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Experimental Study on the Effect of Temperature Up-Step on Human Thermal Perception and Skin Temperature between Activity Intensities at Low Ambient Temperatures

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Abstract: In the north of China, during winter, a large number of activities (such as leisure, work, sightseeing and sports) are engaged in. This paper mainly focuses on human thermal perceptions of outdoor activities in a winter climate, especially the change in thermal perceptions when humans enter a temporary rest space with a shelter effect. A climate chamber was applied in our experiments, and temperature up-steps of 4, 8 and 12 °C were set, respectively. Twenty four college students were invited to engage in activities of different intensities, such as standing, walking (slowly) and biking. Through questionnaire survey and field measurement, the subjects' thermal sensation, thermal comfort and skin temperature were obtained. Hypothesis testing and non-linear regression methods were introduced to analyze experiment data. Major results were as follows. After temperature up-step changes, thermal sensation and skin temperature reach steady state within 30 min. However, the change in skin temperature caused by a short-term thermal experience does not disappear completely within 40 min. In addition to the influence of ambient temperature changes, activity intensity also influenced the variation in thermal sensation (subjective) and skin temperature (objective). These study results provide a scientific reference for future research and design of a temporary rest space in low ambient temperatures. Experimental studies including broader age groups and outdoor field tests are valuable for future research.

Keywords: temperature up-step; activities; thermal sensation; cold area; shelter effect

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1. Introduction

1.1. Background

The Beijing 2022 Winter Olympics increased enthusiasm to participate in ice and snow sports. Nearly two-thirds of China are classed as cold and severe cold areas, reserved ice and snow sports. Ice and snow sports are certainly appealing entertainment in winter. Compared to professional athletes, amateurs usually need more time to recover and rest in indoor temporary rest places. However, the inner condition of temporary places is usually poor. There are only some temperature up-steps caused by a shelter effect between outdoors and temporary places. The thermal environment of temporary rest places is very important for amateurs participating in winter sports, and can be enhanced to further improve the quality and experience of ice and snow sports. In addition, some temporary rest places also need to be built for practitioners exposed to low ambient temperatures for a long time and tourists in ice and snow scenic spots.

The number of articles on outdoor human thermal perception is increasing greatly. Many recent studies focus on warmer climates, such as southern China, Southeast Asia, America and islands in the Mediterranean [1–8]. While Ozarisoy [9] describes the relation between thermal comfort and energy use, it is important to carry out research in cold and severe cold areas, since outdoor conditions are usually very bad in winter. Chen et al. conducted an outdoor thermal sensation and thermal comfort survey in Harbin City (a severe cold area in China) a year ago, and concluded that thermal comfort is affected by regional and seasonal diversity [10]. The study focused on annual variation in human thermal sensation. Lu et al. investigated outdoor thermal sensation features in severe cold areas. The investigation showed that ambient temperature has a greater effect on thermal sensation in winter [11].

In addition to the ambient temperature itself, the temperature step will be one of the key factors that affects peoples' experience when migrating between different thermal environments, for example from outdoors to semi-outdoors or indoors. Therefore, it is indispensable to study the effect of temperature up-steps on human thermal perception.

The effect of a temperature step on human thermal perception has been studied for several decades. In the 1960s, Gagge et al. [12] carried out an early experiment on temperature steps by climate chamber experiments, with two fundamental findings about thermal sensation and skin temperature. In recent years, with the improvement in comfortable environments and the implementation of energy conservation and carbon reduction policies, relevant research on thermal comfort and thermal sensation have attracted more attention. Related research generally focused on the effect of temperature steps on human thermal perception under summer conditions in the tropical and subtropical zones. These temperature steps represent the temperature difference between an air-conditioned room and outdoors, or the temperature difference between an air-conditioned room and a naturally ventilated room. The effects of a temperature step on human thermal perception (such as thermal comfort and thermal sensation) and skin temperature were the main research contents. The variation in thermal sensation and thermal comfort under a temperature step (30~20 °C) was studied [13], and the effects of ambient two-direction temperature changes on subjects' thermal perceptions were also researched [14,15]. Xiong et al. [14] further analyzed the relationship between the whole thermal sensation and part thermal sensation. Mihara et al. [15] the time taken for thermal responses to reach steady state by least squares approximation. Focusing on conditions of higher ambient temperature, Qi et al. [16] carried out an artificial climate chamber experiment to simulate step change under different temperatures (26 °C~28/30/32 °C~26 °C), wind speed and clothing thermal resistance, and found an "overshooting phenomenon" of thermal sensation during step change. These study conclusions showed that among thermal environment parameters, the ambient temperature is the most important factor. Studies on temperature steps, thermal neutral temperature, the variation rate of ambient temperature and human thermal perceptions (such as thermal comfort and thermal sensation) were also involved. Nagano et al. [17] studied the difference in neutral temperature caused by temperature steps by using regression analysis. Combining the results for subjective evaluation and physiological response, Liu et al. [18] analyzed the correlation between thermal sensation and skin temperature and the corresponding variation rate. Further, the influence of temperature steps on human physiological health also attracted more attention. Perspiration, nausea, giddiness, accelerated respiration and heart rate [19], as well as changes in the immune system, the thermal metabolism system [20], dopamine and blood oxygen saturation [21], caused by temperature steps were investigated. In addition, researchers focused on special groups, and found further results about temperature steps on gender, age and occupation. Xiong et al. [22] analyzed gender differences in the reaction to temperature steps. Wang et al. [23] studied the reaction of older groups to temperature steps. In the University of Malaya, the impact of temperature steps on the subjective perception of ten female students was studied [24]. Liu et al. [25] analyzed the impact of temperature steps on the thermal perception and learning performance of Chinese college students. In previous research, scholars conducted in-depth analysis on the impact of temperature steps on thermal perceptions in tropical and subtropical areas. The results showed that temperature steps of 4 [26], 5 [27] and 6 °C [28] result in significant changes in human thermal perception.

