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Can personal control influence human thermal comfort? A field study in residential buildings in China in winter

Maohui Luo [a,b], Bin Cao [a], Xiang Zhou [b,*], Min Li [a], Jingsi Zhang [b], Qin Ouyang [a], Yingxin Zhu [a]

[a] Department of Building Science, Tsinghua University, Beijing 100084, China
[b] College of Mechanical and Energy Engineering, Tongji University, Shanghai 200092, China

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ABSTRACT

Due to the impetus of climate change and the consequential need to conserve energy, the adaptive comfort model has gradually become a popular focus of thermal comfort research, representing one of the most sweeping changes across the field in the past few decades. However, the mechanism behind the adaptive model, especially with regard to certain key hypotheses, still requires further clarification. To offer more solid support for the hypothesis that people with greater personal control tend to accept wider ranges of indoor thermal environments, we designed an investigational study in which occupants in residential apartments had different degrees of personal control over their space heating systems. Through statistical analysis of the thermal responses of each group, considerable differences in thermal comfort were observed, although occupants in the experimental groups experienced quite similar comfort-related thermal parameters. The results show that occupants with personal control had 2.6 °C lower neutral T_{op} and expressed lower expectation to change their current thermal conditions than those without the capability of personal control. These findings provide support for the adaptive model and can serve as a valuable reference for the design of more efficient space heating systems.

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Nomenclature

T_a	indoor air temperature (°C)
T_g	black globe temperature (°C)
T_{op}	operative temperature (°C)
RH	relative humidity (%)
v	air velocity (m/s)
MRT	mean radiant temperature (°C)

1. Introduction

In light of growing concerns about climate change and the resulting need to reduce building energy consumption, more and more researchers have begun to think differently about the ways in which thermal comfort conditions should be delivered to building occupants. During the past few decades, one of the most sweeping changes in the field of thermal comfort research was the emergence and gradual popularization of the adaptive comfort model [1]. Compared with Fanger's Predicted Mean Vote (PMV) model [2], which predicts human subjective sensation through objective thermal parameters, the adaptive comfort model emphasizes the role occupants play in maintaining their own thermal comfort [3]. Based on the presumption that people can actively adapt themselves to their thermal environment rather than merely accepting it passively, the adaptive comfort model considers occupants as integral components of the comfort 'system', instead of just calculating the steady state heat balance of the human body. The legitimacy of the adaptive comfort model has been recognized, as it has been adopted by ASHRAE Standard 55 [4,5] and EN 15251 [6]. However, the mechanism behind the model remains unknown.

To increase the rigor of the adaptive model and extend its scope of application, many thermal comfort studies have been carried out in various climatic conditions and different building types in order to modify the model [7]. Indeed, numerous studies have offered support for the adaptive model. For example, de Dear [8] collected a quality-ensured database from worldwide field experiments to establish the adaptive model. To explain the philosophy behind the model, Brager et al. [9] attributed thermal adaption to three processes: physiological acclimatization, behavioral adjustment, and psychological habituation or expectation. They also

Abbreviations: TSV, thermal sensation vote; TCV, thermal comfort vote; MET, metabolic rate; CLO, clothing insulation.

* Corresponding author. Tel.: +86 13671923505.
E-mail address: zhouxiang@tongji.edu.cn (X. Zhou).

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Table 1
Summary of the surveyed buildings.

	Location	Survey period	Number of apartments	Space heating system	Personal control over indoor thermal environment	
BJ-A	Beijing	Dec. 2012–Feb. 2013	Background level: 45 Detailed level: 15	District heating supply	No	
BJ-B	Beijing	Dec. 2012–Feb. 2013	Background level: 41 Detailed level: 17	Individual household gas boiler heating	Free to adjust	
SH-C	Shanghai	Dec. 2012–Mar. 2013	Detailed level: 20	Air-source heat pump	SH-C-1 SH-C-2	Free to use Unable to use

pointed out that behavioral adjustment and psychological expectation had greater influence on thermal adaptation in buildings in relatively moderate conditions compared to the slower process of acclimatization. Based on the understanding that occupants' current thermal perceptions were somehow related to their past thermal experience, Cao [10] designed a field study to examine people's adaptability to cold or hot environments. The results showed that long-term indoor thermal history strongly influenced thermal neutrality, which provides direct support for the adaptive hypothesis that thermal comfort involves not only pure heat balance, but also other factors like past thermal experience. To verify the effects of physiological acclimatization on human thermal adaptation, Yu [11] demonstrated in climate chamber experiments that subjects who were acclimated to naturally ventilated environments had a significantly stronger capacity for physiological thermoregulation than those who were acclimated to air-conditioned environments.

