Partial- and whole-body thermal sensation and comfort, Part I: Uniform environmental conditions

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Abstract

Subjects exposed to uniform environments were polled for their local and overall (whole-body) thermal sensation and comfort. Sensation and comfort for local body parts vary greatly. In cool environments, hands and feet feel colder than other body parts. The head, insensitive to cold but sensitive to warm, feels warmer than the rest of the body in warm environments. Overall sensation and comfort follow the warmest local sensation (head) in warm environments and the coldest (hands and feet) in cool environments. Subjects evaluate neutral conditions as "comfortable", never "very comfortable", and overshoot of sensation and comfort during whole-body step-changes is small.

Keywords: Local sensation, local comfort, overall sensation, overall comfort, comfort overshoot

Introduction

There has been limited research on how people respond, physiologically and subjectively, to the thermal non-uniformities encountered in buildings, vehicles, and the outdoors. Such non-uniformities (in air temperature, air movement, radiation, and conduction to surfaces) affect the skin temperatures of the body's various parts, affecting a person's overall thermal sensation and comfort in complex ways. Even in spatially and temporally uniform environments, the body's skin temperatures are distributed non-uniformly, as are local sensations and local comfort. Most previous experimental research and modeling have involved whole-body heat transfer, whole-body (mean) skin temperature, and whole-body measures of thermal sensation and comfort. They do not address the local variability implicit in people's physiology and in their environments.

In 2002 we conducted a series of tests to discover the relationships between skin and core temperatures and the resulting sensation and comfort responses. The tests were used to develop predictive models of local- and overall sensation and of local- and overall comfort. The skin and core temperature responses from the tests are presented in Huizenga et al. (2004), and the models are described in Zhang et al. (2003 and 2004).

This two-part paper describes the intra-personal differences we observed in sensation and comfort, both among the local body parts, and between the local parts and the perceived whole body sensation and comfort . The paper also describes sensation and comfort response patterns seen during rapid changes in the environment. These observations may have application in future environmental control of buildings and vehicles. Part I covers spatially uniform environmental conditions (both stable and transient). Part II covers spatially and temporally non-uniform environmental conditions in which body segments were individually heated and cooled.

Method

The experiments tested three types of conditions: uniform/stable environments (32 tests), step-change transients between two different uniform environments (5 tests), and heating/cooling of local body parts under cool/warm ambient environments (242 tests, in Part II).

Subjects were tested in a controlled environment chamber one at a time. The test sequences lasted roughly three hours, starting with the subject being preconditioned to the day's test conditions in a heated Jacuzzi bath (typically 15 minutes). 27 subjects participated in total, 15 females and 12 males, mostly college students, from 20 to 51 years of age. Skin temperatures were simultaneously measured for each body segment by a harness of 28 thermocouples, with data collected every 5 seconds. Thermocouples were 36 gauge wire, soldered to a thin 9mm copper disk for improved contact with the skin, held to the skin with porous medical tape. The time constant of these sensors was five seconds. Core temperature was measured every 20 seconds using a CorTemp™ ingestible thermometer pill (HTI Technologies, Inc.). Subjective sensation and comfort responses were periodically requested via the computer screen.

Because the project was planned to develop thermal sensation and comfort models based only on skin and core temperatures and their rates of change, it was not necessary to have fixed environmental test conditions, and a wide range of environments were tested. Because of the differences in our environmental test conditions , we did most of our analyses in terms of intra-subject comparisons, using paired t-tests. These two papers examine the relationships of sensation and comfort between local body parts and the whole body during asymmetries and transients in the subjects' skin temperature.

Uniform/stable conditions were examined in 32 tests, at ambient temperatures from 16-32 ºC. We divided these tests into categories based on subjective response by the subjects: 10 'warm', 3 'slightly warm', 8 'neutral', 6 'slightly cool', and 5 'cold'. Thirteen subjects participated, with no subjects repeating a given condition. Results representing the stable (steady-state) conditions were taken after 60 minutes in all but the neutral tests, where the subjects were exposed for 120 minutes.

During these tests, the subjects wore a leotard and socks (0.32 clo, clothing insulation level, 1 clo = 0.155 m^2ºC/W) in order to hold the thermocouple harness in place.

Uniform/transient conditions were created in 5 tests, to examine the response to temperature step-changes affecting the whole body. Five different subjects participated, moving between two chambers. The temperatures were between two chambers with a temperature difference around 9ºC, were experienced by the subjects in two orders: 'hot' – 'cool' – 'hot', or 'cool' – 'hot' – 'cool'. The subjects stayed in a starting condition for 60 minutes, then stepped to a different environment and stayed for another 60 minutes, and then returned to the original environment and stayed for another 60 minutes. In these tests the subjects only wore undergarments, in order to allow us to compare our results with previous tests by deDear and Ring (1993).

