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Subjective Responses to Thermal Stress for the Outdoor Performance of Smart Clothes

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Objective: The aim of this study was to explore the influence of outdoor weather conditions on subjective responses during physical activity.

Background: The largest difference between indoor and outdoor conditions is the existence of the sun. The heat load from the sun has an influence on the heat gain of the human body and the intense degree of solar radiation affected thermal comfort.

Method: Thirty eight people were exposed to a range of climatic conditions in the UK. Weather in England does not have extremely hot and cold temperature, and the current study was conducted under warm (summer and autumn) and cool (spring and summer) climates. Measurements of the climate included air temperature, radiant temperature (including solar load), humidity and wind around the subjects. Subjective responses were taken and physiological measurements included internal body temperature, heart rate and sweat loss.

Results: This study was conducted under four kinds of environmental conditions and the environmental measurement was performed in September, December, March, and June. The values for sensation, comfort, preference, and pleasantness about four conditions were from 'neutral' to 'warm', from 'not uncomfortable' to 'slightly comfortable', from 'slightly cooler' to 'slightly warmer', and from 'neither pleasant nor unpleasant' and 'slightly unpleasant', respectively. All subjective responses showed differences depending on air temperature and wind speed, and had correlations with air temperature and wind speed ($p<0.05$). However, subjective responses showed no differences depending on the radiant temperature. The combined effects of environmental parameters were showed on some subjective responses. The combined effects of air temperature and radiant temperature on thermal sensation and pleasantness were significant. The combined effects of metabolic rate with air temperature, wind speed and solar radiation respectively have influences on some subjective responses. In the case of the relationships among subjective responses, thermal sensation had significant correlations with all subjective responses. The largest relationship was shown between preference and thermal sensation but acceptance showed the lowest relationship with the other subjective responses.

Conclusion: The ranges of air temperature, radiant temperature, wind speed and solar radiation were 6.7℃ to 24.7℃, 17.9℃ to 56.6℃, 0.84ms^{-1} to 2.4ms^{-1}, and 123Wm^{-2} to 876Wm^{-2} respectively. Each of air temperature and wind speed had significant relationships with subjective responses. The combined effects of environmental parameters on subjective responses were shown. Each radiant temperature and solar radiation did not show any relationships with subjective responses but the combinations of each radiant temperature and solar radiation with other environmental parameters had influences on subjective responses. The combinations of metabolic rate with air temperature, wind speed and solar radiation respectively have influences on subjective responses although metabolic rate alone hardly made influences on them. There were also significant relationships among subjective responses, and pleasantness generally showed relatively high relationships with comfort, preference, acceptance and satisfaction.

Application: Subjective responses might be utilized to predict thermal stress of human and the application products reflecting human subjective responses might apply to the different fields such as fashion technology, wearable devices, and environmental design considering human's response etc.

Keywords: Thermal sensation, Thermal comfort, Pleasant, Preference, Thermal environment, Smart clothes

1. Introduction

The largest difference between indoor and outdoor conditions is the existence of the sun. The heat load from the sun has an influence on the heat gain of the human body (Nielsen et al., 1988; Parsons, 2014), and the intense degree of solar radiation affects thermal comfort (Hodder and Parsons, 2007; Nikolopoulou and Lykoudis, 2006). Heat exchange from radiation is distinct from convection, which has an influence only on the surface of skin; radiative heat affects the deep tissue of the human body (Givoni, 1976). The sun, the largest source of radiation, exists in the outdoor thermal environment, and exposure to radiation increases or decreases skin temperature. Additionally, McIntyre (1980) suggested that thermal sensation changes much more quickly than body temperature if the ambient temperature alters rapidly. Human beings perceive warmth or cold by detecting the temperature via nerve endings below the surface of the skin. Outdoor weather conditions are capricious, and some factors such as air velocity and solar radiation fluctuate rapidly and frequently.

