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Thermal adaptation in hot and humid outdoor conditions

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Abstract
In order to clarify the thermal psychological and physiological response of the human body in hot outdoor environments, subject experiments were conducted in a climate chamber during summer and winter. Even though the experimental conditions are the same in summer and winter, seasonal differences are found in the thermal psychological and physiological response. The comfortable skin temperature calculated using the regression method is well matched with the Griffiths' method. When the actual skin temperature shifts from the comfortable level, the risk of overheating increases. This might be a useful index for predicting the overheating risk in hot outdoor conditions.

Keywords
hot environment, outdoor, thermal comfort, core temperature, water loss, comfortable skin temperature, overheating

1. Introduction

Thermal adaptation is one of the methods employed to avoid overheating outdoors. The outdoor environment changes frequently and people are likely to be exposed to high temperatures and humidity within a day, week or month. People ample about, walk quickly, or even run outdoors, which boosts their metabolic rate. People also move from comfortable indoor environments to the hot outdoors. Furthermore, in this era of globalization, people are constantly travelling from one region/season (e.g. southern hemisphere/winter) to another (e.g. northern hemisphere/summer). Due to the seasonal adaptation, people may have different thermal expectations, which might be an important factor in defining the risk of overheating. How people adapt to various hot outdoor conditions is not clearly understood. We need to investigate the psychological and physiological responses of the human body by considering the aforementioned factors. In order to evaluate hot outdoor environments, subject experiments were conducted in a climate chamber during summer and winter, with the main objectives being:

- to clarify the thermal psychological and physiological response,
- to investigate seasonal differences under the same experimental conditions,
- to examine thermal adaptation,
- to estimate the comfortable skin temperature, and
- to predict the risk of overheating.

2. Method

Tables 1, 2 and 3 present an overview, the experimental conditions, and the cases. The experimental conditions were the same in summer and winter. Figures 1 and 2 show the experimental setup and schedule. The subjects are 39 healthy male and female university students. After changing into special attire for the experiment, the subjects rest for 60 minutes in an anteroom (in front of the experiment room) which was maintained at about 27°C. Then, they moved into the experiment room and stayed for 60 or 45 minutes. During this period, their skin temperature, core temperature and water loss were measured. Based on ISO 9886 (2004), the skin temperature is measured every minute at eight points using a portable temperature logger and probe. The core temperature was measured as the tympanic temperature every five minutes using an infrared radiation sensor. The amount of sweating and bodily water lost, including the amount of evaporation due to breathing, and the weight decrease were measured every five minutes using a precise scale. They also recorded a thermal sensation vote, thermal comfort and thermal tolerance every five minutes (Appendix 1). The total number of samples collected was 1,807.

Five experiment cases were designed by changing the air temperature (T_a), relative humidity (RH) and metabolic rate (met). Case 1 represents the standard case, and a metabolic rate of 1.0 was achieved by sitting in a chair in a resting condition. Cases 2 and 3 were set to determine the effect of activity, and Cases 4 and 5 were set to determine the effect of high relative humidity and high air temperature respectively.

All the experiments were conducted under still air conditions (0.1 m/s). In Cases 2 and 3, the subjects walk on a treadmill at speeds of 0.9 m/s and 1.4 m/s. For the safety of the subjects, the experimental span for Cases 2 and 3 was shortened to 45 minutes. Each subject wore a standard set of clothes (0.3 clo) in all cases, namely a white T-shirt and white short pants.

Table 1 Outline of the experiment

Experiment	Season	Date	Number of subjects		Case
			Male	Female	
A	Summer	1 to 15 August 2005	6	7	1, 2, 4, 5
B	Winter	9 to 23 January 2006	6	6	1, 2, 3, 4, 5
C	Summer	14 September to 5 October 2006	7	7	1, 2, 3

Table 2 Experimental conditions

Case	Environmental conditions				Human body conditions		Number of subjects	
	Air temperature (°C)	MRT (°C)	Relative humidity (%)	Air movement (m/s)	Metabolic rate (met)	Clothing (clo)	Male	Female
1					1.0		19	20
2			50		2.0		19	20
3	35	35		0.1	3.0	0.3	13	13
4			70		1.0		12	13
5	40	40	50				12	13

Table 3 Experimental method and equipment

Description	Method	Equipment	Interval (min.)
Core temperature	Tympanic temperature	Morishita Jintan Company: S-30	5
Skin temperature	Eight points (forehead, right back, left upper chest, right upper arm, left lower arm, left hand, right anterior thigh and left calf)	Gram Corporation: LT-8	1
Water loss	–	Sartorius: IS150IGG	5