During all the tests, the subjects occupied themselves with computer activities of their own choosing. They had Internet access, email, and a driving game to choose from. During these activities they were periodically presented with a popup survey on the computer screen, requesting their thermal sensation and comfort for 19 body parts, as well as for their whole body (described as "overall sensation" and "overall comfort"). When the skin temperature was steady, sensation and comfort questions were asked for each local body part and for the whole body. During the skin temperature transients caused by the step-changes, the subjects answered 5 sensation and comfort questions about their whole body and random selected parts, in time intervals increasing from one to three minutes.

The sensation scale is similar to the ASHRAE 7-point scale, adding "very hot" and "very cold" to accommodate the extreme environments that may be encountered in vehicles (9-point scale: 4-"very hot", 3-"hot", 2-"warm", 1-"slightly warm", 0-"neutral", -1-"slightly cool", -2-"cool", -3-"cold", -4-"very cold"). The comfort scale ranges from "just comfortable" (+0), to "comfortable" (2), to "very comfortable" (4), "just uncomfortable" (-0), to "uncomfortable" (-2), to "very uncomfortable" (-4). This comfort scale differs from that of most previous thermal comfort research in that it differentiates levels of comfort on the positive side as well as the negative side. The usual scale range includes "intolerable", "very uncomfortable", "uncomfortable", "slightly uncomfortable", and "comfortable".

Examples of the sensation and comfort scales are shown in Figure 1. There is a gap between "comfortable" and "uncomfortable" to force subjects to explicitly determine whether their perceived thermal state falls in the overall category of "comfortable" or "uncomfortable". The transient and asymmetrical test conditions make both scales necessary, because people might feel cool or warm locally but be either comfortable or uncomfortable, depending on their whole-body thermal state or the previous thermal state of a local body part.

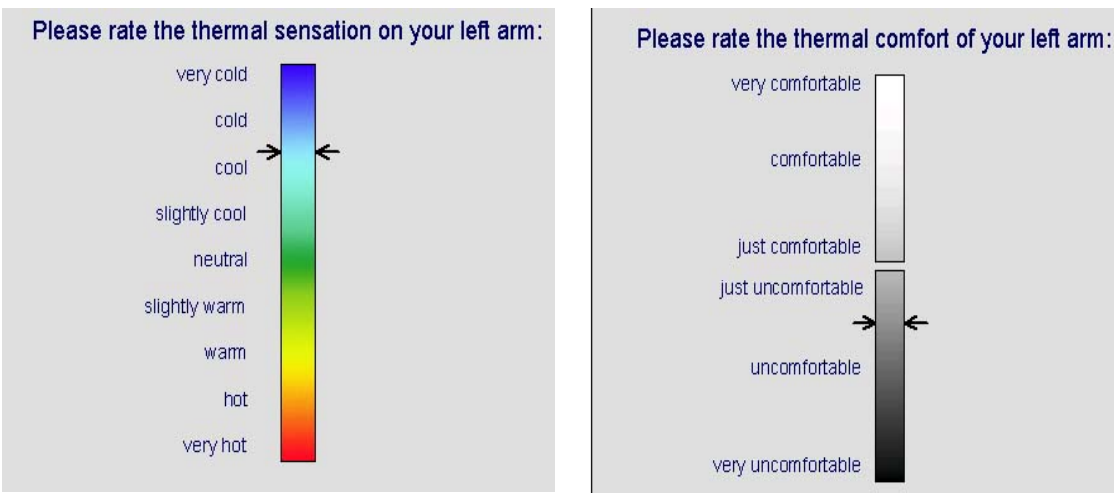


Figure 1. Thermal sensation and comfort scales

Results

I. Sensation and comfort in stable (steady-state) conditions

The tests in stable environments are reported here in the order: *neutral, cold, slightly cool, slightly warm, warm,* based on the subjects' whole-body sensation votes. Sensations and comfort for the various body parts are presented, together with the subject's rating of their overall sensation and comfort. The sensation and comfort values are last vote of each test of a given environment, polled when the subjects had reached steady state. The relative differences between local body parts perceptions are analyzed by paired t-tests. The effects of local sensations on overall sensation are described next, with weights obtained by regression. The most sensitive areas of the body (the head for warm conditions, and the feet, hands, and back for cool conditions) are then examined in more detail.

A. Neutral uniform environment

A typical subject's sensation and comfort votes stabilized within half an hour of starting the test (there was an unavoidable temporary metabolic increase associated with putting on the thermocouples and leotard at the beginning of the tests). Once stabilized, they varied only slightly with sensation at zero. (Figure 2 is a typical example for the neutral environment). This subject rated the environment as "comfortable" (2 on the comfort scale). In steady-state conditions, the neutral environment was never rated as "very comfortable" (4 on the comfort scale). Of the eight neutral/steady-state tests, there were three rating the neutral condition as 2 ("comfortable"), one rating between 1 and 2, three between 0 ("just comfortable") and 1, and only one around 3. As we will see in Part 2, "very comfortable" votes happened only during transients when a thermal stress was suddenly removed, or in stable but non-uniform environments when the cool or warm feeling from one or more body parts acted to reduce whole-body discomfort. This may have interesting implications for air conditioning, since buildings are controlled to provide steady-state neutrality.

