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Assessment of thermal comfort under transitional conditions

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ABSTRACT

This paper explores thermal comfort assessments under transitional states. Toward this end, multiple groups of participants moved in a laboratory building through a number of spaces with different thermal conditions. The thermal sensation and comfort evaluations of the participants were assessed before transition, immediately after the spatial transition, and after a short period of adaptation. The main objective of the study was to compare participants' thermal comfort assessments immediately after a spatial transition with those of thermally adapted participants. The results suggest that changes in people's thermal sensation vote (TSV) subsequent to a thermally relevant transition from one room to another, are consistent with the temperature difference between the two rooms. Transition-related changes in thermal comfort vote (TCV), however, are more consistent with a proposed new measure of the "thermal distance" between the two rooms, namely the effective temperature difference ($\Delta\theta_{\text{eff}}$). This measure compares the distance to comfort temperature before and after the transition.

1. Introduction

Heating, ventilation, and air-conditioning technologies and systems are typically used to provide desirable indoor thermal environments for human occupancy. However, if occupants go through spatial transitions involving noticeable temperature differences, typical thermal comfort evaluation schemes which are geared toward thermally adapted individuals (see, for example, ASHREA Standard 55 [1] and ISO 7730 [2]) may not apply. People are frequently exposed to such transitional states, for example when they enter or exit a building or when they move through differentially tempered rooms within a building. A disregard of thermal evaluation processes pertaining to transitional states may result in inappropriate temperature settings, inefficient thermal controls, and poor thermal comfort conditions.

Subjective thermal sensation and comfort evaluations of transitional states have been addressed in past research. For example, the thermal sensation responses immediately after a transition involving temperature increase have been reported to be close to the responses after adaptation, whereas the thermal sensation responses immediately after a temperature decrease dropped initially to return to a stable level after adaptation [3]. Chun and Tamura [4] conducted a field study in underground shopping malls where subjects were exposed to continuous temperature changes as they moved between different spaces. Authors emphasize the importance of temperature change for the perception of thermal comfort. Chun and Tamura [5] also conducted a laboratory-based study involving subjects walking through controlled cambers in sequence. They suggest that thermal comfort perception at a certain point in time is influenced by antecedent thermal conditions. Arens et al. [6] investigated thermal sensation and thermal comfort in time series including rapid temperature changes. Their results show that the thermal sensation and thermal comfort reach their final state shortly after a spatial transition. Likewise, Nakano [7] suggests that transitions involving large temperature intervals towards thermal neutrality result in correspondingly large improvement of thermal comfort feedback. Hwang et al. [8] demonstrated differences between the thermal comfort perception of visitors versus resident staff in public spaces. In a recent paper, Chen et al. [9] studied thermal sensation as well as skin temperature after a transitional state. They suggest that temperature difference should be limited to 4 K in order to maintain adequate thermoregulatory function. Parkinson et al. [10] indicated that sudden changes in ambient temperature can induce thermal pleasure, given a positive alliesthesial effect. However, the same environmental step change invoked a displeasure response when the core temperature was stable.

In the present study, our specific objective was to investigate people's thermal sensation and comfort assessments as a consequence of moving through spaces with distinct thermal conditions.

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Specifically, thermal sensation vote (TSV) and thermal comfort vote (TCV) of thermally adapted people were captured before they moved from one space to another. The same votes were collected immediately after transition and following a brief period of thermal adaptation. The subjective expressions of thermal conditions were analyzed in the context of collected indoor environmental data (air temperature and relative humidity) during the experiments. The results were compared with calculations based on conventional thermal comfort models. Moreover, the collected data was processed to identify those variables that influence people's thermal sensation and comfort subsequent to a thermally relevant spatial transition.

2. Research design

The objective of the study was to obtain empirical data needed to address the following research questions:

- Do thermal sensation votes of thermally adapted participants in pre-transitional state agree with predictions of standard (steady-state) thermal comfort models?
- Do thermal sensation votes of participants immediately after a spatial transition (involving temperature change) differ from the predictions of standard (steady-state) thermal comfort models, and if yes, to which extent?
- Do changes in thermal sensation and thermal comfort votes after moving from one room to another correlate with temperature difference between the two rooms?
- To which extent can post-transitional thermal comfort votes be predicted based on the temperature difference between the two rooms involved in the spatial transition?

