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Thermal history and adaptation: Does a long-term indoor thermal exposure impact human thermal adaptability?

Haoran Ning, Zhaojun Wang *, Yuchen Ji

School of Municipal and Environmental Engineering, Harbin Institute of Technology, Harbin, China

HIGHLIGHTS

- Warm and cool heating environments were investigated in winter.
- Human thermal adaptation can be impacted by different heating experiences.
- A higher thermal comfort zone was formed in warm exposure environment.
- Neutral temperature was still 1.9 °C higher in warm exposure after clothing standardization.
- The study has implication for rational heating temperature set in winter.

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ABSTRACT

Harbin is located in China's severe cold area with a long and cold winter. Currently, some buildings are overheated in winter, which not only waste energy, but also may weaken human adaptability to the cold climate. A long-term field tracking study was carried out from 2013 to 2015 covering two space heating periods in Harbin. Two types of residential heating environments, respectively warm exposure and cool exposure environments were investigated to discover relation between different indoor heating temperatures and human thermal responses. Totally, 36 residents volunteered as participants. The subjective survey and environmental parameters monitoring were simultaneously conducted. The results show that all participants could adapt to their thermal environments well. But the participants' thermal adaptation was evidently discrepant in different exposures. The neutral temperature was 1.9 °C higher in warm exposure than cool exposure sample after clothing insulation standardization, which suggests the possible effects of physiological and psychological adaptation. The discrepancy between AMV and PMV was greater in cool versus warm exposure. The results indicate that a higher thermal comfort zone might be formed for the residents exposing to a high indoor heating temperature for a long period in winter. Furthermore, a broader acceptable temperature range was presented in this climate area than ASHRAE steady-state comfort zone in winter. These findings have far-reaching implication for reasonable energy use.

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1. Introduction

A fundamental and conceptual reorientation has taken place in thermal comfort study over the last 20 years. Namely, the adaptive thermal comfort has become the mainstream study instead of the physical determinism of Fanger's comfort model [1]. And the adaptive thermal comfort model has been presented in existing thermal comfort standards, such as EN15251-2007 [2] and ASHRAE 55-2013 [3]. The only thermal environmental parameter in the adaptive model is outdoor mean monthly temperature or some sort of running mean outdoor temperature. And some studies have underpinned the adaptive model in the standards and developed its application [4–9]. Meanwhile, a great amount of worldwide field surveys have carried out about adaptive thermal comfort. Generally, the studies indicate that people have a wider thermal comfort range in naturally ventilated environment than that in air-conditioned environment. And people's thermal comfort range is commonly beyond the limits of steady-state thermal comfort range [10,11]. Moreover, most relevant field studies also report that human neutral temperatures are evidently discrepant in different seasons in the same area [12–17] and the neutral temperatures are significantly different in different climates [18–23]. These results verify that people have thermal adaptability to the climates.

* Corresponding author.
E-mail address: wangzhaojun@hit.edu.cn (Z. Wang).

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However, most adaptive models ascribe the effect of the comfort temperature to the outdoor climate, ignoring the importance of indoor thermal experiences. As a matter of fact, the indoor thermal environments can also influence human thermal comfort and adaptation. Currently, some researches have begun to focus on this point. For instance, Yu et al. pointed that a long-term exposure to stable air-conditioned environment might weaken people's thermal adaptability to hotness [24]. Cândido et al. [25] found that occupants who were constantly exposed to air conditioned or free running buildings tended to prefer such buildings. These results suggest an "addiction" to static indoor thermal environments. Luo et al. [26] pointed that building occupants could adapt to the thermally neutral lifestyle more easily and long-term comfortable indoor thermal history could raise occupants' thermal expectation. Clearly, most previous studies about the effects of indoor thermal experiences to human thermal comfort and adaptation mainly focus on the air-conditioned or naturally ventilated buildings. Or some researches about heated buildings concentrate on adaptive differences in different seasons or climate zones [27–30] or different occupants' background [26]. But, how the thermal experience based on different heating temperatures in winter affects occupants' comfort and adaptive performance has not been subject to much research. Meanwhile, the adaptive factors are difficult to confirm separately.

