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Human thermal sensation and comfort in a non-uniform environment with personalized heating

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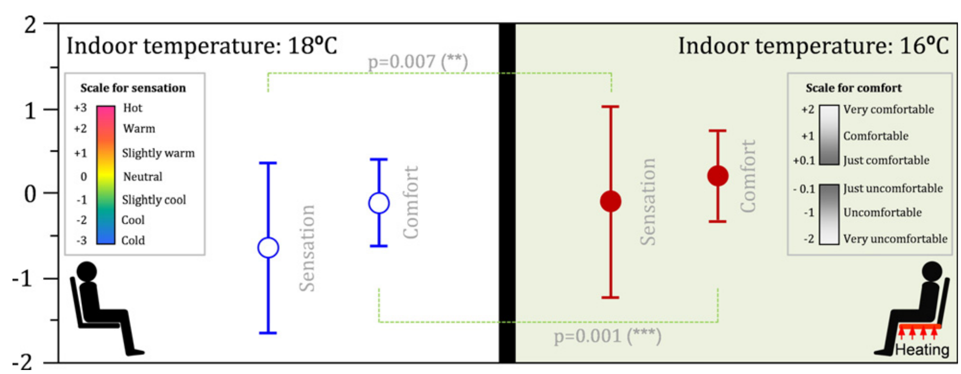
HIGHLIGHTS

- Personalized heating significantly improves human thermal sensation and comfort.
- Personalized heating provide warmer sensation and better comfort in cool environment.
- Thermal sensation and comfort in overall body is affected by local body parts.
- Mean skin temperature of human body can be increased by local heating.
- High mean skin temperature increases overall thermal sensation and comfort.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: Thermal comfort in traditionally uniform environment is apparent and can be improved by increasing energy expenses. To save energy, non-uniform environment implemented by personalized conditioning system attracts considerable attention, but human response in such environment is unclear.
Objectives: To investigate regional- and whole-body thermal sensation and comfort in a cool environment with personalized heating.
Methods: In total 36 subjects (17 males and 19 females) including children, adults and the elderly, were involved in our experiment. Each subject was first asked to sit on a seat in an 18 °C chamber (uniform environment) for 40 min and then sit on a heating seat in a 16 °C chamber (non-uniform environment) for another 40 min after 10 min break. Subjects' regional- and whole-body thermal sensation and comfort were surveyed by questionnaire and their skin temperatures were measured by wireless sensors. We statistically analyzed subjects' thermal sensation and comfort and their skin temperatures in different age and gender groups and compared them between the uniform and non-uniform environments.
Results: Overall thermal sensation and comfort votes were respectively neutral and just comfortable in 16 °C chamber with personalized heating, which were significantly higher than those in 18 °C chamber without heating ($p < 0.01$). The effect of personalized heating on improving thermal sensation and comfort was consistent in subjects of different age and gender. However, adults and the females were more sensitive to the effect of personalized heating and felt cooler and less comfort than children/elderly and the males respectively. Variations of

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the regional thermal sensation/comfort across human body were consistent with those of skin temperature. *Conclusions:* Personalized heating significantly improved human thermal sensation and comfort in non-uniform cooler environment, probably due to the fact that it increased skin temperature. However, the link between thermal sensation/comfort and variations of skin temperature is rather complex and warrant further investigation.

1. Introduction

The rapidly growing world energy use has raised concerns over exhaustion of energy resources and heavy environmental impacts such as global warming and air pollution (Pérez-Lombard et al., 2008). Buildings use between 20% and 40% of total energy consumption in developed countries (Energy Information Administration, 2014). Building energy use in developing countries, such as China, has been increasing rapidly in recent years (Moser and Meier, 2006; Peng et al., 2015). The upward trend in energy demand will continue in the future, given the continuing growth in population, increasing demand for building services and comfort levels, together with the rise in time spent inside buildings.

The building industry nowadays is facing two major challenges: the increased concern for energy reduction and the growing need for comfort improvements (Veselý and Zeiler, 2014). Thermal comfort and energy efficiency have therefore been the focus of recent building-related studies (Holmes and Hacker, 2007; Yoshino et al., 2006). Heating, ventilation and air-conditioning (HVAC) systems use a very large portion, over 60%, of total building energy (Pérez-Lombard et al., 2008). The high energy consumption of traditional HVAC systems is largely due to the uniform control of indoor air temperature and maintenance of the air temperature within a narrow 2 °C range (Hoyt et al., 2015). However, a recent survey showed that the overall satisfaction with thermal comfort was found only in 11% of buildings (Hoyt et al., 2015).