Human subjective responses on thermal environment can also be distinguished, depending on different seasons or environmental conditions. McIntyre (1980) suggested that thermal comfort could be more precisely predicted than skin and body temperatures under outdoor conditions. So to predict subjective responses such as thermal comfort can be used for the development of smart clothes because thermal comfort is related to the equilibrium of human body. People described their preference for warmth under cool weather conditions, and the sensation of coolness could be considered an undesirable state. The sensation of coolness is a desirable state, however, under warm weather conditions. Therefore, subjective responses would be appropriate to predict human physiological responses, depending on the change in the weather conditions. Subjective responses that human experience could also be the easiest way to assess whether human perceive thermal strain related to weather, clothing, or activity level, so that smart clothing to predict or reflect subjective responses also help human health and performance.

The ordinary person can control his or her exposure to outdoor thermal environments according to his or her preferences, but in working environments such as construction sites and agriculture, people must work outdoors even in hot or cold conditions, regardless of outdoor or severe weather conditions. In addition, weather in spring and autumn is quite changeable, and tomorrow's weather can be quite different from today's weather. Outdoor workers might not be able to choose adaptive behavior, such as changing clothing, and even the ordinary person may fail to choose clothing with optimal clothing insulation in relation to the weather for a particular day. These factors such as weather conditions and clothing can affect work efficiency and productivity. Therefore, it is important to predict whether human feel hot or cold in order to prevent thermal stress or to develop smart clothes for the achievement of thermal comfort while they are exposed to outdoor environments.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2003) and ISO 7730 (2005) define thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment". Thermal comfort and thermal sensation are two opposite elements, and the spectrum can run from uncomfortably cold to uncomfortably warm or hot across comfortable or neutral sensation. Thermal comfort can also be defined as the state of lack of irritation or discomfort from heat and/or cold, or involving pleasantness (Givoni, 1976).

Human experiences the fluctuations of the thermal environment as they move to and from indoor and outdoor environments. The everyday weather they experience is quite different. For example, it would contribute to energy saving if human subjective responses can be predicted by changing the temperature. For this purpose, numerous thermal indices have been developed, and studies concerning the validation of thermal indices have been conducted. Using subjective responses would be convenient in order to predict thermal states of humans. If smart clothes are developed in order to achieve or predict thermal comfort and prevent thermal stress during working, it would help to improve performance and productivity, and to protect human health.

The human body has a capability for maintaining heat balance within wide limits of the environmental variables through vasodilatation and vasoconstriction, sweat secretion, and shivering. Furthermore, the thermal sensation under a certain activity level affects the thermal load on the human body. In the comfort condition, the thermal load will be equal to zero. In other environments, the mean skin temperature and the amount of sweat secretion will change in order to maintain the heat balance of the body. Hence, the thermal load indicates the physiological strain on the body, and it is assumed that the thermal sensation of an activity level is related to this strain. Therefore, the aim of this study was to explore the influence of outdoor weather conditions on subjective responses during physical activity.

2. Methods

2.1 Participants

Thirty eight males had a part in this study (Figure 1). Four experiments were carried out in once in each season (Table 1). All

Figure 1. Experiment site and subjects

Table 1. Physical characteristics of subjects [mean (SD)]

Subject	Age (yrs)	Height (m)	Weight (Kg)	BSA* (m^2)
Autumn experiment (n=10)	26 (3.37)	1.78 (0.047)	74.7 (8.55)	1.92 (0.115)
Winter experiment (n=8)	21 (0.99)	1.79 (0.030)	72.1 (3.95)	1.90 (0.050)
Spring experiment (n=10)	24 (2.57)	1.78 (0.076)	75.3 (6.28)	1.93 (0.114)
Summer experiment (n=10)	27 (10.04)	1.72 (0.070)	68.4 (8.48)	1.80 (0.110)
Total (n=38)	24.5 (4.24)	1.77 (0.056)	72.6 (6.82)	1.89 (0.098)

*: BSA means Body Surface Area (m^2) (DuBois & DuBois[5])

participants were healthy undergraduate/graduate students and academic staffs. They filled the informed consent form after being instructed the experiment procedures as well as the aim of the experiment.

