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Effects of exposure to winter temperature step-changes on human subjective perceptions

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ABSTRACT

An experimental study about the effect of three different air temperature step-changes (S10: 20 °C–10 °C–20 °C, S20: 20 °C–0 °C–20 °C, S40: 20 °C– −20 °C–20 °C) on human health and thermal comfort was conducted in severe cold area of China. Nine male and nine female subjects who have been accustomed to the local climate were recruited. Their subjective responses were measured by questionnaires. Besides, skin temperature was also monitored during the experiment. Results show that time effect of symptoms including cold hands or feet, dizziness, running or stuffy nose, dry throat and shiver is significant, indicating the dynamic effects of temperature alterations. Besides, the symptoms of running or stuffy nose was lagged to reach the highest percentage especially in large step condition S40. The most sensitive parts to temperature alterations are extremities like foot and hand. Significant differences in thermal sensation of local parts are mainly observed between small (S10) and large (S40) temperature steps, or medium (S20) and large (S40) steps. There exist asymmetries in human responses to temperature alterations showing as more intensive effect of down-steps than its counterparts in up-step situation. Psychological lead, the change in thermal perception being far ahead of that in skin temperature, was detected in both down-step and up-step; however, the leading phenomenon in up-step is less intensive than that in down-step.

1. Introduction

Temperature alterations are common phenomenon in daily life. For example, in summertime people always encounter sudden cooling when they step into air-conditioned buildings from hot outdoors, followed by sudden heating when exiting air-conditioned environments to the outdoor. Similar situations of temperature up-step and down-step also occur frequently in wintertime. Sometimes the temperature difference between indoor and outdoor environments can be pretty large. For example, in the winter of Northeast China, the outdoor temperature can be as low as −20 °C while the indoor temperature is about 20 °C or higher, causing the temperature step of 40 °C or larger.

Many studies have already been conducted to explore thermal transients. Gagge exposed three males in shorts to step-changes consisting of 28 °C and 48 °C/17.5 °C and firstly identified the 'overshooting' and 'hysteresis' phenomenon [1]. Nagano designed several down-step conditions with different initial high temperatures (37 °C–31/28/25 °C, 34 °C–28/25/22 °C) and regressed two formulas to describe the variation of neutral temperatures [2]. Chen adopted temperatures of 32 °C, 28 °C and 24 °C to develop step-change situations normally found in summer of Taiwan and concluded that step-change of 4 °C caused no significant physiological variations [3] while Zhang simulated typical temperature steps in Guangzhou and recommended acceptable conditions for transitional spaces in Chinese hot-humid areas [4]. Liu conducted a warm-neutral-warm transient environment experiment (32/30/28 °C–25 °C–32/30/28 °C) and implied that heat loss from skin surface rather than the body heat loss was an effective indicator to predict thermal comfort [5]. Similarly, there are also some other studies concentrating on neutral-to-warm situations [6–9]. We also extended the temperature range (37 °C–32/26/22 °C–37 °C) and implemented an experiment to stimulate summer conditions [10,11].

However, as shown above, previous studies mostly focused on summer condition while little attention was paid to winter situation. In winter, conditions of sudden cooling and rewarming are familiar. There exist some studies about the influence of cooling

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simulation on human [12–16]. However, on the one hand, these research are mainly focused on medical treatment or the underlying physiology such as the skin sympathetic vasoconstriction [14], cardiac function [15] and thermogenesis [16]; on the other hand, cold stress in these papers are not typical situations in human daily life. Du [17] studied the effects of cool-neutral-cool thermal alterations on human responses, but temperature steps in that study (12/15/17 °C–22 °C–12/15/17 °C) are relatively small. In this study, we intensified the cold environment to lower temperature levels to explore human responses to both temperature up-steps and down-steps in winter, aiming to provide basic data for the understanding of human reactions to step changes. The specific objectives include observing dynamic features of human response to temperature step changes and inspecting the effects of temperature step magnitude and direction on human responses.

2. Methods

2.1. Subjects

Nine male and nine female subjects who were born and raised in severe cold area of China. were recruited, and their anthropometric information including body mass index (BMI) [18] and body surface area (As) [19] is shown in Table 1. In the warm room (20 °C), their clothing insulation was about 1.2 clo (long legs and sleeves, sweater, trousers, socks, shoes) [20]. When moving to cold environment, subjects would put on their down jackets (about 0.5 clo), leading to the clothing insulation up to around 1.7 clo. Similarly, they would take off down jackets when entering the warm room for the cold one just as they do in real life. All protocols were approved by the university's ethics committee. Verbal and written informed consents were obtained from each subject prior to the participation.