Considering the great differences in ambient temperatures and clothing conditions between winter and summer, human thermal perceptions caused by temperature steps should be different from each other. However, there were a small number of experimental studies on temperature steps at low ambient temperatures. Some studies mainly focused on medical treatment such as cardiac mechanics and function [29], thermogenesis and thermoregulation [30], and vasomotor responses and thermoregulatory mechanisms [31]. In addition, research on building thermal environment and thermal perceptions mainly focused on the temperature difference between indoor space and outdoors. Xiong et al. [32,33] selected two activities (office and walking) and two levels of clothing insulation (1.2 clo and 1.7 clo), and adopted a climate chamber to investigate human thermal perceptions, skin temperatures and electrocardiograph caused by typical temperature differences (20 °C~10/0/−20 °C~20 °C) between indoor space and outdoors in severe cold cities in China. Local thermal sensation and physiological reactions, such as cold hands or feet, dizziness and giddyness, runny nose, and dry throat, were also analyzed. Wu et al. [34] studied human thermal perceptions when exposed to extreme cold and neutral environments. The results have great significance for extreme cold protection. Yu et al. [35] focused on the influence of the temperature step between a temporary place (such as supermarkets) and ambient environments on thermal neutral temperature. The study took Tianjin city as an example, and discussed the acceptable temperature ranges of a temporary place.

Although there are some studies on the effect of a temperature step at low ambient temperatures, from the perspective of activity intensities, only a few papers involve different activity intensities (not only sedentary state). Mihara et al. [15] investigated the effects of a temperature step caused between air-conditioned rooms and outdoors at warm temperatures with two different metabolic rates. Lu and Li [36] adopted sitting as a low-metabolic-rate activity and adopted walking as middle-metabolic-rate activity in the field test. Under summer conditions, a low-metabolic-rate activity (such as sedentary state) could be chosen. However, under winter conditions, humans need to stay at low ambient temperatures for a long time. Considering heat balance in the human body, humans generally need to engage in certain metabolic rate activities at low ambient temperatures. Thus, when experiments on human thermal perceptions at low ambient temperatures are carried out, adopting activities at different metabolic rates, representing work and sports, etc., is necessary.

1.2. Study Goals

It can be concluded from the literature review that the influence of temperature steps on human thermal perceptions needs to be studied further. To make a temporary rest space play a better role in outdoor activities at low ambient temperatures, this paper studied the change in thermal perception and body temperature regulation when humans are confronted with temperature up-steps in a winter climate through a shelter effect of a temporary space e. The specific goals of this study were: (1) analyzing the temporal changes in thermal sensation, thermal comfort and skin temperature under temperature up-steps; (2) examining the effect of different metabolic rates (activity intensities) on subjective thermal sensation and objective skin temperature changes; and (3) studying the relationship between subjective thermal sensation and objective skin temperature following temperature up-steps. As more and more people hope to spend activity time outdoors in winter, our goal is to demonstrate the body temperature regulation events under different temperature up-steps and metabolic rates in winter conditions. This research may also help architects to set suitable temperatures for a temporary rest space with a shelter effect.

2. Materials and Methods

2.1. Experimental Platform

The experiments were carried out from November of 2019 to April of 2020 in a climate chamber at Harbin Institute of Technology (located at the Harbin city-center). Harbin city (45°41′ N 126°37′ E) is the capital of Heilongjiang province in China, which is a severe cold area, and belongs to Climate Zone 7 according to ASHRAE 169-2020 [37]. The heating season of Harbin city is 176 days, and the average air temperature of one heating season is below −10 °C.

The climate chamber (length × width × height = 8.4 m × 4.2 m × 3.1 m) was separated into two sections (Room A and Room B) by a 150 mm thick steel plate and a polyurethane insulation layer, which was arranged as insulation. Air in the two rooms was processed by refrigeration units, heaters and humidifier. Ceiling supply and sidewall return were adopted. Room air temperature could be set in the range of −40~40 °C, with an accuracy of ±0.2 °C (Room A had a range of −40~40 °C and Room B had a range of −10~40 °C). The RH could be controlled between 10% and 90%, with an accuracy of ±3%. Air velocity could be adjusted between 0.1 and 4 m/s, with an accuracy of ±0.3 m/s. A schematic representation of the climate chamber at Harbin Institute of Technology is shown in Figure 1. The area covered by the subject and equipment is approximately 1.2 m^2, and the occupancy rate is lower than 8% in each room.

