EVALUATION OF THE PMV THERMAL COMFORT INDEX IN OUTDOOR WEATHER CONDITIONS

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INTRODUCTION

It is generally accepted that the world's climate is changing and it is causing an increase in minimum and maximum temperatures and an increase in the number of extreme events such as heat waves, heavy rain and droughts. There is a requirement for a valid and reliable index to represent weather conditions to which people are exposed so that the physiological strain and hence possible health effects on people can be anticipated.

Fanger (1970) produced the Predicted Mean Vote (PMV) for assessing thermal comfort and it has been widely used (ISO 7730). The PMV is an index which predicts the thermal sensation of people based on the seven-point scale(+3 hot, +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool, -2 cool, -3 cold). For the evaluation of the thermal environment, it is important to know human responses to various thermal conditions as well as to know the diversity of human responses. The aim of this study was to evaluate the PMV thermal comfort index when applied to predicting the thermal sensations of people outdoors.

METHODS

Four group experiments were conducted in the U.K. to determine human responses to outside condition, one for each season of the year. There were September 2007(Group A), December 2007(Group B), March 2008(Group C) and June 2008(Group D).

Environmental measurement

Environmental conditions were recorded around the subjects. Air temperature and humidity were measured using a whirling hygrometer. In addition, dry and wet bulb temperatures were measured using shielded thermistors and black globe temperature was measured at the same place as the dry and wet bulb temperatures were measured in the sun. Radiation levels were measured using a Skye pyranometer SP 1110. Air velocity was measured using a B&K anemometer and an Oregon weather station WMR 928 NX. All measurements were taken at 1.2m above the ground. Clothing worn varied with conditions and all items were a white cotton short sleeved shirt or a white cotton/polyester long sleeved shirt or a grey cotton/polyester sweat shirt, blue jeans, underwear, socks and trainers. 0.59clo consisted of a short sleeved shirt, blue jeans, underwear, socks and trainers. 1.07clo consisted of a long sleeved shirt. a sweat shirt, blue jeans, underwear, socks and trainers and 1.13clo consisted of a short sleeved and a long sleeved shirts, a sweat shirt, blue jeans, underwear, socks and trainers.

Physiological measurement

The subject was weighed minimally clothed before and after the 'exposure' using Mettler 1D1 Multi-range Digital Dynamic Scales, and the difference of weights was considered as sweat production (Parsons, 2003). Aural temperature was measured during the exposure using thermistors. Heart rate was measured using a Polar sports tester.

Subjective measurement

A subjective questionnaire was completed by the subjects every ten minutes for Group A and B and every five minutes for Group C and D throughout the 60 minute exposure. The ISO 11-point thermal sensation scale was used (ISO 10551). Subjects gave ratings of thermal sensation, comfort, stickiness, preference, pleasantness, acceptance, satisfaction and Borg's Rate of Perceived Exertions (Borg's RPE, Borg(1998)).

Male students were involved as participants in this study(Table 1).

Table 1. Physical characteristic of participants [mean (SD)]

Group	Age	Height(m)	Weight(Kg)	BSA*(m^2)
A (n=10)	26(3.37)	1.78(0.048)	74.7(8.55)	1.92(0.115)
B (n=8)	21(0.99)	1.79(0.03)	72.1(3.95)	1.90(0.051)
C (n=10)	24(2.57)	1.78(0.076)	75.3(6.28)	1.93(0.114)
D (n=10)	27(10.04)	1.72(0.07)	68.4(8.48)	1.80(0.110)

*: BSA means Body Surface Area(m^2)

Procedures

Body weight was measured(participants wearing only underwear). Aural thermistors and heart rate monitors were fitted. Their fully clothed body were weighed before a step test. The participants exercised for 60 minutes in an open space facing the sun, performing a step test in time to a metronome set at a rate of 80bpm on a vertical rise of 100mm which can be estimated as providing a heat production of 204Wm^{-2} (ACSM, 2006). The subject was advised to alter the choice of lead foot periodically to avoid unequal leg strain. Every minute the subjects' physiological measurements and the environmental parameters were recorded. And a subjective questionnaire was completed every five or ten minutes. At the end of the experiment, subjects' shorts only and clothed weights were measured. Participants in Group A started at the same time but participants in Group B, C, and D started differently with approx. five minutes intervals between participants. This allowed measurements of their body weight just before and after 60mins exposures.

