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Partial- and whole-body thermal sensation and comfort, Part II: non-uniform environmental conditions

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Abstract

Subjects were exposed to sequences of partial-body cooling and warming over a period of three hours. Skin temperatures, core temperature, thermal sensation, and comfort responses were collected for nineteen local body parts, and for the whole body. This paper relates local thermal sensations and comfort to skin and core temperatures, and examines how the thermal sensation and comfort perceived for individual body parts affect thermal sensation and comfort perceived for the whole body. Overshoot in sensation and comfort is stronger when local body parts are cooled or warmed than when the whole body experiences a step-change.

Keywords: Thermal sensation, thermal comfort, body-part sensitivity, comfort overshoot, asymmetric environments, transient thermal environments

Introduction

This is the second part of a two-part paper on thermal sensation and comfort. Both are based on a series of human subject tests in which physiological and subjective (thermal sensation and comfort) measurements were made for many parts of the body. Part I contains the introduction and 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. A previous paper in this journal (Huizenga et al., 2004), describes the experimental arrangements in more detail, together with the results of the experiment's physiological measurements.

Method

We conducted 242 tests in which local body parts were individually cooled or warmed, and then allowed to recover. Seated in a controlled-environment chamber at one of several ambient temperatures, subjects had one or two defined body parts exposed to air of a different temperature passing through air-sleeves. There were 19 defined body parts tested: head, face, neck, breathing zone, chest, back, pelvis, and both of: upper arms, lower arms, hands, thighs, lower legs, and feet.

Upon arrival, the subjects swallowed a radio pill to measure their core temperature, and then were immersed in a Jacuzzi bath for 15 minutes. The temperature of the Jacuzzi was preconditioned to match the ambient test conditions of the day. Then we applied a 28-thermocouple skin-temperature harness and covered it with a leotard. The subjects then sat in a mesh chair and occupied themselves with computer activities while beginning to answer thermal sensation and comfort questionnaires. They did this for 40 to 60 minutes before the first local cooling or heating was applied to a body part.

Air sleeves for cooling/heating the 19 body parts were custom-designed for each part (they are described in detail in Zhang 2003). They were velcroed onto the leotard to secure their edges, and had outlets which directed the exhaust air away from the body. The air volume going through

the air sleeves was large enough to assure a constant air temperature within the area covered by the air-sleeve, and the sleeve temperature was set to achieve the desired local skin temperature. The leotard and socks next to the skin prevented the subjects from perceiving the motion of the air passing through the sleeve. Figure 1 shows an example of the air-sleeve during a back-cooling application. In this example, the cooling air is supplied through the back of the mesh chair, and the air sleeve connects between the edges of the seat back and of the subject's back segment. The exhaust manifold at the neck directs the outgoing air away from the head region, and contains some fiberpile insulation to prevent the back of the head from being radiatively cooled by the sleeve nearby.

Figure 1. An air sleeve for back cooling. A total of nineteen body parts were heated and/or cooled during the tests.

In a typical 3-hour experiment we conducted a sequence of 3 tests in which individual body-parts were cooled (or warmed) and allowed to recover. After each cooling/warming application, the sleeves were removed and the body allowed to return to steady state for a period of 30 minutes. An example is presented in Figure 2, in which the parts head, hand, and pelvis were each cooled for 15 to 20 minutes (until the subject's sensation and comfort reached steady state). The local skin temperatures are presented as lines in the figure. In pilot tests we could detect no effect of varying the order of the sequential tests.

At 1- to 3-minute intervals, the subjects were presented with a pop-up survey on the computer screen, requesting their thermal sensation and comfort for a subset of the 19 body parts, as well as for their whole body (described as "overall sensation"). Figure 2 also shows the local and overall *sensations* obtained in this manner. During fast transients the subjects answered 5 questions during each pop-up: the sensation and comfort for the overall body, and sensation and comfort for the local body part that was experiencing local cooling/warming. The 5th question could be either sensation or comfort for a body part different than that being warmed or cooled. The purpose of adding the fifth question was to distract the subjects' attention from the body part that is actually being warmed or cooled. When the skin temperature was not changing rapidly, sensation and comfort questions were asked for all 19 local body parts and for the whole body.

Figure 2. Skin temperature, local and overall sensation for three local cooling applications in one

Table 1 presents the tests of individual body parts. We conducted more tests of local cooling in warm environments (205) than of local heating in cool environments (37) because the project focus was on air-conditioning of automobiles.