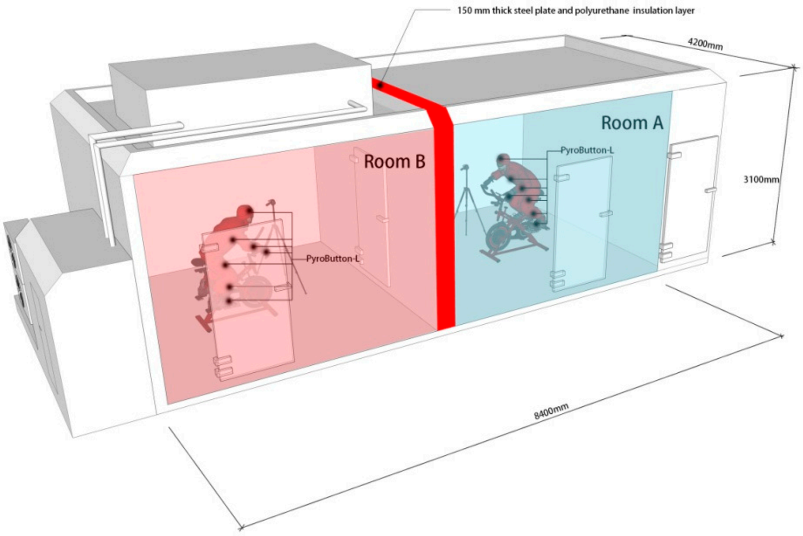


Figure 1. A schematic representation of the climate chamber.

The experimental design focused on thermal sensation, thermal comfort and skin temperature changes under different temperature up-steps. In order to realize the preliminary quantitative comparison, tasks of two intensities with different metabolic rates were chosen here to represent common winter outdoor activities, such as leisure, work and sports. In [38], subjects were invited to ride a spinning bike at a fixed speed (20 km/h). The metabolic rates of the two activities were estimated according to ISO-7730: 2005 [39]. Biking is adopted as high activity, which is approximately 2.5 met. Standing and walking (slowly) are adopted as light activity, which is approximately 1.5 met.

2.2. Subjects

A total of 24 university students (including 12 female) were recruited. Anthropometric information of participants is shown in Table 1. Healthy university students, who were not taking any prescription medication at the time, were recruited as subjects. Since caffeine, alcohol, strong tea, and intense physical activity can stimulate the human central nervous system and affect human perception, subjects were required to avoid caffeine, alcohol, strong tea, and intense physical activity at least one day before the experiment. In order to reduce the impact of clothing differences on experimental results, all subjects were asked to wear uniform ski suits (approximately 1.5 clo). Estimation of thermal insulation of clothing ensembles was based on ISO-7730: 2005 [39].

Table 1. Main information of participants.

Gender	No.	Age (Years)	Height (cm)	Weight (kg)	BMI [1] (kg/m^2)	As (m^2)
Male	12	24 ± 2	178.9 ± 5.9	74.1 ± 8.6	23.2 ± 2.5	1.8 ± 0.1
Female	12	22 ± 2	165.4 ± 3.0	50.0 ± 3.7	18.3 ± 1.9	1.5 ± 0.1
All	24	23 ± 2	172.2 ± 8.3	62.1 ± 13.9	20.7 ± 3.3	1.6 ± 0.2

[1] BMI and As represent body mass index and body surface area.

This study was approved by the professors' associates in the School of Architecture and the Key Laboratory of Cold Region Urban and Rural Human Settlement Environment Science and Technology at Harbin Institute of Technology. Written informed consent was acquired from all participants before the experiment began. Participants were informed about the goal and content of the experiment, privacy, and data protection. Participation in the experiment was voluntary. Biological samples were not collected.

2.3. Measurements

Experimental instruments used to measure the environmental variables and skin temperature are listed in Table 2. Air velocity was lower than 0.1 m/s. During the experiment, the mean radiant temperatures were always relatively similar to the corresponding air temperatures.

Table 2. Experimental instruments.

Measurement	Type	Specification
Air temperature	BES-02B	Range: −20~70 °C; accuracy: ±0.3 °C
Relative humidity	BES-02B	Range: 0~100%; accuracy: ±3%
Air velocity	FLUKE 925	Range: 0 m/s~25 m/s; accuracy: ±0.01 m/s
Global temperature	JTR 04A	Range: −20~125 °C; accuracy: ±0.2 °C
Skin temperature	PyroButton-L	Range: −10~65 °C; accuracy: ±0.1 °C

During this study, subjects noted their thermal sensation and thermal comfort according to a ASHRAE 7 point continuous voting scale [40]. Subjects' skin temperatures were measured on seven body positions, as shown in Figure 2. Skin temperature was calculated as seven local skin temperatures expressed in Equation (1) [19].

$$t_{skin} = 0.07t_{head} + 0.35t_{trunk} + 0.14t_{forearm} + 0.05t_{hand} + 0.19t_{thigh} + 0.13t_{leg} + 0.07t_{foot} \quad (1)$$

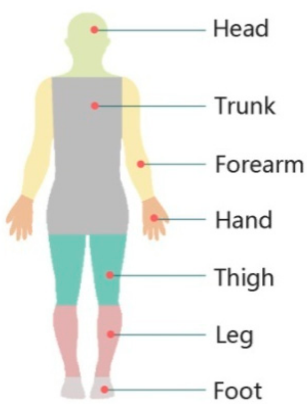


Figure 2. Skin temperature measurement locations.

