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Acceptable temperature steps for transitional spaces in the hot-humid area of China

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A R T I C L E I N F O

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A B S T R A C T

Transitional spaces account for a large proportion of building area and have significant impacts on human thermal comfort. This study conducted an experiment on the effect of temperature steps in transitional spaces on human thermal comfort. Thirty local people from the hot-humid area of China were recruited as subjects and exposed to different steps between a neutral temperature of 26 °C and non-neutral temperatures ranging from 20 to 32 °C in a climate chamber. The subjective and physiological response results show that warm sensation overshoots occurred under sudden heating, with the probability depending on both the step magnitude and the initial temperature, and cold sensation overshoots occurred in the warm-neutral steps. An asymmetric phenomenon was identified as the mean thermal sensation vote in the neutral condition changed significantly before and after steps. The subjective responses were anticipatory as they led changes in skin temperature, and the thermal comfort and acceptability responses were more anticipatory as they led changes in thermal sensation. The relationships between thermal sensation and the skin temperature change rate were identified, indicating that the skin temperature change rate caused a sensation that compensated for the sensation caused by the skin temperature itself. Step magnitudes no larger than 3 °C were proposed as acceptable temperature steps for transitional spaces in the hot-humid area. This study extends the understanding of the temperature step effect and provides valuable references for designing transitional spaces in the hot-humid area.

1. Introduction

A transitional space is a multifunctional space connecting the indoor and outdoor spaces of a building. Transitional spaces account for 10%–40% of the total area in various buildings [1] and serve to buffer the pressure from outside, avoid the negative impacts of extreme weather conditions and meet people's requirements for transitions between outdoors and indoors.

The summer is long, hot and humid and the winter is short and temperate in the hot-humid area of China. In this area, transitional spaces are often designed and constructed for good natural ventilation and passive cooling. For instance, halls are widely built in folk houses such as the Cantonese *san-xiang-liang-lang* and the *si-dian-jin*, *xia-shan-hu* in Chaoshan, and lobbies and courtyards in modern commercial and office buildings are typical transitional spaces. People may encounter temperature step changes that make them uncomfortable when passing through transitional spaces. It is important to study the effect of temperature steps on human thermal comfort and to provide acceptable temperature steps for transitional spaces in the hot-humid area.

Early in 1967, Gagge et al. [2] carried out the first experiment on temperature steps in a climate chamber with three subjects and revealed two fundamental findings: 1) the anticipatory effect, in which the reporting of thermal sensation and comfort leads the change in body temperature; and 2) the skin temperature change rate may cause an additional thermal sensation. More studies were conducted subsequently. Nagano et al. [3] conducted a chamber experiment on warm-cool steps with thirty subjects. They revealed the overshoot phenomenon, in which thermal sensation initially overshoots then gradually increases after sudden cooling. They also found that in identical conditions, thermal sensation and skin temperature changed with the condition before the steps, and such

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change may last for 50 min. In an experiment with sixteen subjects, Chen et al. [4] observed the overshoot phenomenon in the temperature down-steps but not in the up-steps and reported that thermal sensation correlated with skin temperature more strongly than with skin moisture and transepidermal water loss. Zhang et al. [5] carried out a chamber experiment on step changes in temperature and humidity with thirty subjects. They observed the anticipatory effect in all conditions, identified overshoot in a neutral-warm step, and concluded that both skin temperature and its change rate over time had significant impacts on dynamic thermal sensation changes. In the study by Zhao [6], the overshoot phenomenon was observed in sudden cooling, and this was further explained by the differences in depth and distribution density between the warm and cold skin sensors. Liu et al. [7] exposed twenty subjects to warm-neutral-warm steps and found sensation overshoots in all steps. Some other chamber studies [8–11] found the similar results.

The main findings from the previous chamber experiments are summarized as follows: 1) thermal sensation and thermal comfort are anticipatory, leading the body temperature change after a temperature step, and this anticipatory effect is most striking for cooling and less so for heating; 2) sensation overshoot can be observed under both warm-cool/neutral steps and the converse, while more overshoots are reported for the former than the latter; 3) humans are more sensitive to cooling than heating, and sudden cooling induces a larger variation in thermal sensation; and 4) human thermoregulatory reactions are rapid and effective in sudden heating, showing a small variation in skin temperature and short stabilization time, and are slow and less effective in sudden cooling, showing a large variation in skin temperature and long stabilization time.