Undoubtedly, China today is a large energy-consuming and carbon-emitting country although its per capita index is relatively lower compared with other major economies around the world. It has become the largest energy consuming and CO_2 emission country in 2009 [31]. The building sector is a dominating energy consumption field in many countries. Kwok and Rajkovich [32] reported that the building sector accounted for 38.9% of the total primary energy requirement in America, of which 34.8% was for HVAC system (heating, ventilation and air conditioning). In China, the annual building energy consumption has soared from 243 million tce (tons of standard coal equivalents) to 687 million tce over the last 15 years [33]. In 2020, about 35% of total national energy use is projected for the building sector and HVAC system inevitably account for a high proportion [34,35]. Currently, most researches on energy conservation of HVAC system mainly aim at systematic optimization, renewable energy utilization and passive building design. Nevertheless, occupants' thermal behaviors and adaptation to thermal environment can also considerably influence building energy consumptions. Wan et al. pointed that given the growing awareness and recognition of adaptive thermal comfort, raising the summer air-conditioning set point temperature by 1–2 °C could have great energy saving and hence mitigation potential [36].

China is a geographically vast country with different climate zones. According to Chinese code [37], five climate zones are totally defined. They are respectively termed as severe cold, cold, hot summer and cold winter, hot summer and warm winter, and temperate zones shown in Fig. 1. Among Chinese climate zones, the centralized heating was required for urban buildings in winter in severe cold and cold zones. And these two climatic zones account for a vast area in Chinese mainland including 19 provinces and 134 major cities. For the past few years, the centralized heating area presents a tendency of sharp increasing year by year. Since 2005, there is a growth rate of 200–300 million m^2 by average per year. The centralized heating area is 4.36 billion m^2 in 2010 and soars to 6.11 billion m^2 in 2014. So far, the centralized heating consumes nearly 25% of total energy cost annually in China [33]. Therefore, a suitable indoor design temperature for space heating is very important to save energy and reduce carbon emission.

Harbin (45°41′N 126°37′E) is a large capital city in the severe cold area of China. There is a severe cold and long winter in this metropolis. The mean daily highest/lowest outdoor temperatures in January are −13 °C/−25 °C [30]. The centralized heating is applied in winter and its operating time usually lasts nearly half a year. Previous studies revealed that the occupants had adaptability to the local cold climate and thermal neutral temperature was lower compared with the occupants at low latitudes [38]. Meanwhile, the neutral temperature was close to the indoor air temperature [39]. However, the local occupants often expose themselves to the indoor heating environment in winter to avoid the freezing coldness outside. Additionally, the indoor heating space is relatively enclosed in winter. Therefore, does the long-term indoor heating experience impact human thermal comfort and adaptability? And what are the possible differences of thermal responses if the occupants expose them to different heating temperatures during the winter? To answer these questions, a long-term field investigation was conducted during space heating periods in Harbin. Two groups of participants respectively exposed to warm and cool heating environments were surveyed to discover the interaction between indoor heating experiences and thermal adaptation. Meanwhile, the energy-saving potential is analyzed and the practical implication is elaborated according to the study.

This study aims:

1. To investigate residents' thermal perception and performance under different heating experiences in winter.
2. To discover the differences of residents' adaptive responses between warm and cool exposure groups.

2. Research methods

2.1. Research time and samples

The field study was carried out in two types of residential thermal environments, respectively "slightly warm to neutral" exposure and "slightly cool to neutral" exposure environments during two heating periods in Harbin. To make them concise, the terms of "warm exposure" and "cool exposure" were correspondingly used in the paper. The warm exposure sample was surveyed from October 20 to April 20, 2013–2014 and the cool exposure sample was surveyed from October 20 to April 20, 2014–2015. Most of participants' apartments were heated by the centralized heating system with radiator heating terminal. Only one participant's home was heated with floor heating terminal. According to the Chinese standard [40], the residential indoor air temperature should be required within 18–24 °C in winter in the severe cold zone. However, to reduce the residents' complaints, the upper limit 24 °C even higher heating temperature is usually applied as the actual indoor heating temperature in winter. Therefore, the upper limit temperature 24 °C is considered as an index for warm exposure sample recruitment. The mean indoor air temperatures in warm exposure samples were close to or over 24 °C. Notwithstanding, some residential apartments are heated close to the lower limit of indoor air temperature during winter in Harbin. So, some apartments with lower indoor air temperature were investigated to compare the adaptive differences. And the mean indoor air temperatures in cool exposure samples were around 20–22 °C. 36 residents (age ranges from 26 to 72, gender ratio is nearly 1:1) volunteered as the participants in this study. Among them, 20 occupants lived in warm apartments and 16 participants lived in cool apartments. All the participants have been living in Harbin for more than 20 years and they have fully adapted to the local climate. The samples' information is shown in Table 1.

The BMI (Body Mass Index) links to the fat layer that can influence heat transfer between the inner body and its ambient thermal condition [41]. Therefore, the index may become a factor to affect human thermal sensation. Meanwhile, some studies also found that BMI affected people's sensitivity to thermal history [42,43]. According to WHO (World Health Organization), BMI can be cate-

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