The experimental condition and scene are shown in Figure 3.

Figure 3. The experimental condition and scene.

2.4. Experimental Procedures

The lowest temperature, −12 °C, selected in this experiment is similar to the average outdoor air temperature in heating seasons in severe cold areas in China [41]. As described in Table 3, four ambient temperatures (0, −4, −8 and −12 °C) were set in Room A; a fixed ambient temperature (0 °C) was set in Room B. The temperature up-steps were 4, 8 and 12 °C, respectively. To avoid order effects, subjects were required to experience the four ambient temperatures in different orders.

Table 3. Experimental temperatures.

Conditions	Stage 1 (Room A)		Stage 2 (Room B)	
	T (°C)	RH (%)	T (°C)	RH (%)
S0 [1]: 0 to 0 °C	0.1 ± 0.3	43.9 ± 4.7	0.2 ± 0.2	42.8 ± 5.5
S4: −4 to 0 °C	−4.1 ± 0.4	44.9 ± 5.1	0.2 ± 0.3	42.3 ± 3.9
S8: −8 to 0 °C	−7.9 ± 0.3	45.8 ± 4.6	0.3 ± 0.3	41.6 ± 3.3
S12: −12 to 0 °C	−12.0 ± 0.3	47.0 ± 5.3	0.2 ± 0.2	43.2 ± 4.2

[1] S0 was used as a reference condition only.

To ensure subjects reached initial thermal balance, a period of preparation was used. As shown in Figure 4, subjects spent approximately 15 min in Room A (a climate chamber with lower temperatures). During preparation, temperature sensors were attached to subjects. Then, the subjects were told to sit, stand or walk in Room A to mitigate the effect of a short-term thermal experience. After preparation, subjects began to engage in low activity (including sitting, standing or walking) or high activity (biking). This period of activities in Room A takes 20 min. Then, subjects entered Room B (a climate chamber with a higher temperature), which is directly adjacent to Room A. They engaged in the same activities for another 40 min. Each test included 60 min with subjects skin temperature monitored. As shown in Figure 4, the duration of each test is 75 min (including 15 min for preparation). Subjects were asked to fill out questionnaire at 0, 1, 3, 5, 10, 20, 30 and 40 min. Every subject engaged in two activities of different intensities (low activity and high activity) at four temperatures (S0, S4, S8 and S12), as shown in Table 3. The conceptual framework of the experimental study is expressed in Figure 5.

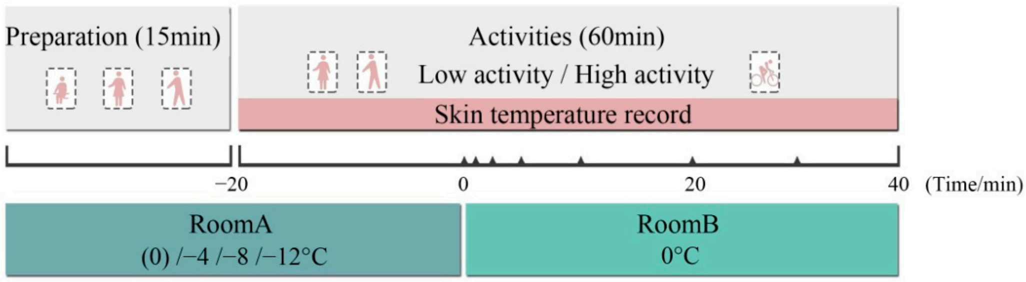


Figure 4. Experimental procedures. Survey points were set at the 0, 1st, 3rd, 5th, 10th, 20th, 30th and 40th min.