2.2 Experimental protocol

Four experiments were carried out in the U.K. once in each season; September 2007 (autumn), December 2007 (winter), March 2008 (spring) and June 2008 (summer). Thermal sensation, thermal comfort, thermal preference, acceptance and satisfaction were recorded while subjects did a step test for one hour facing the sun. Environmental parameters as well as physiological responses were also measured. The ethical advisory committee at Loughborough University approved the protocol of this study.

2.3 Environmental measurement

Environmental conditions were measured every minute near by the subjects conducting step tests. A whirling hygrometer was used for recording air temperature and humidity. A pyranometer (Kipp and Zonen CM11, Holland) was used for measuring direct solar radiation. An anemometer (Brüel & Kjær MM 0038, Denmark) and a weather station (Orgon WMR 928 NX, USA) were used to record air velocity. 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 for autumn and summer experiments consisted of a short sleeved shirt, blue jeans, underwear, socks and trainers. 1.07clo for spring experiment consisted of a long sleeved shirt, a sweat shirt, blue jeans, underwear, socks and trainers and 1.13clo for winter experiment consisted of a short sleeved and a long sleeved shirts, a sweat shirt, blue jeans, underwear, socks and trainers. The clothing insulation was measured using a thermal manikin (Victoria, Espergerde, Denmark) in a climate chamber.

2.4 Physiological measurement

A Multi-range digital dynamic scale (Mettler 1D1, Mettler Toledo, USA) was used to weigh the subject minimally clothed before and after a step test for 60 minutes, and the difference of weights was considered as sweat production (Parsons, 2014). A thermistor was used for measuring aural temperature during the exposure every minute. A Polar sports tester (Polar Electro, Kempele, Finland) was used for measuring heart rate. ACSM suggests how to find the estimated value of metabolic rate through step height and step speed. The formulae are provided below. This is based upon metabolic rates determined by indirect calorimetry for a range of stepping conditions. The rate of oxygen consumption VO_2 is given by:

$$VO_2\left(mL \cdot kg^{-1} \cdot \min^{-1}\right) = 0.2 \cdot (stepping \quad rate) + 1.33 \times 1.8 \cdot (step \quad height)(stepping \quad rate) + 3.5 \quad mL \cdot kg^{-1} \cdot \min^{-1} \qquad (1)$$

$$(Stepping \quad rate = steps \cdot \min^{-1}; step \quad height = meters)$$

$$METs = \frac{VO_2\left(mL \cdot kg^{-1} \cdot \min^{-1}\right)}{3.5}$$

$$Metabolic \quad rate = METs \times 58.15 \qquad (2)$$

The metabolic rate can be found out through oxygen consumption rate and the energetic equivalent (EE) of oxygen can convert oxygen consumption rate into metabolic rate.

The energetic equivalent is decided by the type of metabolism which can be expressed by the respiratory quotient (RQ) (RQ is the CO_2 produced divided by the O_2 consumed, it is related to efficiency of congestion). Respiratory exchange ratio (RER) and respiratory quotient (RQ) are calculated as VCO_2/VO_2 and are no unit variables. RER and RQ are considered as synonym under steady-state conditions. Therefore, a mean RQ of 0.85 and EE of 5.68W·h/LO_2 can be used for figuring out the metabolic rate. In this case, the carbon dioxide production rate is not needed (ISO 8996, 2004).

$$M = EE \times Vo_2 \times \frac{1}{A_{Du}} \tag{3}$$

where

Vo_2 is the oxygen consumption rate, in litres of oxygen per hour;

EE is the energetic equivalent, in watt hours per litre of oxygen (W·h/LO_2)

M is the metabolic rate, in watts per square metre

A_{Du} is the body surface, in square metres, given by the Du Bois formula

$$A_{Du} = 0.202 \times W_b^{0.425} \times H_b^{0.725} \tag{4}$$

in which

W_b is the body weight, in kilograms

H_b is the body height, in metres.

Individual differences; participants' weight or their body surface area were not considered in equations (1) and (2), and equation (3) was used for adjusting participants' weights and their body. VO_2 from equation (1) was multiplied by participant's weight, and the unit, $mLkg^{-1}min^{-1}$, was converted into L/h.