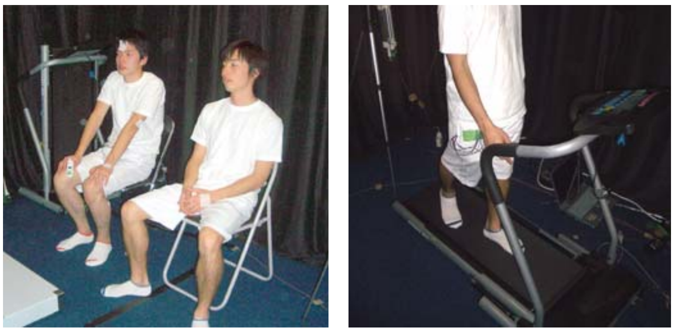

Fig. 1. Photos of the experimental conditions

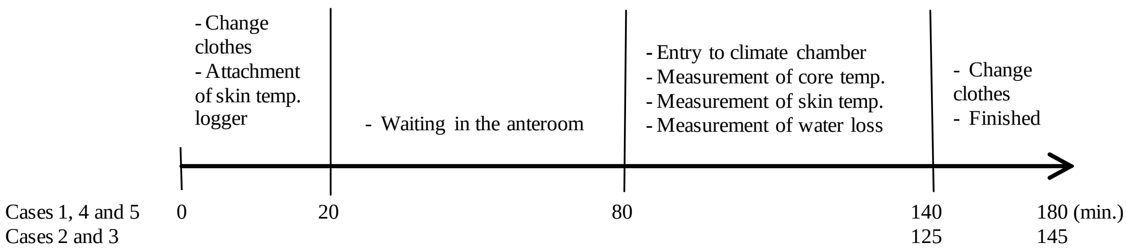

Fig. 2. Schedule of the experiments

3. Results and discussions

In this analysis, the seasonal difference between the summer and winter experiments was analyzed in the paper. However, from the objective of a hot environment evaluation, the summer results are appropriate for any further application. The winter results might be applicable to people who travel from a winter climate (e.g. north hemisphere) to a summer climate (e.g. south hemisphere) within a short time (i.e. by plane).

3.1 Psychological factors

As the experiment progressed, the thermal sensation of each case gradually changed from 'slightly warm' to 'hot', and the subject felt hotter during the summer experiments than in the winter experiments (Fig. 3, Appendix 1). The results indicate that it is not possible to stay for prolonged periods in a hot environment. In the case of high metabolic rates (2 and 3 met), the seasonal differences of the thermal sensation were smaller than with a low metabolic rate (1 met). As for the effect of temperature, the seasonal difference in the thermal sensation of Case 1 (35°C) was larger than in Case 5 (40°C). As for the effect of humidity, the seasonal difference in thermal sensation for Case 1 (50%) was also larger than in Case 4 (70%). These results are similar for thermal comfort and thermal tolerance (Figs. 4 and 5, Appendix 1). The correlation coefficient between the psychological factors was higher during the summer experiments except for thermal comfort and thermal tolerance (Table 4).

Table 4 Correlation coefficient between psychological factors

Season	Number of observations	TS:TC	TS:TT	TC:TT
Summer	1,049~1,059	0.75	0.61	0.68
Winter	708	0.55	0.43	0.70
All	1,757~1,767	0.68	0.56	0.72

TS: Thermal Sensation, TC: Thermal Comfort, TT: Thermal Tolerance, All correlation coefficients are statistically highly significant (p<0.001)

3.2 Physiological factors

As the experiments progressed, the core temperature gradually increased, with the value for summer experiments higher than winter experiments (Fig. 6). However, the mean skin temperature is higher in the first half of the summer experiments, while the opposite is true in the second half of the experiments (Fig. 7). The reason could be that while the experiment is in progress, the cumulative water loss gradually increases (Fig. 8), and thus the mean skin temperature is lowered due to the latent heat lost from evaporation. Such cumulative water loss was higher among men than women (Fig. 9). The results showed that subjects adapt to the hot environment by changing their core temperature, skin temperature and through water loss.

Saito *et al.* (1992) also conducted experiments in an environment with an air temperature of 34°C and relative humidity of 50% in various seasons, which is similar to Case 1. Clothing insulation was rated at 0.4 clo. They also found similar seasonal differences in the mean skin temperature.

The correlation coefficient between physiological factors is higher in the winter experiments except for the mean skin temperature and water loss (Table 5). The correlation coefficient of the core temperature and mean skin temperature in winter is higher than in the summer experiments (Fig. 10). This may relate to seasonal differences in water loss. The reason could be that if the air temperature is high, the skin temperature increases, and consequentially the core temperature also increases.

Table 5 Correlation coefficient between physiological factors

Season	Number of observations	T_c:T_{sk}	T_c:W	T_{sk}:W
Summer	1,049~1,062	0.40	0.28	0.40
Winter	675~705	0.69	0.50	0.35
All	1,724~1,767	0.48	0.39	0.33

T_c: Core temperature (°C), T_{sk}: Skin temperature (°C), W: Cumulative water loss (g/m^2), All correlation coefficients are statistically highly significant (p<0.001)