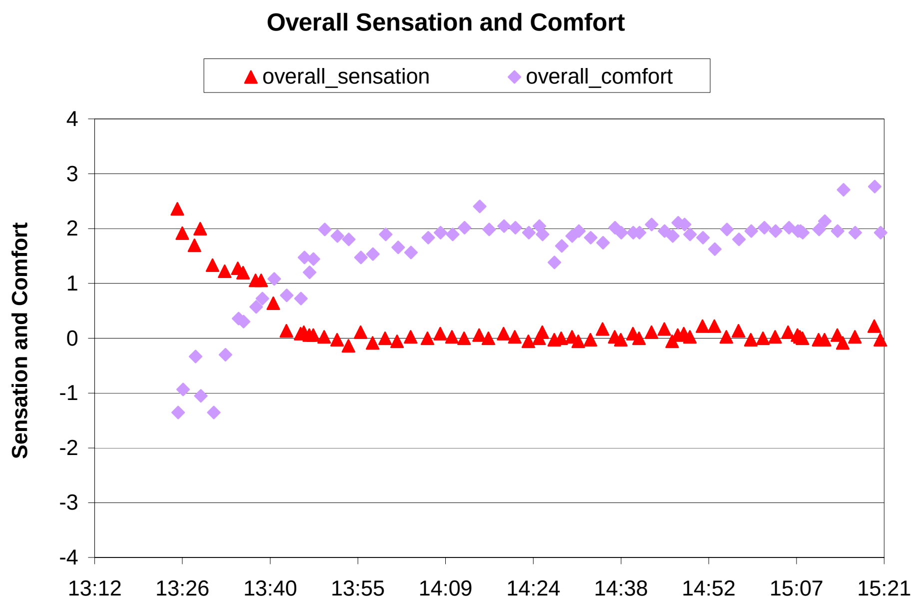


Figure 2. Sensation and comfort votes in one neutral condition test

Under these neutral conditions, although overall sensation is near neutral, the local sensations of the individual body parts vary (Figure 3). The face (and head region), hand, and arm feel warmer than neutral (paired t-tests show that only face and hand are significantly different from neutral, $p < 0.03$); the trunk (chest, back, and pelvis) feels close to neutral; and the foot feels cooler than neutral ($p = 0.03$). This is consistent with the distribution of skin temperatures on the body, in which the feet are cooler than other parts because blood circulating to the extremities is cooled en route. The distribution of skin temperatures shown here is similar to that given by Olesen and Fanger (1973). Breathing zone temperatures are not strictly comparable to any skin temperature, but as an indicator we show the skin temperature of the adjacent cheek in Figure 3.

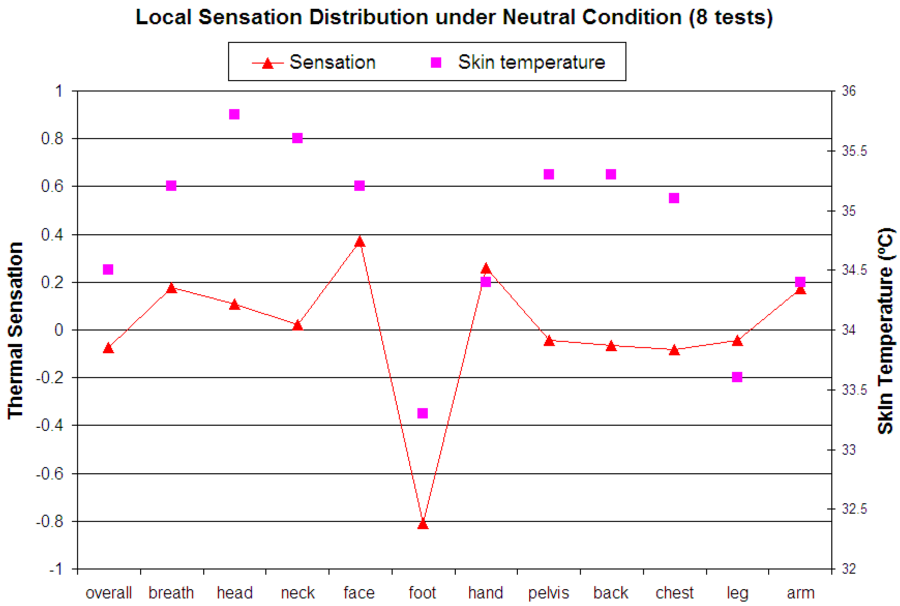


Figure 3. Sensation votes and skin temperatures under neutral conditions (average of 8 vary

s, p < 0.01)

and trunk (back, chest, and pelvis, p < 0.03), followed by the arms (p < 0.05). Vasoconstriction is affecting hands, arms, feet and legs. The head region (breathing zone, neck, head, and face) is rated much less cold than the extremeties (leg, foot, arm, hand, p < 0.02), but not significantly warmer than the trunk (back, chest, and pelvis, p < 0.3), with the breathing zone the least cold. The sensation difference from the least cold sensation (breathing zone) to the coldest (hand) is more than 2.5 units on the sensation scale. In spite of this large variation, the *overall* sensation closely follows the coldest local sensations, hand and foot (marked by circles).

