Title

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Thermal Sensation and Comfort in Transient Non-Uniform Thermal Environments

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Abstract
Most existing thermal comfort models are applicable only to steady-state, uniform thermal environments. This paper presents summary results from 109 human subject tests that were performed under non-uniform and transient conditions. In these tests, local body areas of the subjects were independently heated or cooled while the rest of the body was exposed to a warm, neutral or cool environment. Skin temperatures, core temperature, thermal sensation and comfort responses were collected at one to three minute intervals. Based on these tests, we have developed predictive models of local and overall thermal sensation and comfort.

Key Words
Thermal sensation, thermal comfort, model, asymmetry, transient.

1.0 Introduction

The majority of human comfort tests have been done under steady state conditions in thermally uniform environments (Nevins et al. 1966; McNall et al. 1967; Fanger 1970; Rohles and Wallis 1979). Far fewer tests have been done in transient uniform conditions (Gagge et al. 1967; Griffiths and McIntyre 1974) and even less have been done under steady-state conditions in non-uniform thermal environments (e.g. Wyon et al. 1989; Bohm et al. 1990). Taniguchi has done a limited amount of work investigating the effects of cold air on facial skin temperature during transient conditions in an automobile (Taniguchi et al. 1992), but no other body areas were considered.

The two most common thermal sensation models are Fanger's PMV (Fanger 1970) model and the TS and DISC indices obtained from ET* and skin wettedness in Gagge's 2-Node model (Gagge et al. 1970). Both of these models are based on uniform, steady-state test data and although they work quite well under those conditions, they have severe limitations under transient and spatially non-uniform conditions.

There are a few models for non-uniform conditions. Wyon, Bohm, and others developed Equivalent Homogenous Temperature (EHT) to characterize non-uniform environments and defined upper and lower comfort bounds for each body segment. This approach is limited to the clothing and metabolic conditions tested and applies only to steady-state conditions. Matsunaga proposed a simplified Average Equivalent Temperature (AET) as a basis for predicting PMV (Matsunaga et al. 1993). Hagino developed a model limited to a specific set of test conditions that used a weighted average of local comfort from the head, upper arm, thigh, and foot to predict overall thermal sensation (Hagino and Hara 1992).

Wang and Fiala proposed models for transients in spatially uniform conditions (Wang 1994; Fiala 2002). Wang's model uses a static term from Fanger's model and a transient term based on the rate of heat storage in the skin. Fiala's model uses skin temperature, skin temperature rate of change, and core temperature in a regression based on human subject data from the literature and from physiological model results. Guan (Guan et al. 2003) developed a model for transient environments which uses skin temperature for the static term and the rate of heat gain for the dynamic term. Recent work by Frank has shown that skin temperature and core temperature have equal weighting for predicting thermal sensation (as opposed to thermal regulation) in uniform conditions (Frank et al. 1999).

No model exists that can predict thermal sensation in non-uniform, transient conditions. This paper describes such a model.

2.0 Human subject experiment

2.1 Experimental set up

The human subject tests were carried out in the Controlled Environmental Chamber at UC Berkeley during January to mid August 2002 (Zhang 2003). To create transient and non-uniform environments, we put human subjects in a thermally uniform chamber and then locally applied cooling or heating air using air-sleeves attached to individual body segments. Figure 1 shows a subject with a sleeve attached to her back. Local heating and cooling was applied to 11 separate body areas: head, face, breath, neck, chest, back, pelvis, arm, leg, hand, and foot.

A separate set of tests was carried out in an automobile in a climate-controlled wind tunnel at the Delphi Harrison facility in Lockport, NY. These tests simulated conditions found in vehicles during both hot and cold weather. The test conditions covered a large temperature range (–23.3 to 43 °C) with and without

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solar radiation. During these tests, the human subjects were allowed to adjust the HVAC settings to their preference. The results of these tests were mostly used for model validation.