However, despite these significant achievements, one controversial hypothesis of the adaptive model remains largely unresolved: occupants in naturally ventilated buildings can achieve thermal comfort in a wider range of indoor temperatures compared to occupants in centrally controlled air-conditioning buildings because of the increased levels of personal control afforded by approaches like operable windows [3]. The main question is whether the capability of personal control can improve or deteriorate human thermal comfort. There exist two central academic opinions related to this problem. Fanger et al. [12] assumed that occupants with low degrees of personal control believe it is their destiny to live in non-neutral environments, thus resulting in lower thermal comfort expectations. According to this assumption, occupants with fewer opportunities for personal control would demonstrate better thermal response when the thermal environment varied from neutral. In contrast, Nikolopoulou [13] hypothesized that people with high levels of control over the source of discomfort would be less irritated by it, thereby greatly reducing their negative emotional responses. Nikolopoulou's opinion, which essentially states that high degrees of personal control can contribute to high thermal acceptance, is quite similar to the central notion of the adaptive comfort model. Many comparative experiments have attempted to explain the relationship between personal control and thermal response. For example, Brager et al. [14] conducted a field study in a naturally ventilated office building, and found that occupants with more opportunities to operate windows reported temperatures closer to neutral than those who had less capability to control the windows, even though both groups were exposed to very similar thermal environments. Goto et al. [15] conducted a similar longitudinal study in six Japanese buildings, but they reported no considerable differences in occupants' thermal perception in the two groups of buildings. Zhang [16,17] conducted field investigations in a hot and humid climate, and found that occupants in naturally ventilated buildings reported lower neutral temperatures than those in air-conditioned buildings.

To resolve these inconsistencies, further research is still needed. In accordance with previous researchers' contributions, we designed a field study to answer the following two questions: (1) To what degree do different approaches of personal control influence human thermal perception? (2) Are lower degrees of personal environmental control equivalent to lower thermal expectations?

2. Methods

2.1. Outline of investigation

Two cities, Beijing and Shanghai, were selected for this investigation due to their different climate zones and variety of space heating facilities. In total, 139 apartments were surveyed and divided into three groups according to the degree of personal control over space heating. Group BJ-A and group BJ-B were the experimental groups, while group SH-C was used to test the results.

As shown in Table 1, occupants in apartments with district heating supply (BJ-A) had no direct way to control the indoor thermal environment, meaning this group of occupants had to accept their thermal environment passively. For group BJ-B, occupants could control the indoor thermal environment by adjusting individual space heating systems. It is noteworthy that the surveyed apartments in group SH-C were divided into two subsets, SH-C-1 and SH-C-2, according to whether occupants were able to use space heating. Apartments in subset SH-C-1 were equipped with air-source heat pumps for space heating, and occupants were allowed to use space heating freely. Although apartments in subset SH-C-2 were also equipped with air-source heat pumps, the occupants were not able to use space heating.

All other aspects of the selected apartments, such as the presence of operable windows, the age of the building, and the spatial layout, were similar in the initial background survey. Moreover, no significant differences existed among subjects in terms of other characteristics such as age, gender, and annual income.

2.2. Environmental parameter measurement and subjective questionnaires

Our methodology included simultaneous measurements of physical parameters and subjective questionnaires. Table 2 lists the

Table 2
Content of measurements and questionnaires.

	Physical measurements	Survey questionnaires	
		Building information	Comfort performance
Background study Detailed study	T_a, T_g, and RH T_a, T_g, v, RH, and meteorological station	Building characteristics, lifestyle, etc.	Clothing situation, TSV, TCV, thermal preference, thermal acceptance, etc.

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