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Thermal sensation and thermal comfort in changing environments

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ABSTRACT

It is the purpose of this study to investigate thermal sensation (TS) and thermal comfort (TC) in changing environments. Therefore, 10 subjects stayed in a 30 °C, 50% relative humidity for 30 min in summer clothes and then moved to a 20 °C room where they remained seated for 30 min (Hot to Reference - HR). Similarly, 11 subjects moved from a 10 °C, 50% relative humidity to a 20 °C environment (Cold to Reference – CR) dressed in winter garments. TS (9 point scale from −4 (very cold) to +4 (very hot)) decreased from 1.5 ± 0.4 (mean ± SD) to −0.8 ± 0.8 for HR and increased from −1.7 ± 1.4 to 0.8 ± 0.9 for CR. TC (5 point scale from 0 (comfortable) to +4 (extremely uncomfortable)) dropped from 1.5 ± 0.5 to 1.2 ± 0.4 for HR and from 1.9 ± 0.7 to 1.3 ± 0.4 for CR. The difference in TS between HR and CR at the end of period in 20 °C illustrates the considerable dependence of thermal sensation on exposure history. It is therefore recommended to increase room temperature when it is hot outside and decrease room temperature when it is cold outside in order to maintain a neutral thermal sensation.

1. Introduction

Humans are homeotherms and controlling body core temperature is easier in stable thermal environments. It is therefore not surprising that most scientific studies address thermal sensation and thermal comfort under stable environmental conditions such as during office work. However, it has been recognized that thermal transients have an important effect on thermal sensation [1]. There seems to be a recent interest revival regarding thermal comfort in changing thermal environments [2–5]. Additionally, the recent revisions to ASHRAE-55 regarding the thermal environment for human occupancy encouraged the discussion on the influence of outdoor temperatures on indoor comfort [6]. This paper intends to add to the pool of information. More specifically we intend to investigate transients from a mildly warm environment to a reference temperature of 20 °C and from a mildly cold environment to the reference temperature with a focus on thermal sensation.

Thermal sensation is a standard parameter in most thermal experiments. It is uniformly defined in ISO 7730 [7] and ASHRAE standard 55 [8] with a scale ranging from −3 (cold) to +3 (hot). The scale is sometimes extended to −4 (very cold) to +4 (very hot) to cover a wider range [9,10]. Mostly, thermal sensation and its derivation PPD (percentage of dissatisfied people) are used to assess satisfaction with the climate. Thermal comfort is defined by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) as the condition of mind that expresses satisfaction with the thermal environment. In our study we used a 5-point scale (0 comfortable, +4 extremely uncomfortable) [9]. Thermal comfort can be partially influenced by different contextual and cultural factors but it is primarily an effect of the heat exchange between the body and the environment [11].

When the environment suddenly changes in temperature, it takes time to adapt and to change to a new thermal equilibrium [12]. Dahlan & Gital [2] found that the changes in thermal sensation scores after a temperature change are dependent on the temperature difference between the two environments. Participants' thermal comfort changed to more comfortable after a drop of ambient temperature from 35 °C to 24 °C and became more uncomfortable after an increase of ambient temperature from 24 °C to 35 °C ($\Delta T=11$ °C). Gagge et al. [9] described the phenomenon overshoot. When a person moves between two environments with different ambient temperatures, thermal sensation scores in the second environment are affected by the previous environment. More recently, Du et al. [3] performed a study including three experiments on this topic and observed a small overshoot in thermal sensation when participants moved from a cool room (resp. 12 °C, 15 °C and 17 °C) to a 22 °C room. What they also found was that thermal experience has a large influence on people's thermal sensation. When the participants moved from the neutral room back to the cold room (2nd transient) the thermal sensation scores dropped immediately after the transient, and then slightly increased (approximately 0.5

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units). Liu et al. [4] reported a study of also three experiments where they investigated the transient from hot to a reference temperature close to thermal neutrality. They found that TS scores decreased sharply when a person moves from a hot room (resp. 32 °C, 30 °C and 28 °C) to a room of 25 °C and a large negative overshoot occurred. After the transient from the 25 °C room to the hot room, TS scores increased and a positive overshoot occurred. However, TS values were lower than the TS scores when the participant stayed in the hot room the first time. These two studies could be used to describe how persons respond to changes in ambient temperature. However, the neutral room has a different temperature in both studies, resp. 22 °C [3] and 25 °C [4]. This means that the two studies cannot be compared to each other in order to find the difference in the response between a hot-neutral change and a cold-neutral change. Xiong et al. [5] performed a study to investigate the effect of a change in ambient temperature on, among others, thermal sensation. They performed three experiments including a change of ambient temperature from resp. 32-26-22°C to 37°C and back to resp. 32-26-22°C. They concluded that all transients had a significant effect on thermal sensation. When the difference in ambient temperature increased, the effect on thermal sensation became more pronounced. When the temperature development was 22–37 °C-22 °C, the change in thermal sensation was 3 units while when the temperature development was 32–37 °C-32 °C, the change in thermal sensation was only 1 unit.

