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# Observations of upper-extremity skin temperature and corresponding overall-body thermal sensations and comfort

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## Abstract

This paper explores how upper extremity skin temperatures correlate with overall-body thermal sensation and comfort. The study's motivation was that skin temperature measurements of the finger, hand, and forearm might be useful in monitoring and predicting people's thermal state. Subjects in a range of test chamber temperatures had their subjective perceptions of overall thermal sensation and comfort collected by repeated surveys. A positive temperature gradient (finger warmer than the forearm) of as much as 2 K was seen when subjects felt warm and hot, while a negative temperature gradient (finger colder than the forearm) as much as 8.5 K was seen for cool and cold subjects. A useful warm/cold boundary was found at a finger temperature of 30°C, for both steady state and transient conditions. When finger temperature was *above* 30°C, or finger-forearm skin temperature gradient was above 0 K, there was no cool discomfort. When finger temperature was *below* 30°C, or the finger-forearm skin temperature gradient was less than 0 K, cool discomfort was a possibility. Finger temperature and finger-forearm temperature gradient are very similar in their correlation to overall sensation. We also examine how overall sensation is affected by actively manipulating the hand's temperature.

*Keywords:* Thermal Sensation, Thermal Comfort, Skin Temperature, Temperature Gradient, Finger, Hand, Forearm, Comfort Threshold, Occupant Survey

## 1. INTRODUCTION

It is known that human extremities play an important role in human thermal regulation. Vasoconstriction and vasodilatation vary blood flow to hands and other extremities to control the heat loss from the skin to environment. As a result, cold hands indicate that the body is acting to retain heat; warm hands indicate the body is acting to lose heat. The hand temperature is probably the body's most sensitive indicator of thermal state. Glabrous skin, which includes the nail bed, finger, hand, and arm, has many arteriovenous anastomoses (AVA)'s, valves that control vasoconstriction and vasodilatation [1,2,3]. The number of AVA's in the hand and fingers is much greater than in the rest of the body surface, and their opening and closing varies the hand temperature across a wide range. They are primarily controlled by signals from the hypothalamus, and so their actions represent overall body thermal state.

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Humphreys et al. [4] proposed that the skin temperature of the hands might be used instead of, or together with, the temperature of the surroundings in predicting the thermal comfort of people in buildings. He measured 2000 fingertip temperatures and overall thermal sensation votes from 200 office workers during the course of one year in the UK. He found a bimodal finger temperature distribution occurring in moderate thermal environments, with a large peak at 35°C and a weaker peak at 26°C. He compared the correlation of these sensation votes with globe temperature (a combination of air and radiant temperatures which represents human exposure to the thermal environment), and the correlation of sensation votes with globe temperature plus fingertip temperature. By adding finger temperature to globe temperature in fitting thermal sensation vote, he significantly improved the correlation coefficient from 0.31 to 0.43. He concluded that adding finger temperature to the temperature of the surroundings could be useful in explaining some of the variation in sensation votes that one sees in building occupant surveys.

In addition to surveys, one might imagine novel ways to monitor and predict an occupant's thermal state in real time, for example, by monitoring their finger and environmental temperatures with small sensors mounted in a ring, watch, steering wheel, computer mouse, keyboard, etc. How well might such concepts work? Although Humphreys' finger temperatures correlate with thermal sensation, they still vary substantially among people expressing the same thermal sensation, exceeding 10°C among people feeling neutral or cooler than neutral. This variability might limit the accuracy of any method that uses fingertip temperature as a predictor of thermal sensation or comfort.

In this paper, we use data acquired in a laboratory study to explore Humphreys' hypothesis: that the finger temperature, or a combination of air and finger temperatures, might predict thermal sensation. It has been shown that the temperature difference between forearm and fingertip can indicate the onset of vasoconstriction [5]. We speculate that the extent of the vasoconstriction leads to a conscious sensation of cold in our tests. We therefore examine whether the *gradient* of skin temperatures, from finger to hand to forearm, might improve the predictive ability over using finger temperature alone. Much of this examination is done under steady conditions under which the subject has reached thermal sensation equilibrium. The gradient down the extremity will be seen to be the opposite in warm conditions as it is in cold conditions. We also look at gradients between forehead temperature and the extremity temperatures, since the forehead is, like the hand, a skin surface that is exposed to the environment and potentially subject to being remotely sensed. In automobile environment, the forehead skin temperature has been shown to be correlated with overall thermal sensation [6].

Since we are also interested in real-time prediction of future comfort, we also look at thermal behavior during thermal transients, during which the hand is cooling or warming. Here the cross-over point in thermal gradient is of interest. In addition, we observe a finger temperature fluctuation pattern that occurs in many subjects when they are near thermal neutrality; there may be some predictive utility in this.