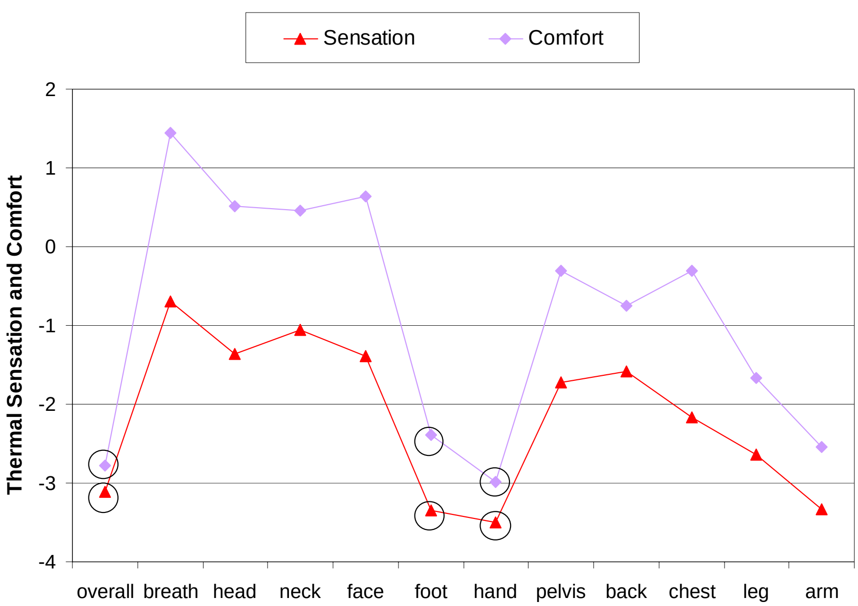


Figure 4. Local and overall thermal sensation and comfort in uniform/cold environment (average of 5 tests)

It is interesting to see that although the *whole-body* sensation is cold and the local sensations for the head region are also cool, the local *comfort* for all the head parts is on the comfortable side. The comfort for the remaining body parts is all uncomfortable, with considerable variation. The overall comfort follows the worst local comfortable votes closely (marked by circles), the head region comfort exerting little apparent influence.

C. Uniform/slightly cool environment

Under less severe cold, the variation in sensation ratings is less extreme, 1.5 scale units (Figure 5, average of 6 tests). As in the cold tests, the breathing zone is rated as significantly warmer than all body parts ($p < 0.05$), but not significantly warmer than the neck ($p = 0.1$). The foot is significantly cooler than the head region and trunk ($p < 0.05$), but not significantly cooler than the back. Unlike the cold tests there is now a difference between foot and leg ($p = 0.05$), presumably due to reduced vasoconstriction in the leg.

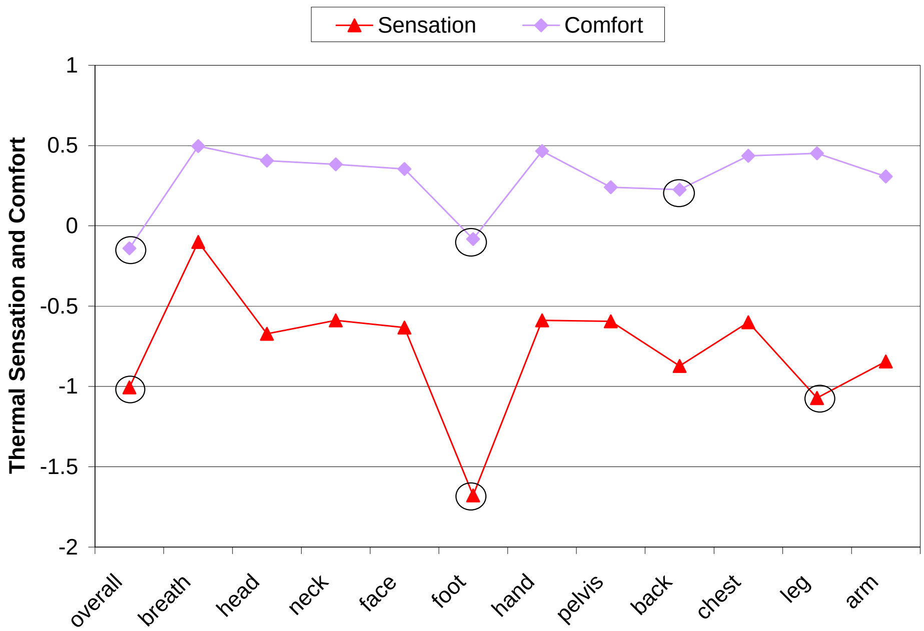


Figure 5. Local and overall thermal sensation and comfort in uniform/slightly cool environment (average of 6 tests)

With the milder local sensations, overall *sensation* does not equal the coolest sensation (of the feet), as it did in the colder tests, but is midway between the feet and the rest of the body.

