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Thermal comfort when moving from one environment to another

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Abstract

A laboratory experiment was conducted to examine the immediate thermal sensation when walking from one set of thermal conditions to another. Participants were exposed to three different controlled conditions for 30 minutes (warm, neutral, cool) in an environmental chamber on three occasions. They then moved from the chamber to an outside area (slightly cool). Skin temperature, subjective thermal sensation and comfort were recorded throughout the experiment.

Results showed no significant difference between males and females for skin temperature or thermal sensation score. When comparing scores between the chamber and outside, significant differences in sensation were observed. When the three outside sensations were compared, significant differences were found between the scores following the cool and neutral conditions and the cool and warm conditions. When scores following the warm and neutral conditions were compared, no significant difference in sensation was observed. Therefore, when entering an environment that is cooler than the previous one, sensation immediately changes. For the cool condition, PMV was shown to be inaccurate at predicting sensation both inside and outside the chamber; however, the gradient of the AMV and PMV lines were the same indicating that the error may be inherent.

After a change of environment, there is an immediate change in sensation. Following the two warmer chamber conditions (neutral and warm) sensation immediately reduced to a point that was under-predicted by the PMV model. The model is, therefore, unsuitable for use on these occasions. Following the cool condition, sensation immediately increased, the magnitude of which (although not the actual value) was calculated by PMV. These results suggest that when entering an environment that is similar to or slightly warmer than the first, sensation will increase at a proportion that can be predicted by the PMV model. Data collected from this study will be used to suggest improvement to the PMV model to enable its use when moving from one environment to another.

Introduction

Thermal comfort research has focused, primarily, on steady-state conditions in buildings (e.g. Nevins et al. 1966, Bell and Watts 1971, de Dear and Auliciems 1985, Schiller et al. 1988, de Dear and Fountain 1994, Kaynakli et al. 2003). Increasingly, research is branching out into other areas such as transient or non-steady-state conditions (e.g. Chun and Tamura 1998, Zhang et al. 2004, Chun and Tamura 2005, Nakano et al. 2006, Chun et al. 2008), outside environments (e.g. Spagnolo and de Dear 2003, Nikolopoulou and Lykoudis 2006, Huang 2007) and transport (e.g. Nicol et al. 1973, Rohles and Wallis 1979, Ford 1988, Burch et al. 1991, Underwood and Parsons 2005). The purpose of these areas of research is to further understand human response to environments and to improve design in these areas to increase thermal comfort.

Existing research suggests that when a person moves from one environment to another, their experience of the new environment is affected by their sensation in the previous environment (Jones and Ogawa 1992, de Dear et al. 1993, Chun and Tamura 1998, Arens et al. 2006, Chun et al. 2008). There is conflicting evidence as to the type and extent of this affect, for instance Jones and Ogawa (1992) state that there is a lag in sensation and that it can take at least half an hour to reach a steady-state condition. Conversely it is also suggested that there can be an 'overshoot' in sensation when entering a new environment, for instance, when entering a cold environment from a previously warm environment, sensation is cooler than PMV would predict (de Dear et al. 1993, Arens et al. 2006).

Understanding how humans subjectively perceive the environment following a step-change in conditions can aid the design of that space. For instance, if it is cold and wet outside and warm inside, persons entering may experience a build-up of condensation on clothing. This may be perceived as discomfort with the space until the body has adapted to the new conditions. Understanding the relationship between the physical (condensation build-up) and the subjective (ratings of discomfort) enables designers to select environmental parameters that can adapt to the occupant's needs. Another example of this is when the environment outside is hot, occupant's may initially prefer conditions cooler than predicted by PMV but then, over time, may gradually require an increase in temperature.

The purpose of this experiment was to determine how sensation changes when moving to a new environment with the long-term aim of creating a model predicting human sensation during this process. The PMV is widely used as a tool to predict thermal comfort, however, it was developed for use in steady-state environments and may not be applicable when predicting thermal sensation in a transient environment. Data from the current study will be used to improve the PMV for use in transient environments. This will then be applied to train journeys to predict sensation immediately after boarding a train and then further combined with work conducted by Underwood (2006) and Stennings (2007) to enable sensation throughout a train journey to be predicted.