The skin temperature thresholds corresponding to the edge of the thermal sensation neutral zone, and to the onset of discomfort, can be determined from the data. This requires us to quantify the relationships between thermal sensation and comfort; the data also allow us to examine this.

Finally, the extremity temperatures might be manipulated to provide overall comfort in a quickly-acting and/or energy-efficient manner. 'Task-ambient air conditioning systems' essentially do this by warming or cooling specific local body parts to affect the body's overall sensation.

## 2. METHODS

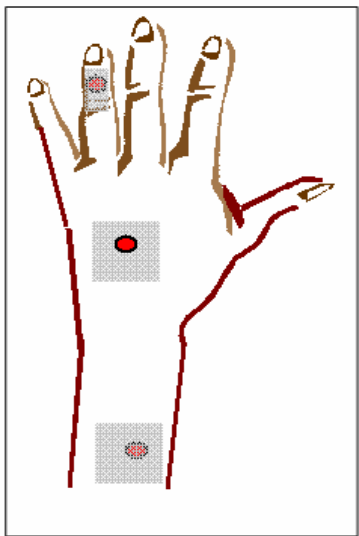
Thermal physiology tests were carried out in the Controlled Environmental Chamber at UC Berkeley from January to August 2002, in which 19 body segments, singly and in combination, were heated and cooled to determine local- and overall comfort relationships. The physiological responses (skin and core temperatures) during these tests are described in [7] and subjective responses in [8, 9]. We focus here on two types of tests during which additional temperatures were taken on the upper extremities in order to examine the relationships between arm, hand, and finger skin temperatures and whole-body thermal comfort: 1) tests in *uniform, steady-state* thermal conditions controlled to produce overall sensations ranging from *cold* to *hot*, and 2) *local segment* tests in which the subject's left hand was cooled or heated for a period of 20 minutes, followed by a recovery period after the stimulus was removed.

A total of 23 of these tests were performed, in which 17 subjects participated. Subjects sat performing voluntarily selected work at a computer (Figure 1) in a range of temperatures from cold through neutral to hot. Upper-extremity (finger, hand, and forearm) temperatures were measured at three locations: the dorsal side of the 4<sup>th</sup> finger of the left hand, dorsal side of the left hand, and dorsal side of the left forearm (Figure 2). The forehead and other head temperatures were also measured. In the local segment tests, heated or cooled air was supplied to the hand through an air sleeve covering the hand segment (Figure 3).

Tests were done one subject at a time. Upon their arrival, subjects swallowed a core-temperature-measuring radio pill, spent 15 minutes in a bath preconditioned to the temperature of that day's test, and then put on the thermocouple harness measuring 28 body locations. Aside from those at the hand and head locations, the thermocouples were covered by a thin elastic long-sleeved leotard and socks (clothing insulation value was 0.32 clo based on manikin measurement). Skin temperatures were measured with fine 36 gauge thermocouples every 5 seconds (accuracy level  $\pm 0.1^\circ\text{C}$ ). Core temperature was measured at 20-second intervals (accuracy level  $\pm 0.1^\circ\text{C}$ ). Subjective perception of overall thermal sensation and comfort was surveyed via the computer screen at 1 to 3 minute intervals. The surveys used 9-point analog scales (Figure 4). For sensation, the scale ranged from -4 "very cold" to 4 "very hot"; for comfort, it ranged from +0.1 "just comfortable" to 4 "very comfortable", and -0.1 "just uncomfortable" to -4 "very uncomfortable". The comfort screen is split in the middle to force a judgment. The movement of the left hand was not restricted.



**Fig 1. Subject in test chamber**



**Fig 2. Thermocouple locations**



**Fig 3. Subject during hand cooling test**

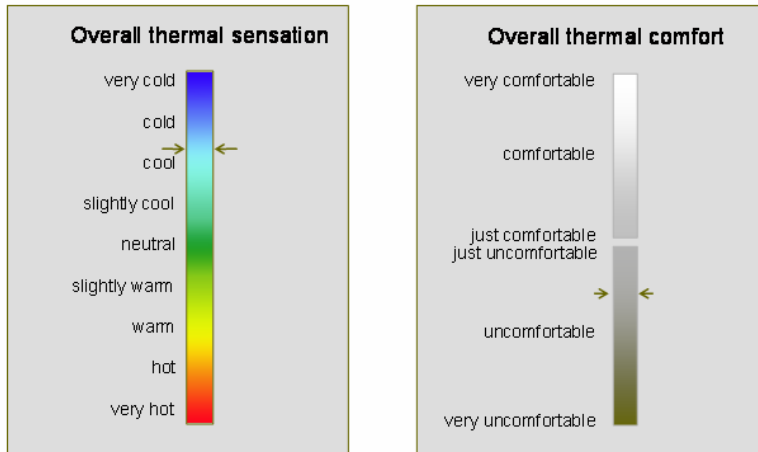


Fig 4. Nine-point analog scales

### 3. RESULTS

#### a) Time-series skin temperatures under uniform, steady-state conditions

The observed patterns of skin temperatures, sensation votes and comfort votes are complex and might first be examined in typical examples of time-series results for a range of test conditions. The example for each test condition was chosen to point out features that we observed in most or all of that condition's tests.