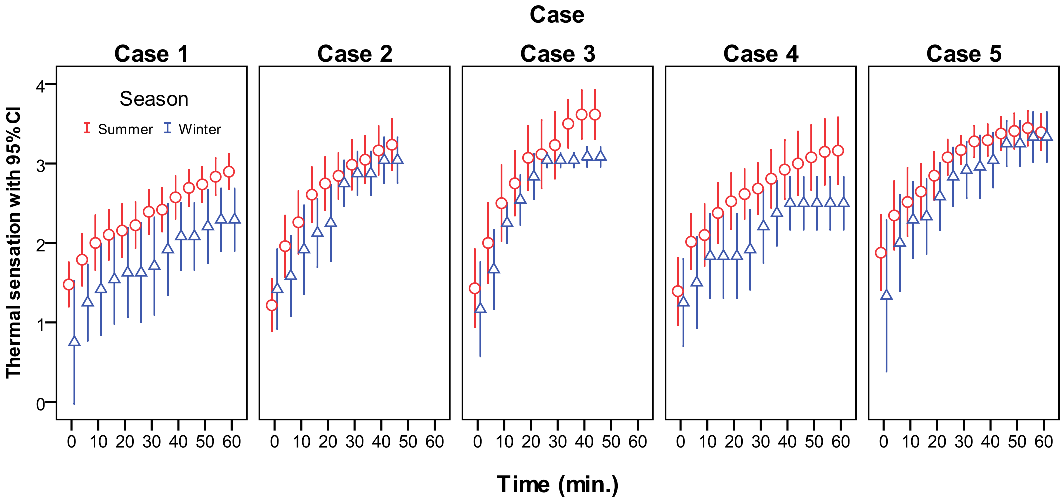

Fig. 3. Thermal sensation with 95% confidence intervals

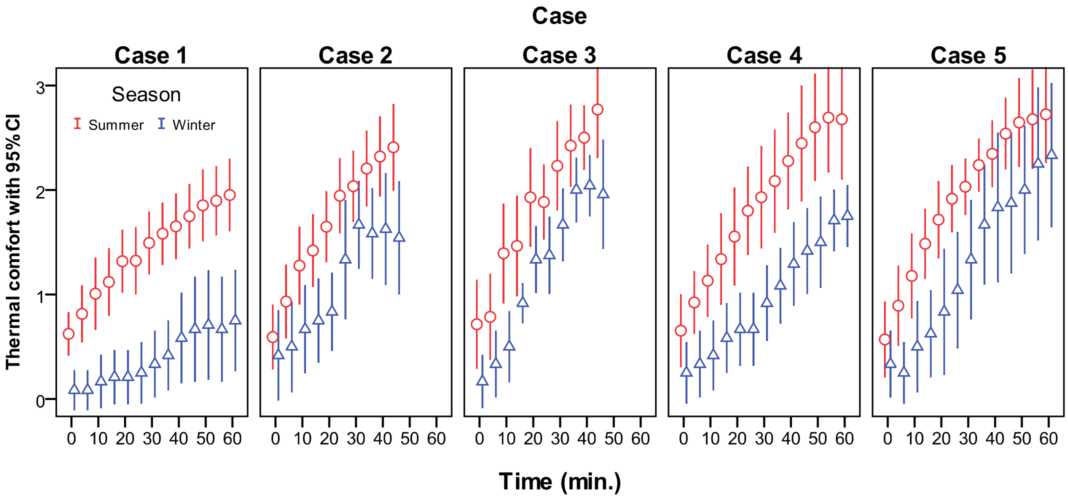

Fig. 4. Thermal comfort with 95% confidence intervals

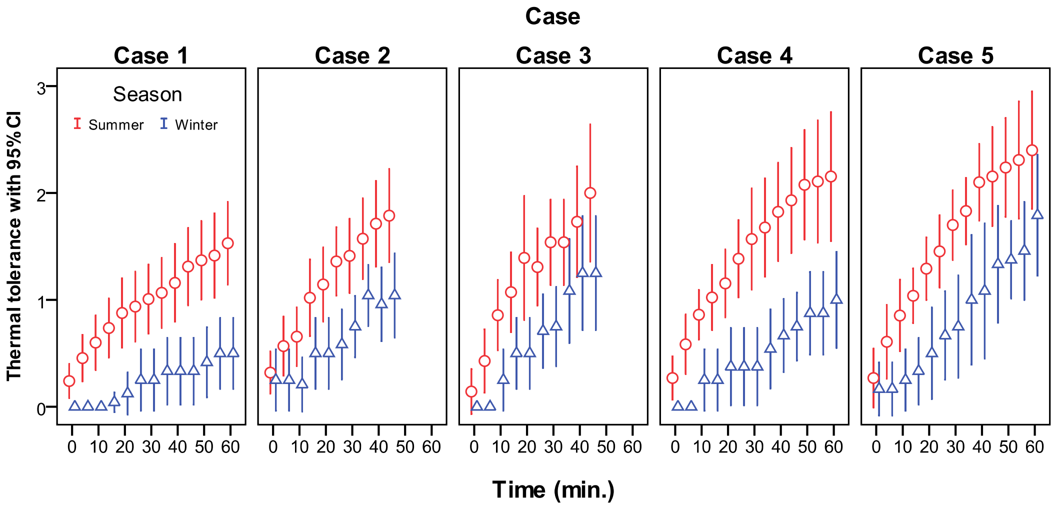

Fig. 5. Thermal tolerance with 95% confidence intervals

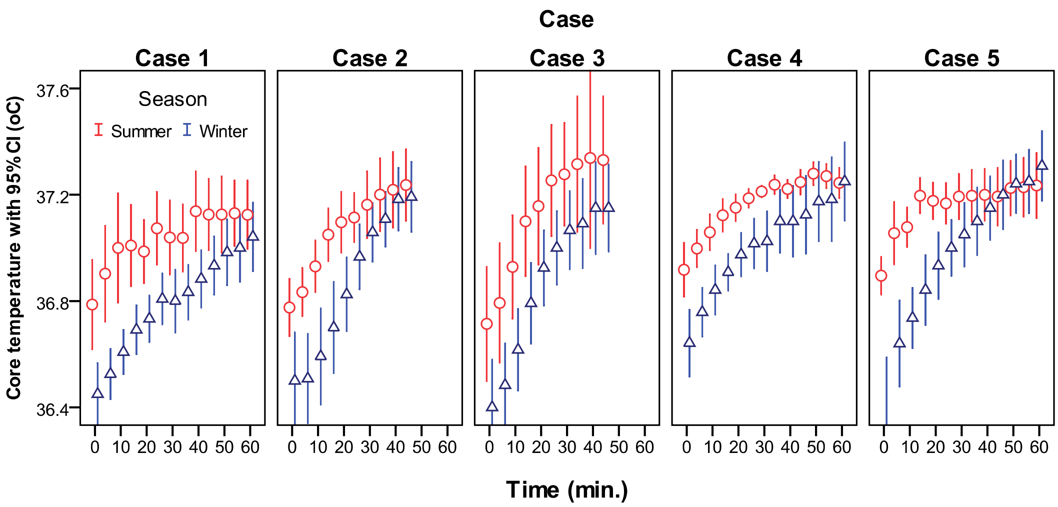