Method

Subjects

12 males and 12 females (Table 1 details the physical data for the subjects) participated in the experiment which was conducted between January and September 2009 at Loughborough University.

Table 1 Mean physical data of participants (SD in brackets)

Subjects	Age (yrs)	Weight (kg)	Height (m)
Males (12)	23.70 (3.26)	79.50 (13.23)	1.82 (0.08)
Females (12)	23.28 (2.21)	62.79 (10.13)	1.64 (0.07)
All (24)	23.49 (2.73)	71.14 (14.34)	1.73 (0.11)

Experimental Design

Each participant was required to attend the Environmental Ergonomics laboratory on three occasions and was exposed to one of three environmental conditions in a thermal chamber each time. The environmental conditions were designed to elicit three different subjective sensation values. The order of conditions was determined by 8, 3 x 3 latin squares.

Prior to entering the chamber, thermistors were attached to the body according to the 4-pont Ramanathan method (Ramanathan 1964). The thermistors were then attached to a Grant 2010 data logger programmed to log at 1 second intervals. Participants were weighed before wearing a standardised clothing ensemble consisting of a t-shirt (100% cotton), jumper (30% polyester, 70% cotton) and jeans (100% cotton). Participants were weighed before and after entering the chamber and subjective thermal comfort questions were also asked at this time.

After entering the chamber, participants were required to score using subjective thermal comfort scales every 5 minutes until 30 minutes had elapsed. Participants were weighed once more and then exited into a temperature regulated area where they immediately reported on their thermal comfort. Participants were weighed for 5 minutes (at 1 minute intervals) after exiting the chamber and then nude once more. The layout of the chamber and exit area is illustrated in Figure 1.

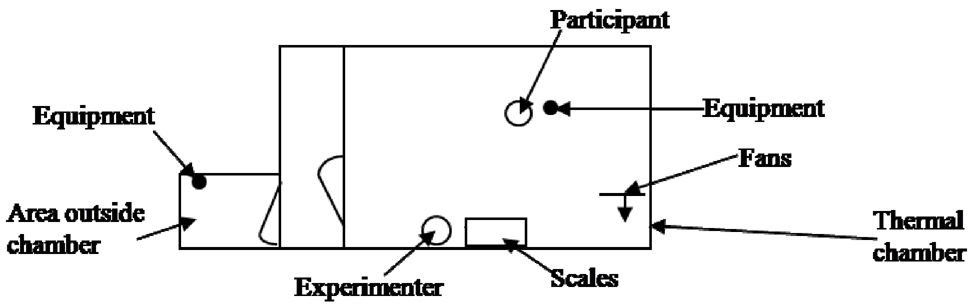

Figure 1 Chamber layout

Subjective data

Participants were asked to report on their thermal comfort using six scales; thermal sensation, preference, pleasantness, comfort, stickiness and draught (Figure 2 and Figure 3). Participants were allowed to select any number or label that corresponded with their opinion of the environment.

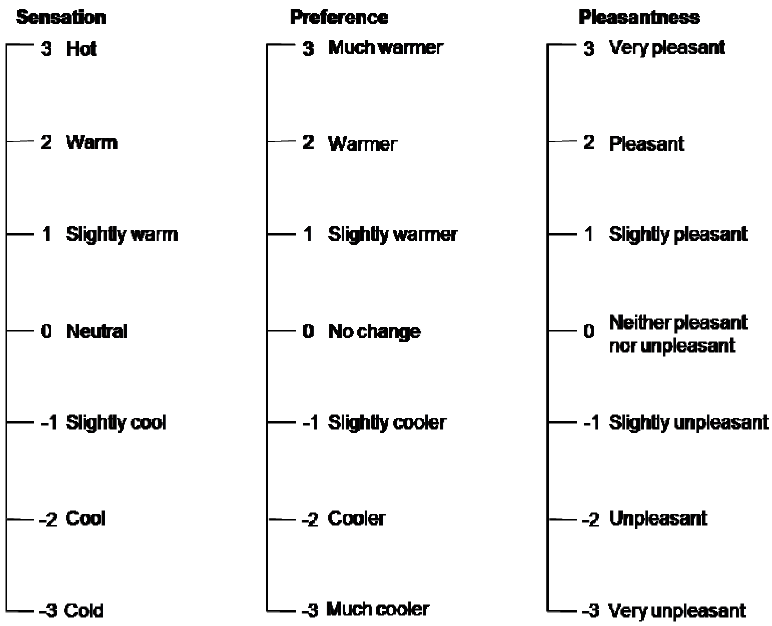

Figure 2 Subjective scales (a)