The conditions tested were *hot* (29-31.5°C), *warm* (28-29°C), *neutral* around (27°C), slightly cool (17.5-20.7°C), and *cold* (15.6-17°C). Figure 5~9 show temperature measurements and the corresponding thermal sensations of subjects in each of these conditions.

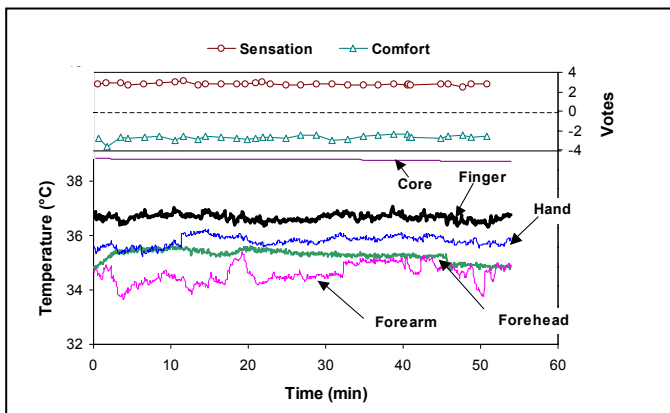


Fig 5. Hot condition test ( $T_{\text{chamber}}=31^{\circ}\text{C}$ )

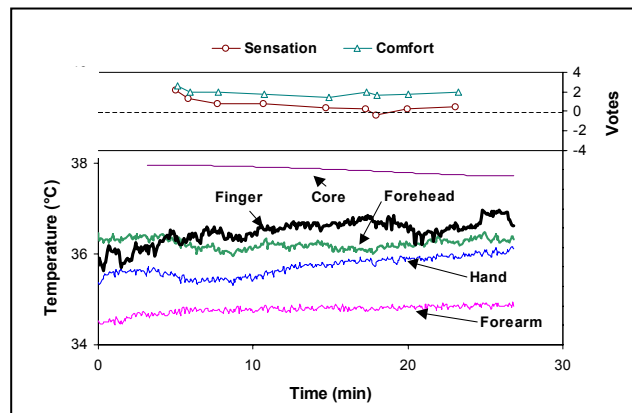


Fig 6. Warm condition test ( $T_{\text{chamber}}=28.2^{\circ}\text{C}$ )

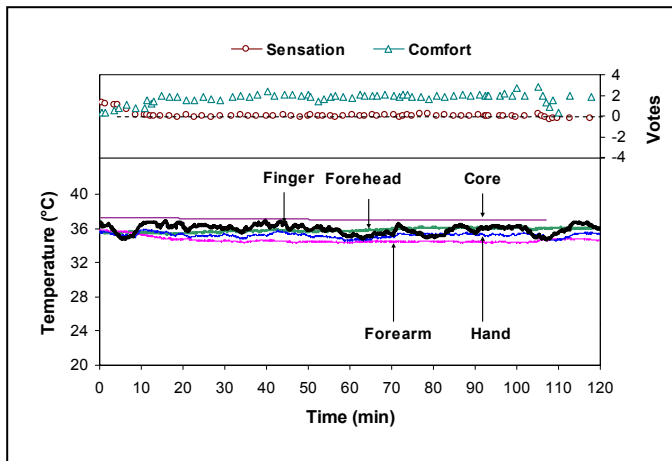


Fig 7. Neutral condition test ( $T_{\text{chamber}}=25.5^{\circ}\text{C}$ )