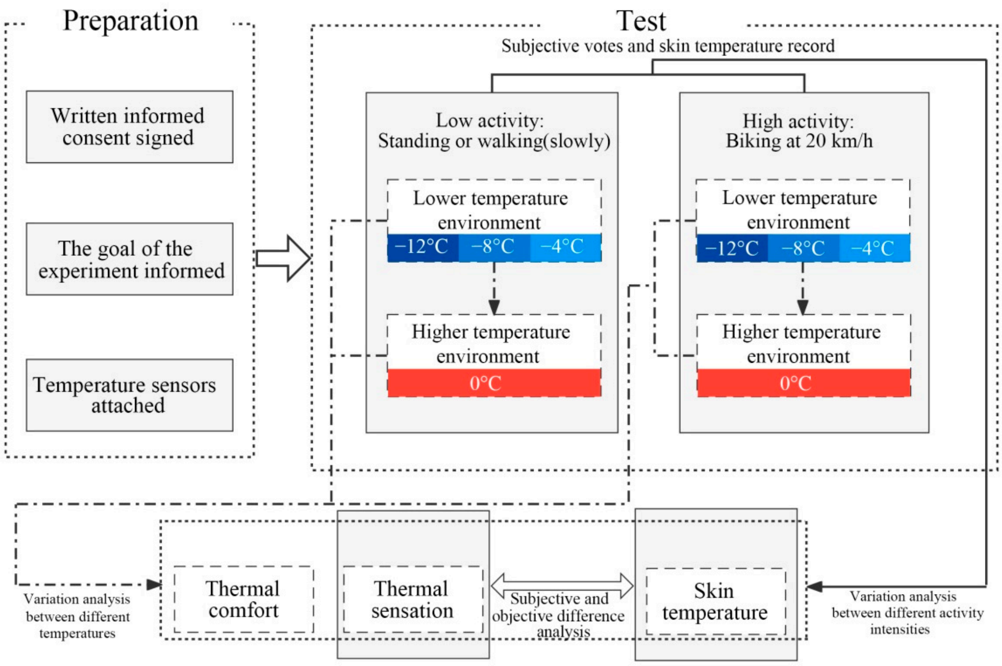


Figure 5. The conceptual framework of the experimental study.

2.5. Data Analysis

Student's *t*-test was applied in this paper. SPSS 22.0 was used to implement statistics and analysis. The significance level was $p < 0.05$.

Subjective evaluation results were fitted by a non-linear regression method to estimate the time taken to reach steady state (Equation (2)), as in [15].

$$y = A + B \cdot \exp(-t/\tau) \quad (2)$$

where y is the predicted or measured result, A and B are regression equation coefficients, t is the elapsed time (in min), and τ is the time constant (in min). In Equation (2), the predicted or measured results reach steady state when they reach 95% of the whole change. This is the time taken to reach steady state for the predicted or measured results, corresponding to 3τ [15].

3. Results

3.1. Thermal Sensation

Subjects' thermal sensation under different temperatures is shown in Figure 6.

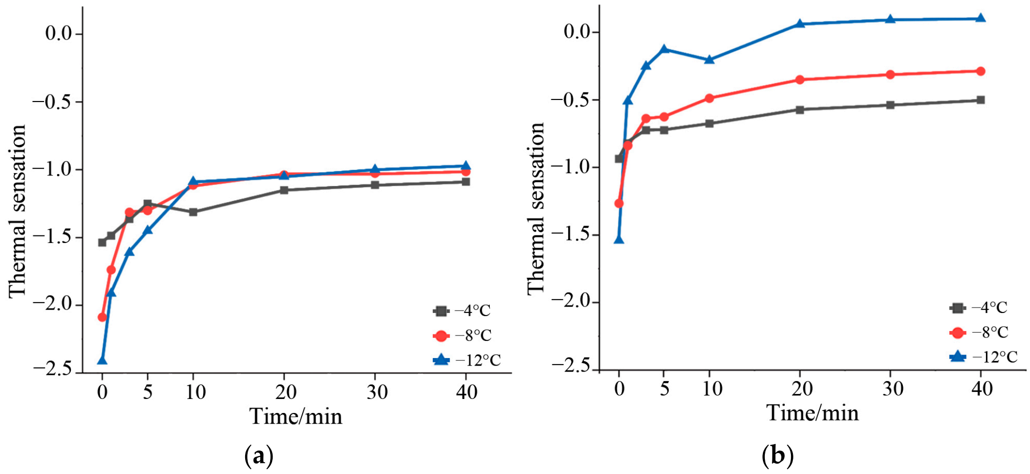


Figure 6. Thermal sensation. (**a**) Low activity; (**b**) high activity.

In Figure 6, comparing thermal sensation at 0 and 40 min, the increase in thermal sensation was 0.45, 1.08, and 1.44 for S4, S8 and S12 under the low activity condition, while the increase in thermal sensation was 0.44, 0.98, and 1.64 for S4, S8 and S12 under the high activity condition. Thus, there was an increase in thermal sensation with an increase in temperature up-step. In the last survey (40 min), under the low activity condition, thermal sensation was similar, i.e., −1.09, −1.01 and −0.98, for S4, S8 and S12, as shown in Figure 6a; under the high activity condition, thermal sensation was quite different, i.e., −0.50, −0.29 and 0.10, of S4, S8 and S12, as shown in Figure 6b.

Further, Figure 6 shows that the thermal sensation was higher for S12 than for S8 and S4. In other words, there was an increase in temperature up-step with an increase in the difference in thermal sensation, especially in the thermal sensation under the high activity condition. A slightly warm thermal sensation was noted after 20 min for S12. The main reason for this was that humans maintain a high metabolic rate at a high activity level, thus producing more heat.

A non-linear regression method was employed to estimate time taken to reach steady state for thermal sensation. The results, calculated by Equation (2), are shown in Table 4. Further analysis and discussion will be carried out in the discussion chapter (Section 4.1).

Table 4. The time taken to reach steady state for thermal sensation and skin temperature.

Conditions	Thermal Sensation		Skin Temperature	
	Low Activity	High Activity	Low Activity	High Activity
S4	9.72 [1]	16.42	14.71	17.06
S8	9.78	25.00	25.39	27.78
S12	15.03	26.26	27.45	26.17

[1] The time taken to reach steady state was considered as 3τ in Equation (2), min.