Fig. 6. Core temperature with 95% confidence intervals

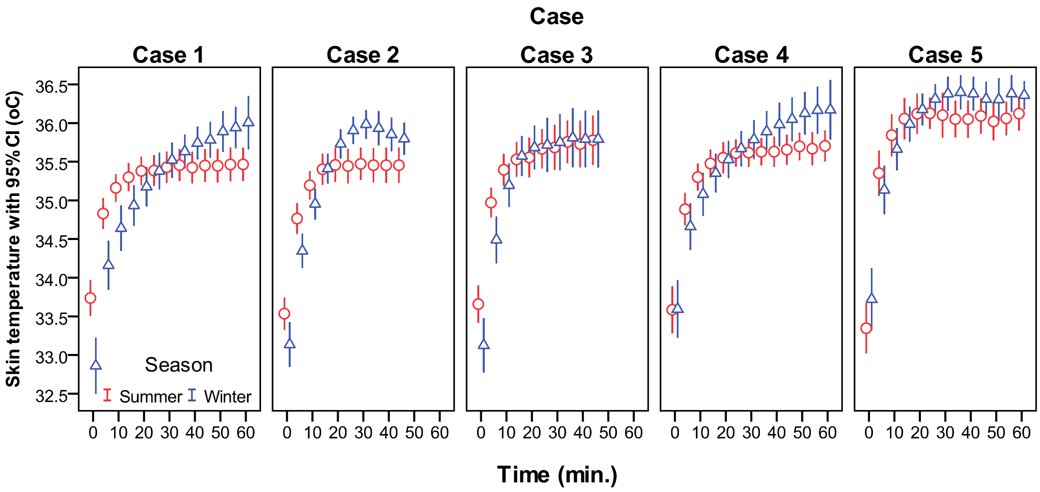

Fig. 7. Skin temperature with 95% confidence intervals

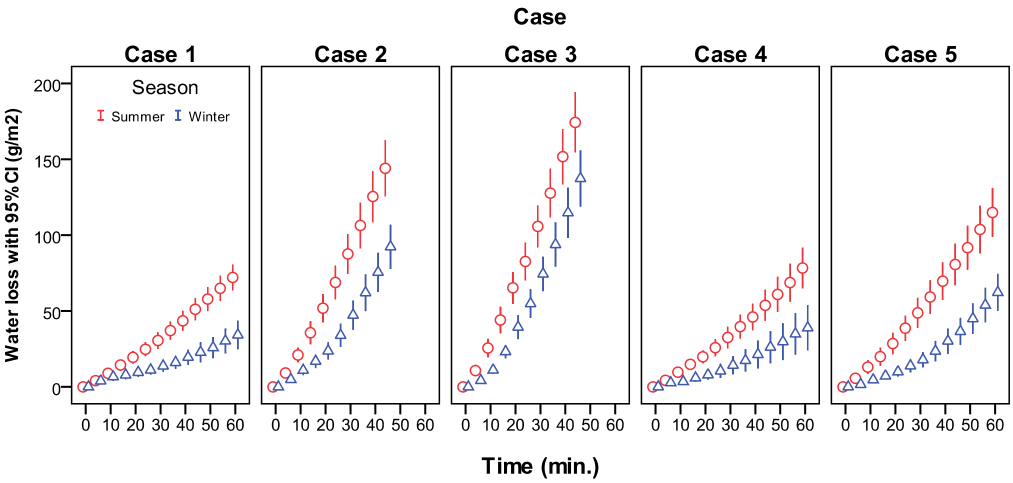

Fig. 8. Cumulative water loss with 95% confidence intervals

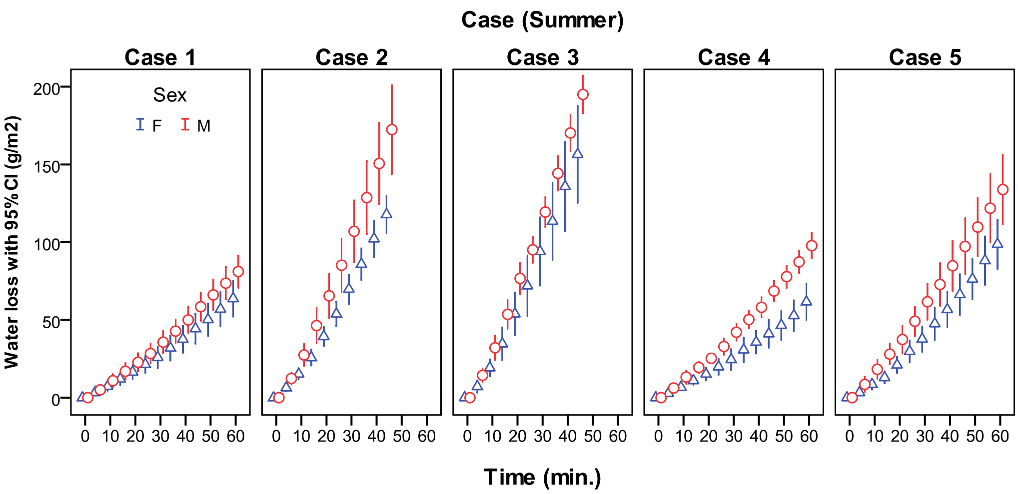

Fig. 9. Cumulative water loss with 95% confidence intervals for male and female subjects

