Transient thermal sensation and comfort resulting from adjustment of clothing insulation

T. Goto[a,*], J. Toftum[b], P.O. Fanger[b], H. Yoshino[a]

[a]*Department of Architecture and Building Science, Tohoku University, Japan;* [b]*International Centre for Indoor Environment and Energy, Technical University of Denmark, Denmark*

ABSTRACT
This study investigated the transient effects on human thermal responses of clothing adjustments. Two different levels of activity were tested, and the temperature was set to result in a warm or cool thermal sensation at each activity level. The subjects (12 females and 12 males) wore identical uniforms and were asked to take off or don a part of the uniform after they had adapted to the experimental conditions for more than 20 min.

Independent of the activity level, the thermal sensation votes responded immediately to the adjustment of clothing insulation and reached a new steady-state level within 5 min after both up-step and down-step of clothing insulation. It was similar to stepwise changes of temperature and humidity except that the thermal sensation vote after down-step of clothing insulation did not overshoot obviously.

INDEX TERMS
Clothing; Thermal comfort; Transients

INTRODUCTION
Clothing insulation has considerable impact on human thermal sensation and comfort. Existing steady-state models can estimate the resultant effect of changing clothing insulation. For example, donning a typical jacket (≈0.35 clo) will ultimately shift the preferred temperature downward by more than 2°C (Olesen, 2000). People usually adjust clothing insulation at their own initiative, and it is one of the most important behavioural thermoregulatory actions. An adjustment may be triggered by a person's current discomfort and expectation of a higher degree of comfort after the adjustment has been made.

Transient effects of thermal sensation and comfort of changes of temperature or other environmental parameters as well as of changes of activity level are described in the literature (e.g. de Dear *et al.*, 1989, 1993; Goto *et al.*, 2002), but no information is available on the temporal effects of changing the clothing insulation, despite this being one of the most prevalent behavioural actions taken to maintain comfort. This study investigated the transient effects on thermal sensation and comfort after stepwise increase or decrease of clothing insulation.

METHODS
Human subject experiments were performed at two different activity levels. At each activity level, only the clothing insulation was changed, whereas the thermal environment was kept constant.

Twenty-four subjects (12 females and 12 males) participated as volunteers. They were university students with an average age of 23.8 years, and were paid for their participation. The experiments were carried out in two adjacent and interconnecting climate chambers at the Technical University of Denmark. During the experiments, subjects wore the designated uniform consisting of a cotton T-shirt, thin cotton trousers, socks and light shoes and their

* Corresponding author. E-mail: goto@sabine.pln.archi.tohoku.ac.jp

own underwear. A sweatshirt made of 70% cotton and 30% polyester was used for adjustment of clothing insulation by donning or removing. The clothing insulation of this ensemble without a sweatshirt was 0.65 clo and with the sweatshirt 1.03 clo, as determined by a thermal manikin at standing posture.

Each subject participated in two experimental sessions as shown in Table 1, each with a duration of 90 min. Figure 1 shows the timeline of the experiments. An experimental session commenced with subjects getting dressed in the uniforms without sweatshirts prior to entering the first chamber. In one experiment, subjects adapted to the environment during 30 min, before donning the sweater. The first chamber was kept at a constant air temperature of 23°C, and the subjects were resting on a chair (low activity: ≈1 met). Twenty minutes after donning the sweater, subjects moved into the adjacent chamber and started walking on a treadmill (high activity). During the subsequent 20 min, the subjects adapted to the new activity level and the environmental conditions in this chamber. Then they removed the sweatshirt again, and kept walking for 20 more minutes. The second chamber was kept at a constant air temperature of 17°C. The other experimental session followed the same timeline, but the subjects wore the uniforms with sweatshirts before entering the first chamber and took off the sweatshirts in the first chamber after 30 min. In the second chamber, subjects donned the sweaters again. The first chamber was kept at 26°C and the second chamber at 13°C.