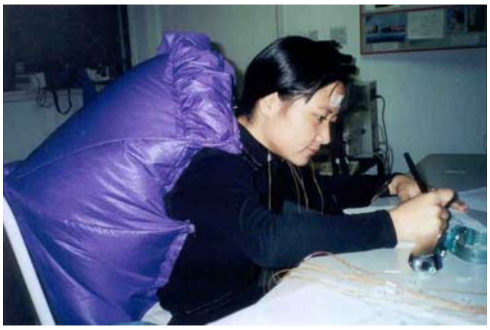

Figure 1. An example of the heating/cooling air sleeve attached to the subject's back.

2.2 Measurements

We measured skin temperature using thermocouples at 28 locations (5-second intervals) and core temperature (20-second intervals) using an ingestible temperature device (CorTemp™ thermometer pill from HTI Technologies, Inc.) with a radio transmitter. We collected subjective perception of overall and local thermal sensation and comfort using 9 point analog scales:

sensation: -4 very cold, -3 cold, -2 cool, -1 slightly cool, 0 neutral, 1 slightly warm, 2 warm, 3 hot, 4 very hot

comfort: +0 just comfortable to 4 very comfortable; -0 just uncomfortable to -4 very uncomfortable

Subjects responded to subjective questions at one to three minute intervals.

3.0 Observations

3.1 Impact of local thermal sensation on overall thermal sensation

The influence of local sensation on overall sensation is different for different body parts. Segments such as the back and the chest are very dominant at influencing overall sensation. When these segments were cooled, overall sensation typically followed local sensation for the cooled segments. For other segments such as the hand and the foot, the impact of local sensation is much less. Figures 2 and 3 shows that although hand skin temperature and hand sensation changed dramatically during local cooling the change in overall sensation was much less than that found during back cooling.

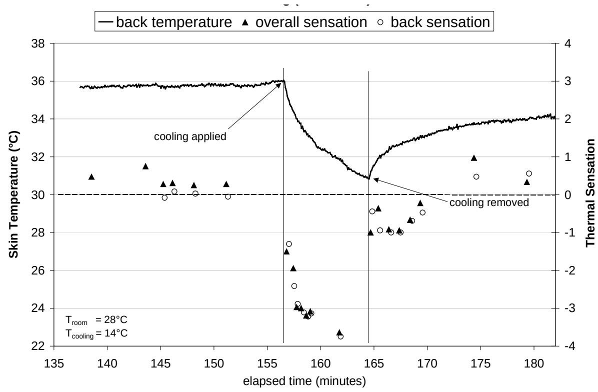

Figure 2. Back and overall sensation during a back cooling test

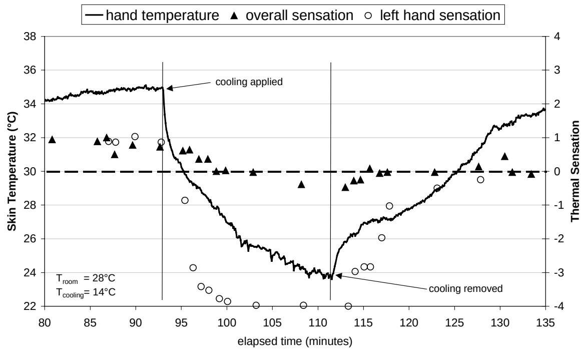

Figure 3. Hand and overall sensation during a hand cooling test

4.0 Models to predict thermal sensation and comfort

Based on the test results and literature, we developed four models to predict local and overall sensation and comfort.

4.1 Local thermal sensation model

We defined a setpoint for each body part as the skin temperature when the whole body was in a neutral condition. Figure 4 shows head sensation vs. forehead skin temperature from 43 tests of steady-state- and asymmetrical conditions. As forehead skin temperature became colder ($T_{forehead} - T_{forehead,set} < -2$), the head sensation leveled off, in a way that is effectively described by a logistic function. On the warm side ($T_{forehead} - T_{forehead,set} > 0$) the sensation did not level off as clearly because the skin temperature change is small in this region. Gagge at al. (1967) also found the same effects for the whole body, on both the cold and warm sides.