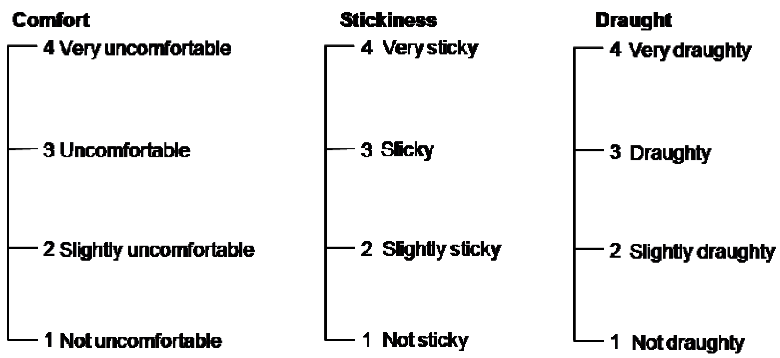

Figure 3 Subjective scales (b)

Environmental conditions

Physical parameters were logged using an Eltek/Grant Squirrel data logger at 10 second intervals. Air temperature inside and outside the chamber was measured with two thermistors at standing head and waist height. Radiant temperature was measured using a black globe thermometer at sitting head height. A Vaisala HUMICAP 180 meter measured relative humidity and air velocity was measured using a Biral hot wire anemometer both of which were fixed at sitting head height.

Statistical analysis

The results of the subjective scores were analysed using a Friedman's ANOVA and a post-hoc Wilcoxon Signed Ranks test. Skin temperatures were analysed using t-tests and a oneway ANOVA and a post hoc Tukey's HSD.

Results

Environmental Conditions

Figure 4 to Figure 7 show the mean environmental conditions in the thermal chamber during the experiment (neutral = blue, cool = pink, warm= yellow, bars show standard deviation). Both air temperature and mean radiant temperature were completely independent for each of the three experimental conditions. Although relative humidity was different on each occasion, the corresponding partial pressure of water vapour in the air was the same.

