctuating nature of natural solar radiation levels, it is thought that further investigation into the affects of clothing colour in different intensities of solar radiation is needed before an accurate corrective factor to account for these can be created.

9.5 PMV_{Model}

A model has been derived to assess local thermal comfort for passengers on a rail carriage. The PMV (ISO 7730) gives the basis for the general assessment of the environment and corrective factors have been added to account for:

1 The affects of exposure to varying intensities of direct solar radiation

2 The effects of exposure to a cold window of temperature 5 ± 1°C

The model has been evaluated using data from field trails and laboratory experiment and outperforms existing thermal comfort models in terms the correlation of its' outputs with the actual mean vote of subjects at the same point in time and space.

9.5.1 Limitations of PMV_{Model}

It should be noted that, due to the applicable conditions of a cold window (of temperature 5 ± 1°C) not being measured in any of the field trials, PMV_{Model} was validated for these conditions using the laboratory data from which it was derived. This has obvious implications for the argument that the model is just and valid in real world situations and whilst the corrective factor appears to work well for relevant conditions, further validation studies should be conducted to ascertain whether this is the case.

It should also be noted that whilst the model performs well in predicting thermal sensation responses of a range of solar radiation intensities, it has not yet been discovered whether the relationship between the temperature of the window to which people are exposed and their resultant affect on their thermal comfort is also linear. For window temperatures above the 5 ± 1°C range, a linear relationship would assume a gradual regression of output scores towards neutral (PMV = 0), with a corresponding increase in window temperature; and an increase towards 'cool' (PMV = -2) for decreases. Temperatures below 0 °C would cause icing and an assumed linear relationship should end here due to the possible psychological affects that this may have. A model that could be considered for predicting the affects of window temperatures outside of the range, and on the assumption of a linear relationship, is given below.

$$\mathbf{PMV_{Window}\ (linear) = PMV - \frac{5\ (^{\circ}C)}{Window\ temperature\ (^{\circ}C)}}$$

For window temperatures ≥ 5°C and ≤ 20°C

Window temperatures < 5°C are considered to = 5°C

Further work should be undertaken to investigate the extent to which the fore mentioned relationship is linear before this model can be accepted.

10 Conclusions and recommendations for future work

10.1 Conclusions

The PMV has been shown to provide an accurate assessment of thermal sensation and comfort in moderate to cool thermal environments ($-1.6 \leq PMV \leq 0.5$) with the absence of the environmental stimuli investigated (direct solar radiation or exposure to a cold window).

PMV was found however, to underestimate the affects of high levels of direct solar radiation in cool environments ($PMV = -1.5 \pm 0.1$) when outputs were compared to the Actual Mean Vote of participants. This is in accordance with findings reported by Hodder (2002) in neutral environments ($PMV = 0 \pm 0.5$).

Current models given in ISO 7730 for predicting the affects of draught and asymmetric thermal radiation on thermal comfort did not perform well when there outputs were compared with the Actual Percentage Dissatisfied (APD) vote of participants.

PMV_{Solar} (Hodder and Parsons, 2002) has been validated and found to perform well at a lower range on the PMV scale; the ambient environment wit the absence of direct solar radiation being ‘cool’ (PMV = -1.5 $\pm$ 0.1).

Exposure to a cold window of temperature 5 $\pm$ 1°C was found to have a significant affect on thermal comfort; decreasing subjects’ thermal sensation rating by one scale unit.

There was found to be a significant affect on thermal comfort due to clothing colour, when coupled with exposure to $500Wm^{-2}$ of direct solar radiation. The complexity and increased margin for error associated with having two variables has resulted in the exclusion of a corrective factor to account for such conditions in the derived predictive comfort model.

An empirically derived model has been created to provide a prediction of individual passengers’ thermal comfort on rail carriages. The PMV_{Model} is based on the model given in ISO 7730 for the assessment of moderate thermal environments but contains corrective factors to account for the affects of exposure to direct solar radiation and a cold window. PMV_{Model} provided an accurate prediction of peoples subjective sensation rating in a given environment and outperformed existing thermal comfort models in field studies.