The overall *comfort* remains closest to the least comfortable vote (feet), although the rest of the body parts are now on the comfortable side.

D. Uniform/slightly warm environment

The sensation distribution shows that the head region is perceived the warmest, with the breathing zone sensation less warm compared to the head, face, and neck (Figure 6). The overall sensation is closest to those of the head region. Most body parts are comfortable, excepting the head region (head, neck, and face) and (inexplicably) the hand. The overall comfort follows the worst local discomfort votes as seen in the cool environments; in this case, the worst votes are shared by the head and hand. The results were not statistically significant because of the small sample size.

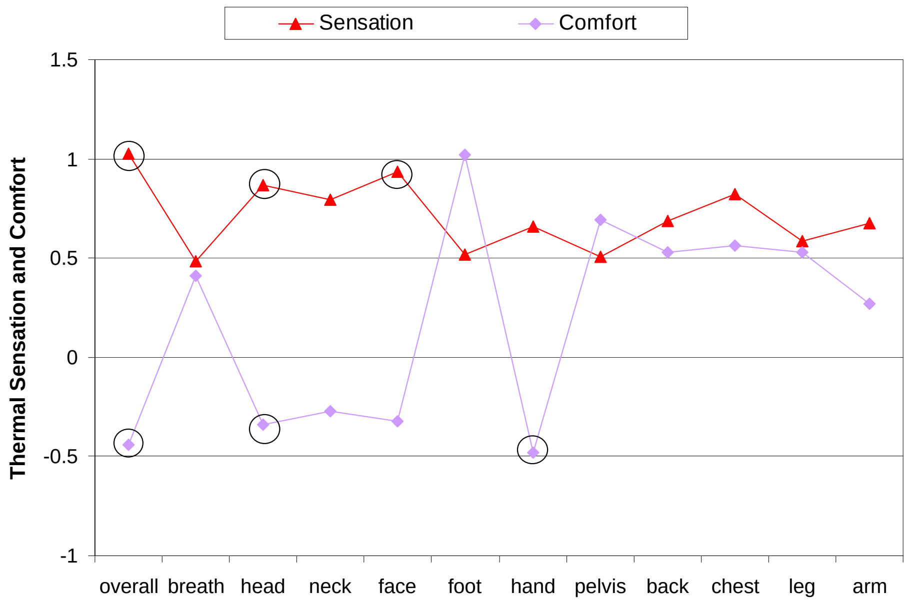


Figure 6. Local and overall thermal sensation and comfort in uniform/slightly warm environment (average of 3 tests)

E. Uniform/ warm environment

The variation in sensation between body parts is greater than for the slightly warm environment, but smaller than for the comparable cold environment. Figure 7 shows the average of 10 tests in a warm environment, varying about 1.5 scale units from the head or face (sensation 2.3) to the feet (sensation 0.8). Unlike in the cold environment where the overall sensation is driven by the vasoconstricted extremities, in the warm environment the overall sensation follows the head region sensation (the warmest local sensation) closely.

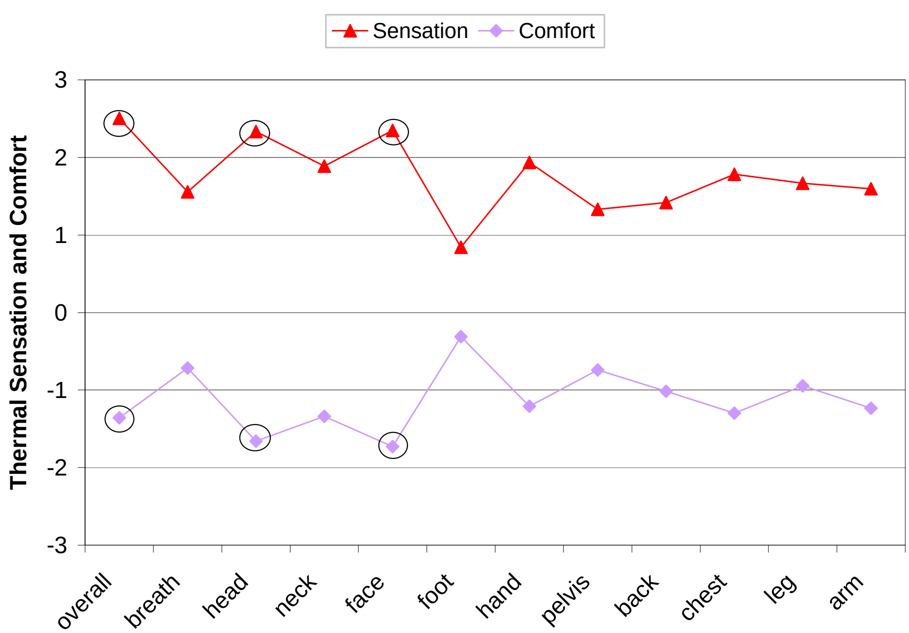


Figure 7. Local and overall thermal sensation and comfort in the uniform/warm environment (average of 10 tests)

The head and face are significantly warmer than trunk, leg, foot, and arm ($p < 0.02$), but not significantly warmer than the hand ($p < 0.06$). The hand is well dilated in the warm environment. The breathing zone is perceived as less warm than head and face ($p < 0.05$). The breathing zone's lower sensitivity is also seen in the slightly warm tests and (for cold sensations) in both the cold tests. Except for the foot, the hand, arm, and leg are not significantly different from the trunk ($p < 0.5$). A possible explanation is that in warm conditions the hand, arm, and leg are well dilated.