Table 1. Number of tests for local body part cooling or heating

	head	face	neck	breath	back	u.back	l.back	chest	pelvis	u.arm	l.arm	hand	thigh	l.leg	foot
cooling	13	25	11	13	15	10	9	17	13	12	12	17	10	10	18
heating	1	3	3	3	4	0	0	4	2	4	4	3	1	1	4

Results

In the following sections we present examples of effects or patterns that we consistently observed in our data. Differences in our environmental test conditions preclude more quantitative methods at this point. The examples in the figures are selected from all the test results to show what we found to be typical and useful effects. Each example shows an effect that was observed in most or all comparable tests. The effects are intrapersonal and relative, relating perceptions of different body parts to overall perceptions, or describing rates of change of perceptions.

A. Effects of individual body parts on overall sensation and comfort in warm ambient conditions.

The body's overall thermal sensation is affected differently by the cooling of individual body parts. Some body parts (back, chest, and pelvis) strongly influence overall thermal sensation, which closely follows the local sensation of these parts during both local cooling and recovery (Figure 3a). At the same level of cooling, as measured by local sensation, the hands and feet have

much less impact on overall sensation (Figure 3b). During a hand cooling and its recovery, the hand itself may feel very cold while the overall sensation only drops from slightly warm to neutral. The impacts on overall sensation from the back, chest, and pelvis are significantly different from those of the hand (paired t-tests, all $p < 0.01$). For the same change in local sensation, the drop in skin temperature from cooling the hand is 12 °C, while the drop for the back is 4 °C. The large difference in hand skin temperatures is caused by vasoconstriction, which is typically far greater in the extremities than the body's trunk (back, chest, pelvis). It could be that the rates of hand cooling in this study were too high to let the hands release heat to effectively cool the whole body. Other body parts (head region, arms and legs) have an intermediate influence on the body's overall thermal sensation.

Figure 3. Overall and local sensations during local body part cooling and recovery

The comfort values for the back, hand, and overall comfort during cooling/recovery behave similarly to the sensation values: overall comfort follows back comfort closely but is not much affected by hand comfort.

B. Effects of individual body parts on overall sensation and comfort in cool conditions.

The influence of local warming of the trunk on overall sensation appears to be smaller than that of local cooling. For example, in Figure 4a, warming the back to a given level of sensation has half the effect on overall sensation than cooling the back has in Figure 3a. However the differences measured in all trunk region tests are not statistically significant. Hand warming (Figure 4b) has insignificant effect on overall sensation, the same as with cooling (Figure 3b). Interestingly, the finger temperature range seen in Figure 4b is greater than that of the hand, reaching 2°C higher, because the fingertips exhibit considerable vasodilation under local warming.

Figure 4. Overall and local sensations during local body part warming and recovery

Comfort under local warming behaves similarly to sensation: the back comfort has half the effect on overall comfort than it did under cooling, and hand comfort has a small effect.

C. Anticipation and overshooting in local sensation and comfort

In some tests, both local sensation and local comfort showed a tendency to anticipate or initially exceed their final states during transients. We term this *overshoot*. We found that the overshoot for comfort is more pronounced than that for sensation. We also found that *local* comfort overshoot is more pronounced than the *overall* comfort overshoot, as seen in the step-change tests presented in Part I.

In all our tests, “very comfortable” feelings (with a scale value close to 4) occurred only when a body thermal stress was being relieved by the local cooling/warming, when perceived stimuli tend toward restoring homeostasis. Figure 5a shows that when a subject was uncomfortably warm, the application of face cooling created a short-duration (4-minute) overshoot in his/her comfort responses. Figure 5b shows the comfort responses during the application and removal of back cooling. When cooling was applied to the back and the body was warm, there was one “very comfortable” vote, which quickly disappeared because the cooling was too strong (the overall sensation became “slightly cool”). When the strong back cooling was removed, the comfort overshoot to “very comfortable” for 5 minutes. Once homeostasis is reestablished the comfort votes reach the steady value of 2 “comfortable”.

These findings corroborate the theories of Cabanac (1997) and Kuno (1995), who pointed out that highest levels of pleasantness are associated with transient conditions, and are of short duration.

b. During back cooling and its removal

Figure 5. Sensation comfort overshoot

Thermal sensation also displays overshoot, but the magnitude of overshoot is smaller than for comfort (it does not tend to significantly exceed the final state as can occur with comfort). Sensation overshoot is observed more in terms of anticipation—the rate of change of sensation change relative to skin temperature change. Similar to comfort, local sensation overshoots are larger than the whole-body sensation overshoots during step-change tests presented in Part I.