10.2 Future research

- The derived PMV_{Model} provides an accurate prediction of thermal comfort in rail carriages but has only been validated for certain conditions (i.e. exposure to a cold window) using the laboratory data from which it was derived. The model should there for be validated in field studies that incorporate such conditions.

- PMV_{Solar} has now been tested and validated in moderate/neutral (PMV = 0 $\pm$ 0.5) and cool (PMV = -1.5 $\pm$ 0.1) environments but not yet in warm conditions. The effect or solar radiation on people who are already warm should be investigated.

- PMV_{Window} quantifies the affects of a cold window (of temperature 5 $\pm$ 1°C) on thermal comfort by means of a predicted decrease in thermal sensation vote. Further research should be conducted, using windows of higher and lower temperatures, to investigate whether the relationship between window temperature and thermal sensation vote is linear.

- The combined affect of differing intensities of direct solar radiation and clothing colour on thermal comfort should be further investigated before a corrective factor for clothing colour can be incorporated into a predictive model.

- Further field trials should be conducted at night and/or in cold conditions, to investigate the effects of cold windows on thermal comfort.

11 References

Berglund L and Fobelets A (1987)
Subjective human response to low-level air currents and asymmetric radiation, *ASHRAE Transactions 93 1 (1987), pp. 497–523*

Blazejczyjk, K. (2000)
Absorbtion of Solar radiation by man, in J. Werner and H. Hexamer (Eds), *Environmental Ergonomics IX, pp, 43-46, Aachen, Germany: Shaker Verlag, ISBN 3-8265-7648-9*

Bouzidi, M. and Mezerhab A, (2006)
Computation of thermal comfort inside a passenger car compartment, *Applied Thermal Engineering 26(14-15): 1697-1704.*

Chun C, Kwok A and Tamura A (2004)
Thermal comfort in transitional spaces—basic concepts: literature review and trial measurement, *Building and Environment, Volume 39, Issue 10, October 2004, Pages 1187-1192*

Cohen, J. (1988).
Statistical power analysis for the behavioural sciences. *Hillsdale, NJ: Erlbaum*

de Dear RJ, Brager GS, Cooper D. (1997)
Developing an adaptive model of thermal comfort and preference. Final report *ASHRAE RP-884. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers; 1997*

de Dear, R.J., G.S. Brager, (1998).
"Developing an Adaptive Model of Thermal Comfort and Preference", *ASHRAE Transactions, vol.104(1), pp. 27-49*

Dufton, A. F., (1929)
The eupatheostat, *Journal of scientific instruments, 6, 249-251.*

Fanger, P. O. (1970).
Thermal Comort, *Danish technical press.*

Fanger P. O,. Melikov A. K, Hanzawa H. and. Ring J (1988)
Air turbulence and sensation of draught, *Energy and Buildings, Volume 12, Issue 1, 24 April 1988, Pages 21-39*

Fanger, P. O and Pedersen, C. L. K., (1977)
Discomfort due to air velocities in spaces, *Proceedings of Conference: Institut International du Froid, Commissions B1, B2 and E1, Belgrade, 289-296*

Gagge, A. P., Burton, A. C. and Bazett, H. C., (1941)
Apractical system of units for the description of the heat exchange of man with his thermal environment, *Science NY, 94, 428-430*

Givoni, B. (1976)
Man Climate and Architecture, *2nd edn, London: Apllied Science*

Griefhahn B., Bewertung von Zugluft (1999)
Arbeitsplatz, Fb 828, Schriftenreihe der Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, Dortmund, 1999.