Student's *t*-test was employed in this paper to analyze the difference in subjective voting results at all survey time points (after entering Room B). The significance level of Student's *t*-test was 0.05 ($p < 0.05$). The analysis results are shown in Table 5.

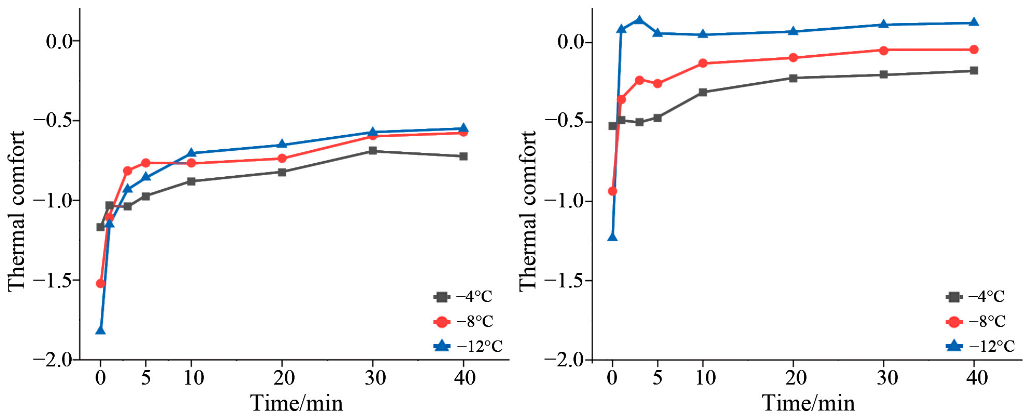
Table 5. Significance level of thermal sensation and thermal comfort.

Time (Min)			0	1	3	5	10	20	30	40
Thermal sensation	Low activity	S4	0.097	0.568	0.720	0.818	0.822	0.677	0.787	0.580
		S8	0.010	0.028	0.275	0.392	0.471	0.633	0.901	0.892
		S12	0.006	0.016	0.019	0.019	0.411	0.499	0.320	0.744
	High activity	S4	0.055	0.688	0.914	0.745	0.844	0.701	0.689	0.592
		S8	0.008	0.034	0.082	0.693	0.858	0.659	0.691	0.780
		S12	0.000	0.000	0.011	0.014	0.036	0.056	0.126	0.134
Thermal comfort	Low activity	S4	0.067	0.123	0.278	0.256	0.387	0.635	0.882	0.972
		S8	0.008	0.014	0.047	0.095	0.198	0.104	0.581	0.673
		S12	0.002	0.017	0.020	0.049	0.181	0.784	0.977	0.955
	High activity	S4	0.020	0.081	0.083	0.085	0.398	0.805	0.815	0.957
		S8	0.001	0.009	0.023	0.057	0.101	0.320	0.358	0.696
		S12	0.001	0.010	0.011	0.012	0.033	0.036	0.057	0.320

Table 5 displays significance levels of subjects' responses (thermal sensation). The differences in thermal sensation among subjects for S4, S8 and S12 were eliminated within 20 min, which was similar to the results for time taken to reach steady state, as shown in Table 4.

3.2. Thermal Comfort

Subjects' thermal comfort under different temperatures is shown in Figure 7.



(**a**) (**b**)

Figure 7. Thermal comfort. (**a**) Low activity; (**b**) high activity.

The variation in thermal comfort between 0 and 40 min was similar to that of thermal sensation. In Figure 7, comparing thermal comfort at 0 and 40 min, the increase in thermal comfort was 0.44, 0.95, and 1.27 for S4, S8 and S12 (low activity), and 0.35, 0.89, and 1.36 for S4, S8 and S12 (high activity).

Figure 7 describes the change in thermal comfort under all three conditions (S4, S8 and S12). When the ambient temperature of Room B was kept at 0 °C, different temperature up-steps still caused some influences on thermal comfort in the last survey (40 min). Under low activity and high activity conditions, the difference in thermal comfort between S4 and S12 was 0.18 and 0.30, respectively. There was an increase in temperature up-step, with an increase in the difference in thermal comfort. When the ambient temperature was the same at 0 °C, the vote results for S12 were higher than those of S8 and S4. Due to the impression of a lower-temperature environment, an "overshooting phenomenon" appeared in S12 under the high activity condition, which was also observed by Qi et al. [16] and Chen et al. [26].

The significance levels of subjects' responses (thermal comfort) were analyzed by Student's *t*-test. As shown in Table 5, the differences in thermal comfort among subjects for S4, S8 and S12 could be eliminated within 30 min, which was similar to the results for time taken to reach steady state, as shown in Table 4. The variation study on the difference among subjects' responses with elapsed time will be carried out in the discussion chapter (Section 4.2).

3.3. Skin Temperature

Subjects' skin temperature under different temperatures is shown in Figure 8.

