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The underlying linkage between personal control and thermal comfort: Psychological or physical effects?

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ABSTRACT

In this paper we explore the influence of personal control over space conditioning systems on occupants' thermal comfort perception. It aims to identify the psychological effects of perceived control as well as the physical impacts when the controllable approaches are utilized. A chamber experiment was conducted, the results from which indicate that subjects with perceived control tended to report more positive comfort perception. The severer the thermal conditions were, the more subjects wanted to use personal control approaches, thus corresponding to stronger psychological effects. When personal control approaches were utilized appropriately, even a slight improvement in thermal conditions could significantly alleviate subjects' thermal discomfort complaints. These findings provide support to the adaptive comfort theory and can serve as reference for the design of personal environmental control systems.

1. Introduction

Thanks to the technologies of heating, ventilation and air conditioning (HVAC) in buildings, people have been able to create comfortable indoor thermal environment. However, an increasing number of modern buildings tend to provide thoroughly constant and uniformly neutral indoor climate at the expense of high energy consumption [1], which does not necessarily benefit occupants' thermal comfort and health [2,3]. Considering the significant amount of energy consumed by HVAC services in large economic entities such as United States [4], Europe [5], and China [6,7], it is essential to rethink about the real thermal demand of building occupants and to explore energy efficient ways to meet their requirements, rather than maintaining thoroughly neutral thermal conditions.

1.1. Increasing popularity of the adaptive comfort theory

There are mainly two philosophies that underpin current indoor thermal comfort assessments. One is based on heat balance calculation [8], while the other is known as adaptive thermal comfort model [9]. Compared with the heat balance approach, the adaptive comfort theory emphasizes that non-physical factors also play important roles in occupants' thermal comfort evaluation [10]. It is believed that in a real environment, people do not only passively accept the thermal stimuli, but also positively interact with the environment through the "human–environment" feedback cycle. In 2004 the adaptive model [11] was adopted in AHSRAE Standard [12] for natural ventilated buildings, alongside the Predicted Mean Vote and Predicted Percentage Dissatisfied (PMV-PPD) index for buildings using HVAC equipment. From then, the adaptive approach has been gradually incorporated into standards, such as ASHRAE Standard 55 [13], Europe EN 15251 [14], China GB/T 50785 [15], etc.

With the development of the adaptive thermal comfort theory in past two decades, efforts have been paid to enrich the theory and to provide supports for updated models. In late 1990s, the ASHRAE RP-884 project assembled a quality-controlled thermal comfort database covering the major climate regions. Outcomes derived from the database underpinned the adaptive theory and its implications [16]. After that, Nicol and Humphreys [17,18] initiated the SCATs project and conducted a longitudinal survey in 26 office buildings in Europe. To explain the philosophy behind the adaptive model, de dear and Brager classified the adaptive processes as physiological acclimation, behavioral adjustment and psychological expectation [11]. Yao et al. [19] proposed a theoretical adaptive model based on the "Black Box" theory by adopting an adaptive coefficient to represent the adaptive factors. In a word, the adaptive comfort theory has become a popular focus [9], representing one

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Nomenclature

T_a	indoor air temperature (°C)
T_g	black globe temperature (°C)
RH	relative humidity (%)
v	air velocity (m/s)
PMV	Predicted Mean Vote
HVAC	heating, ventilating, and air conditioning
Std	standard deviation

of the most thorough changes of tendency in the thermal comfort research field.

1.2. Effectiveness of personal environmental control

Personal environmental control can be utilized in different ways, varying from local ventilation outlets or fans, radiant or convective heaters, temperature controlled surfaces on chairs, desks, floors, etc. Driven by the benefits of both comfort improving and energy saving [20,21], a number of such devices have already existed. These devices are feasible to meet individual comfort requirements which differ due to variation in gender, age, body mass, metabolic rate, clothing, and thermal adaptation [22–24]. Therefore, they can result in much higher satisfaction rate than it is in uniformly conditioned space [25]. Meanwhile, they offer opportunities to save space conditioning energy since it is possible to expand the temperature control range [1]. Brager et al. [26] conducted a field study in a naturally ventilated office building, which showed occupants with more opportunities to operate windows voted thermal sensation closer to neutral than those who had less capability to control windows. Luo et al. [27] conducted a survey in residential buildings in winter and found occupants with personal control on space heating systems had higher satisfaction. Langevin et al. [28] re-analyzed the data of three case buildings from the RP-884 database in a more detailed way, and reported significant correlations indeed appeared between comfort evaluation and perceived control variables even in air-conditioned buildings. The concept and benefit of personal environmental control have been well summarized recently in Ref. [29].