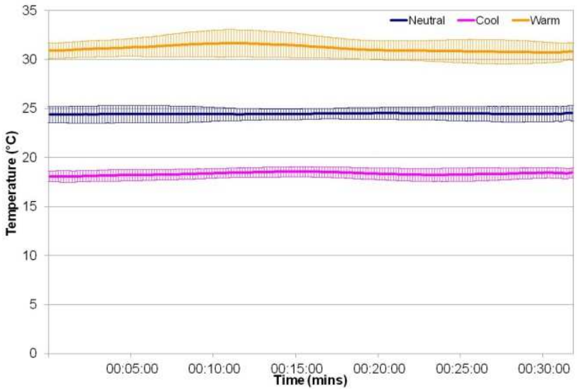

Figure 4 Mean air temperature

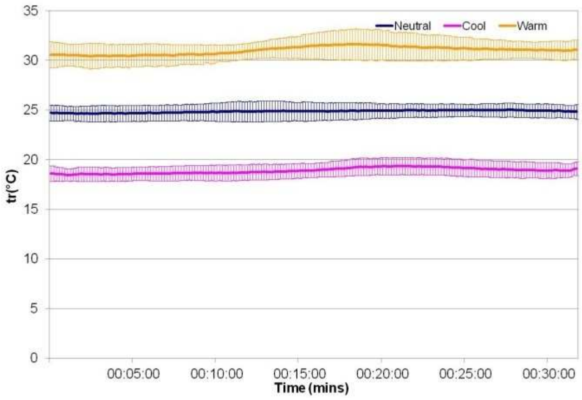

Figure 5 Mean radiant temperature

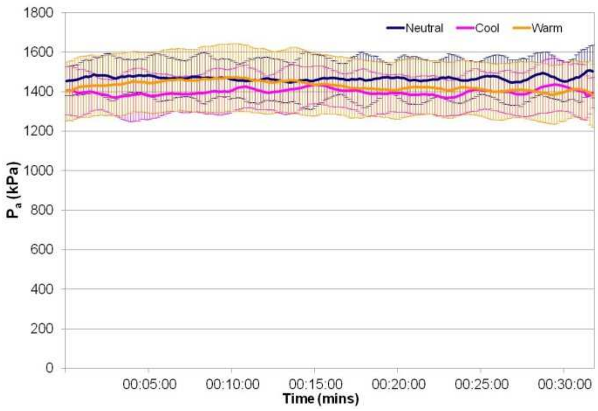

Figure 6 Mean partial pressure of water vapour in air

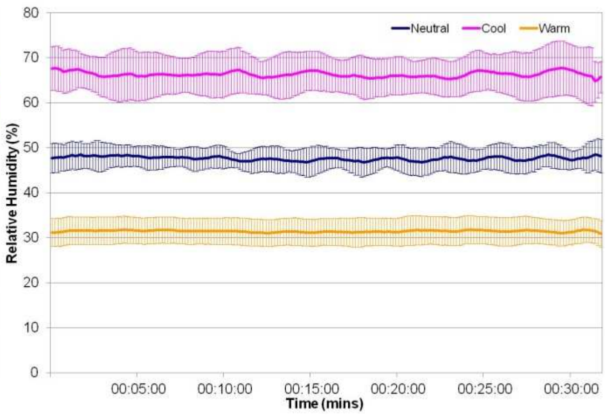

Figure 7 Mean relative humidity

PMV for each of the three chamber conditions was calculated and the values obtained are shown in Table 2 with the mean environmental conditions. On average, the warm conditions were close to the predicted settings; however, the neutral conditions were slightly warmer than neutral and the cool conditions were between slightly cool and cool.

Table 2 Mean environmental conditions inside the chamber (SD in brackets)

	Neutral	Warm	Cool
t_a (°C)	24.3 (0.7)	30.9 (1.0)	18.6 (0.6)
t_r (°C)	25.0 (0.8)	31.4 (1.0)	18.9 (0.9)
RH (%)	47.2 (2.7)	31.2 (1.5)	67.2 (6.9)
v (ms^{-1})	0.26 (0.1)	0.25 (0.1)	0.28 (0.1)
PMV	0.3 (0.2)	1.9 (0.2)	-1.3 (0.2)

Table 3 details environmental conditions once participants had exited the chamber. The table shows there are slight variations in conditions; however these are not statistically significant. The variation occurred as a result of the conditions in the thermal chamber, for instance the warm chamber condition resulted in slightly warmer air temperature outside the chamber. The calculated PMV indicates that participants entered an environment that was between neutral and slightly cool.

Table 3 Mean environmental conditions outside the chamber (SD in brackets)

	Neutral	Warm	Cool
t_a (°C)	18.8 (1.2)	19.5 (1.6)	18.1 (1.3)
t_r (°C)	18.2 (1.5)	18.9 (2.0)	17.7 (1.3)
RH (%)	51.0 (9.5)	48.0 (9.3)	52.1 (6.7)
v (ms^{-1})	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)
PMV	-0.6 (0.3)	-0.4 (0.3)	-0.6 (0.2)

Table 2 and Table 3 demonstrate that following the neutral and warm conditions, participants entered a cooler environment than the chamber condition and following the cool condition, participants entered a warmer environment.

Mean skin temperature

The mean of participant’s mean skin temperature was calculated according to gender and condition, the results of which can be seen in Figures 8 to 10. Each graph is marked with the time of entry to and exit of the thermal chamber (vertical dotted lines, female = blue, male = red). The graphs show an initial decrease in skin temperature due to nude weighing of participants, skin temperature increases once the clothing is put on.