The described studies were mostly performed in Asia. A comparison of thermal comfort between Asia and Europe has not yet been made, but one could imagine that the requirements of a thermal comfortable environment are different due to the climate and acclimatization status. Consequently, the results of these field studies cannot be directly applied in the Netherlands. Further, in the previous described studies the different experiments were performed on the same day. Thus the participants' body in the second and third test could already be heated or cooled due to the previous tests and thereby affect the results. Therefore, the aim of this study was to investigate thermal sensation and thermal comfort in changing environments. We hypothesize that thermal sensation in a reference room temperature of 20 °C differs significantly after a period of cold and heat exposure, independent of thermal status of the body.

2. Materials and methods

2.1. Subjects

11 Healthy Dutch subjects (7 males and 4 females) participated in this study. Females were aged 26 ± 5 (Mean ± Standard Deviation) years, had a height of 167 ± 8 cm and body mass of 60 ± 4 kg. Males were aged 24 ± 5 years, had a height of 181 ± 7 cm and body mass of 78 ± 4 kg. The subjects did not perform heavy exercise prior to the experiment and did not consume coffee two hours prior to the experiment. The subjects were fully informed of the goals, protocol and possible risks before giving a written consent to participate in the experiment. The study was approved by the Ethics Committee of the VU University (Amsterdam, The Netherlands).

2.2. Experimental design

The experiments were scheduled in two morning sessions lasting two hours, with three days in between. The experiments were carried out in the climatic chamber at TNO Soesterberg (the Netherlands) in the last week of August 2015. The average maximum temperature in August in the Netherlands is 22 °C, and this was also the maximum hourly temperature during the days of the experiment (https://data.knmi.nl/datasets).

The first session involved the transition from a simulated summer environment (30 °C, 50% relative humidity) to a reference environment (20 °C, 50% relative humidity) abbreviated as HR. The second session involved the transition from a simulated winter environment (10 °C, 50% relative humidity) to the reference environment (20 °C, 50% relative humidity) abbreviated as CR. The choice of temperature and relative humidity for the summer and winter environment was based on weather reports of the Royal Netherlands Meteorological Institute (KNMI). The subjects were dressed in standardized summer- and winter clothing. For the summer scenario this was underwear, shorts, a T-shirt, socks and low shoes (about 0.2 Clo [13]). In the winter scenario this was underwear, jeans, a long sleeve shirt (with or without buttons), a winter jacket, socks and shoes (about 1.12 Clo [13]).

The subjects was seated in the climatic chamber set to the summer/winter environment and sat there for 30 min. Thereafter (at t=30 min), they proceeded to the chamber set to the reference environment of 20 °C and sat there for 30 min. In both climatic chambers the participants did not change their clothing.

2.3. Measurements and methods

The measurements were executed in two adjacent climatic chambers (only 3 m apart) with temperature control better than 0.2 °C, humidity control ranging from 10%RH to 90%RH (only above 4 °C) with an accuracy of 2% (above +25 °C) or 5% (below +25 °C) and air displacement of less than 0.2 m/s (Weiss Enet, Tiel, The Netherlands). The core temperature (Tre) was assessed using a rectal thermometer (Yellow Springs Instruments 400 series, Yellow Springs, OH, USA) read using a resistance meter (Velleman DVM 851, Gavere, Belgium). The rectal thermometer was inserted 10 cm beyond the anal sphincter and the cable was fixed to the lower back with tape. The measurements were repeated every five minutes. Skin temperature was measured every minute with an accuracy of 0.0625 °C using iButtons (DS19221, Maxim Integrated Products Inc., Sunnyvale, CA, USA) [14] placed on C5 in the neck, the right scapula under the spina scapula, the dorsal side of the left hand and on the muscle belly of m. tibialis anterior of the right leg. A weighted average of the temperatures of the four locations resulted in the mean skin temperature (Tsk) [15].

Mean body temperature (Tb) was calculated according to Burton [16].

Thermal sensation was assessed every 5 min using a 9-point scale (from −4=very cold to +4=very hot) and thermal comfort was assessed every 5 min using a 5-point scale (from 0=comfortable to +4=extremely uncomfortable) [10]. Body mass (including clothing) was measured on a weighing scale (Sartorius F300S, Göttingen, Germany) before the experiment. The height was measured using a stadiometer (SECA 222, Apeldoorn, the Netherlands) before the experiment.

2.4. Data analysis

For the analysis of rectal temperature (Tre), mean body temperature (Tb), thermal sensation (TS) and thermal comfort (TC) discrete values at each fifth minute of the experiment were selected. Skin temperature (Tsk) was determined every minute. One female subject was removed from the dataset for the HR condition due to missing data.

Statistical analyses were performed using Statistica 13.1 (Dell Inc.). To examine if and to what extent transients influence thermal comfort and thermal sensation, a Wilcoxon rank sum test was performed for TS and TC before- and after transient as dependent variables for each condition. To define the effect of transients on mean skin, mean body and rectal temperature, independent sample T-tests were performed. P values lower than 0.05 were accepted as significant.

3. Results

Table 1 summarizes the average Tre, Tb and Tsk as well as TS and TC before and after the transient for males, females and both genders grouped.