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Study on human skin temperature and thermal evaluation in step change conditions: From non-neutrality to neutrality

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ABSTRACT

The purpose of this study was to explore how the human body adapts to an environment as the temperature changes, and to describe the relationship between the objective skin temperature and subjective thermal evaluation. The influence of short-term thermal experience, which based on minutes and hours scale, could be considered on the prediction of thermal sensation. Usually, the indoor temperature set point is close to neutral, in which state the heat transfer between environment and human body is at a low level. Therefore, we mainly focused on the changes from non-neutral to neutral, to observe the effects of thermal experience in neutral environment. A chamber experiment was conducted with 20 subjects and used five conditions. The control group was maintained at 26 °C. The other conditions consisted of two phases in which subjects were exposed to a hot or cold temperature for a period of time and then go into a 26 °C room, which is considered a neutral environment. We measured the skin temperature on the chest, upper arm, and lower limb. The subjects were asked to complete thermal evaluation questionnaires about thermal sensation, thermal comfort, and thermal acceptance. The skin temperature of subjects varied for the different conditions. We found that even if a poor thermal environment was improved slightly, the thermal satisfaction of subjects increased significantly. This study describes two methods for the prediction of thermal sensation, and the results contribute to our understanding of the mechanism of adaptive thermal comfort.

1. Introduction

The development of technology allows people to create indoor environment according to their requirements. More and more buildings have been in pursuit of a steady state indoor environment at the expense of high-energy consumption [1,2]. In addition, the single and general control standards of a steady state thermal environment may ignore climate differences, or do not consider dynamic changes in human activities [3]. It is necessary to carefully think over the real demand, and then determine efficient strategies to maintain an appropriate thermal environment.

1.1. Current state of the research

Thermal comfort is a concept used to describe mental satisfaction with the thermal environment, and it is usually assessed by subjective evaluation [4]. The Predicted Mean Vote (PMV) model, which was established by Fanger, is the most recognized thermal comfort models. This model as developed using principles of heat balance and experimental data collected in a controlled climate chamber under steady state conditions [5]. On the other hand, an adaptive model proposed by de Dear and Brager, emphasized that human body could adapt to the surroundings in three ways: physiological acclimatization, behavioural adjustment, and psychological habituation [6,7]. The development of this theory based on hundreds of field studies with the idea that occupants dynamically interacted with their environment. And this model provided us a dynamic perspective in thermal comfort research.

Generally, the PMV model is applied to air-conditioned buildings, some studies indicate that the comfortable temperature range of these buildings is becoming narrower than before [8]. This leads to an increased consumption of energy by HVAC systems [9,10]. However, Arens found that thermal comfort satisfaction could hardly be improved by steady state control even with high precision control [11]. Additionally, being in a constant air conditioned environment for a long time reduced the excitability of hot or cold stimulation, and did harm to human health [12]. In contrast, the

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Nomenclature

TAV	Thermal acceptance vote
TCV	Thermal comfort vote
TSV	Thermal sensation vote
TSV_{pre}	Previous TSV
$T_{s\text{-}chest}$	Skin temperature of chest, °C
$T_{s\text{-}upperarm}$	Skin temperature of upper arm,°C
$T_{s\text{-}lowerlimb}$	Skin temperature of lower limb, °C
$T_{s\text{-}m}$	Mean skin temperature, °C
$T_{s\text{-}m\ pre}$	Previous $T_{s\text{-}m}$, °C
T_a	Air temperature, °C
T_{mr}	Mean radiant temperature, °C
△TAV	Changes of TAV
△TCV	Changes of TCV
△TSV	Changes of TSV
$\triangle T_{s\text{-}m}$	Changes of $T_{s\text{-}m}$, °C
Q_s	Heat loss of human body, W/m^2
C	Heat loss by convection, W/m^2
R	Heat loss by radiation, W/m^2
E	Heat loss by skin diffusion, W/m^2
S	Heat loss by evaporation of sweat secretion, W/m^2
A_{Du}	Human body area (by DuBois), m^2
f_{cl}	Ratio of the surface area of the clothed body to the hide body
h_c	the convective heat transfer coefficient, W/m^2 °C
p_s	Saturated vapour pressure at skin temperature, Pa
p_a	Vapour pressure at air temperature, Pa
W	Body weight, kg
H	Body height, m

adaptive model focused more on the role of humans in an indoor environment, and analysed the problem with a dynamic viewpoint. This theory is widely accepted, and is expected to become the prevalent trend [13]. However, the details of the adaptive thermal comfort model are not yet clear [14]. The mechanism and the logic of adaptive processes need to be characterized [15] to explain the key issues of adaptive comfort and more comprehensively develop this theory [16].