When equation (1) is added to equation (3), the equation (5) will be below (Kwon, 2009),

$$\begin{aligned} M &= 5.68 \times VO_2 \times W_b \times 60 \times \frac{1}{1000} \times \frac{1}{A_{Du}} \\ &= 0.341 \times VO_2 \times W_b \times \frac{1}{A_{Du}} \end{aligned} \tag{5}$$

2.5 Subjective measurement

A subjective questionnaire was composed of thermal sensation, comfort, preference, pleasantness, acceptance, and satisfaction (Table 2). The ISO extended 11-point thermal sensation scale was suitable for the experiments because they were conducted in outdoor thermal environments with the sun which have wider range than indoor thermal conditions (ISO 10551, 2001). Subjects voted ratings of the questionnaire every ten minutes for autumn and winter experiments and every five minutes for spring and summer experiments throughout the 60 minute exposure. Recording subjective responses every five minute allowed noticing sensitive change of subjective responses by fluctuated weather conditions.

2.6 Procedure

Body weight was measured (participants wearing only underwear). Aural thermistors and heart rate monitors were fitted. Their

Table 2. Subjective scales

Thermal sensation	Thermal comfort	Preference	Pleasantness	Acceptance	Satisfaction
5 Extremely hot	4 Very uncomfortable	3 Much warmer	3 Very pleasant	0 Acceptable	0 Satisfied
4 Very hot		2 Warmer	2 Pleasant	1 Unacceptable	1 Dissatisfied
3 Hot	3 Uncomfortable	1 Slightly warmer	1 Slightly pleasant		
2 Warm		0 No change	0 Neither pleasant nor unpleasant		
1 Slightly warm	2 Slightly uncomfortable	-1 Slightly cooler	-1 Slightly unpleasant		
0 Neutral		-2 Cooler	-2 Unpleasant		
-1 Slightly cool	1 Not uncomfortable	-3 Much cooler	-3 Very unpleasant		
-2 Cool					
-3 Cold					
-4 Very cold					
-5 Extremely cold					

fully clothed body was weighed before exercises. The subjects took a step test in an open site confronting the sunshine for 60 minutes, performing the exercise in time to a metronome set at a pace of 80bpm which can provide a moderate work rate. A vertical rise of the step was 100mm. 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. Subjects completed a subjective questionnaire every five or ten minutes. At the end of the experiment, subjects' shorts only and clothed weights were measured before the experiment began. Participants in autumn experiment concurrently started but participants in Groups B, C, and D began individually with the interval of approximately five minutes between subjects. This allowed measurements of their body weights just before and after 60mins exposures, rather than having a queuing delay.

2.7 Data analysis

Spearman correlation analyses were conducted for finding out the relationships between environmental parameters and subjective responses and among subjective responses. Multivariate analyses were conducted for figuring out the combined effects of environmental parameters.

3. Results

3.1 Environmental measurement

Four experiments were conducted in Loughborough, the U.K. The autumn experiment was performed in September, 2007 around 1pm, and the winter experiment was performed in December, 2007 around 12pm. The spring experiment was performed in March, 2008, and the summer experiment was performed in June, 2008 around 1pm. This study was conducted under four kinds of environmental conditions and the environmental measurement was performed in September, December, March, and June. The ranges of air temperature (t_a), mean radiant temperature (t_r), and solar radiation were 6.7℃ to 24.7℃, 17.9℃ to 56.6℃, and 123Wm^{-2} to 876Wm^{-2} respectively (Table 3).