RESULTS

Environmental measurements

The range of environmental conditions for the four group experiments are shown in Table 2. All participants of Group A were exposed to the same environment but participants of Group B, C, and D were exposed to slightly different environmental conditions. There were various environmental conditions from warm to cool environments between groups, and 6 ºC to 25 ºC for air temperature, 13 ºC to 57 ºC for mean radiant temperature, 0.8 m/s to 2.5 m/s for wind speed, 106 Wm^{-2} to 898 Wm^{-2} for solar radiation, and 0.59 clo to 1.13 clo for clothing.

Table 2. Range of mean environmental conditions over 60mins [mean (SD)]

	Group A	Group B	Group C	Group D
Air temperature, t_a(ºC)	24.7(1.12)	6.1 ~ 7.1	13.6 ~ 13.9	20.5 ~ 20.8
Mean radiant temperature, t_r(ºC)	49.5(8.3)	13.2 ~ 25.9	37.1 ~ 49.2	56.3 ~ 57
Air velocity, v(ms^{-1})	0.84(0.393)	0.86 ~ 1.39	2.14 ~ 2.47	1.5 ~ 1.65
Relative humidity, ø(%)	61(5.16)	67 ~ 71	62 ~ 67	53 ~ 54
Solar radiation(Wm^{-2})	446(169.14)	106 ~ 149	340 ~ 490	850 ~ 898
Clothing(clo*)	0.59	1.13	1.07	0.59

* clo is a unit which gives an estimate of clothing insulation on human body. For example, 0clo is for a nude person, 1.0clo the insulation of a 'typical business suit' etc.

Physiological measurements

The range of final physiological responses for four group experiments are shown in Table 3. Internal body temperature was different among participants in Group A but no difference in Group D which had warm environmental condition. In respect of heart rate, it was varied between participants for all groups although they conducted the same activity. Sweat production was high in warm environmental conditions and low in cool environmental conditions as expected.

Table 3. Final physiological data after 60mins [mean (SD)]

	Group A	Group B	Group C	Group D
Aural temperature, t_{au}(ºC)	37.3(0.28)	35.5 ~ 36.9	35.6 ~ 37.9	37(0.21)
Heart rate (bpm)	105(21.53)	74 ~ 113	70 ~ 133	91(9.11)
Sweat evaporated (gh^{-1})	471(77.16)	66 ~ 101	125 ~ 233	238(73.35)

Subjective measurements

The range of final subjective responses for four group experiments are shown in Table 4. Final subjective responses between participants within groups were different. Group A and D showed higher than 'slightly warm' for thermal sensation and no 'not uncomfortable' for comfort. A few participants voted unacceptable and dissatisfied for the thermal environment in each group.

Table 4. Final subjective data after 60mins [mean (SD)]

	Group A	Group B	Group C	Group D	Scale point
Sensation	2.5(0.76)	-1 ~ 2	-2 ~ 3	2(0.82)	-2 cool, -1 slightly cool, 2 warm, 3 hot
Comfort	2.5(0.53)	1 ~ 2	1 ~ 3	2.1(0.37)	1 not uncomfortable, 2 slightly uncomfortable, 3 uncomfortable
Stickiness	2.8(0.63)	1 ~ 2	1 ~ 3	2.4(0.75)	1 not sticky, 2 slightly sticky, 3 sticky
Preference	-1.5(0.69)	-1 ~ 1	-2 ~ 1	-1.2(0.67)	1 slightly warmer, -1 slightly cooler, -2 cooler
Pleasantness	-1.38(0.49)	-1 ~ 1	-1 ~ 1	-0.3(1.14)	-1 slightly unpleasant, 1 slightly pleasant
Borg's RPE	11(3.13)	6 ~ 11	6~ 16	9.6(2.12)	6 no exertion at all, 9 very light, 11 light, 17 very hard