Figure 4 also shows that the head sensation was modified by the whole-body thermal state. The same forehead skin temperature felt relatively warmer when the rest of the body was colder (solid squares: overall sensation from –3.5 to –2.5, open squares: overall sensation from –2 to -1) and colder when the rest of the body was warmer (open triangles: overall sensation from –0.5 to 0.5, solid triangles: overall sensation form 2 to 3).

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Testing local sensations for hand, forehead, and neck, Hildebrandt also found that for a constant local skin temperature, the local sensation became warmer when the overall environment was cooler (Hildebrandt, Engel et al. 1981).

Our proposed local thermal sensation model incorporates these three considerations. (1) The local

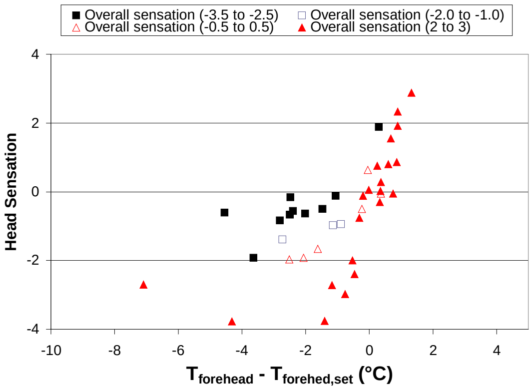

Figure 4. Head sensation and forehead skin temperature. The head sensation is influence by the whole-body thermal state.

sensation model is represented by a logistic function of local skin temperature. As the local skin temperature gets further away from the local skin temperature set point, the sensation reaches the sensation scale limits (+4 and –4). (2) The model is not symmetric for warm and cool conditions. The slope of the curve is steeper on the warm side to reflect the smaller range of tolerable skin temperatures above the setpoint compared to below the setpoint. (3) Local thermal sensation is not solely a function of local skin temperature; it is also influenced by the overall thermal state of the body, as shown in Figure 4. For a given local skin temperature, the local sensation is perceived as warmer if the whole body is colder, and colder if the whole body is warmer. Our model of local thermal sensation is therefore a group of contours representing various levels of overall body thermal state (Figure 5).

In our model, we use mean skin temperature to represent overall body thermal state.

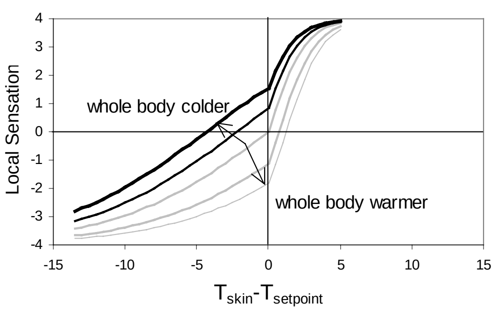

Figure 5. Local sensation model.

A transient term, a function of the time derivatives of skin and core temperatures, is added to the steady-state model to predict local thermal sensation under transient conditions.

4.2 Local thermal comfort model

Under steady-state conditions, thermal sensations farther from neutral are generally perceived as less comfortable. However, in transient conditions many researchers have demonstrated that during hyperthermia or hypothermia, cold or warm stimuli (respectively) to the hand, forehead, and neck are experienced as very pleasant (Cabanac 1972; Mower 1976; Attia and Engel 1981). In fact, local comfort under these conditions is higher than under uniform conditions.

Figure 6 presents results from 30 foot cooling/warming tests. They compare favorably to findings by the above researchers. (1) When the whole body was neutral (gray circles), adding foot cooling reduced foot comfort. There were no ‘very comfortable’ votes (above 2) shown in any of our neutral whole body tests. (2) The ‘very comfortable’ votes occurred when the whole body was warm or cold and the foot was cooled or warmed in the opposite direction to relieve discomfort. When the whole body was warm, foot cooling was perceived as ‘very comfortable’ (votes reached 3, triangles on the upper left); when the whole body was cold, foot warming was perceived as ‘very comfortable’ (squares on the upper right). The local sensation where the *maximum* comfort happened shifted towards cold or warm based on the body’s thermal state. (3) As local sensation continued towards very cold or very warm, the local comfort started to drop (triangles on the lower left). (4) When the whole body was cold, adding foot cooling was perceived as uncomfortable (squares on the lower left). The discomfort was greater than when the whole body was neutral (circles) or warm (triangles).