D. The effect of the rate of change in skin temperature on sensation; simultaneous heating and cooling of hands

During transients, the derivative of skin temperature has a stronger influence on sensation than skin temperature itself, because the firing rate of thermoreceptors is 5 – 10 times higher during a change in temperature than under steady conditions (Hensel 1982). We can see the distinction between skin temperature and rate of skin temperature change in a test when the right hand was cooled while the left hand was warmed (Figure 6), an effect accurately explained by John Locke in 1690.

In this single test, the room air temperature was 30°C and the subject felt warm. When cool air (20°C) was applied to the right hand and warm air (38°C) was applied to the left hand simultaneously, the right hand felt slightly cool and the left hand warm (Figure 6a). After 20 minutes, both thermal stimuli were removed. While the left hand skin temperature was still higher than the right hand skin temperature, its sensation was cooler (reversed sensation). The negative and positive derivatives of the left and right hands after the stimuli were removed appear to dominate the hand thermal sensations.

a. Thermal sensation

b. Thermal comfort

Figure 6. Overall, left and right hand thermal sensations during left hand warming and right hand cooling

It is interesting to notice that the overall thermal sensation became cooler during the simultaneous right hand cooling/left hand warming, even though the left hand thermal sensation went up 2 scale units from neutral to “warm” while the right hand thermal sensation went down 1 scale to “slightly cool”. We might speculate, but cannot distinguish here, whether this overall cooling is due to humans being more sensitive to cooling than warming, or that since the whole body was warm before the application of the thermal stimuli, the sensation difference between the whole body and the slightly cool right hand was larger than the sensation difference with the slightly warm left hand, and attracted more of the subject’s attention.

Both hands experienced warm and cool sensations while they were warmed, cooled, and when the stimuli were removed. Figure 6b plots all their coincident sensation and comfort votes. It shows that both hands behaved similarly, and that cooling was more comfortable than warming. Because the whole body was warm, the subject could clearly perceive warming (either active warming or removal of cooling) as a comfort reduction, and cooling (either active cooling or removal of warming) as increasing comfort.

E. Breathing zone: warming vs. cooling

Subjects exposed to warm breath intake air showed a strong negative response. Of all the local heating tests we did in cold environments, the tests in which breath intake air was warmed were the only ones in which subjects’ local and overall comfort decreased.

In the test shown in Figure 7a, the room air was 20°C and warm air for breathing zone heating was 37°C. Before the application of the breathing zone heating, the subject’s overall sensation was very cold (-3) and overall comfort was low (scale -3), between “uncomfortable” (scale -2) and “very uncomfortable” (scale -4) (they are not shown in this figure). The breathing zone sensation was -1.5, between slightly cool (-1) and cool (-2). Its comfort was on the comfortable side. The breathing zone comfort started positive at +1 and declined significantly right after the application of heating, reaching -2.5, even though the whole body was cold and this heating acted to offset it.

Cooling of breathing air produced dramatically different results than heating. In the warm-environment test shown in Figure 7b, the overall sensation declined from warm (2) to neutral (0), while the breathing zone sensation declined from neutral (0) to cool (-2) (not shown in this figure). Both the corresponding overall and breathing zone comfort increased greatly (about 2 – 3 comfort scales).

a. Breathing zone comfort declined after local breathing air was warmed in a cold environment

b. Breathing zone and overall comfort enhanced after local cooling applied in warm environment

Figure 7. Breathing zone comfort preferences

That people are comfortable with breathing zone cooling can be seen from another example where mild local cooling (28°C supply air temperature) was sequentially applied to the breathing zone, leg, and chest (Figure 8). The room air temperature was 30°C. The only treatment that gave a positive comfort response was cooling the breathing zone. Leg cooling did not produce any influence on overall comfort, while chest cooling (even at 28°C) was considered excessive and so had an initial negative impact on the overall comfort.