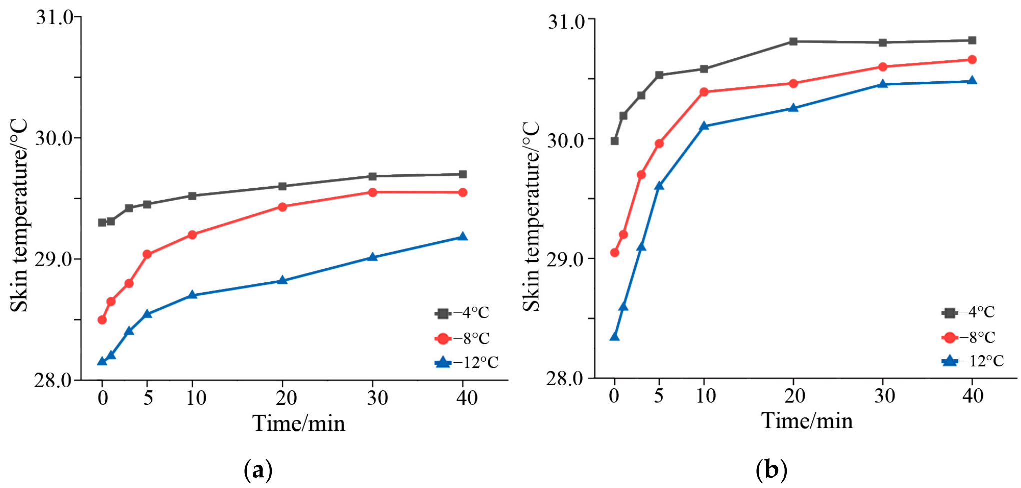


Figure 8. Skin temperature. (**a**) Low activity; (**b**) high activity.

In Figure 8, comparing skin temperatures at 0 and 40 min, the increase in skin temperature was 0.40, 1.05 and 1.03 °C for S4, S8 and S12 under the low activity condition, while the increase in skin temperature was 0.84, 1.51, and 2.14 °C for S4, S8 and S12 under the high activity condition. The increases in skin temperature under the high activity condition was significantly higher than that under the low activity condition.

As shown in Figure 8, skin temperatures for S4, S8 and S12 were 29.70, 29.55 and 29.18 °C under the low activity condition, and 30.82, 30.56 and 30.48 °C under the high activity condition (40 min). The skin temperature of S4 was obviously higher than that of S12. The higher the ambient temperature before the temperature up-step, the higher the skin temperature. This result was different to the variation in subjective evaluation results. It could be seen that after 40 min, the skin temperature was still influenced by the short-term thermal experience.

In addition, the difference in skin temperatures between S4 and S12 was 0.52 °C under the low activity condition (40 min), and the difference in skin temperatures between S4 and S12 was 0.34 °C under the high activity condition (40 min). Therefore, the variation in subjects' skin temperature is affected by the intensity of activities.

The time taken to reach steady state for human skin temperatures is shown in Table 4. Further analysis and discussion will be carried out in the discussion chapter (Section 4.1).

To analyze subjective and objective differences in the effect of temperature up-steps, the relationship between mean skin temperature and human thermal sensation was studied and expressed in Figure 9. (Yellow intervals represent the difference of thermal sensation, and blue intervals represent the difference of skin temperature.)

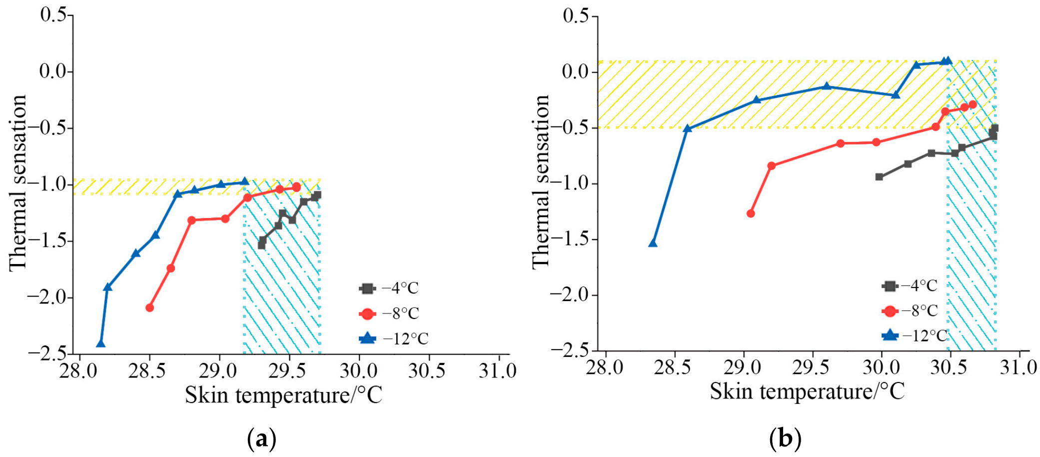


Figure 9. Relationship between mean skin temperature and human thermal sensation. (**a**) Low activity; (**b**) high activity.

As shown in Figure 9, under the low activity condition, the thermal sensations for S4, S8 and S12 in the last survey were relatively similar, but the skin temperatures were quite different. Under the high activity condition, the thermal sensation of S4, S8 and S12 in the last survey were quite different, but the skin temperatures were relatively similar (40 min). Further analysis and discussion will be carried out in the discussion chapter (Section 4.3).