Unlike the distribution of local comfort seen in the cold environment, all the local comfort levels are uncomfortable, with the head region perceived as the most uncomfortable. The overall discomfort value is close to the level of the head region discomfort, and could be predicted by the worst one or two local comfort values. This is consistent with each of the other warm and cool environments tested. (unfortunately we did not initially ask for local comfort votes in the neutral case, and do not have sufficient data to generalize about that case).

F. Regressions of local sensation vs. overall sensation

The sensations from individual body parts influence overall sensation to differing extents. Table 1 shows regressions correlating local sensation with the whole-body sensation under uniform environments. The slopes exceed 1 for head, face, breathing zone, back, and pelvis, meaning that when the subject feels one unit sensation change in these parts, the whole body experiences the change as more than one unit. These body parts are less sensitive than the whole-body to environmental differences, and the overall sensation can therefore be expected to vary more in different uniform stable environments than these body parts do. Body parts with slopes near 1 (chest, arms, legs) have the same sensitivity to environmental differences as does the whole-body. With one unit change in local sensation, the overall sensation also changes one unit. Parts with smaller slopes (less than 1 for hand and foot) are more sensitive to environmental differences, so when they feel one unit change, the overall sensation changes less than one unit. These parts are at the ends of extremities where vasodilatation and vasoconstriction are strongest (Wang et al. 2005). Their widely varying skin temperatures cause them to be highly responsive sensors of the environment, but they do not influence the body's overall sensation to the same degree.

*Table 1. Regressions correlating the local body parts with the whole-body thermal sensations under stable conditions. Whole-body thermal sensation = a * Local thermal sensation + b*

	a	b	R^2
Head	1.23	–0.400	0.86
Face	1.20	–0.437	0.85
Breathing	1.34	–0.235	0.54
Chest	1.16	–0.026	0.81
Back	1.23	+0.072	0.76
Pelvis	1.34	+0.075	0.69
Arm	1.00	+0.155	0.83
Hand	0.95	+0.039	0.85
Leg	1.14	+0.166	0.88
Foot	0.88	+0.606	0.69

The head region (face, head, neck, and breathing zone) has substantial (-0.4) negative intercepts, and the foot, leg, and arm have positive intercepts. The foot has the largest positive intercept (0.6). The intercepts for other body parts (chest, back, pelvis, and hand) are near zero. The difference in intercepts indicates that different body parts do not feel the same in a neutral uniform environment. When the whole-body thermal sensation is zero, the thermal sensation from the head region is above zero and the thermal sensation from the feet is below zero.

G. Upper and lower back thermal sensations:

In 25 of the tests, we requested the thermal sensation of the upper back and lower back simultaneously, in addition to our standard question about the entire back (described in the figures above as 'back'). David Wyon (2001) had commented that the lower back is particularly sensitive to cooling, so we added questions to see if there is a difference between upper and lower back sensations.

Figure 8 compares upper back and lower back thermal sensations. The thermal sensation for the upper back is warmer than for the lower back (paired t-test, significant at $p = 0.002$). When the lower back sensation is neutral (scale value 0), the upper back feels warm (scale value 0.3). When the upper back is neutral, the lower back is already cool. These sensation results apply also to comfort (not shown here). In warm environments, the upper back feels warmer (and more uncomfortable) than the lower back. In cool environments, the lower back feels colder (and more uncomfortable) than the upper back.