Guodong Ye, Changzhi Yang, Youming Chen and Yuguo Li (2003)
A new approach for measuring predicted mean vote (PMV) and standard effective temperature (SET*), *Building and Environment, 38(1): 33-44*

Havenith G, Holmer I and Parsons K C. (2002)
Personal factors in thermal comfort assessment: clothing properties and metabolic heat production, *Energy and Buildings 34(6).*

Hensel, H, (1981)
Thermoreception and temperature regulation, *London: Academic press*

Hodder S, and Parsons K C. (2002)
The effect of the intensity of simulated solar radiation on human thermal comfort, *Phd thesis, Loughborough University*

Houghton, F. C. and Yagloglou, C. P. (1923)
Determining equal comfort lines, *Journal of ASHVE, 29, 11-21*

Houghton, F. C. and Yagloglou, C. P. (1924)
Cooling effect on human beings produced by various air velocities, *Jounal of ASHVE, 30, 193*

Huang, J. (2006)
Thermal parameters for assessing thermal properties of clothing, *Journal of Thermal Biology 31(6): 461-466.*

ISO Standard 8996 (2004)
Ergonomics: Determination of metabolic heat production

ISO Standard 7730 (2005)
Moderate thermal environments- Determination of the PMV and PPD Indices and Specification of the conditions for Thermal Comfort'

ISO Standard 9920 (2003)
Ergonomics of the thermal environment. Estimation of the thermal insulation and evaporative resistance of a clothing ensemble

ISO Standard 10551 (1995)
Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales

ISO Standard 14505 (2005)
Test method for the assessment of thermal comfort using human subjects

Kazuhiko Matsunaga, Fujio Sudo, Syouichi Yoshizumi, Shinichi Tanabe (1996)
"Evaluating thermal comfort in vehicles by subjective experiment, thermal manikin, and numerical manikin." *JSAE Review 17(4): 455.*

Khalifa, A. J. N and Marshall, R. H (1990)
Validation of heat transfer coefficients of interior building surfaces using real sized indoor test cells, *International journal of heat and mass transfer, Vol 33, No 10, pp 2219-2236*

Kurnitski,J, Jokisalo J, Palonen J, Jokiranta K and Seppänen O (2004)
Efficiency of electrically heated windows, *Energy and Buildings, Volume 36, Issue 10, October 2004, Pages 1003-1010*

Langkilde G., Gunnarsen L, Mortensen N (1985)
Comfort limits during infrared radiant heating of industrial spaces. *CLIMA 2000, Copenhagen.*

Larsson U, Moshfegh B and. Sandberg M (1999)
Thermal analyses of super insulated windows (numerical and experimental investigations). *Energy and Buildings* 29 *(1999), pp. 121–128*

Li Yi, Mao Aihua, Wang Ruomei, Lou Xiaonan, Wang Zhong, Hou Wenbang, Zhou Liya and Lin Yubei (2006)
Smart—a virtual system for clothing thermal functional design, *Computer-Aided Design, Volume 38, Issue 7, July 2006, Pages 726-739*

Maidment G and Missenden J (2002).
Evaluation of an underground railway carriage operating with a sustainable groundwater cooling system, *International Journal of Refrigeration, Volume 25, Issue 5, August 2002, Pages 569-574*

McIntyre, D. A (1980)
Indoor Climate, *London: Applied Science*

McNeill, M B and Parsons, K. C (1999)
Appropriateness of international heat stress standards for use in topical agricultural environment, *Ergonomics, 42(6), 779-797*

Mezrhab A and. Bouzidi M (2006).
Computation of thermal comfort inside a passenger car compartment, *Applied Thermal Engineering, Volume 26, Issues 14-15, October 2006, Pages 1697-1704*

Milne and Roche. (2004)
"Effects of Window size and thermal mass in building comofrt using an intelligent ventilation controller." *Solar Energy 77(1): 421-434.*

Nevins, R G (1971)
Thermal Comfor and Draughts, *Journal de Phsiologie, 13, 356-358*

Nicol F, Humphreys M. (1995).
Standards for Thermal Comfort, *Chapman and Hall.*

Nicol J. F.and Humphreys M. A (2002)
Adaptive thermal comfort and sustainable thermal standards for buildings *Energy and Buildings, Volume 34, Issue 6, July 2002, Pages 563-572*

Nicol, J F and Humphreys M A. (2002a).
"The validity of ISO-PMV for predicting comfort votes in every-day thermal environments." *Energy and Buildings 34(6): 667-684.*

Ohnaka, Hodder and Parsons (2005).
"The effects of simulated solar radiation to the head and trunk on the thermal comfort of seated subjects." *Environmental Ergonomics 3(1): 305-311.*