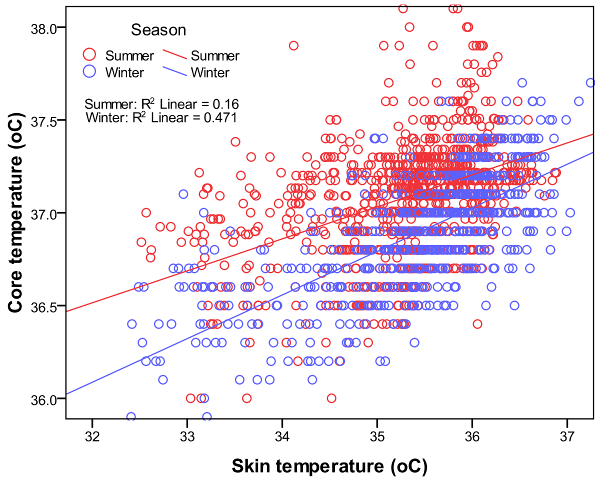

Fig. 10. Relationship between core and skin temperatures

Table 6 Correlation coefficient between psychological and physiological factors

Season	Number of observations	Thermal sensation (TS)			Thermal comfort (TC)			Thermal tolerance (TT)		
		TS:T_c	TS:T_{sk}	TS:W	TC:T_c	TC:T_{sk}	TC:W	TT:T_c	TT:T_{sk}	TT:W
Summer	1,036~1,049	0.25	0.47	0.47	0.21	0.48	0.49	0.35	0.52	0.41
Winter	678~708	0.48	0.51	0.46	0.47	0.43	0.53	0.38	0.37	0.44
All	1,714~1,757	0.37	0.47	0.48	0.38	0.39	0.54	0.41	0.39	0.47

T_c: Core temperature (°C), T_{sk}: Skin temperature (°C), W: Cumulative water loss (g/m^2), All correlation coefficients are statistically highly significant (p<0.001).

3.4 Prediction of the comfortable temperature

3.4.1 Regression method

The correlation coefficient between psychological and physiological factors is shown in Table 6. The correlation coefficient of the thermal sensation and skin temperature is high (Table 6, Fig. 11), and the following regression equations are obtained.

Summer experiments: TS=0.553 T_{sk}-17.0 (n=1036, r=0.47, p<0.001) (1)

Winter experiments: TS=0.512 T_{sk}-15.9 (n=678, r=0.51, p<0.001) (2)

The regression coefficient was similar during both summer and winter experiments. Even though there are only a few data readings around neutral, when we predict the comfortable (neutral) skin temperature using these equations, it would be 30.7°C and 31.1°C for the summer and winter experiments respectively. In summer, subjects felt hotter than in winter, and thus the comfortable skin temperature is lower in summer.

The experimental air temperature in this research was higher than in existing research, and thus the comfortable skin temperature in this research is lower than existing research (Table 7). However, if we extract temperatures where the subjects voted ‘neutral’, ‘comfortable’ and ‘tolerable’, the results are similar to existing research (Table 8).

The data was averaged for each case and voting time, and the results are shown in Fig. 12. The correlation coefficient of thermal sensation and skin temperature is high for both summer and winter experiments (r=0.83). The results showed that the accuracy of the regression model is improved by the average data. Similarly, when we analyze the relationship between the thermal sensation and core temperature, the correlation coefficient is high for both summer and winter experiments (Fig. 13).

Table 7 Comfortable skin temperatures based on existing research

References	Season	Comfortable skin temp. (°C)
de Dear *et al.* (1991)	-	33.1
Fanger *et al.* (1974)	Summer	33.2 (Morning), 33.7(Evening)
Hayakawa *et al.* (1988)	Summer, Winter	30 ~ 34
Hayakawa *et al.*(1989)	Summer	33.5 ~ 34
Horikoshi *et al.* (1975)	Spring	33.5 ~ 34
Isoda *et al.* (1975)	Summer, Autumn, Winter	33.5 ~ 34.5
Jeong *et al.* (1997)	Summer, Spring, winter	33 ~ 35
Kubo *et al.* (1992)	Spring ~ Summer	32.5 ~ 34
Kubo *et al.* (1997)	Summer	33 ~ 34
Miyamoto (2007)	Winter	33.1 (male), 33.6 (female)
Ogawa *et al.* (1974)	Winter ~ Spring	33
Okuma *et al.* (2007)	Summer	33.8
Okuma *et al.* (2008)	Winter	33.5
Sassa *et al.* (2000)	Summer	33.9
Sassa *et al.* (2001)	Winter	34
Sassa *et al.* (2001)	Summer	32.2 ~ 34.2
Shimura *et al.* (1996)	Summer	33 ~ 34
Tanabe and Kimura (1986)	Summer	33.9
Tsuzuki *et al.* (1991)	Autumn	32.5
Tsuzuki *et al.* (1992)	Summer	28 ~ 33
Winslow and Herrington (1949)	-	33.5

Table 8 Environmental conditions of subjects when voting 'neutral', 'comfortable' and 'tolerable'