1.3. Statement of the problem: the missing linkage between personal control and thermal comfort

All the above studies provide some references related to positive effects of personal control, while there also exists difference voices announcing that personal control had no impact on occupants' comfort or working performance [30]. Thus, based on the current small body of empirical evidences, researchers have not reached a consensus on whether and how personal control affects thermal comfort perception yet. Furthermore, when personal control approaches were utilized by occupants, the physical thermal conditions would be changed. We need to figure out if the observed improvement of comfort is due to the psychological effects, or it is because of the change of physical conditions. Based on this concern, Zhou et al. [31] once demonstrated that the thermal comfort improvement was merely due to psychological factors. However, is there any evidence from the opposite side to support the effects of physical condition changing? Most of the previous studies did not adequately clarify this issue: how dose personal control link to thermal comfort perception? To answer this question, more solid evidences are needed, especially those derived from chamber studies with variable controlled methods.

1.4. Objective of this study

Building on previous researchers' contribution to the issue of psychological adaptation, this study aims to figure out: (1) whether the effect of personal control is merely caused by psychological relief or also benefit from the improvement of physical conditions? (2) Is it possible to describe the psychological effects in a straightforward way (in this paper, the psychological effect of personal control on space conditioning systems was referred as "*perceived control*")?

2. Methods

2.1. Climate chamber

As shown in Fig. 1, the experiment was carried out in a climate chamber, which has been utilized to conduct similar comfort related studies such as work performance [32], dynamic thermal comfort with airflows [33], physiological adaptation [3], etc. It has two rooms which can be controlled independently by using two air handling units (AHU). The heater, humidifier, and cooling coil in AHUs are controlled by a computer program that minimizes the deviation between the measured thermal parameters and their set-points. The precisions of air temperature and relative humidity control are ±0.2 °C and ±5%, respectively. In the chamber, conditioned air is supplied from a ceiling perforated panel and exhausted through a raised floor. The background air velocity was validated with omnidirectional anemometers (SWEMA 03+) at three heights (1.1, 0.6, and 0.1 m above the floor). The measured background air velocities (< 0.1 m/s) were ensured lower than the sensible threshold (0.2 m/s), which has no significant impacts on subjects' thermal comfort perception. Twenty-four thermocouple thermometers with ±0.2 °C precision were distributed in three height levels (1.5, 1.0, and 0.5 m above the floor) to monitor the uniformity and stability of the thermal environment. The measured temperatures were utilized as feedback values for the control program. It is noteworthy that there is a door between the two independent rooms. Subjects can move from one room to another when it is necessary.

2.2. Experimental protocol

The overall experimental protocol is shown in Fig. 2. Considering the fact that air temperature has obvious effect on comfort perception and is also easy to control, it was chosen as the control variable in this experiment. And five temperature cases (31, 28, 26, 24, 21 °C), ranging from hot to cold conditions, were selected to represent different thermal environments. During the experiment, air temperatures (five temperature cases were ordered randomly), relative humidity (maintained in 50 ± 5%) and globe temperatures (similar with air temperatures) were monitored by Thermal Comfort Monitoring Station (LSI) with a precision for temperature measurement of ±0.1 °C (15–35 °C) and a precision for relative humidity measurement of ±3% (20–80%). The monitoring sensors were placed 0.5 m from the subject and 1.1 m above the floor. The room temperature outside the chamber was controlled close to the air temperature inside, which ensures the globe temperature inside the chamber be stable and be close to the air temperature. Hence, subjects' thermal comfort perception was mainly influenced by air temperature inside the chamber. As shown in Fig. 2, four experimental phases were designed to fulfill the objectives of this study.

Phase 1: preparation and adaptation. At the beginning of this period, subjects were supposed to be calm down, to change clothes and to learn about experimental procedures. After that, they spent