Olesen B. W (1985)
Local Thermal Discomfort, in Bruel Kjaer, *Technical review No1. Copenhagen*

Olesen B. W. and Parsons K. C (2002)
Introduction to thermal comfort standards and to the proposed new version of EN ISO 7730, *Energy and Buildings, Volume 34, Issue 6, July 2002, Pages 537-548*

O'Neill D H and Whyte, R T (1985)
Predicting heat stress in complex thermal environments, *Report of National Institute of agricultural engineering, Sisloe, UK*

Parsons K C, (2003)
Human thermal Environments, *Taylor and Francis, 2nd Edition.*

Ramanathan, N. L. (1964)
A new weighting system for mean surface temperature of the human body, *Journal of Apllied Physiology, 19: 531-533*

Rohles, F. H, and Wallis, P.., (1979)
Comfort criteria for air conditioned automotive vehicles, *Society of automotive engineers, SAE INC, 790122.*

Roller W. L. and. Goldman R. F (1968)
Prediction of solar heat load on man, *J Appl Physiol, May 1968; 24: 717 - 721.*

Smith, Philips and Sweeney (1983)
Environmental Science, *Longman Scientific and Technical.*

Stringer P and Canter D. (1975).
Environmental Interaction, *Surrey University Press.*
Toftum J., Melikov A.K, Rasmussen L.W., Kuciel A.A, Cinalska E.A, Tynel A,. Bruzda M, Fanger P.O (2000)
Human Response to Air Movement. Part 1. Preference and Draught Discomfort, *ASHRAE Project 843-TRP, Technical University of Denmark, Denmark, 2000.*

Toftum J. and Nielsen R. (1996)
Impact of metabolic rate on human response to air movements during work in cool environments. *International Journal of Industrial Ergonomics 18 4 (1996), pp. 307–316*

Toftum J., Zhou G, Melikov A (1997)
Airflow direction and human sensitivity to draught, *in: Proceedings of CLIMA 2000, Brussels, 1997.*

van Hoof J and Hensen L.M (2007)
Quantifying the relevance of adaptive thermal comfort models in moderate thermal climate zones, *Building and Environment, Volume 42, Issue 1, January 2007, Pages 156-170*

Vaughan and Parsons (2004)
"The effects of side on exposure to solar radiation on human thermal comfort *contemporary Ergonomics 2004*

Vernon, H. M. and Warner, C. G., (1932)
The influence of the humidity of the air on capacity for work at high temperatures, *Journal Hygiene Cambridge, 32, 431-462.*

Wales, Parsons and Naylor. (2005).
"The effects of colour and fit of clothing on thermal Comfort in the sun." *contemporary Ergonomics 1: 227-231.*

Wang (2006).
A field study of the thermal comfort in residential buildings in Harbin." *Building and Environment 41(8): 1034-1039.*

Wyon, D. P (1986)
The effects of indoor climate on productivity and performance: A review (in Swedish), *WS and Energi, 3, 59-65*

Yagloglou, C. P and Miller, W, E. (1925)
Effective temperature with clothing, *ASHVE Transactions, 31, 89.*

Appendix A1

Examples of questionnaires used in laboratory experiments and field trials

Questionnaire 1 **Used in Chapter 3**

Questionnaire 2 **Used in Chapter 5**

Questionnaire 3 **Used in Chapter 7**

THERMAL COMFORT ASSESSMENT

Date: ____________ Subject: ____________
Time: ____________ Age: ____________
Session: ____________ Height: ____________

first, pre, 0, 5, 10, 15, 20, 25, 30, post

1 THERMAL ENVIRONMENT

Please rate on these scales how YOU feel NOW:

	Overall	Head left	Head right	Trunk left	Trunk right	Arms left	Arms right	Upper legs left	Upper legs right	Lower legs left	Lower legs right	Feet left	Feet right
7 very hot													
6 hot													
5 warm													
4 slightly warm													
3 neutral													
2 slightly cool													
1 cool													