Table 3. Environmental conditions at 1.2m during exposure times [mean (SD)]

Experiment	Air temperature t_a (℃)	Mean radiant temperature t_r (℃)	Wind speed v (ms^{-1})	Relative humidity (%)	Solar radiation sr (Wm^{-2})	Clothing (clo*)	Metabolic rate Met (Wm^{-2})
Autumn expt	24.7 (1.12)	49.5 (8.3)	0.84 (0.393)	61 (5.16)	446 (169.14)	0.59	163 (9.4)
Winter expt	6.7 (0.41)	17.9 (5.18)	1.1 (0.19)	69 (1.69)	123 (15.05)	1.13	159 (5.44)
Spring expt	13.7 (0.14)	44.2 (3.64)	2.4 (0.11)	65 (2.04)	434 (49.9)	1.07	164 (6.6)
Summer expt	20.8 (0.12)	56.6 (0.27)	1.57 (0.05)	54 (0.49)	876 (19.5)	0.59	159 (11.24)
Average in total	17.1 (5.93)	43.3 (15.77)	1.5 (0.87)	61 (6.46)	488 (286.9)	0.85 (0.295)	161 (8.5)

*clo is a unit which gives an estimate of clothing insulation on human body. For example, 0clo is for a nude person.

3.2 Physiological measurement

For the autumn experiment, average final aural temperature, heart rate, and evaporative sweat loss were 37.3℃, 105bpm, and 471gh^{-1} respectively. For the winter experiment, average final aural temperature, heart rate, and evaporative sweat loss were 36.3℃, 91bpm, and 80gh^{-1} respectively. Regarding the spring experiment, final aural temperature, heart rate, and evaporative sweat loss were 36.6℃, 99bpm, and 175gh^{-1} respectively. In terms of the summer experiment, average final aural temperature, heart rate, and evaporative sweat loss were 36.6℃, 91bpm, and 238gh^{-1} respectively.

3.3 Subjective measurement

Participants voted on their thermal sensation, comfort, preference, pleasantness, acceptance, and satisfaction. The average range of thermal sensation was -1 to 3.5 for autumn experiment, -2.8 to 2.0 for winter experiment, -2 to 3 for spring experiment, and -1 to 3 for summer experiment. Subjects felt from 'slightly cool' to between 'hot' and 'very hot' in the average of four experiments. The standard deviation for winter experiment was the highest and the one for autumn experiment was the lowest (Table 4). The average range of thermal comfort during one hour exposure was 1 to 4 for autumn experiment, 1 to 3 for winter experiment, 1 to 4 for spring experiment, and 1 to 4 for summer experiment. Subjects felt from 'not uncomfortable' to 'very uncomfortable' in the average of four experiments. The standard deviation for autumn experiment was the highest and the one for winter experiment was the lowest (Table 4). The average range of thermal preference was -3 to 0 for autumn experiment, -1 to 2 for winter experiment, -2 to 1 for spring experiment, and -2 to 2 for summer experiment. Subjects felt from 'much cooler' to 'warmer' in the average of four experiments. The standard deviation for summer experiment was the highest and one for autumn experiment

Table 4. Subjective results in 60 minute exposure time [mean (SD)]

	Sensation	Comfort	Preference	Pleasantness	Acceptance	Satisfaction
Autumn expt	2.0 (0.83)	2.1 (0.72)	-1.2 (0.63)	-0.7 (0.97)	0.30 (0.455)	0.35 (0.472)
Winter expt	0.2 (1.14)	1.5 (0.52)	0.5 (0.72)	0.2 (0.52)	0.06 (0.224)	0.02 (0.132)
Spring expt	0.9 (1.04)	1.4 (0.68)	-0.5 (0.73)	0.1 (0.99)	0.06 (0.225)	0.06 (0.225)
Summer expt	1.6 (0.98)	1.7 (0.63)	-0.6 (0.84)	0 (1.24)	0.09 (0.289)	0.12 (0.319)
Average in total	1.2 (1.16)	1.6 (0.69)	-0.5 (0.91)	-0.1 (1.08)	0.1 (0.32)	0.1 (0.33)

was the lowest (Table 4). The ranges of acceptance and satisfaction in the average of four experiments were 0.06 to 0.3 and 0.02 to 0.35 respectively.

3.4 Subjective responses vs environmental parameters

All subjective responses showed differences depending on air temperature and had correlations with it (Table 5). Air temperature out of environmental parameters showed the highest correlation coefficients with subjective responses. Thermal sensation and comfort increased as air temperature increased. Subjects tended to feel 'slightly uncomfortable' rather than 'not uncomfortable'. However, preference and pleasantness decreased as air temperature increased. Subjects tended to feel slightly unpleasant as air temperature increased. Acceptance and satisfaction increased as air temperature increased. Subjects tended to feel unacceptable and dissatisfied as air temperature increased. However, all subjective responses showed no differences depending on the radiant temperature.