2.2. Conditions and measurements

The experiment was conducted in Qiqihaer (47.38°N, 123.92°E), a typical city in severe cold area of China. The heating period in Qiqihaer is from October to April. In the month of January 2016 when this experiment was carried out, the monthly mean temperature was −19 °C; the average low temperature and high temperature were −24 °C and −14 °C.

We created three different conditions including both up-steps and down-steps (S10: 20°C–10°C–20 °C, S20: 20°C–0°C–20 °C, and S40: 20°C– −20°C–20 °C) to simulate subjects' first encountering sudden cooling and then undergoing sudden warming. Two rooms were applied to develop these temperature step conditions. The warm room was set at 20 °C with floor heating system, which meets the requirement of 18–24 °C for indoor design temperature in winter [21]. The cool room was set at 10 °C and 0 °C to represent temperature levels in non-heating room and the outdoor situation in hot-summer and cold-winter zone. Furthermore, −20 °C was also developed to stimulate the outdoor temperature level in winter of severe cold area.

Environmental parameters in both cold and warm rooms were monitored. The measurement site was placed at the center of each room. All instruments used in the experiment are listed in Table 2. The air temperature and relative humidity were recorded every 10 s. The air velocity was also measured. Besides, the mean radiant temperature was computed from the globe temperature. As shown in Table 3, the relative humidity in all rooms was controlled in the range of 20%–60%. Air temperatures were kept around the nominal values. The air speed was less than 0.1 m/s. The mean radiant temperature was close to air temperature during the experiment.

Questionnaires containing health self-reported symptoms, fatigue, thermal sensation and comfort were conducted (Table 4). Fatigue was assessed using Japanese subjective fatigue check-list which is made up of 25 items and is divided into 5 subtypes [22]. Participants answered each item using five-point discrete scale from +1 (none) to +5 (extremely severe).

Skin temperature was monitored using PyroButton (OPULUS Ltd, America) with the precision of 0.2 °C and resolution of 0.0625 °C. The sample frequency of Pyrobutton was set at 10 s which means that skin temperature was measured every 10 s. Subjects' local temperatures were measured on 7 body parts; they are neck, upper arm, lower arm, back, chest, upper leg and lower leg. As shown in Eq. (1), mean skin temperature is the weighted average of these local values [23].

$$t_{msk} = 0.098t_{\text{neck}} + 0.082t_{\text{upper arm}} + 0.114t_{\text{lower arm}} + 0.162t_{\text{back}} + 0.166t_{\text{chest}} + 0.172t_{\text{upper leg}} + 0.206t_{\text{lower leg}} \quad (1)$$

2.3. Experimental procedure

The experiment was performed in January, 2016. All subjects were not currently taking prescription medication and were asked to avoid caffeine, alcohol, and intense physical activity at least 12 h prior to the experiment. After arrival, they firstly stayed in the warm room for half an hour and had the Pyrobutton attached to the skin using vapor permeable surgical tape. Then the experiment began. Each test lasted for 105 min and was divided into three stages (Fig. 1). First, subjects stayed in the warm room doing office work for 45min (MET = 70 W/m^2). Then they moved to the cool room for a 15-minutes' stroll (MET = 100 W/m^2) followed by a 45-minutes' office work in warm environment. During the experiment, skin temperature was monitored during the whole test. Subjects' fatigue was investigated at the end of stage 1 and stage 3, namely the 35th and 100th min. Health aspects, thermal sensation and comfort were investigated at the 35th, 45th, 58th, 61st, 64th, 67th, 70th, 80th, 90th and 100th min. Local thermal sensations were also asked several times. Actually it is ideal to arrange questionnaire survey at the same frequency after both down-step (stage 2) and up-step (stage 3), but it is unrealistic to conduct the investigation in down-step as many times as in up-step since temperature at the stage 2 can be as cold as −20 °C. So we chose to focus on subjects'

Table 1
Anthropometric information of participants.

Gender	NO.	Age (years)	Height (cm)	Weight (kg)	BMI (kg/cm2)	As (m^2)
Male	9	30 ± 3	171.9 ± 4.4	73.4 ± 6.9	24.9 ± 2.6	1.8 ± 0.1
Female	9	30 ± 4	163.8 ± 3.7	60.0 ± 6.8	22.4 ± 2.4	1.6 ± 0.1
All	18	30 ± 3	168.1 ± 5.7	66.9 ± 9.6	23.6 ± 2.8	1.7 ± 0.1

Note: BMI and As are abbreviations of body mass index and body surface area, respectively.