	Overall	Head left	Head right	Trunk left	Trunk right	Arms left	Arms right	Upper legs left	Upper legs right	Lower legs left	Lower legs right	Feet left	Feet right
4 very uncomfortable													
3 uncomfortable													
2 slightly uncomfortable													
1 not uncomfortable													

	Overall	Head left	Head right	Trunk left	Trunk right	Arms left	Arms right	Upper legs left	Upper legs right	Lower legs left	Lower legs right	Feet left	Feet right
4 very sticky													
3 sticky													
2 slightly sticky													
1 not sticky													

2

Please rate on the scale how YOU would like to be NOW:

much warmer | warmer | slightly warmer | no change | slightly cooler | cooler | much cooler

3

Please rate on the scale how YOU feel NOW in this thermal environment:

very pleasant | pleasant | slightly pleasant | neither pleasant nor unplesant | slightly unpleasant | unpleasant | very unpleasant

4

Please indicate how acceptable YOU find this thermal environment NOW:

acceptable ☐ unacceptable ☐

5

Please indicate how satisfied YOU are with this thermal environment NOW:

satisfied ☐ dissatisfied ☐

Comments, (Main source of discomfort): ______________________________

THERMAL COMFORT ASSESSMENT

Date: ______________ Subject: ______________
Time: ______________ Age: ______________
Session: ______________ Height: ______________

0, 5, 10, 15, 20, 25, 30, pre-rad, 0, 5, 10, 15, 20, 25, 30, post

1 THERMAL ENVIRONMENT
Please rate on these scales how YOU feel NOW:

	Overall	Head left	Head right	Trunk left	Trunk right	Arms left	Arms right	Upper legs left	Upper legs right	Lower legs left	Lower legs right	Feet left	Feet right
7 hot													
6 warm													
5 slightly warm													
4 neutral													
3 slightly cool													
2 cool													
1 cold													

	Overall	Head left	Head right	Trunk left	Trunk right	Arms left	Arms right	Upper legs left	Upper legs right	Lower legs left	Lower legs right	Feet left	Feet right
4 very uncomfortable													
3 uncomfortable													
2 slightly uncomfortable													
1 not uncomfortable													

	Overall	Head left	Head right	Trunk left	Trunk right	Arms left	Arms right	Upper legs left	Upper legs right	Lower legs left	Lower legs right	Feet left	Feet right
4 very sticky													
3 sticky													
2 slightly sticky													
1 not sticky													

2
Please rate on the scale how YOU would like to be NOW:

much warmer | warmer | slightly warmer | no change | slightly cooler | cooler | much cooler

3
Please rate on the scale how YOU feel NOW in this thermal environment:

very pleasant | pleasant | slightly pleasant | neither pleasant nor unplesant | slightly unpleasant | unpleasant | very unpleasant

4
Please indicate how acceptable YOU find this thermal environment NOW:

acceptable ☐ unacceptable ☐

5
Please indicate how satisfied YOU are with this thermal environment NOW:

satisfied ☐ dissatisfied ☐

Comments, (Main source of discomfort): ______________________________

Date:____________ Time:____________ Experimental time:__________ Subject:____________

1. Thermal Environment. Please rate how YOU feel NOW:

	Overall	Head	Trunk		Arms		Upper legs		Lower legs/Feet	
			Left	Right	Left	Right	Left	Right	Left	Right
3 hot										
2 warm										
1 slightly warm										
0 neutral										
-1 slightly cool										
-2 cool										
-3 cold										

	Overall	Head	Trunk		Arms		Upper legs		Lower legs/Feet	
			Left	Right	Left	Right	Left	Right	Left	Right
4 very uncomfortable										
3 uncomfortable										
2 slightly uncomfortable										
1 not uncomfortable										

	Overall	Head	Trunk		Arms		Upper legs		Lower legs/Feet	
			Left	Right	Left	Right	Left	Right	Left	Right
4 very sticky										
3 sticky										
2 slightly sticky										
1 not sticky										

	Overall	Head	Trunk		Arms		Upper legs		Lower legs/Feet	
			Left	Right	Left	Right	Left	Right	Left	Right
4 very draughty										
3 draughty										
2 slightly draughty										
1 not draughty										