Table 5. Spearman correlation between environmental parameters and subjective responses

		Sensation	Comfort	Preference	Pleasantness	Acceptance	Satisfaction
ta	χ^2	511.766	240.021	621.064	464.756	56.026	60.051
	df	294	147	336	294	21	21
	p	0.000	0.000	0.000	0.000	0.000	0.000
	Spearman correlation	0.527	0.347	-0.542	-0.331	0.242	0.308
v	χ^2	416.837	210.113	424.140	454.887	50.646	60.143
	df	322	161	368	322	23	23
	p	0.000	0.006	0.023	0.000	0.001	0.000
	Spearman correlation	-0.211	-0.229	0.137	0.202	-0.165	-0.177
SR	χ^2	–	–	–	–	97.525	98.154
	df	–	–	–	–	75	75
	p	–	–	–	–	0.041	0.050
	Spearman correlation	–	–	–	–	–	–
Metabolic rate	χ^2	750.225	384.291	1065.829	1007.343	94.672	128.466
	df	308	154	352	308	22	22
	p	0.000	0.000	0.000	0.000	0.000	0.000
	Spearman correlation	-0.268	–	–	0.114	–	–

All subjective responses showed differences depending on the wind speed and had correlations with it. Thermal sensation and comfort decreased as wind speed increased. Subjects tended to feel 'not uncomfortable' as wind speed increased. However, preference and pleasantness increased as wind speed increased. Subjects tended to prefer 'no change' and feel 'slightly pleasant' as wind speed increased. Acceptance and satisfaction decreased as wind speed increased. Subjects tended to feel acceptable and satisfied as wind speed increased. On the other hand, all subjective responses also showed differences depending on the metabolic rate but thermal sensation and pleasantness only had correlations with it (Table 5). Sensation decreased and pleasantness increased as metabolic rate increased. Subjects tended to feel neutral and slight pleasant as metabolic rate increased.

3.5 Combined effects of environmental parameters on subjective responses

The combined effects of environmental parameters on subjective responses are showed in Table 6. The combined effects of air temperature and radiant temperature on thermal sensation (F=3.526, p=0.001) and pleasantness (F=5.265, p=0.000) were statistically significant. The combined effects of air temperature and radiant temperature had influences on sensation and pleasantness although radiant temperature alone did not affect any subjective responses. The combined effects of air temperature and metabolic rate on all subjective responses were statistically significant (p=0.000 for all subjective responses except preference (p=0.001)). The range of F-value on the combined effects between air temperature and metabolic rate was between 1.655 and 5.477, and preference and satisfaction showed the lowest and the highest respectively. The combined effect of radiant temperature and solar radiation on thermal sensation was statistically significant (F=5.442, p=0.006). The combined effect of radiant temperature and solar radiation had an influence on thermal sensation although solar radiation alone did not make an influence on it.

The combined effects of wind speed and metabolic rate on acceptance (F=1.538, p=0.003) and satisfaction (F=1.523, p=0.003) were statistically significant. The combined effects of solar radiation and metabolic rate on all subjective responses expect comfort were statistically significant. The range of F-value on the combined effects of solar radiation and metabolic rate was between 1.350 for sensation (p=0.048) and 1.776 for satisfaction (p=0.001). The combinations of metabolic rate with air temperature, wind speed and solar radiation respectively have influences on subjective responses. Interestingly, thermal comfort was affected only by the combined effect of air temperature and metabolic rate. Acceptance and satisfaction were influenced by the combined effects of wind speed and metabolic rate.

Table 6. Combined effects of environmental parameters on subjective responses

	ta	tr	v	sr	Met
ta	.	sensation, pleasantness			all
tr	sensation, pleasantness	.			–
v	–	–	.		acceptance, satisfaction
sr	–	sensation	–	.	all except comfort
Met	all	–	acceptance, satisfaction	all except comfort	.