To pursue these questions, a physical (laboratory) setting in our Department (Building Physics and Building Ecology, Vienna University of Technology, Vienna, Austria) was selected. Fig. 1 schematically illustrates this setting and the experiment's spatial arrangement. Here, E denotes the external environment (open courtyard) and M is a general (unconditioned) 8 by 10 m laboratory space (height = 5 m). A and B are two equally sized mockup office rooms (3 by 4 m, height = 2.5 m). M was mechanically ventilated throughout the two phases of the experiment (conducted in winter and spring). However, it was not thermally controlled (cooled) during the spring session. A basic level of heating was provided during the winter session. A and B were either heated or cooled according to the experimental setup and seasonal conditions.

The facility is equipped with a monitoring system facilitating the continuous collection of data regarding thermal conditions in the test spaces. Specifically, indoor air temperature, relative humidity, CO_2 concentration, and illuminance levels were monitored during all experiments.

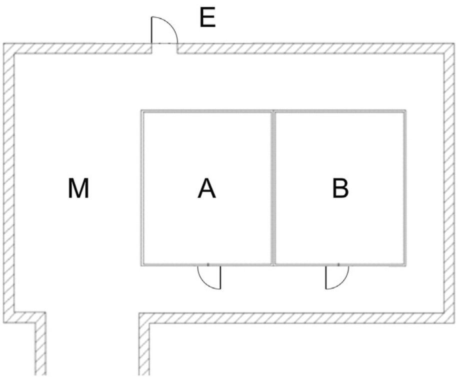

Fig. 1. Schematic illustration of the test spaces.

Ideally, experiments should be conducted in different times during the year, such that different outdoor conditions and corresponding clothing variations are captured. Given practical constraints and available resources in our case, we were able to conduct the experiments with participants (students at the Vienna University of Technology) in spring and winter 2012. The number of participants in the spring session was 313 (56% female, 44% male) and in the winter session 84 (43% female, 57% male). The mean age of spring session participants was 22 ± 3 and that of the winter session participants 26 ± 3. Given the difference in the number of participants in winter and spring, statistical analyses was not only conducted for the entire data set, but also separately for winter and spring.

Participants were divided into multiple groups, each consisting of 6 individuals. The composition of the groups was basically random. However, to the extent possible, equal number of male and female participants were assigned to each group.

All groups went to a sequence of spatial transitions as summarized in Table 1. Prior to each transition (walking from one room to another), participants were adapted to thermal conditions in sedentary position. In literature [6,11,12], adaption phases of 10–20 min have been found appropriate. In our experiments, participants spent at least 15 min in sedentary state. The thermal resistance of the participants' clothing (expressed in units of clo), which remained unchanged throughout the experiment, was documented based on visual inspection [13] at the beginning of the experiment (0.6 ± 0.15 clo during the spring session and 1.2 ± 0.18 clo during the winter session). Immediately after each transition, the participants' thermal sensation and comfort vote was assessed via a questionnaire. After an adaptation phase of approximately 15 min (also in sedentary position), votes were collected again.

The spring experiments were conducted in the beginning of May 2012 over a period of 5 days. The outdoor temperature (*E*) range in this period was between 11 and 30 °C. The temperature of the space *M* fluctuated slightly around 24 °C. The winter experiments were conducted in the middle of December 2012 over a period of 2 days. The outdoor temperature (*E*) range in this period was between 0 and 4 °C. The temperatures of the unconditioned space *M* fluctuated slightly around 21 °C. In both spring and winter sessions, the temperatures of the heated cell (A) and the cooled cell (B) were kept at 27 °C and 17 °C respectively. All experiments were conducted during daytime (from 9 am to 6 pm).

Participants were requested to express their thermal sensation vote (TSV) using a 7 points scale (−3: cold, −2: cool, −1: slightly cool, 0: neutral, 1: slightly warm, 2: warm, 3: hot) [1] and their thermal comfort vote (TCV) using a 6 points scale (−3: very uncomfortable, −2: uncomfortable, −1: just uncomfortable, 1: just comfortable, 2: comfortable, 3: very comfortable) [11]. In the treatment of the results, the votes of the six participants constituting each group was averaged and processed for further analyses and interpretation. The main reason for this approach was the fact that all members of each group were exposed to the exactly same

Table 1
Overview of the spatial transitions (see Fig. 1 for room symbols) and the respective number of participants.

	Spatial transition	Number of participants	
		Spring	Winter
1	M_A	154	41
2	M_B	152	38
3	A_M	155	42
4	B_M	158	42