Our model predicts local comfort as a function of local and overall thermal sensation. As overall thermal

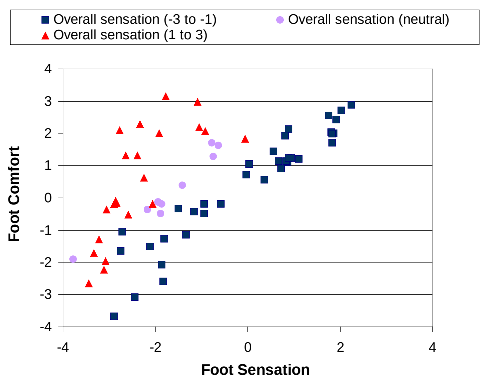

Figure 6. Foot sensation and comfort. The foot comfort is influence by the whole-body thermal state.

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sensation is cooler, a warm local sensation is increasingly comfortable. Conversely, as the overall sensation is warmer, a warm local sensation becomes increasingly uncomfortable. The shifts to cold and warm are not necessarily equal, so the local thermal comfort model is asymmetric (Figure 7). We fit this model to each of the body segments we studied.

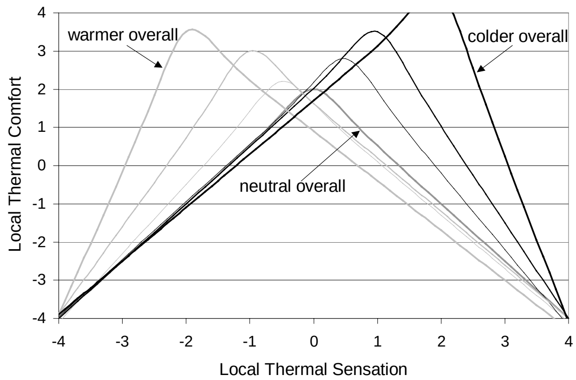

Figure 7. Local thermal comfort model

4.3 Overall thermal sensation model

Overall thermal sensation is predicted from local thermal sensations by using a weighted average. In establishing weights for the different body parts, we found three effects: (1) As local sensation diverges from that of the rest of the body (e.g. a cold hand contrasted to a warm body), the weight becomes larger. This increase is linear for most body parts. Figure 8 shows an example for the back (circles are the original test data, lines are the best linear fits). (2) Certain body segments dominate the influence on overall sensation (as shown in Figure 2). These body parts have larger weights. The differences could be due to segment size

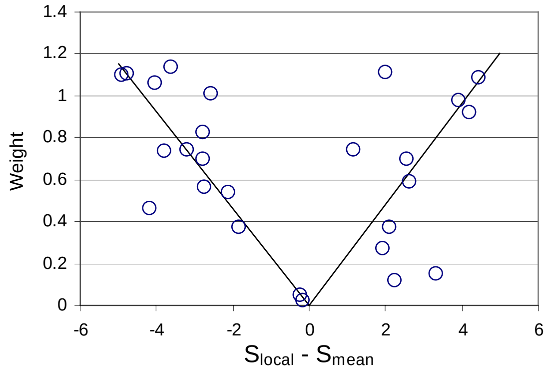

Figure 8. Weight as a function of the difference between local and the rest body thermal sensation. The solid line is the best linear fit of the data.

or thermal sensitivity. (3) Segments also differ in their sensitivity to warm and cold. We observed from our tests that the head, face, neck, and breathing are more sensitive to heating than cooling, therefore the weights for heating are larger than for cooling. Based on the above three effects, we developed linear models to calculate weights for all body parts. Figure 9 shows the linear model for back, face, and hand.