–: there is no significant relationship.

3.6 Relationships among subjective responses

The relationships among subjective responses are shown in Table 7. Comfort, preference, pleasantness, acceptance and satisfaction showed differences depending on thermal sensation. Thermal sensation had significant correlations with all subjective responses. The highest relationship was shown in preference and the second largest one was shown in comfort. Comfort, acceptance and satisfaction had positive relationships with thermal sensation but preference and pleasantness had negative relationships with thermal sensation. Subjects preferred slightly cooler and felt slightly uncomfortable and slightly unpleasant as thermal sensation increased. Subjects tended to feel unacceptable and dissatisfied as thermal sensation increased.

Preference, pleasantness, acceptance and satisfaction showed differences depending on thermal comfort. Preference and pleasantness had negative relationships with comfort but acceptance and satisfaction had positive relationships with comfort. Thermal comfort showed the highest relationship with pleasantness. Subjects preferred slightly cooler and felt slightly unpleasant as subjects felt slightly uncomfortable.

Pleasantness, acceptance and satisfaction showed differences depending on preference. Pleasantness had positive relationships with preference but acceptance and satisfaction had negative relationships with preference. Subjects felt slightly unpleasant, unacceptable and dissatisfied as they preferred cooler. Acceptance and satisfaction showed differences depending on pleasantness and had negative relationships with it (Table 7). Acceptance and satisfaction showed the highest relationships with pleasantness. Therefore, pleasantness generally showed higher relationships with the other subjective responses.

Table 7. Spearman correlations among subjective responses

		Comfort	Preference	Pleasantness	Acceptance	Satisfaction
Sensation	χ^2	752.588	1291.648	998.798	88.151	82.225
	df	98	224	196	14	14
	p	0.000	0.000	0.000	0.000	0.000
	Correlation coefficient	0.526	-0.632	-0.496	0.319	0.336
Comfort	χ^2		1416.673	1193.487	102.733	102.139
	df		112	98	7	7
	p		0.000	0.000	0.000	0.000
	Correlation coefficient		-0.494	-0.586	0.392	0.394
Preference	χ^2			2838.859	73.719	93.395
	df			224	16	16
	p			0.000	0.000	0.000
	Correlation coefficient			0.575	-0.303	-0.378
Pleasantness	χ^2				158.824	156.299
	df				14	14
	p				0.000	0.000
	Correlation coefficient				-0.414	-0.443

4. Discussion

Thermal comfort could be more precisely predicted than skin and body temperatures under outdoor conditions (McIntyre, 1980) and subjective responses of human can also be distinguished, depending on different seasons or environmental conditions. The present study was to explore the influence of outdoor weather conditions on subjective responses during physical activity and figured out the relationship among subjective responses.

This study was conducted under four kinds of environmental conditions in September, December, March, and June. Thermal sensation was slightly warm when subjects felt between slightly uncomfortable and not uncomfortable. Thermal sensation on the cool-side was hardly observed in 'not uncomfortable' and 'slightly uncomfortable'. Subjects felt 'neither pleasant nor unpleasant', and feeling 'not uncomfortable' did not mean feeling pleasant. Cabanac (1971) considered hedonistic people would seek out a pleasant environment and a pleasant environment would be related to something enjoyable. Thermal comfort relates more to a lack of discomfort and contentment. Man is a pleasure seeker, so designing environments for pleasure is a goal (de Dear, 2009). However, it seems to be hard to achieve thermal pleasantness rather than thermal comfort in outdoor weather environments based on the current study although the correlation between pleasantness and comfort was the largest and subjects tended to feel slightly unpleasant when they felt slightly uncomfortable.