Table 1 Conditions of the two experimental sessions
(T_a = air temperature; MRT = mean radiant temperature)

	In the first chamber	In the second chamber
Session 1	Low activity T_a = MRT = 23°C, 30% RH 0.65 → 1.03 clo	High activity T_a = MRT = 17°C, 40% RH 1.03 → 0.65 clo
Session 2	Low activity T_a = MRT = 26°C, 30% RH 1.03 → 0.65 clo	High activity T_a = MRT = 13°C, 50% RH 0.65 → 1.03 clo

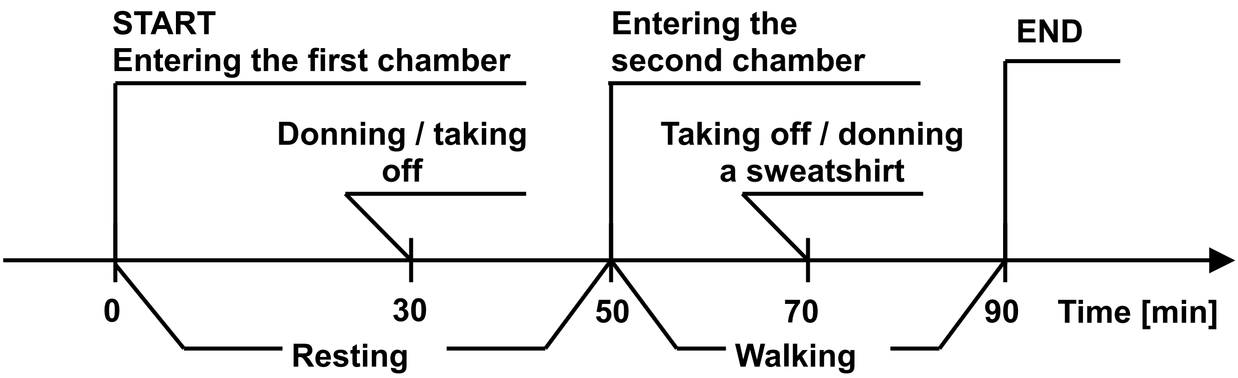


Figure 1 Timeline of an experimental session.

In both chambers, the mean radiant temperature was equal to the air temperature and the air velocity was low (<0.2 m/s). The air humidity in the first chamber was about 30% when the air temperature was 23°C as well as 26°C. The humidity in the second chamber was about 40% when the air temperature was 17°C and 50% when the air temperature was 13°C. The activity level in the second chamber was given by the relative work load of each subject, not by the absolute work load, because thermal sensation correlates with the relative work load (Goto *et al.*, 2002). Actually, the walking speed was determined to be the 20% relative work load of each subject, and the average speed was 0.8 m/s, which corresponded to 145 ± 25 W/m^2 (≈2.5 met). The temperatures of 23 and 13°C were selected to facilitate a neutral steady-state thermal sensation after up-step of clothing insulation, and the air temperatures of 26 and 17°C were selected to facilitate a neutral thermal sensation after down-step of clothing insulation. These temperatures were determined by the PMV model.

Subjects answered questions regarding thermal sensation on a nine-point scale (ASHRAE seven-point scale with very hot and very cold), thermal comfort, thermal acceptability and temperature preference every 5 min during the experimental sessions. However, subjects answered the questions every minute for 5 min after the adjustments of their clothing insulation. Heart rate was measured on all subjects, and skin temperature (head, chest, back, upper arm, hand, anterior thigh, posterior thigh, shin, calf) and relative humidity next to the skin (chest, back, anterior thigh) were measured on eight subjects.

RESULTS

Average thermal sensation, skin temperature and skin wettedness observed when subjects were engaged in low activity in the first chamber are presented in Figure 2 for two different air temperatures and the opposite clothing changes. Figure 3 shows the measurements with high activity in the second chamber. The skin temperatures were the averaged values of the measurements on eight subjects. One of the skin temperature measurements noted as 'All' represents the mean skin temperature of whole body ($\overline{T_{sk}}$). Mean skin temperature was calculated as an area-weighted average of measurements using the following formula, which was modified from Nishi *et al.* (1975):

$$\overline{T_{sk}} = 0.07*T_{head} + 0.175*T_{chest} + 0.175*T_{back} + 0.14*T_{upper\ arm} + 0.05*T_{hand} + 0.095*T_{anterior\ thigh} + 0.095*T_{posterior\ thigh} + 0.10*T_{shin} + 0.10*T_{calf} \quad (1)$$

The values of 'Trunk' and 'Lower body' are the area-weighted average of chest and back, and anterior thigh, posterior thigh, shin and calf, respectively.