Analysis of PMV and actual thermal sensation

The range of PMV and measured thermal sensation votes are shown in Figure 1. For outdoor weather conditions, the PMV index was increased to include +4 very hot and +5 extremely hot. For Group A the PMV values varied between 3.3 ~ 4.2 which meant around ‘hot’ to ‘very hot’ for 60minutes. Participants in Group B and C were exposed to slightly different environmental conditions, and Group B showed the PMV range of -0.2 ~ 0.8 which meant around ‘neutral’ and ‘slightly warm’. Group C had the PMV range of 0.2 ~ 2.2 which meant around ‘neutral’ to ‘warm’. In the case of Group D, the environmental conditions among participants were not significantly different($p<0.05$) and the PMV range was 2.7 ~ 3.6 which meant around ‘hot’ and ‘very hot’. On the other hand, the results of thermal sensation votes had wider ranges than the range of PMV. The range of sensation of Group A was -1 ~ 3 which meant around ‘slightly cool’ to ‘hot’ for 60minutes. The thermal sensation of Group B was -2.8 ~ 2 which meant around ‘cold’ to ‘warm’. The result of sensation in Group C was -2 ~ 3 which meant around ‘cool’ to ‘hot’. Group D showed the range of -1 ~ 3 which meant around ‘slightly cool’ and ‘hot’.

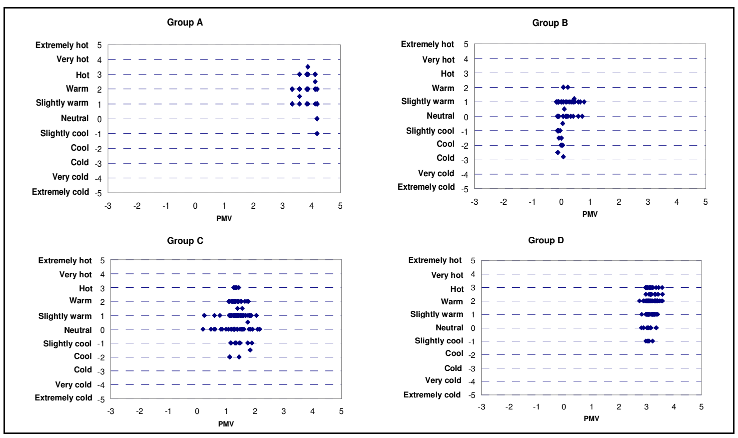

Fig. 1 Scatter plot of the measured thermal sensation and PMV by groups.

The correlation between the actual thermal sensation and PMV is shown in Figure 2. Pearson correlation was $r=0.511$ and the relationship was significant at the 0.01 level. The PMV values showed narrower range than the measured thermal sensation for all groups and the PMV had higher values than actual thermal sensation for all groups. Olesen and Parsons (2002) also pointed out the lack of validity of the PMV.

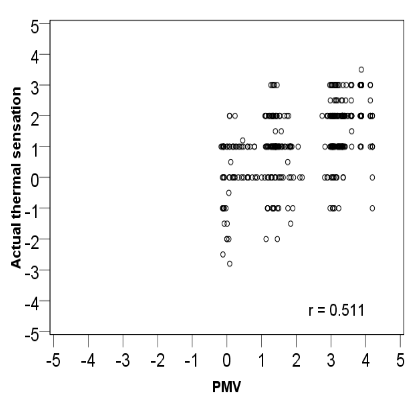

Fig. 2 Pearson correlations between the measured thermal sensation and PMV for four groups.

CONCLUSIONS

Group A in September, 2007(t_a : 25°C)

1. The PMV values were higher than the actual thermal sensation.
2. The PMV range was 3(hot) to 4(very hot) but the range of the actual thermal sensation was -1(slightly cool) to 3(hot).

Group B in December, 2007(t_a : approx. 7°C)

3. The PMV values were similar to the actual thermal sensation.
4. The PMV range was 0(neutral) to 1(slightly warm) but the range of the actual thermal sensation was -3(cold) to 2(warm).

Group C in March, 2008(t_a : approx. 14°C)

5. The PMV values were higher than the actual thermal sensation.
6. The PMV range was 0(neutral) to 2(warm) but the range of the actual thermal sensation was -2(cool) to 3(hot).

Group D in June, 2008(t_a : approx. 21°C)

7. The PMV values were higher than the actual thermal sensation.
8. The PMV range was 2.7(hot) to 3.6(very hot) but the range of the actual thermal sensation was -1(slightly cool) to 3(hot).

Overall, the PMV values were higher than the actual thermal sensation for all seasons, and the PMV range was 0(neutral) to 4(very hot) but the range of the actual thermal sensation was -3(cold) to 3(hot).

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