Figure 8. Overall thermal sensation and comfort for three local cooling applications in one test

F. Feet: sensation and comfort in transient and steady-state conditions.

Application of heat to both feet under cold conditions produced a strong local and overall comfort reaction, illustrated in Figure 9a and b. In this test sequence, heat was applied sequentially to the neck, two feet, and breathing zone. Warming the two feet caused the strongest increase in both local and overall thermal comfort, much stronger than warming the neck. Conversely, warming the breathing zone reduces both local and overall comfort, as was also seen above in Figure 8a.

Before the foot warming, its sensation was slightly cool and comfort neutral, although the instep temperature approached 26°C, well below the normal neutral foot temperature (between 32°C and 33°C, Olesen and Fanger, 1973). This suggests adaptation to the cold conditions, caused by sensory fatigue (Stevens 1960). During the warming and after its removal, the dramatic changes in foot sensation and comfort were caused by the rate of change of skin temperature.

a. Thermal sensation

b. Thermal comfort

Figure 9. Local and overall thermal sensation and comfort during heating to neck, two-feet, and breathing zone in cold environment

Figure 10 shows comfort when foot cooling and heating was applied to warm, neutral, and cool bodies for 20-minute periods. The comfort and sensation had reached steady state within this time, and showed no signs of further change. When the whole body was cool/cold the perceived foot comfort for warmed feet reached scale values around 3 (square symbol). The same high levels were reached when the body was warm/hot, and the feet cooled (triangle symbol).

The figure also shows that when the whole body sensation is perceived as thermally neutral, the foot sensation is consistently cooler than the body (circle symbol). This is perceived as comfortable, but not at high comfort scale values of 2 or above.

Figure 10. Higher comfort votes appear when foot cooling/heating act to remove overall thermal stress

Discussion

Much heating, ventilating, and air-conditioning (HVAC) research has focused on uniform, stable and neutral indoor conditions. The focus has been on minimizing discomfort to some acceptable level, which for the ASHRAE and ISO standards is 20 percent of the building population. Environmental asymmetries and transients are quite rigorously restricted in these standards as potential sources of discomfort.

In the tests reported here, people perceived neutral conditions as comfortable, but not as “very comfortable”. The “very comfortable” votes happened *only* in asymmetrical environments, when the local cooling/heating helps remove some level of whole body thermal stress, *and/or* during transients, in which comfort perception anticipates and overshoots the coincident skin temperature. These results suggest a possible new perspective on environmental asymmetries and transients, where one might encourage them rather than to avoid them as sources of discomfort. It might be feasible to achieve higher levels of thermal comfort or pleasure than are currently possible, through appropriately designed asymmetrical and transient thermal environments.

Of these two, asymmetrical environments (either steady-state or transient) produced higher levels of comfort than uniform transients (in which the whole body is exposed to a step-change). In the step-change test described in Part I, the comfort level only reached scale values around 1. In Figure 5 we see transients of local body parts producing comfort levels approaching 4 (“very comfortable”). Under steady state asymmetry, foot comfort reached values of 3 (Figure 10).

This suggests opportunities for task-conditioning (TAC) systems in buildings, in which local cooling/heating creates asymmetrical environments for the occupant. Asymmetrical transients are probably more easily implemented in buildings than whole-body transients. In addition, cooling or heating a single body part is less likely to go too far and cause the whole body to become uncomfortable.

TAC systems are also energy-efficient and individually controllable, allowing the potential for zero percent of the occupants being uncomfortable in buildings (Bauman et al, 1998).

These might be important design considerations for TAC systems:

- In transient and steady state, subjects preferred the breathing zone to be cool.
- Local heating of the breathing zone lowers comfort, even in cold conditions.
- Warming the feet is very effective at enhancing comfort.
- The rate of change of skin temperature has a stronger effect than skin temperature in sudden transient conditions, as seen in the example where the two hands were simultaneously warmed and cooled
- In the design of local cooling systems, the sensitivity of the body’s trunk would be an issue. It is easy to overdo chest cooling and lower back cooling.

There are interesting questions about transients. Repeated short-duration but repeated local cooling/warming are caused by oscillating fans or a pulsing radiant heater—do such devices’ comfort effects rely on overshoot? It also remains a question whether the desirable comfort effects of transients and overshoot can be sustained over long time periods, such as apply to workers in office workstations. Our results show comfort persisting under local asymmetry for periods up to 30 minutes. Experience with climatic asymmetries outdoors suggest that positive comfort can persist for longer periods.

The topic of non-uniform environmental control needs to be investigated further. Our tests were primarily in strong cooling applications, many of them beyond what might be possible in buildings.

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