2. Please rate on the scale how YOU would like to be NOW:

Much warmer | Warmer | Slightly warmer | No change | Slightly cooler | Cooler | Much cooler

3. Please Rate on the scale how YOU feel NOW in this thermal environment:

Very pleasant | Pleasant | Slightly pleasant | Neither pleasant nor unpleasant | Slightly unpleasant | Unpleasant | Very unpleasant

4. Please indicate how acceptable YOU find this thermal environment NOW:

acceptable ☐ unacceptable ☐

5. Please indicate how satisfied YOU are with this thermal environment NOW:

satisfied ☐ dissatisfied ☐

Comments, (Main source of discomfort):________________________

Appendix A2

Participant generic health screening questionnaires

GENERIC HEALTH SCREEN FOR STUDY VOLUNTEERS

It is important that volunteers participating in research studies are currently in good health and have had no significant medical problems in the past. This is to ensure (i) their own continuing well-being and (ii) to avoid the possibility of individual health issues confounding study outcomes.

Please complete the questions in this brief questionnaire to confirm fitness to participate:

If YES to any question, please describe briefly in the spaces provided (eg to confirm problem was/is short-lived, insignificant or well controlled.)

1 **At present,** do you have any health problem for which you are: *(Please tick as appropriate)*

(a) on medication, prescribed or otherwise	**Yes**	☐	**No**	☐
(b) attending your general practitioner	**Yes**	☐	**No**	☐
(c) on a hospital waiting list	**Yes**	☐	**No**	☐

2 **In the past two years,** have you had any illness which required you to: *(Please tick as appropriate)*

(a) consult your GP	**Yes**	☐	**No**	☐
(b) attend a hospital outpatient department	**Yes**	☐	**No**	☐
(c) be admitted to hospital	**Yes**	☐	**No**	☐

3 **Have you ever** had any of the following: *(Please tick as appropriate)*

(a) Convulsions/epilepsy	**Yes**	☐	**No**	☐
(b) Asthma	**Yes**	☐	**No**	☐
(c) Eczema	**Yes**	☐	**No**	☐
(d) Diabetes	**Yes**	☐	**No**	☐
(e) A blood disorder	**Yes**	☐	**No**	☐
(f) Head injury	**Yes**	☐	**No**	☐
(g) Digestive problems	**Yes**	☐	**No**	☐
(h) Heart problems	**Yes**	☐	**No**	☐
(i) Problems with bones or joints	**Yes**	☐	**No**	☐
(j) Disturbance of balance / co-ordination	**Yes**	☐	**No**	☐
(k) Numbness in hands or feet	**Yes**	☐	**No**	☐
(l) Disturbance of vision	**Yes**	☐	**No**	☐
(m) Ear / hearing problems	**Yes**	☐	**No**	☐
(n) Thyroid problems	**Yes**	☐	**No**	☐

(o) Kidney or liver problems	Yes	☐	No	☐
(p) Allergy to nuts	Yes	☐	No	☐
(q) Migraines	Yes	☐	No	☐

(Please tick as appropriate)

Optional questions for female participants

(a) are your periods normal/regular?	Yes	☐	No	☐
(b) are you on "the pill"?	Yes	☐	No	☐
(c) could you be pregnant?	Yes	☐	No	☐
(d) are you taking hormone replacement therapy (HRT)?	Yes	☐	No	☐

Thank you for your co-operation!

Declaration Of Consent

I, ... hereby volunteer to be an experimental participant in a thermal environment experiment during the period of / on

....200 .....

My replies to the above questions are correct to the best of my belief and I understand that they will be treated with the strictest confidence by the experimenter. The purpose of the experiment has been explained by the experimenter and I understand what will be required of me.

I understand that I may withdraw from the experiment at any time and that I am under no obligation to give reasons for withdrawal or attend again for experimentation. I also understand that the experimenter is free to withdraw me from experimentation at any time.

I undertake to obey the laboratory regulations and the instructions of the experimenter regarding safety, participant only to my right to withdraw as declared above.

Signature of Participant .... Date ....

Signature of Experimenter .... Date ....