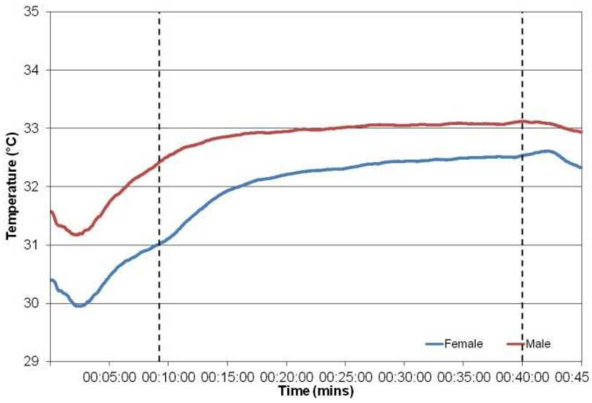

Figure 8 Mean skin temperature – neutral condition

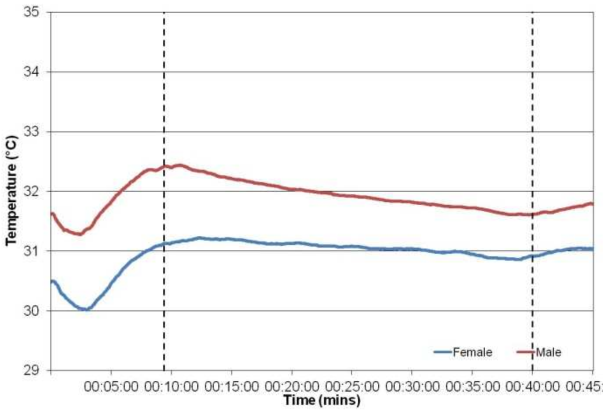

Figure 9 Mean skin temperature – cool condition

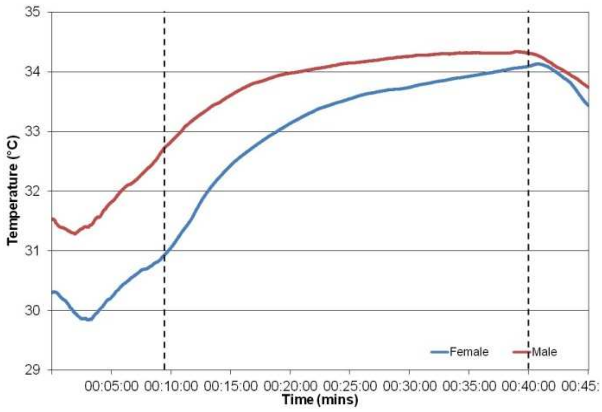

Figure 10 Mean skin temperature – warm condition

It can be seen that in each of the conditions, skin temperature either increases or decreases (according to the condition) on entering the chamber and then starts to plateau. On average, female skin temperature was lower than male skin temperature; however both genders exhibited a similar pattern of temperature change.

An independent samples t-test was conducted to determine if there were significant differences in mean skin temperatures between genders, Results of the test determined that there are significant differences in mean skin temperature at the start of each condition ($p \leq 0.01$ for each condition) and at the end of the neutral and cool conditions ($p \leq 0.05$ for both conditions). There was no significant difference in mean skin temperature at the end of the warm condition.

Figure 11 and Figure 12 show the mean of both male and female mean skin temperature per condition (vertical lines show entry to and exit from the chamber) and it can be seen that for each chamber condition, participants started at a similar temperature during experiment preparation (weighing, oral temperature measurement etc). After entering the chamber, skin temperatures diverged according to the condition they were exposed to resulting in different final skin temperatures. Gradients of skin cooling or warming also varied, for instance following the warm condition, there is a greater rate of skin cooling than following the neutral condition.