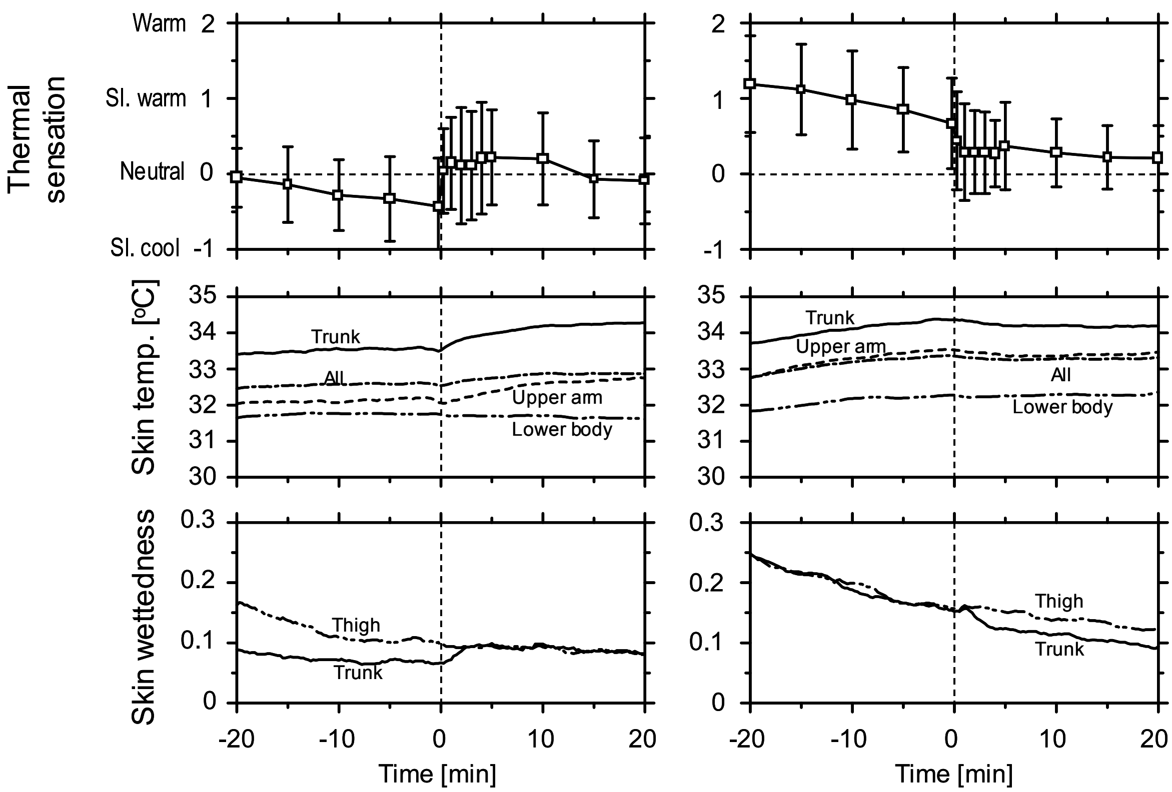
The presented skin wettedness was also the averaged value of the measurements on eight subjects, and calculated from relative humidity next to the skin (RH_i), the temperature measured by the humidity sensors (T_i), the local skin temperature (T_{ski}), air temperature (T_a), and air humidity (RH_a) as follows (Berglund and Cunningham, 1986):

$$w_i = [RH_i*Ps(T_i) - RH_a*Ps(T_a)]/[Ps(T_{ski}) - RH_a*Ps(T_a)] \quad (2)$$

where $Ps(T_i)$, $Ps(T_a)$ and $Ps(T_{ski})$ are the saturation vapour pressures of water at temperatures T_i, T_a and T_{ski}.

In Figures 2 and 3, the time of zero represents the time of the clothing change. Only skin temperature and skin wettedness on the torso was affected by both up-step and down-step of clothing insulation when the subjects were engaged in both low and high activity.

As Figure 2 shows, there was an immediate change of thermal sensation (within 1 min) after an increase/decrease of clothing insulation. During the periods before and after the change of clothing insulation, thermal sensation generally decreased along with the skin wettedness.