4. Discussion

4.1. Time Taken to Reach Steady State

As shown in Table 4, since humans need more time to adapt to larger temperature up-step changes, the time taken to reach steady state for larger temperature up-steps was generally longer.

Under the low activity condition, the time taken to reach steady state for thermal sensation was lower than that for skin temperature. The effect is mainly psychological. This is in line with previous research. In these experiments, every subject's head and hands were exposed to a low-temperature environment, and the cold experienced in these local parts had a significant influence on human thermal sensation. In particular, under the low activity condition, the human body produced less heat. In this condition, a lower ambient temperature played a major role, so human thermal sensation needed less time to reach steady state. Compared with the publication of Mihara et al. [15], the subjects participating in these experiments had higher clothing insulation. Under the low activity condition, since the decay and delay of clothing on temperature up-step change, the human body responded quickly to ambient temperature fluctuation, and thermal sensation needed less time to reach steady state.

Under the high activity condition, human body heat produced more heat. The dissipate heat from the human body had a greater impact on subjects' thermoregulation system and thermal sensation. In this condition, the time taken to reach steady state for skin temperature was similar to that for thermal sensation. A psychological phenomenon was not obvious in this condition.

4.2. Difference Analysis of Subjective Evaluation

As shown in Table 5, for S4, except for thermal comfort under the high activity at 0 min (when subjects were just entering Room B), there was no obvious difference in either thermal sensation or thermal comfort. In this condition, the difference in subjects' responses was very small. The temperature up-step of 4 °C had little influence on the change in thermal sensation or thermal comfort, which was similar to that in [15,26].

As shown in Table 5, for S12, there were significant changes and individual differences in both thermal sensation and thermal comfort within 5–10 min. In particular, individual differences under the high activity condition was more significant, and it took a longer time (another 5–10 min) to eliminate these differences. This was mainly due to both high intensity activity and a large temperature up-step change.

After entering Room B, it took a longer time to eliminate individual differences in thermal comfort (compared with thermal sensation), which was in line with the publication of Mihara et al. [15]. The main reason was that there are more factors determining human thermal comfort. In addition to ambient temperature, metabolic rate and clothing insulation also contribute. Affected by high intensity activity, constant clothing insulation and human individual differences, more time is needed to eliminate these differences.

4.3. Relationship between Mean Skin Temperature and Thermal Sensation

As shown in Figure 9, under the low activity condition, the last thermal sensation results were relatively similar, but skin temperatures were quite different. Under the high activity condition, the last thermal sensation results were quite different, but skin temperatures were relatively similar. In addition, comparing the results shown in Figures 6 and 7, the increased range of thermal sensation was generally greater than that of thermal comfort, which is in line with the study data of Ozarisoy [9]. The main reason was that under the low activity condition, heat dissipation by the human body could not overcome the influence of low ambient temperature. Therefore, there was an obvious difference in the results for skin temperature, while the results for thermal sensation quickly tended towards steady state and were similar at the last survey time point. Under the high activity condition, the metabolic rate of the human body was higher, and subjects' clothing insulation was greater. Heat dissipation by the human body played a major role in the change in human skin temperature. Thus, the results for skin temperature quickly tended towards steady state and were similar at the last survey time point, while there was an obvious difference in the results for thermal sensation.

5. Conclusions

This study evaluated human thermal perceptions on temperature up-step in winter. Major conclusions have been obtained.

(1) The analysis of experiment data showed that: for different temperature up-steps, the results for thermal sensation and skin temperatures reach steady state after 30 min. However, the change in human skin temperature caused by a short-term thermal experience did not disappear completely within 40 min.

(2) After temperature up-steps, an "overshooting phenomenon" caused by a short-term thermal experience may appear in thermal sensation and thermal comfort, but not in skin temperature.

(3) The analysis results show that asynchrony exists between psychological and subjective responses. Thermal sensation quickly tended towards steady state under the low activity condition. However, under the high activity condition, the time taken to reach steady state for thermal sensation and skin temperature was almost the same.

(4) Activity intensity plays an important role in the thermal environment design of buildings, as well as temporary rest spaces with a shelter effect. Under the low activity condition, a temperature up-step change had less influence on thermal sensation, but had a greater influence on skin temperature. Under the high activity condition, a temperature up-step change had a greater influence on thermal sensation, but had less influence on skin temperature.

Comparing with previous studies, in this paper, the human response to temperature up-step under different activity intensities has been quantitatively analyzed. This study can provide some theoretical achievements for the thermal environment design of a temporary rest space to meet different activity needs, which will improve the experience of outdoor activities (especially work and sports) in winter. In spite of the significant research findings of this study, there are still some limitations. First, the human subjects in this study are in the age range of 21–25. Since the age of human subjects may affect metabolic activities, and further affect human thermal perception and skin temperature, future investigations must involve some older subjects to extend the scope of this study. Latent class models may be an effective method to study human thermal perception of different populations. In addition, since the goal of this study is to provide protection for outdoor activities, outdoor field tests will be carried out, and the results for human thermal perception will be studied in the future. Furthermore, to enhance the application value of this study, the effect of temperature up-step on human thermal perception in other climate zones should also be considered in the future.

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