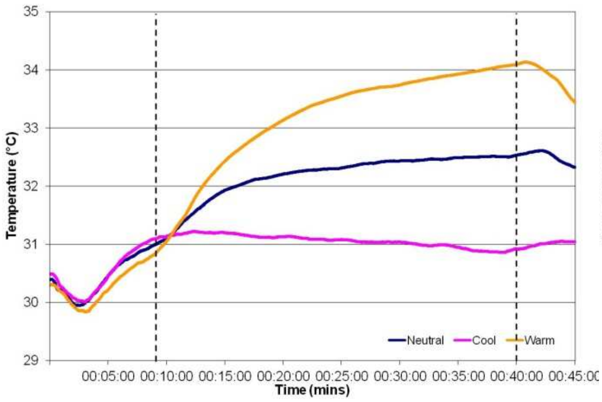

Figure 11 Female mean skin temperature per condition

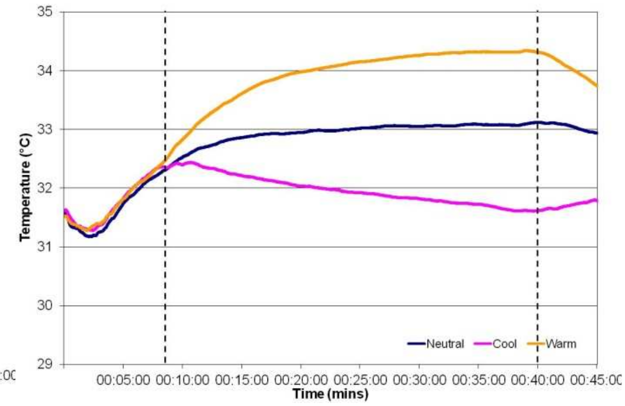

Figure 12 Male skin temperature per condition

A oneway ANOVA was conducted comparing mean skin temperatures at the start and end of the experiment according to gender. There were no significant differences in starting mean skin temperature for males and females. A post hoc Tukey's HSD determined that there was a significant difference between female starting skin temperatures and final skin temperatures in the neutral and warm conditions ($p \leq 0.01$). Males only showed a significant difference between start and end skin temperatures in the warm condition ($p \leq 0.01$). There were also significant differences in end mean skin temperature between each of the three conditions ($p \leq 0.01$) for both males and females.

Subjective data

Conditions

Sensation data throughout the experiment (a priori, during and post chamber exposure) were plotted according to condition and gender (see Figure 13 to Figure 15, females = blue lines, males = red lines). The graphs show that, for the neutral condition, PMV (dotted lines) and Actual Mean Vote (AMV – solid lines) are relatively similar for both genders. In the cool condition, PMV consistently over-predicts sensation throughout the experiment. For the warm condition, PMV more accurately predicts male sensation than female sensation.

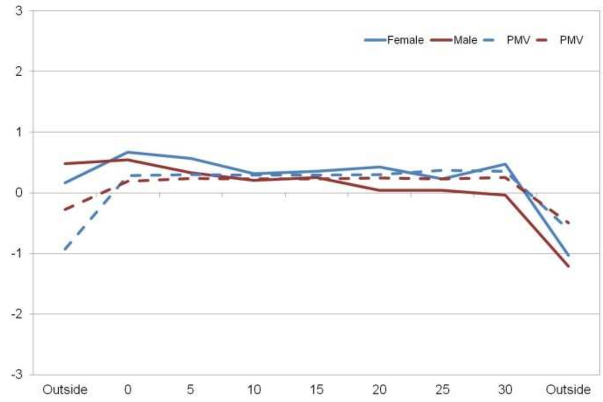

Figure 13 Mean sensation scores and PMV throughout experiment – neutral condition

