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Study on the effects of chair heating in cold indoor environments from the perspective of local thermal sensation

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ABSTRACT

A personal comfort system for heating has the potential to maintain or even enhance the occupants' thermal comfort in cold indoor environments. In this study, the effects of a chair with a heatable backrest and seat cushions were tested by subject experiments at 14 °C, 16 °C, and 18 °C in a climate chamber. The results reveal that compared to the well-insulated chair, the additional active heating has no significant advantage for the overall thermal comfort at 16 °C and 18 °C and has only a limited effect on improving overall thermal sensation and comfort at 14 °C. Due to the production of heat by the human body itself, the back and buttocks, which are the body parts in contact with the chair, would not feel cold as long as the chair's thermal insulation is sufficient. The cold feelings of extremities are the coldest in a cold indoor environment and the main source of the overall cold feeling. Additionally, chair heating cannot improve the local thermal sensation of the extremities, which limits the effect of the chair heating. Therefore, relevant local heating devices should be developed around the extremities. For the chair, sufficient insulation can achieve an effect similar to active heating on thermal comfort when the ambient temperature is not lower than 16 °C.

1. Introduction

In recent years, haze-fog has become a significant environmental problem closely related to Chinese people's lives [1–3], and this problem is more serious in the heating season, especially in northern China [4,5], that is caused by air pollutants being released during the combustion of fossil fuel. In China, where peoples' demand for better indoor environments is rapidly growing, the wintertime indoor temperature has increased significantly over recent decades [6–10], and district space heating in northern urban areas accounted for approximately 24% of the total energy use in the country's building sector [11]. A decreasing indoor temperature during the winter heating period can help to reduce energy consumption and improve the air quality. Hoyt et al. [12] studied the energy saving potential of extended temperature set points and proposed that each decrease of one degree Celsius in the ambient temperature results in approximately 10% savings in heating energy in cold climates. The question is whether occupants' thermal comfort could be guaranteed at lower ambient temperatures.

The personal comfort system (PCS) for heating has the potential to maintain or even enhance occupants' thermal comfort at low ambient temperatures. Zhang [13] reviewed published studies on PCS and proposed the parameter of "correct power" to represent the degree to which a PCS system may "correct" the ambient temperature toward neutrality, which is 2–10 K for cold environments. Among the various kinds of PCSs, the chair is regarded as one of the most popular forms studied by many researchers. Pasut studied the effects of a thermoelectrically heated and cooled chair [14] and a novel energy-efficient chair [15] compared with conventional mesh and cushion chairs and found that both of these two chairs strongly influence the subjects' thermal sensation and comfort at 16 °C, 18 °C, and 29 °C. Deng [16] investigated the effects of thermoelectric chairs and found that the thermal sensation and comfort of the subjects at 16 °C were significantly higher than at 18 °C. Watanabe [17] studied the performance of an Individually Controlled System (ICS), including a convection-heated chair, by using a thermal manikin at room temperatures of 20 °C, 22 °C, and 26 °C. At 20 °C, the maximum whole-body heating effect of the heating chair was equivalent to the effect of a room temperature increase of 5.2 °C. Melikov [18] studied the response of 48 subjects to this ICS and revealed that the thermal and air quality acceptability was significantly higher with the ICS at 20 °C, 22 °C, and 26 °C compared to 22 °C without ICS. Vesely [19] tested the

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effectiveness of a personalized heating system, which consisted of a heated chair, a heated desk mat, and a heated floor mat. The heaters were tested separately and in combination as user controlled. The heated chair, the heated desk mat, and the combined system significantly improved thermal comfort at 18 °C, while the heated chair was found to be the most effective heater. Although chair heating was concluded to be effective in terms of thermal comfort in most of the previous studies above, the experimental ambient temperatures under study were generally higher than 16 °C because chair heating was usually regarded as a "supplement" to space heating in indoor environments. He [20] studied the effect of chair heating assisted by leg-warmers at 14 °C, 16 °C, and 18 °C. He found that the combination of heating chairs and leg-warmers performed better on improving overall sensation and comfort and that independent chair heating could not eliminate the cold discomfort of some body extremities such as feet. More research on chair heating for temperatures not higher than 16 °C actually focused on vehicles rather than on indoor environments. Brooks [21] studied the effect of an automobile seat heated with an encapsulated carbonized fabric at 5 °C, 10 °C, 15 °C, and 20 °C and found that the overall sensations of the participants were maintained higher than "slightly cool" with the heated seat at all temperatures. Oi [22] studied the effect of a heated seat and a foot heater at 10 °C and 20 °C and found that they improved the thermal sensation and comfort of occupants in cool environments. The "neutral" operative temperature for the occupants decreased by approximately 3 °C by using the heated seat or foot heater independently and by 6 °C by using both of them. Zhang researched [23] the influence of a heated or cooled seat with water tubes arranged on the backrest and seat surfaces. The conventional 80% acceptable range of air temperature for subjects was extended by 9.3 °C downwards and by 6.4 °C upwards.