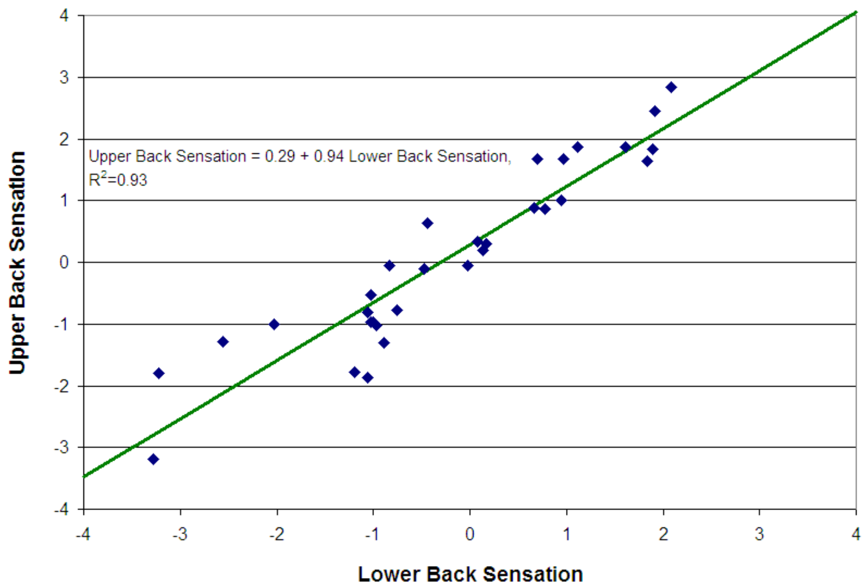


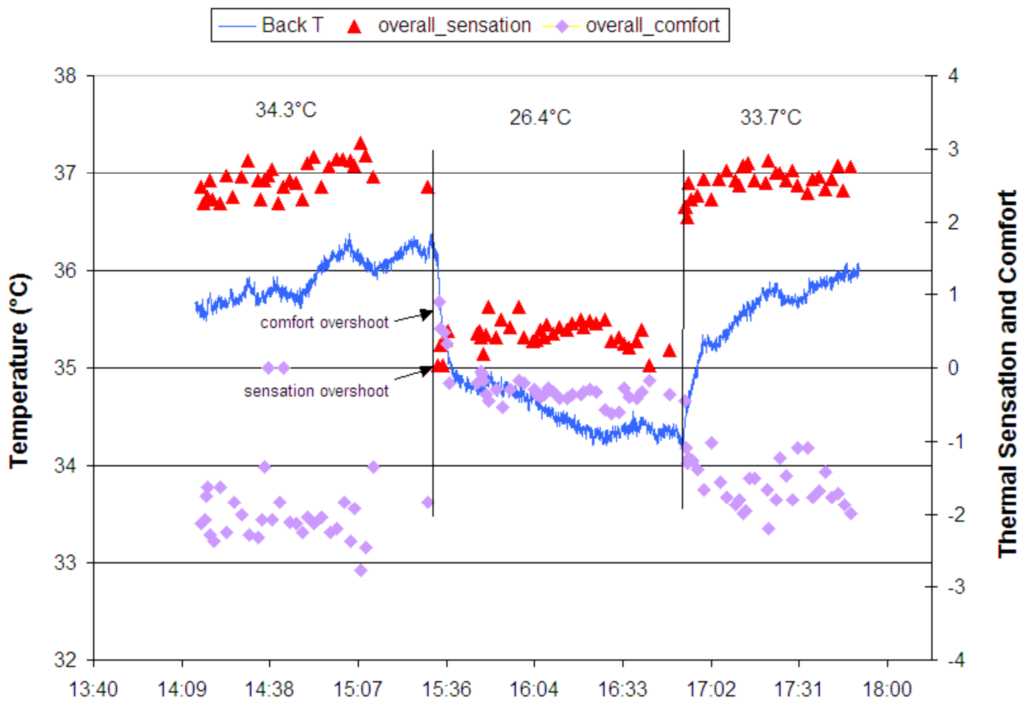
Figure 8. Comparison between upper and lower back thermal sensations

The *head* is perceived as warmer and feet perceived as colder than the rest of the body. Figures 4-7 show that the subjects do not mind a cool sensation in the head region in cool environments, but are sensitive to a warm head-region sensation in warm environments. In Figure 4, although the whole body feels cold and the head region also feels slightly cool, the comfort votes for head region (and only them) are all on the comfortable side. In Figures 6 and 7, with the whole body slightly warm and hot, the head region is perceived as the hottest and the least comfortable.