The limitations of traditional HVAC system have recently led many researchers to develop personalized conditioning systems (PCS), such as personalized ventilation, task conditioning systems, and heated/cooled chair (Amai et al., 2007; Melikov, 2004; Veselý and Zeiler, 2014; Watanabe et al., 2009; Zhang et al., 2010d and 2015). In contrast to the traditional HVAC systems that condition an entire space to create uniform indoor environment, personal systems aim to condition only a relatively small space around the persons that results in a non-uniform environment with a wider range of indoor temperature (Arens et al., 2006a; Shao and Li, 2015). PCS saves energy by enabling the ambient air temperature to be less controlled (Veselý and Zeiler, 2014). The ambient temperature in PCS system could be 4–5 °C higher or lower than the recommended temperature setpoint in traditional HVAC system. It was predicted that the annual energy would reduce approximately 10% by extending the recommended setpoint each 1 °C (Hoyt et al., 2015), and thus an annual energy saving of 40–50% may be achieved in the non-uniform environment equipped with PCS system.

However, the advantage of non-uniform environment with PCS system has rarely been addressed in conventional building design and operation, and also there has been very limited research on human response to the non-uniform environment. Several recent questionnaire surveys have found that PCS system could improve people's subjective thermal comfort (Arens et al., 2006b; Oi et al., 2012 and 2011; Pasut et al., 2015; Veselý and Zeiler, 2014). It is, however, hard to quantify human response to the non-uniform environment, because it depends on very complex physiological sensations of local body parts and their integration (Parkinson and de Dear, 2015; Zhang et al. 2010a,b,c and 2015).

Having in mind the scarce information about human response in the non-uniform environment and unclear relation between partial- and whole-body thermal responses, we experimentally investigated human thermal sensation and comfort in a cooler environment with personalized heating and compared with those in a warmer uniform environment without local heating. Our objective is to evaluate the effectiveness of personalized heating on thermal sensation and comfort of whole body so as to promote its use in practice.

2. Materials and methods

2.1. Experiment

During January 4–10, 2016, we conducted a series of experiments in a climate chamber with a dimension 4.2 m × 3 m × 2.6 m, which resembling a real office environment with a window on the wall. A total of 36 subjects (Table 1), 17 males and 19 females, participated in the experiments. Subjects were composed of three age groups, 6 children (mean age 12 years), 24 young adults (college students with mean age 23 years) and 6 elderly (mean age 59 years). All subjects were selected in good health and their body mass index (BMI) ranged from 18.5 to 22.9, which met the Asian's BMI normal standards. All the selected subjects have no background knowledge about the research topic. The study protocol was reviewed and approved by the Ethics Committee of Central South University, and informed written consent was obtained from each participant before study enrollment.

The experiment consists of 80 min in the chamber and 10 min rest outside the chamber (Fig. 1). Inside the chamber, the relative humidity was maintained at 55 ± 5% and air velocity was less than 0.1 m/s, but the temperature was set at two levels: 18 °C and 16 °C. The rest room outside the chamber was kept at 14 °C and the relative humidity was about 55%. Each experiment involved two subjects, and before experiment we asked the subjects to take a rest so as to calm down in the rest room for 30 min during which we introduced the detailed experimental condition and schedule to the subjects. Subjects were first asked to sit on non-heating seats in 18 °C chamber for 40 min. Then, they took 10 min break in the rest room outside the chamber. During the break, the subjects worked 12 vertical steps to simulate the actual exercise of office staff, the temperature inside the chamber was reset to 16 °C, and the seat was switched to heating mode. After the break, the subjects were asked to sit on heating seats in 16 °C chamber for another 40 min. Subjects were allowed to talk or read in the chamber during the experiment. The seats used in experiment were the same and made of aluminum alloy with thermoelectric materials installed underneath and a thin textile layer covered above. When switched to heating mode, the surface temperature of the seat was maintained at 40 ± 1 °C. During the experiment, the clothing insulation was 0.8 clo for the children and adults but 1.0 clo for the elderly due to the reason that the elderly prefer warm sensation (Khan et al., 1993).

2.2. Skin temperature measurement

Skin temperatures at eight body regions (forehead, chest, back, pelvis, arms, hands, legs and feet) were recorded at every 30 s during the whole experiment using wireless sensors DS1921H iButton with a resolution of 0.0625 °C (Maxim Integrated Products Inc., Sunnyvale, USA). The effectiveness and advantage of measuring skin temperatures by using iButtons were validated (van Marken Lichtenbelt et al., 2006). Mean skin temperature of the whole body was calculated with weighting coefficients based on local skin area ratios of human body (Sakoi et al., 2007). Due to a long time for the skin temperature to be