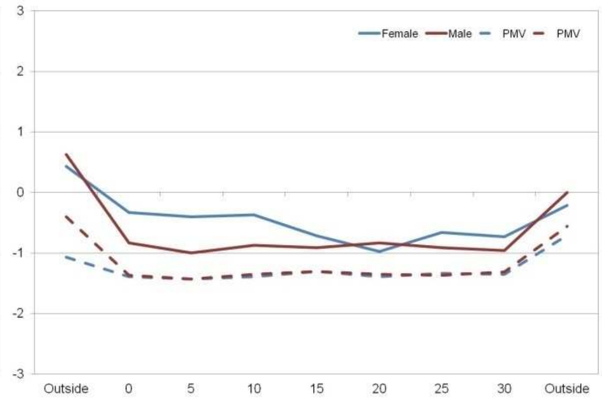

Figure 14 Mean sensation scores and PMV throughout experiment – cool condition

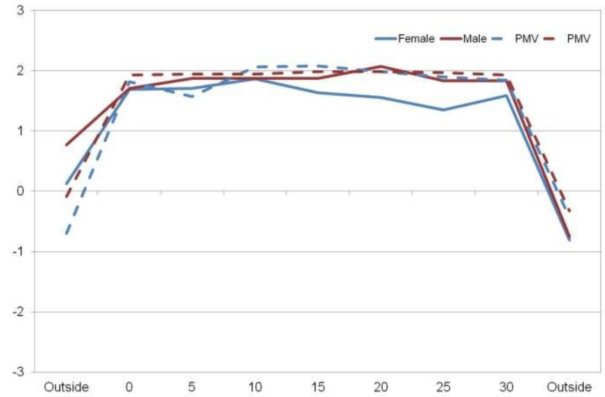

Figure 15 Mean sensation scores and PMV throughout experiment – warm condition

Gender

Male and female votes were compared prior to exiting and on exit of the chamber (see Figure 16). No significant differences in scores were observed and therefore all votes were combined during further analyses.

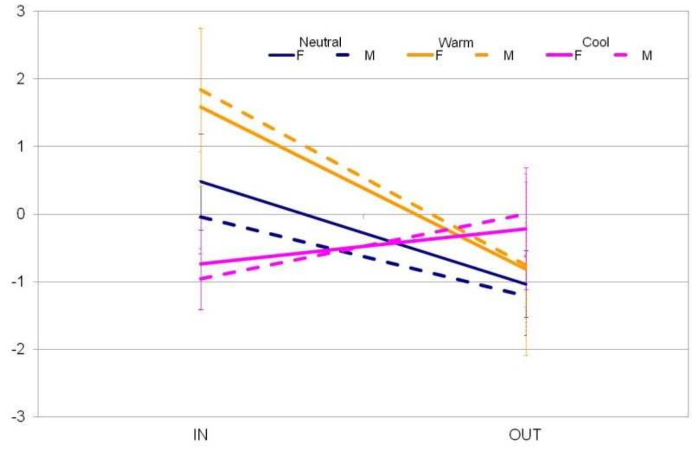

Figure 16 Mean male and female sensation votes

Sensation inside to outside

Significant differences occurred between in and out sensation ($p \leq 0.01$) indicating that the thermal experience outside the chamber was separate from that inside.

Predicted Mean Vote

Graphs of actual sensation and PMV were plotted, (see Figure 17) and showed that during the neutral and warm conditions, PMV was accurate in predicting sensation when in the chamber. However, on exiting, the model was inaccurate and actual sensation was lower than predicted by the model.

During the cool condition, actual sensation was higher than PMV when participants were in the thermal chamber and this relationship was also observed on exiting the chamber.

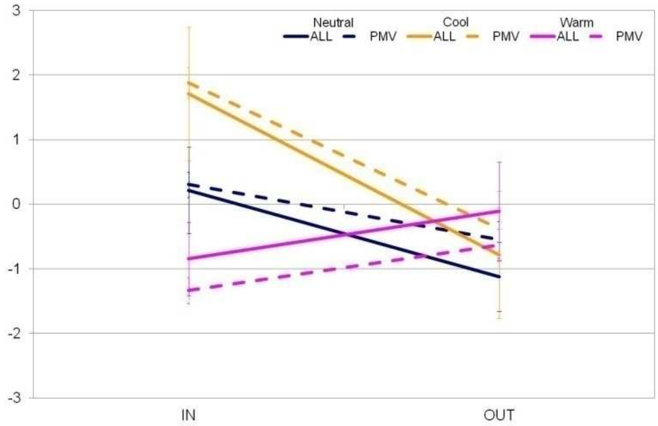

Figure 17 Mean actual sensation vote and PMV

Actual votes were compared against the PMV calculated for each condition. No significant differences between AMV and PMV occurred when in the chamber; however, on exiting, significant differences occurred following each chamber condition ($p \leq 0.05$).

Discussion

Environmental conditions

Table 2 shows that for the neutral (PMV = 0) and warm (PMV = 2) conditions, PMV was close to predicted values with actual values of 0.6 and 1.9. The cool (PMV = -2) condition was slightly warmer than predicted with an actual value of -1.3. The three conditions allowed participants to experience distinct environmental conditions. Table 3 shows that the conditions participants entered after exiting the chamber were similar and therefore any differences in sensation at this point must be a result of the interaction between the two environments.