Field studies have been carried out in semi-open station spaces [12], the underground shopping centers and department stores [13] in Tokyo and in the transitional spaces in Yokohama [14], Bangkok [15] and Taiwan [16]. Field studies are more realistic than chamber experiments in terms of context, human activities and psychological expectations. A large sample is required for field studies to obtain reliable finding due to the highly variable and complex conditions in real transitional spaces. In contrast, in climate chambers, the thermal conditions can be tightly controlled, and the subjective and physiological responses can be accurately measured. A better way to study the effect of temperature steps is to combine chamber experiments and field studies.

Only two chamber experiments and no field studies have been conducted to date on temperature steps in the hot-humid area. The experiments by Chen et al. [4] and Zhang et al. [5] focused on the steps from non-neutral to neutral. Since the steps from non-neutral to neutral and vice-versa exist simultaneously in real life, the present paper aimed to conduct chamber experiments on the temperature steps between neutral and non-neutral conditions with local people from the hot-humid area in order to examine the relationship between human responses and temperature steps and to propose acceptable temperature steps for transitional spaces in the hot-humid area. This study extends the understanding of the temperature step effect and provides valuable references for transitional space design.

2. Methods

2.1. Experimental facilities and conditions

This study was conducted in the South China University of Technology's climate chamber (Fig. 1). The climate chamber contained two adjacent rooms called Room A and B, each with the same dimensions of 3.25 × 3.45 × 3.35 m and connected to each other by an inner door. After cooling, heating and humidifying using air-handling units, air was supplied to the rooms through the suspended ceiling and returned through the raised floors, forming a piston flow and providing uniform thermal and humidity distribution in the rooms. The performances of the climate chamber were tested by the instrument HD32.3 with the range and accuracy in Table 1. The test results were as follows [5]: an air temperature range of 10–40 °C, stability of 0.2 °C, and spatial non-uniformity of less than 0.2 °C; a relative humidity range of 40%–90% and stability of 5%; an air speed below 0.1 m/s; and a mean radiant temperature close to the air temperature.

Five air temperature levels were determined based on real-world conditions, shown in Table 2. According to the Chinese national standard GB 50736-2012 [17], the recommended indoor comfortable temperature is 24–26 °C for cooling by air conditioning. According to the China standard meteorological database [18], the daily minimum, mean and maximum air temperatures are 26 °C, 29 °C and 32 °C, respectively, for a standard summer day in Guangzhou, a typical city in the hot-humid area of China. Based on the above information, the temperature ranges of 23–26 °C and 29–32 °C were designated as the conditions for air-conditioned indoor spaces and outdoor spaces, respectively, and the temperature range of 26–29 °C was designated as the conditions for transitional spaces. The steps between the neutral temperature (26 °C) and the non-neutral temperatures cover the majority of conditions that are encountered in transitional spaces in summer in the hot-humid area. The 20 °C level was added to form four up-steps and four down-steps with magnitudes of 3 °C and 6 °C. The relative humidity was maintained at 50% and the air speed was kept below 0.1 m/s for all conditions.

2.2. Subjects

Thirty college students in good health, half male and half female, were recruited as subjects. They were born and raised in the hot and humid area of China. The subjects' basic information is provided in Table 3.

2.3. Measurements

Skin temperature was measured by using *T* thermocouples. The thermocouples were calibrated in a constant-temperature water tank before being used, and the measurement errors were less than 0.2 °C. To ensure good contact, the thermocouple probe was pressed into two pieces of semicircular smooth copper and attached to the skin surface using breathable medical tape. Per McIntyre (1980), four parts of the human body, including the chest, upper arm, thigh and calf, were selected, and the mean skin temperature was obtained by using:

$$t_{sk} = 0.3\ t_1 + 0.3\ t_2 + 0.2\ t_3 + 0.2\ t_4 \quad (1)$$

where t_{sk} is the mean skin temperature (°C), and t_1–t_4 are the skin temperatures at the chest, upper arm, thigh and calf, respectively (°C).

The subjective responses of thermal sensation, thermal comfort and thermal acceptability were collected using questionnaires. Considering the hot and humid conditions in the experiment, a nine-point extended scale from ISO 15001, containing “Very hot” and “Very cold” degrees, was used for thermal sensation rating (Fig. 2 (a)). A four-point scale by Gagge et al. [2] was used for rating thermal comfort (Fig. 2 (b)), and a continuous scale that is divided between acceptable and unacceptable by Wyon [19] was used for rating acceptability (Fig. 2 (c)). The subjects voted on a computer. All the scales were continuous, and the subjects could vote in any