Description (Scale)	Season	Core temp. (°C)			Skin temp. (°C)			Cumulative water loss (g/m^2)		
		N	Mean	SD	N	Mean	SD	N	Mean	SD
Thermal sensation (Neutral)	Summer	11	36.9	0.2	11	34.1	0.8	11	3.8	5.5
	Winter	23	36.5	0.2	23	34.6	1.0	23	7.7	6.2
Thermal comfort (Comfortable)	Summer	97	36.9	0.3	96	34.5	0.9	97	9.4	12.5
	Winter	242	36.7	0.3	241	35.0	1.1	243	10.4	13.2
Thermal tolerance (Tolerable)	Summer	238	36.9	0.4	237	34.7	0.9	238	24.1	33.5
	Winter	380	36.8	0.3	374	35.1	1.0	381	16.7	23.3

N: Number of observations, SD: Standard Deviation

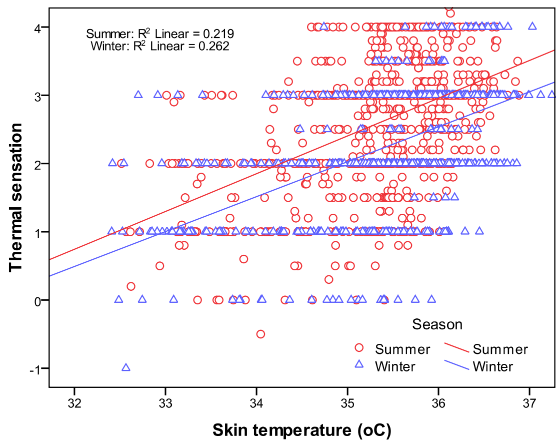

Fig. 11. Relationship between thermal sensation and skin temperature

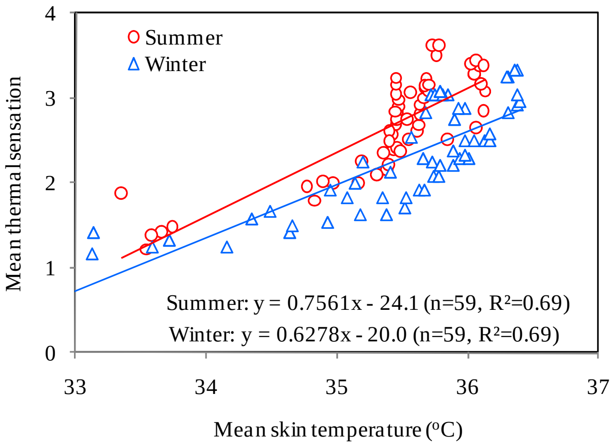

Fig. 12. Relationship between thermal sensation and skin temperature. Each point includes 12 to 27 data readings. All regression coefficients or correlation coefficients are significant (p<0.001).

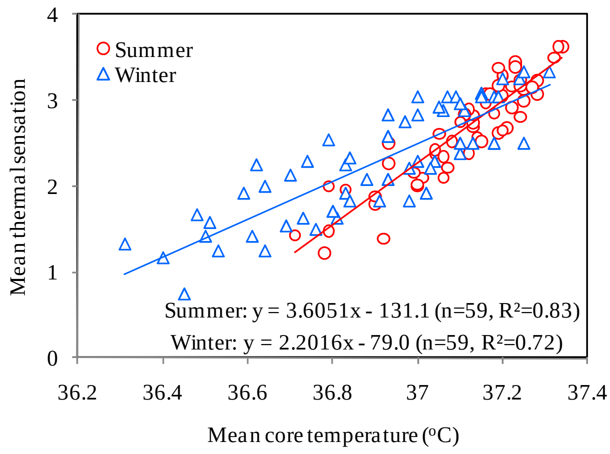

Fig. 13. Relationship between thermal sensation and core temperature. Each point includes 12 to 27 data readings. All regression coefficients or correlation coefficients are significant (p<0.001).

3.4.2 Griffiths' method

Prediction of a comfortable temperature using the conventional regression method sometimes gave an unreliable value for field data (Nicol *et al.*, 1994; Rijal *et al.*, 2002), and thus the comfortable skin temperature also predicted by Griffiths' method (Griffiths, 1990; Nicol *et al.*, 1994; Rijal *et al.*, 2008) was used to validate the comfortable skin temperature calculated using the regression method. In the Griffiths' method, the comfortable temperature can be predicted for each thermal sensation vote, and thus can be analyzed from various aspects. The comfortable skin temperature (T_{skg}) based on the Griffiths' method can be predicted by the following equation.

$$T_{skg}=T_{sk}+(0-\text{TS})/a \qquad (3)$$

where, TS is thermal sensation, T_{sk} is skin temperature (°C), a is the regression coefficient, and 0 is the 'neutral' thermal sensation vote. The regression coefficient is assumed to be 0.5 from Equations (1) and (2).

As the experiment progresses, the comfortable skin temperature based on the Griffiths' method gradually declines (Fig. 14). The reason may be that the skin temperature gradually increases as the experiment progresses (see Fig. 7). That is to say, when the skin temperature is low, the comfortable skin temperature is high, and when the skin temperature is high, the comfortable skin temperature is low. The comfortable skin temperature during the summer experiments is lower than in the winter experiments (Fig. 14). The reason could be that the subjects are more exposed in hot summer environments, and thus they might prefer a lower temperature than winter. The comfortable skin temperature calculated using the Griffiths' method is well matched to the regression method (Table 9). This may be due to the assumption of the regression coefficient of the Griffiths' method, which is obtained from the regression method.