Skin temperature and sensation

Figures 8 to 10 have shown that females had lower skin temperatures but experienced sensations closer to neutral throughout the three conditions (cooler in the warm condition, warmer in the cool condition – see Figure 16). As both genders were wearing the same ensemble, this difference cannot be attributed to the clothing worn. This effect may be as a result of some of the experiments for the female participants' being conducted in the winter. As outside temperatures were colder than that in the chamber, sensation may have been skewed due to seasonal effects with participants rating cooler temperatures as more comfortable (Nikolopoulou and Lykoudis 2006).

Thermal sensation

Results have shown that when moving from one environment to another, there is an instantaneous change in sensation which cannot be predicted by PMV. When moving from a warmer environment to a cooler environment, sensation overshoots the predicted steady-state value. This may be explained by cold receptors being positioned closer to the skin's surface and thereby reacting faster to a downward temperature change (de Dear et al. 1993).

Warm to slightly cool

When moving from a warm environment to a slightly cool environment, participant's sensation overshot the value predicted by PMV and they felt cooler than they would in steady-state. These results agree with results obtained by de Dear et al. (1993) and Arens et al. (2006) who also noted an overshoot in sensation.

Neutral to slightly cool

When participants' moved from the neutral environment to the slightly cool environment outside the chamber, sensation again decreased to a value lower than predicted by PMV. The mean sensation value was lower than that following the warm condition indicating that, in addition to an overshoot, there is also a lag in sensation. For instance, the warmer skin temperature following the warm condition may have resulted in a higher thermal sensation than following the neutral condition.

Cool to slightly cool

The difference between AMV and PMV following the cool condition was the same before and after exiting the chamber indicating that any error may be systematic and that PMV can predict the rate of change when moving from a cooler environment to a warmer one.

Model development

To enable a more accurate prediction of outside chamber sensation, the PMV formula was modified using the following equation to calculate the constant required to determine transient PMV.

$$PMV_{TRANS} = PMV_{OUT} + k(\text{Actual Vote}_{IN} - \text{Actual Vote}_{OUT})$$

In order to calculate k, values were plotted onto a graph (see Figure 18) and therefore k = -0.3464.

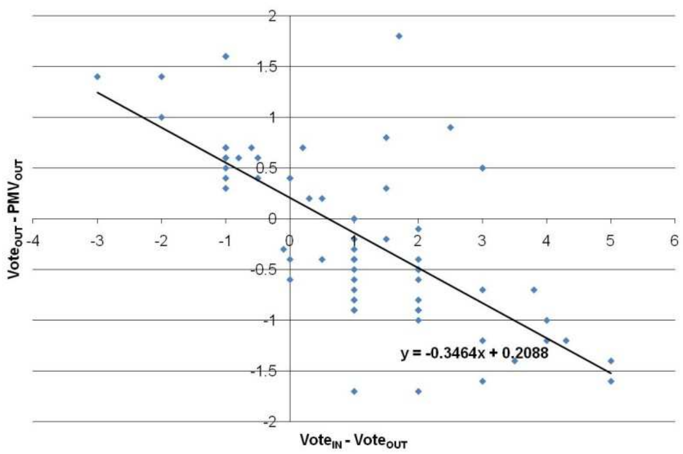

Figure 18 Calculation of k

Therefore the new PMV formula for transient situations is:

$$\mathbf{PMV_{TRANS} = PMV_{OUT} - 0.3464 \cdot (PMV_{IN} - PMV_{OUT})}$$

Conclusions

Participants were exposed, for half an hour, to three different chamber conditions and then entered a new environment. Thermal sensation was recorded throughout and it was noted that there is an instantaneous change in sensation which is related to sensation in the prior environment. When entering a slightly cool environment from a warmer environment, sensation overshoots the predicted PMV to a lower value. A lag in sensation was also observed as sensation following the warm condition was higher than following the neutral condition.

Conversely, when entering a slightly cool environment from a cool environment, sensation is higher than that following warmer conditions. Although there is an overshoot in actual sensation when compared with PMV, it is unclear whether this difference is systematic or not.

A modification to the PMV model has been created that should aid the prediction of sensation when moving from one environment to another. This modification will be validated in further studies and any necessary additional alterations will be made. More detailed information regarding sensation post change of environment will be recorded to determine a time constant for sensation to shift from transient to steady-state values.

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