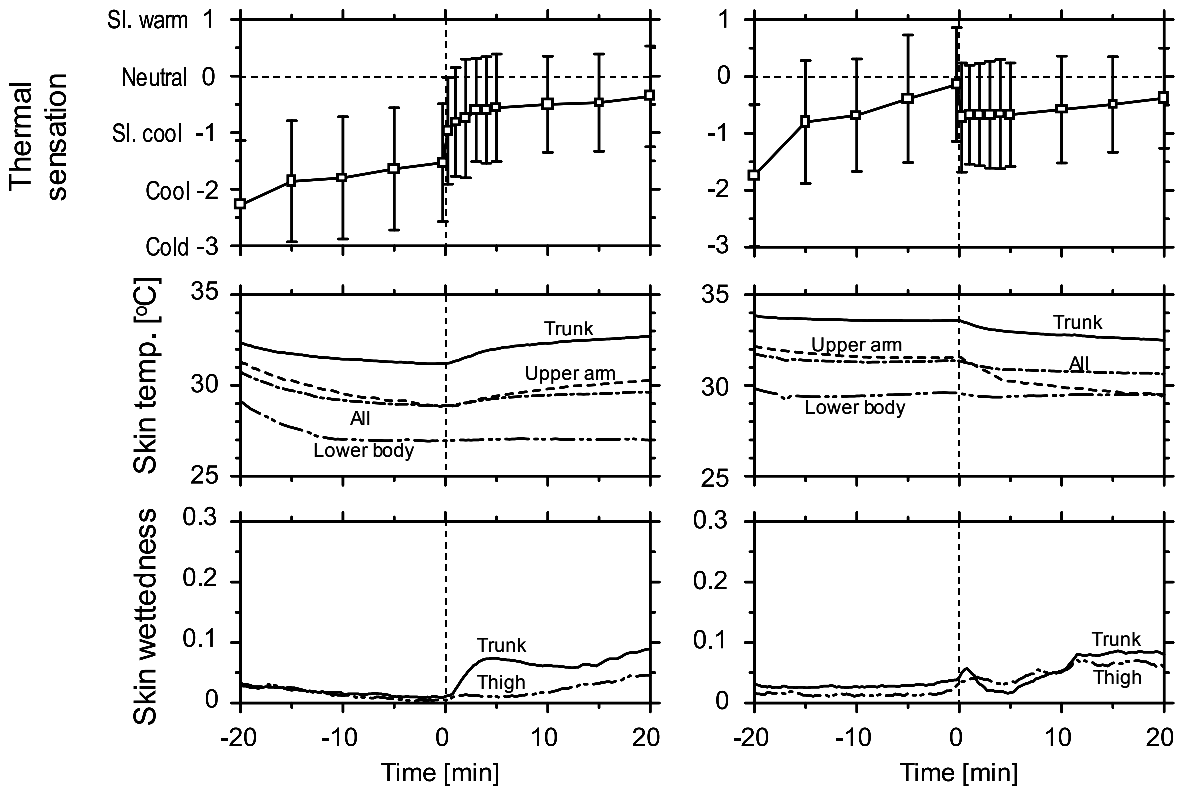


(a) Ta = 23°C, 0.65 → 1.03 clo (b) Ta = 26°C, 1.03 → 0.65 clo

Figure 2 Average thermal sensation, skin temperature and skin wettedness of experiments with low activity.

At the high activity level, the thermal sensation followed the same pattern with low activity (Figure 3). The thermal sensation shifted to the new levels within circa 1 min after the decrease of clothing insulation and within circa 3–5 min after the increase. Then, the thermal sensations after +5 min in both cases seem to be related with the skin wettedness better than with the skin temperature.

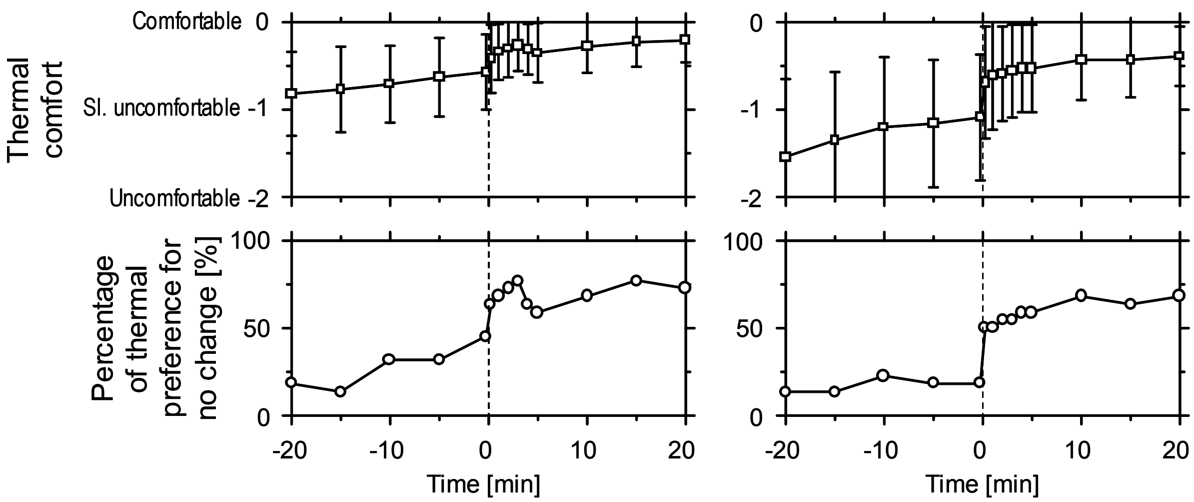
The average thermal sensation in Figure 3(b) was always lower than neutral, although the thermal sensation was expected to be higher than neutral before the decrease of clothing insulation. Probably, the duration of the adapting period was not sufficient to attain steady-state thermal sensation after moving from the high temperature to the low temperature and changing from low activity to high activity.