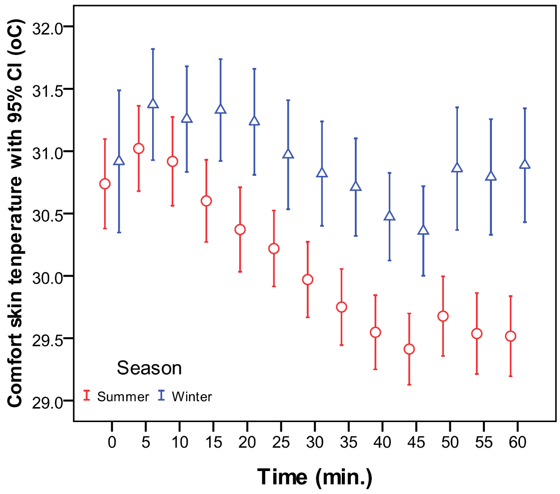

Fig. 14. Comfortable skin temperatures in summer and winter experiments

Table 9 Comparison of comfortable skin temperatures

Season	Comfortable skin temperature (°C)			
	Regression method	Griffiths' method		
		Number of observations	Mean	Standard Deviation
Summer	30.7	1036	30.2	1.6
Winter	31.1	678	30.9	1.6

3.5 Overheating

The difference between the actual and comfortable skin temperatures ($\Delta t = T_{sk}$-T_{skg}) is used to analyze the risk of overheating. People felt too hot when Δt was more than 4°C in both the summer and winter experiments (Fig. 15).

Nicol *et al.* (2009) used logistic regression to predict the overheating risk, and we also applied this method. The logistic regression equations for overheating, based on Δt, are shown in Table 10. The relationship between the probability of overheating (p) and Δt takes the form:

$$\text{logit(p)} = \log\{p/(1-p)\} = b\Delta t + c \quad (4)$$

$$p = e^{(b\Delta t + c)}/\{1+e^{(b\Delta t + c)}\} \quad (5)$$

where b is the regression coefficient for Δt, and c is the constant in the regression equation. The summer overheating risk is significantly higher than in winter experiments for both thermal comfort and thermal tolerance (Figs. 16 and 17). This may be due to the seasonal adaptation of the human body. The results indicate that overheating in the winter experiments might be dangerous for people who travel from winter to summer climates within a short period of time because they might feel less sense of overheating for a given temperature than local people who are already acclimatised to the summer condition. That is to say, when the environment one is exposed to suddenly changes from winter to summer due to travelling, the human body may not respond appropriately in the hot environment. Thus, special consideration may be required to avoid the risk of overheating in such circumstances.

The overheating risk, which was evaluated based on thermal comfort, is higher than the thermal tolerance (Figs. 16 and 17). These results indicate that the degree of overheating risk depends on the evaluation method. In this research, the overheating risk is indirectly defined using thermal sensation, thermal comfort or thermal tolerance. We may need to investigate the overheating risk directly using a similar questionnaire to that used by Robinson and Haldi (2008).

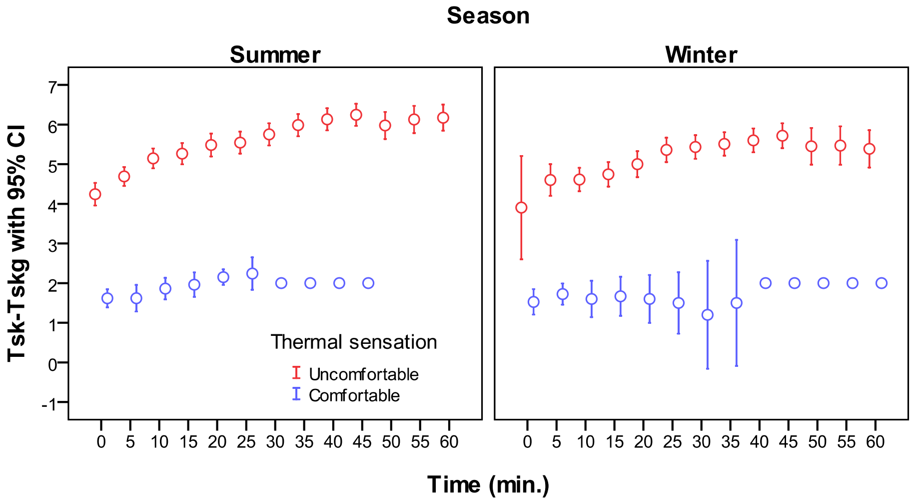

Fig. 15. Difference between actual and comfortable skin temperatures (T_{sk}-T_{skg}) with 95% confidence intervals during summer and winter experiments. The figure is based on a seven-point thermal sensation scale, counting comfortable as the three central categories. The ‘uncomfortable’ categories are assumed to represent an overheating risk.

Table 10 Logistic regression equations for overheating risk

Season	Thermal comfort			Thermal tolerance		
	Equation	n	r	Equation	n	r
Summer	logit(p)=1.404Δt-6.924	1021	0.67	logit(p)=1.042Δt-6.402	1011	0.54
Winter	logit(p)=0.861Δt-5.414	678	0.47	logit(p)=0.827Δt-6.859	678	0.30

logit(p): log{p/(1-p)}, r: correlation coefficient of Cox and Snell

Note: All regression coefficients or correlation coefficients are significant (p<0.001)

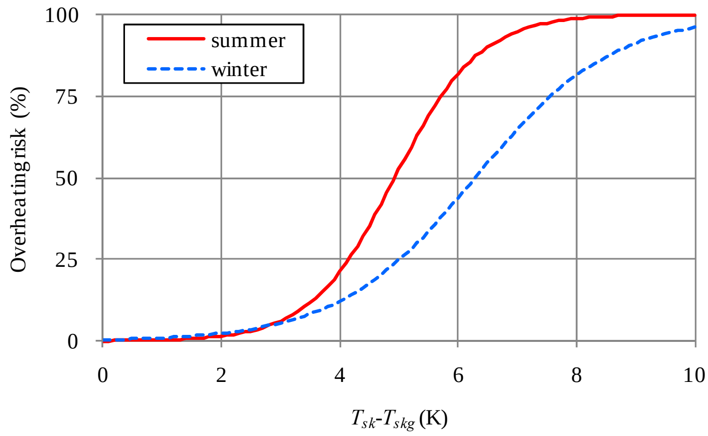

Fig. 16. Proportion of subjects voting 'uncomfortable', 'very uncomfortable', or 'extremely uncomfortable' on the thermal comfort scale (overheating risk) as a function of the difference between the actual and comfortable skin temperatures.