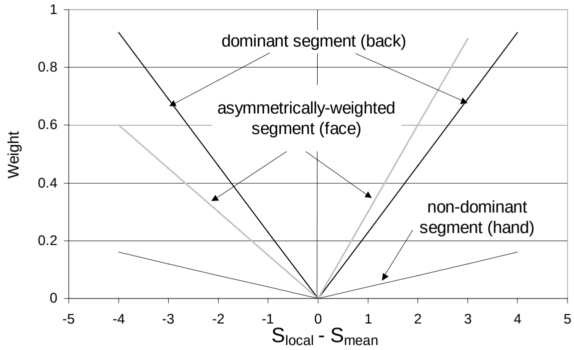

Figure 9. Thermal sensation integration model showing three example segments. Note that a dominant segment like the back has a much higher weighting factor than a non-dominant segment such as the hand. The face shows significant asymmetry between warm and cold sensations.

4.4 Overall comfort model

We explored more than a thousand test data points, and the best model we found for predicting overall comfort was the following simple rule-based approach:

Rule 1: *Overall comfort is the average of the two minimum local comfort votes unless Rule 2 applies.*

Rule 2: *If the following criteria are met:*

- *the second lowest local comfort vote is >–2.5*
- *the subject has some control over their thermal environment*
- *the thermal conditions are transient*

then overall comfort is the average of the two minimum votes and the maximum comfort vote.

The detailed mathematical descriptions of the four models are provided in Zhang (2003).

4.5 Model validation

Validation results show that in general the models predict subjects' votes very well. We used data from the Delphi wind tunnel tests to validate our sensation and comfort models developed from the chamber studies. Unlike the tests performed in Berkeley, the Delphi subjects were allowed to adjust their environment using the vehicle HVAC system.

Figure 10 presents the validation of the overall sensation model. It shows the predicted overall sensation calculated from local sensations vs. actual overall sensations. The R^2 for the overall sensation model is 0.95; quite high considering that these data were not used to develop the model. The standard deviation of residuals is 0.54.

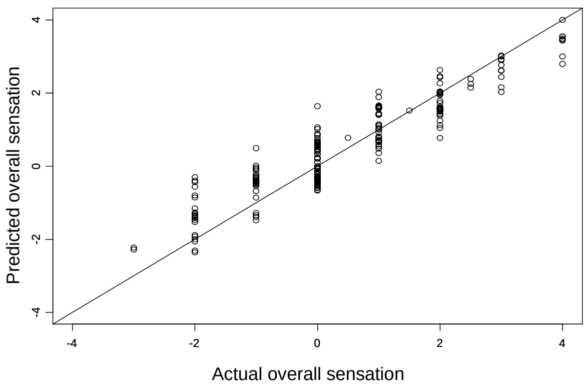

Figure 10. Overall sensation model validation.

Figure 11 presents the validation of the overall comfort model. It shows the predicted vs. actual overall comfort. The overall R^2 for the comfort model is 0.89; the standard deviation of the residual is 0.78.

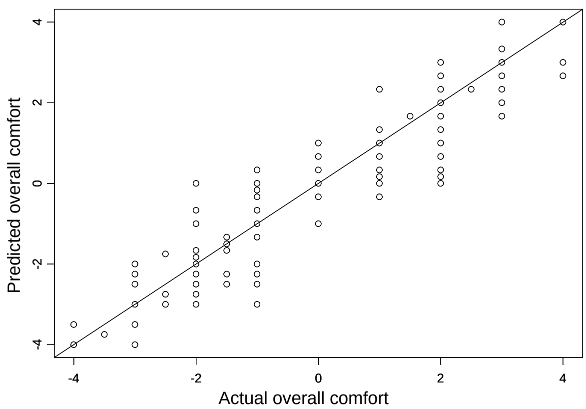

Figure 11. Overall comfort model validation.

5.0 Conclusion

We have developed new sensation and comfort models to predict local and overall sensations, and local and overall comfort in non-uniform transient thermal environments. The models were proposed based on our human subject test results and observations of data from the literature. Our validation work shows that the models predict sensation and comfort with reasonable success. Our next step will be to integrate these models with physiological models (Rugh et al. 2003; Huizenga et al. 2001). Once integrated, these tools will be very useful in designing and evaluating thermal environments.

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