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Partial- and whole-body thermal sensation and comfort—Part II: Non-uniform environmental conditions

Edward Arens*, Hui Zhang, Charlie Huizenga

Center for the Built Environment, University of California, Berkeley, 390 Wurster Hall, Berkeley, CA 94720-1839, USA

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Abstract

Subjects were exposed to sequences of partial-body cooling and warming over a period of 3 h. Skin temperatures, core temperature, thermal sensation, and comfort responses were collected for 19 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

1. 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.

2. 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 min. 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 40–60 min 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

*Corresponding author. Tel.: +1 510 642 1158; fax: +1 510 643 5571.
E-mail address: earens@berkeley.edu (E. Arens).

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to the skin prevented the subjects from perceiving the motion of the air passing through the sleeve. Fig. 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.

In a typical 3-h 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 min. An example is presented in Fig. 2, in which the parts head, hand, and pelvis were each cooled for 15–20 min (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.

Fig. 1. An air sleeve for back cooling. A total of 19 body parts were heated and/or cooled during the tests.

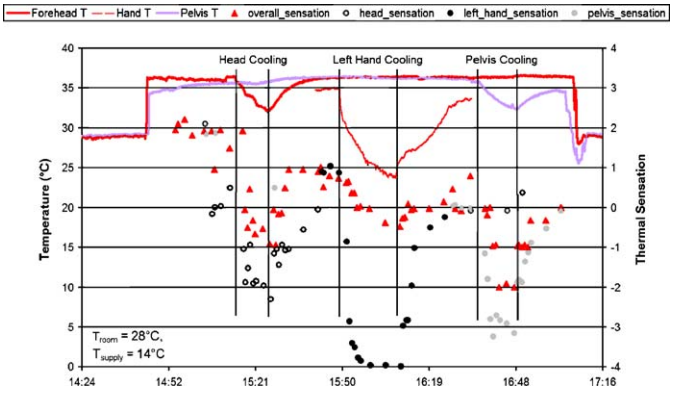

Fig. 2. Skin temperature, local and overall sensation for three local cooling applications in one.

At 1- to 3-min 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"). Fig. 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.

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.

3. 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.

3.1. *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

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