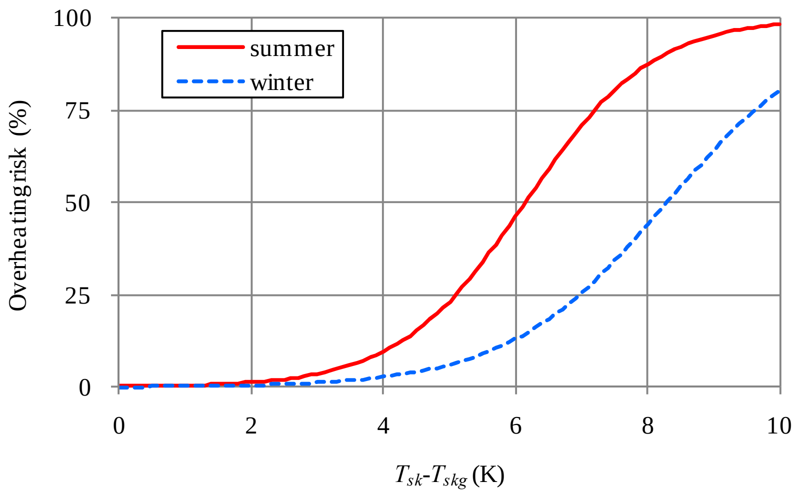

Fig. 17. Proportion of subjects voting 'fairly difficult to tolerate' or 'very difficult to tolerate' or 'intolerable' on the thermal tolerance scale (overheating risk) as a function of the difference between the actual and comfortable skin temperatures

3.6 Relationship between the psychological factors and water loss

Table 6 shows the correlation coefficient of the thermal sensation, thermal comfort, or thermal tolerance and water loss. The correlation coefficient of the water loss and the thermal comfort is highest among the three variables (Table 6). Figure 18 shows the relationship between thermal comfort and water loss. They are highly correlated, and water loss during the summer experiments is more uncomfortable than the winter experiments for a given amount.

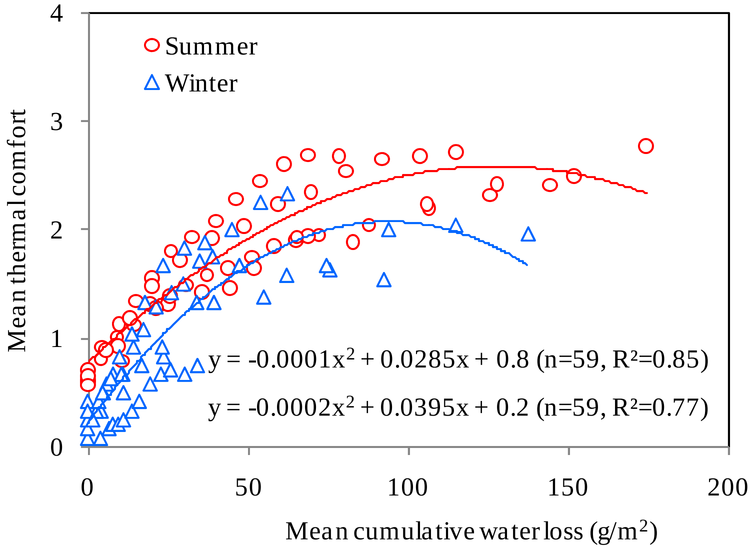

Fig. 18. Relationship between thermal comfort and cumulative water loss. The data was averaged for each case and voting time. Each point includes 12 to 27 data readings. All regression coefficients or correlation coefficients are significant ($p<0.001$).

4. Conclusions

In order to clarify the thermal psychological and physiological response of the human body in hot outdoor environments, subject experiments were conducted in a climate chamber during summer and winter, and the following results are found.

(1) The thermal psychological factors (thermal sensation, thermal comfort and thermal tolerance) and the thermal physiological factors (core temperature, skin temperature and water loss) during the summer experiments were significantly different to the winter experiments. This may reflect the influence of seasonal adaptation.

(2) The comfortable skin temperature predicted by the regression method was 30.7°C in summer, which is well matched to the Griffiths' method.

(3) As the actual skin temperature shifts away from the comfortable skin temperature, the risk of overheating increases. This method can be used to avoid the risk of overheating in hot outdoor environments.

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Appendix 1 Questionnaires for thermal comfort survey

(1) Thermal sensation

Very cold	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	Very hot
-4	-3	-2	-1	0	+1	+2	+3	+4

(2) Thermal comfort

Comfortable	Slightly uncomfortable	Uncomfortable	Very uncomfortable	Extremely uncomfortable
0	1	2	3	4

(3) Thermal tolerance

Perfectly tolerable	Slightly difficult to tolerate	Fairly difficult to tolerate	Very difficult to tolerate	Intolerable
0	1	2	3	4