In fact, lower indoor temperatures were also encountered in practical cases of indoor environment, e.g., the indoor temperature could be very low when space heating is about to start or just stop supplying heat for buildings with central heating systems. In contrast, the indoor temperature of some residential buildings in southern China may also be lower than 18 °C due to cultural habits. Therefore, the ambient temperature of this study was set to 18, 16, and 14 °C. Additionally, the insulation of the chairs was not specifically addressed in previous studies, but it is not difficult for occupants to increase the insulation of chairs by adding thick cushions. Two well-insulated cushions were used in this experiment. In this study, the effects of chair heating on local thermal sensations of different body parts were analyzed in detail, a topic rarely discussed in previous studies.

2. Methods

2.1. Description of the climate chamber and the devices

The experiments were carried out in the climate chamber at Tsinghua University in Beijing, China, during the winter from December 2016 to January 2017. The climate chamber (see Fig. 1) was two small rooms (5 m × 3 m × 2.65 m) built in a large room (9.5 m × 9 m × 4.6 m). Perforated ceiling air supply and return of the chambers ensured a more precise temperature (<±0.3 °C), humidity (<5%) control, and lower air velocity (<0.1 m/s). A refitted chair was used in the experiments. Two brown cushions were fixed on the backrest and seat separately (Fig. 2a). Each cushion was filled with three 1-cm-thick pieces of soft foam that guaranteed the thermal insulation of the cushions (Fig. 2b). A heating wire was arranged uniformly on the top of soft foams, and a layer of tin foil covered the heating wire to further enhance the thermal uniformity of the heating cushion. The cushion surfaces temperature could be set on the control panel (Fig. 2c). The heating power of

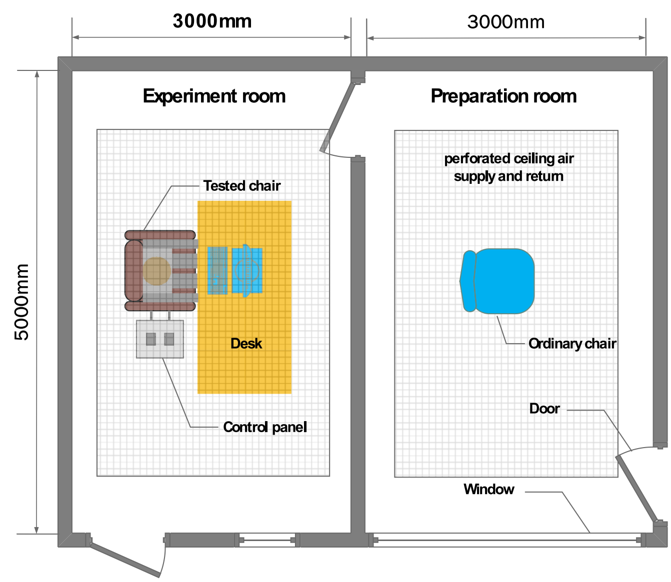

Fig. 1. The experiment and preparation room in this study.

each cushion was approximately 45 W in the experiments, which made the temperature of the cushions rapidly increase. During the experiments, the temperature and heat flow on the surfaces of cushions, which were in contact with the user's back and buttocks, were recorded by the self-recording sensor (Fig. 2d) located in the red square in Fig. 2a. The details of the sensor are shown in Table 1. The sampling interval of the temperature and heat flow data was 5 s. The purpose of recording those two parameters was to observe their changing trends during the experiments.

2.2. Subjects and experimental conditions

There were three different ambient temperature conditions in the experiments, 14 °C, 16 °C, and 18 °C. In case of a possible negative influence on subjects' health and taking into account the capability of temperature control of the climate chamber, we did not even try colder conditions with ambient temperatures lower than 14 °C, although such conditions merit study. The relative humidity of the climate chamber was kept at 50 ± 5%, and the mean radiant temperature was close to the air temperature.

Thirteen healthy university students (7 males and 6 females) participated in each of the three experimental conditions one at a time. Their anthropometric data (mean value and standard deviation) are shown in Table 2. All of the subjects were instructed to avoid caffeine, alcohol, and intense physical activities for at least 12 hours before the experiment. The experimental dates for the female subjects were scheduled during their non-menstrual period. The subjects were allowed to quit during the experiments whenever they felt that the thermal condition became intolerable.

The subjects wore standard clothing during the experiments, which consisted of long-sleeve underwear, a sports sweater, trousers, socks, and shoes. The clothing insulation of the garments for the upper body, the legs and the feet was 0.4 clo, 0.4 clo, and 0.15 clo, respectively [24]. During the experiments, the subjects were asked to remain seated on the seat cushion and lean back to ensure contact with the backrest cushion. The subjects were allowed to engage in computer-based activities. Fig. 3 shows the real scenario of the experiment.