Subjects' preference for thermal sensation were 'no change' or 'slightly cooler' regarding the current range of thermal environment. McIntyre and Gonzalez (1976) noted that people described their preference as warmth under a cool climate, and the expression of cool could be considered as an undesirable state. The expression of cool is a desirable state under a warm climate (McIntyre, 1980). Weather in England does not have extremely hot and cold temperature, and the current study was conducted under warm (summer and autumn) and cool (spring and summer) climates. It was hard to observe thermal sensation on the cool-side of thermal sensation, even though subjects wanted to remain in the thermal environment or subjects described their preference of slightly cooler under both warm and cool climates. So it seemed that the slightly cooler even under both warm and cool climates would be a desirable state in the moderate activity level of $161Wm^{-2}$.

All subjective responses showed the difference depending on air temperature, wind speed and metabolic rate. Subjects tended to feel acceptable and satisfied under perceptible wind. Subjects also tended to feel neutral and slightly pleasant by the increase of metabolic rate, and subjects who had high VO_2 seemed to feel pleasant. The average air temperature was 17.1℃ in the average of four experimental conditions, thermal sensation was sensitive to the change of both air temperature and radiant temperature as well as both radiant temperature and solar radiation. Pleasantness was also very sensitive to the change of both air temperature and radiant temperature. Furthermore, thermal sensation seemed to be also sensitive to the change of both air temperature and metabolic rate as well as both solar radiation and metabolic rate.

The average of solar radiation was $488Wm^{-2}$, and the subjective responses seemed not to be influenced by solar radiation alone due to the large fluctuation. The intensity of solar radiation depending on the seasons had an influence on the change of altitude over a year as well as the amounts of clouds in the sky. However, only solar radiation hardly had influences on subjective responses in the current study which was that the environment in the autumn experiment had a cloud cover of 70% in the sky, and the sun was in and out from time to time and that the environment in the winter experiment had cloud cover of 95% in the sky. Clouds almost covered the sky, and the sun occasionally came out.

The relationships among environmental parameters and subjective responses did not have high correlation coefficients. It seemed that a step test made subjects less sensitive to the change of weather as well as their subjective responses. Because exercising people cannot concentrate on the heat due to physical activity, and they are less sensitive than sedentary persons as McIntyre (1980) pointed out that the change of warm sensation during exercise was two-thirds of one during sitting.

If the number of subjects was much more than the one of the current study, it would be clearer to find the change of subjective responses and get some meaningful regressions. All male subjects took part in the current study, and subjective responses of females could differ with those of males because female subjects could show lower metabolic rate than male subjects. In addition, the lucid outcomes related to subjective responses would come out if all subjects put on the identical clothing. Authors at least showed an understanding of the need for adaptation to the weather, and the clothing in four season were not identical.

5. Conclusions

The ranges of air temperature, radiant temperature, wind speed and solar radiation were 6.7℃ to 24.7℃, 17.9℃ to 56.6℃, $0.84ms^{-1}$ to $2.4ms^{-1}$, and $123Wm^{-2}$ to $876Wm^{-2}$ respectively. Several environmental parameters alone had significant relationships with subjective responses, and all subjective responses showed significant relationships with air temperature and air velocity. Furthermore, the combined effects of environmental parameters on subjective responses were shown, and radiant temperature and solar radiation with other environmental parameters affected subjective responses. The combined effects of air temperature and radiant temperature had influences on thermal sensation and pleasantness although radiant temperature alone did not affect any subjective responses. The combined effect of radiant temperature and solar radiation had an influence on thermal sensation although solar radiation alone did not made an influence on it. The combinations of metabolic rate with air temperature, wind speed and solar radiation respectively have influences on subjective responses although metabolic rate alone hardly made influences on them.

In addition, there were significant relationships among subjective responses. Pleasantness generally showed higher relationships with the other subjective responses such as comfort, preference, acceptance and satisfaction. Subjects tended to feel neutral and not uncomfortable and to prefer no change when they felt slightly pleasant. Subjects tended to prefer slightly cooler and feel slightly unpleasant when subjects felt slightly uncomfortable. Subjects tended to feel slightly unpleasant, unacceptable and dissatisfied as they preferred cooler.

Each radiant temperature, solar radiation and metabolic rate hardly showed relationships with subjective responses but the combinations of each radiant temperature, solar radiation and metabolic rate with other environmental parameters had influences on subjective responses. The diversity of environmental conditions would be required for the future study.

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