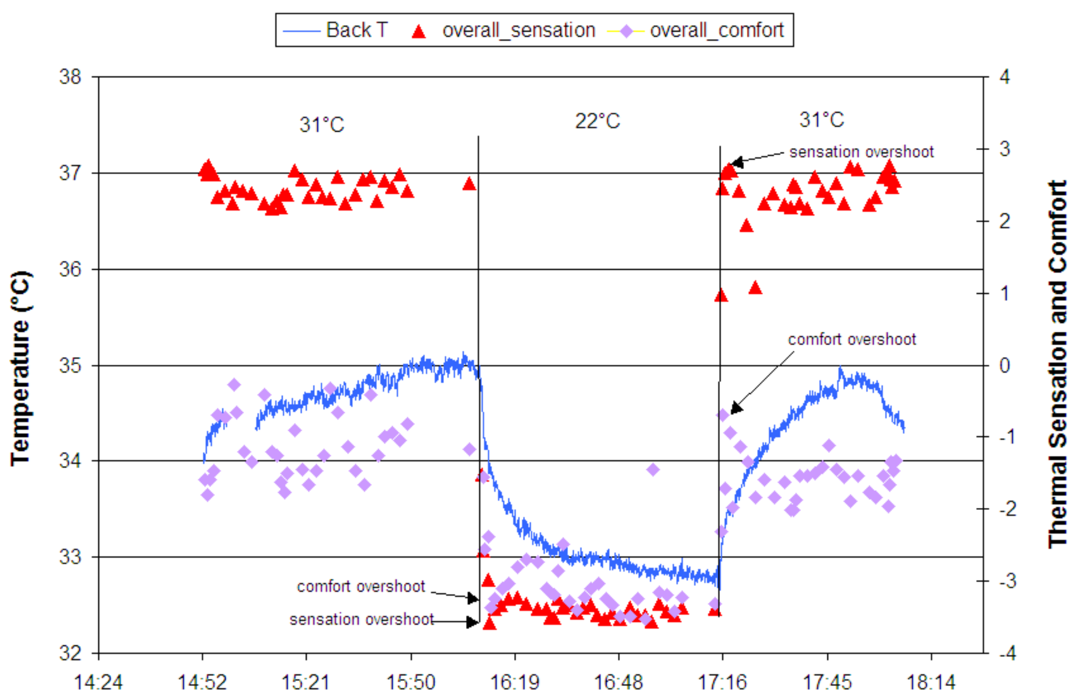
The *feet* almost always feel colder than the rest of the body, and the hand sensations will sometimes be perceived as equally cold. The rest of the body parts have sensation and comfort values that fall between those of the head region and the feet. They normally feel cooler than the head but warmer than the feet.

II. Sensation and comfort during whole-body step-changes

In 5 tests, subjects moved from one environment to another, affecting all body parts equally with a step-change in environmental temperature. In each test, sensation and comfort reached steady state in about 10 minutes, substantially leading the skin temperature change (Figures 9a and b). This psychological anticipation (overshoot) occurred in both sensation and comfort directly after most step-changes. A similar overshoot pattern (in sensation) was observed by de Dear et al., 1993 for milder step changes. We attribute the overshooting phenomenon to the perceived relief of body heat stress. This hypothesis also explains the one instance in Figure 9b (during the upward step-change) where there was no overshoot, because there is no relief of heat stress when going from a slightly warm environment to a hot environment. In general, the levels of these whole-body-induced overshoots are small relative to those we will see in Part II for local cooling and heating, where comfort votes reached 4 (very comfortable). During the whole-body step-change experiments, comfort votes never went above 2 (comfortable).



a. between hot and cool environment



b. between hot and slightly warm environment

Figure 9. Sensation and comfort votes during whole body step-change tests

Discussion

The preference for a cool head and breathing cool air may be an adaptation to encourage brain cooling, as described by Cabanac (1997). In our tests, when conditions are warm, the head sensation is also warm and the head is less comfortable than the whole body, which would encourage behavioral correction. When conditions are cold and the whole body is uncomfortable, the head region is comfortable and perceived as much warmer than the whole body.

The breathing-zone thermal sensation is perceived as warmer than the head, neck, and face sensations in cool and cold environments, and cooler than them in slightly warm and warm environments. This has the effect that the breathing zone is not as sensitive as these other parts of the head region.

The feet are consistently cooler than other body parts in all uniform conditions. They are the major source of discomfort in cool conditions. This suggests environmental control solutions that might be more widely employed in practice. Direct heating of feet in cars and building workstations can be done relatively efficiently with radiant pads or local air supplies (Terano et al. 1997). Radiant floor heating systems, an established technology in buildings, can claim the additional advantage of heating the inherently cool feet of the occupants through conduction.

The difference between the sensitivity of lower and upper back might be addressed in chair and clothing design. The lower lumbar region should be protected from cooling, as with insulation or local heating. The upper thoracic region requires the ability to dissipate body heat, for example through ventilation

Because our subjects' overall sensation closely followed the local sensations which were furthest from neutral, and their overall comfort closely followed the most uncomfortable local body parts, we found that we can best predict overall sensation and comfort using "complaint" models (Zhang 2004). In such models the overall perception is dominated by the one or two most unfavorable local perceptions.

Step-changes show that sensation and comfort reach the final state quickly. The magnitude of overshoot for the whole body is not as great as for the local parts (seen in Part II), but consistent with deDear's finding. Overshoot in comfort sensations might in theory allow building interiors to be controlled in a manner that saves energy. A space allowed to slowly drift over time from an initially comfortable state toward either warm or cool is not noticed by the occupant for considerable lengths of time (as in Gonzalez and Berglund 1978). After the space temperature had drifted, a sudden corrective pulse from the HVAC might be employed to cause comfort overshoot—rapidly correcting the discomfort even before the occupants' physiology has fully responded. It is possible that a cyclical control could be devised to take advantage this favorable hysteresis pattern.

Transients are also created by people moving between differently-conditioned spaces, and these could be designed and operated in ways that maximize comfort or conserve energy. In buildings, this occurs between outdoors, foyers, lobbies, hallways, and eventually offices. Retail stores benefit from the pleasurable temperature changes experienced by customers entering the store from outdoors to indoors.

Acknowledgments

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