Thermal experience refers to the effects of the previous thermal environment, which may affect the human body and thermal perception. This is considered an important part of adaptive thermal comfort research. Gagge [17] studied different physiological responses of the human body when the environmental temperature changed. He found that the response of thermal sensation changed rapidly from a non-neutral environment to a neutral environment. Chun [18] conducted a comparative study with subjects who had different thermal experiences, and the results showed that the subjects who experienced higher temperatures reported lower thermal sensation than those with cooler initial experience. Du [19] did experiments about step-changes in temperature, and reported that heat loss from the human skin surface can be used to predict dynamic thermal sensation. Vecchi [20] used measurements and questionnaires in mixed-mode buildings to explore the impact of prolonged exposure to air-conditioned environments. She found significant differences in occupants' thermal acceptability and cooling preferences based on personal thermal experiences. Other studies of thermal experience also showed differential effects of thermal sensation and thermal comfort when the temperature changed [21–25].

Many studies related to thermal experience have used skin temperature as an observable indicator. Horikoshi [26] found that the responses of local skin temperature to decreasing air temperature from 30 to 20 °C are not necessarily opposite to the responses observed when increasing the air temperature from 20 to 30 °C. Chen [27] investigated the changes in thermal perception and in thermoregulation that simultaneously occurred in response to a temperature step change in a thermal transient. Others studied how to predict thermal sensation in such a condition with short-term thermal experience. De Dear [28] used a dynamic model and performed chamber experiments to describe the thermal sensations resulting from sudden ambient temperature changes. Ring [29] used a model that combined skin, thermoreceptor response, and thermal sensation to study temperature transients. Takada [30] proposed a new model to predict thermal sensation in the non-steady state based on skin temperature and its time differential. Additionally, some studies described the effects of short-term hot or cold stimulus on the human body and found some differences in thermal evaluations compared with steady state evaluations [31,32].

To date, there is no consensus about how short-term thermal experiences influence thermal comfort and thermal adaptation. Most of the previous studies about step-changed temperature were with large temperature differences, which was unclosed to the real scene. In real buildings, the indoor temperature is usually set to neutral. The temperature of transition spaces, such as corridor and other public area are not neglected separately. However, an unchanged stable neutral environment may not be the best setting for energy consumption and for thermal comfort. Therefore, we must develop accurate thermal prediction methods based on parameters that can be easily measured. To set up an appropriate temperature for a current thermal condition, it is important to consider occupants' activities and thermal sensations at the previous moment. This work will assist the design of future spaces for better control of temperature in spaces designed for various functions.

1.2. Objective of this study

This study focused on the influence of short-term thermal experience in a neutral environment on skin temperature, and thermal evaluation. Accordingly, the relationship between objective parameters and subjective evaluations can be used to predict thermal sensation under the condition that short-term thermal experience cannot be ignored.

2. Methods

2.1. Experimental protocol

Considering the adaption of the human body, it is necessary to find a physiological parameter for thermal sensation prediction. Skin temperature is an intuitive indicator, and it is convenient to measure. Therefore, a chamber experiment was designed to observe the influence of short-term experience by the measurement of skin temperature together with the completion of questionnaires. We used the control variable method in this study, and focused on the influential factor of "temperature." In this way, other factors such as humidity and clothing thermal resistance were unified, and set to common, non-extreme values.

There were totally five conditions in this experiment: subjects stayed and transferred 1) from 20 °C to 26 °C; 2) from 23 °C to 26 °C; 3) from 26 °C to 26 °C; 4) from 29 °C to 26 °C; and 5) from 32 °C to 26 °C, as shown in Fig. 1. Among all of these conditions, the one where subjects maintained at 26 °C (from 26 °C to 26 °C) was the control group. Each condition consisted of two phases: in Phase 1, subjects stayed at one temperature, cold (20 °C, 23 °C), neutral (26 °C), or hot (29 °C, 32 °C) for 30 min; and in Phase2, subjects all moved into 26 °C, which was considered as a neutral environment, and stayed for 40 min.