(a) Ta = 13°C, 0.65 → 1.03 clo (b) Ta = 17°C, 1.03 → 0.65 clo

Figure 3 Average thermal sensation, skin temperature and skin wettedness of the experiments with high activity.

Figure 4 shows the thermal comfort and thermal preference during the case of up-step of clothing insulation with 26°C and low activity, and down-step clothing insulation with 13°C and high activity. As these figures show, the thermal comfort and preference followed well the corresponding thermal sensations.



(a) Ta = 26°C, low activity, 1.03 → 0.65 clo (b) Ta = 13°C, high activity, 0.65 → 1.03 clo

Figure 4 Average thermal comfort and the percentage of subjects who prefer no change of the thermal environment (0, comfortable; –1, slightly uncomfortable; –2, uncomfortable; –3, very uncomfortable).

DISCUSSION

In this study, the thermal sensations observed during all experiments were affected by the step changes of clothing insulation but also the changes of other factors. Actually, the thermal sensations with low activity in the first chamber tended to be lower throughout the experiments, which was probably due to stabilization of the metabolic rate. On the other hand, the thermal sensations with high activity in the second chamber tended to be higher throughout the experiments, which was due to too short durations of the experiments to attain steady-state level after moving into cooler environment and changing to higher activity. However, the effects of stepwise changes of clothing insulation could be seen immediately and not longer than 5 min on the thermal sensations, when the subjects were engaged in both low and high activities.

In the previous studies, de Dear *et al.* (1993, 1989) have shown the transient thermal sensation after stepwise changes of temperature and humidity, respectively. They found that people feel instantly warmer as similar level to the final steady-state sensation after up-steps of temperature and humidity. People feel instantly cooler also after down-steps of temperature and humidity, but the immediate thermal sensation overshoots the final steady-state sensation. As compared with these stepwise changes of temperature and humidity, the thermal sensations with up-steps of clothing insulation were almost the same. On the other hand, the thermal sensations with down-steps of clothing insulation did not overshoot obviously, which was different from down-steps of temperature and humidity. The reason may be that the clothing insulation on sensitive parts of body (e.g. face, neck and hands) was not changed.

CONCLUSION

Independent of the activity level, the thermal sensation votes responded immediately to the adjustment of clothing insulation and reached a new steady-state level within 5 min after both up-step and down-step of clothing insulation. It was similar to stepwise changes of temperature and humidity except that the thermal sensation vote after down-step of clothing insulation did not overshoot obviously.

ACKNOWLEDGEMENT

This study was supported by the Danish Technical Research Council (STVF) as part of the research programme of the International Centre for Indoor Environment and Energy established at the Technical University of Denmark for the period 1998–2007.

REFERENCES

Berglund, L.G. and Cunningham, D.J. (1986). Parameters of human discomfort in warm environments. *ASHRAE Transactions* **92** (2B), 732–746.

de Dear, R.J., Ring, J.W. and Fanger, P.O. (1993). Thermal sensations resulting from sudden ambient temperature changes. *Indoor Air* **3**, 181–192.

de Dear, R.J., Knudsen, H.N. and Fanger, P.O. (1989). Impact of air humidity on thermal comfort during step-changes. *ASHRAE Transactions* **95** (2), 236–350.

Goto, T., Toftum, J., de Dear, R. and Fanger, P.O. (2002). Thermal sensation and comfort with transient metabolic rates. *Indoor Air* **1**, 1038–1043.

Nishi, Y., Gonzalez, R.R. and Gagge, A.P. (1975). Direct measurement of clothing heat transfer properties during sensible and insensible heat exchange with thermal environment. *ASHRAE Transactions* **81** (2), 183–199.

Olesen, B. (2000). Guidelines for comfort. *ASHRAE Journal* August, 41–46.