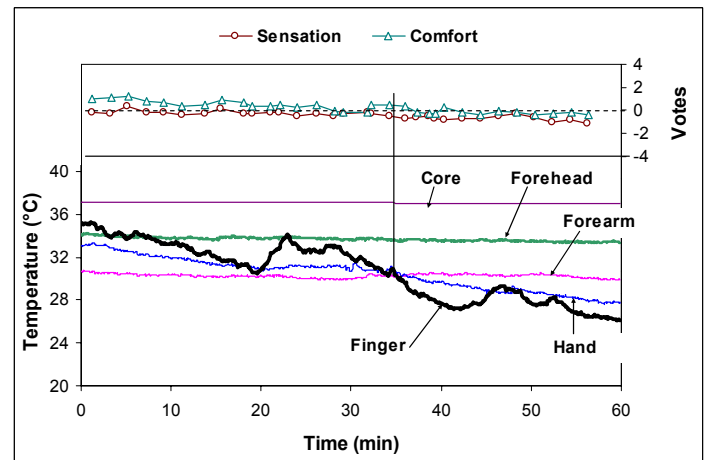


Fig 8. Slightly cool condition test ( $T_{\text{chamber}}=19^{\circ}\text{C}$ )

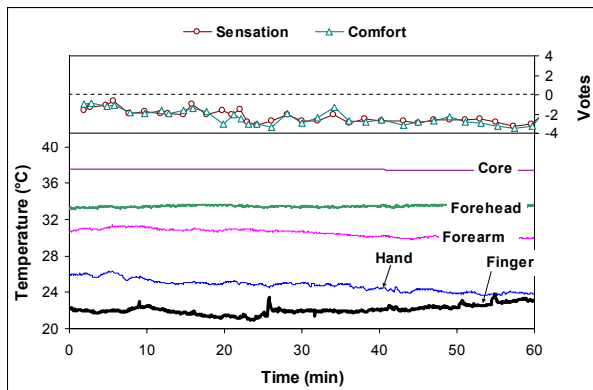


Fig 9. Cold condition test ( $T_{\text{chamber}}=17^{\circ}\text{C}$ )

*Hot, warm:* The subject in Figure 5 felt *hot* (2.82 thermal sensation average during the test) and uncomfortable. The finger temperature averaged  $36.7^{\circ}\text{C}$ , consistently warmer than the hand ( $35.8^{\circ}\text{C}$ ), forearm ( $34.6^{\circ}\text{C}$ ), and forehead ( $35.3^{\circ}\text{C}$ ) with differences of 0.9, 2.1, and  $1.4^{\circ}\text{C}$  respectively. The subject in Figure 6 felt *warm* overall (0.66 thermal sensation average) and comfortable. The spatial temperature distribution across the upper extremity was similar to that in the *hot* condition, but with slightly smaller values: the finger temperature averaged  $36.5^{\circ}\text{C}$  and the differences between finger and hand ( $35.7^{\circ}\text{C}$ ), forearm ( $34.8^{\circ}\text{C}$ ), and forehead ( $36.2^{\circ}\text{C}$ ) were 0.8, 1.7, and  $0.3^{\circ}\text{C}$  respectively. In both *warm* and *hot*, the skin temperature

differences in the extremities were small, but the finger-to-forearm gradient was consistently positive. In the warm condition, the hand and finger temperatures increased slightly throughout the test. Somewhat surprisingly, the forehead temperature was (1°C) lower in the hot condition than in the warm. In hot conditions, the first area to sweat is generally the forehead [10], and this decreases the skin temperature relative to other body parts.

*Neutral:* Figure 7 shows results for a *neutral* condition. The subject felt *neutral* overall (0.10 thermal sensation average) and comfortable. The finger temperature was still (35.9°C) warmer than the hand (35.2°C), forearm (34.6°C), and now was almost equal to the forehead (35.8°C). Throughout the test, the finger temperature fluctuated prominently. In all the eight *neutral* condition tests, we observed fluctuations of around 1-2°C in finger temperatures, occurring roughly at 2 – 5 minute intervals. We believe this fluctuation is evidence of active thermoregulation to maintain thermal neutrality by vasodilatation and vasoconstriction in the blood vessels of the extremities [7]. Near the neutral condition, the body actively regulates the temperature of the exposed fingers to meet its thermoregulatory needs. Fluctuation of this magnitude and frequency did not occur in the hot, warm, slightly cool, or cold conditions (Figures 5, 6, 8, and 9). The fluctuations were not perceived by the subjects. (We also surveyed them for their local hand thermal sensations, which did not change either. The hand data are not displayed here). The lack of sensitivity to hand thermal fluctuations may be caused by the lower density of warm and cold thermal receptors in the hands, relative to areas such as the face and head [11,12,13].

*Slightly cool:* The forearm, forehead, and core temperatures were steady throughout the test (Figure 8). Mirroring the warm test in which hand and finger skin temperatures slowly increased, here they gradually decreased throughout the test. The finger-forearm and finger-hand skin temperature gradients switched from positive to negative at 35 minutes when all three temperatures were identical. The finger temperature also increased twice for a period of about 15 minutes, about 25 minutes apart (3 and 2°C respectively) when it was once at 30.7°C, and once at 27.2°C. These were probably caused by a form of vasodilatation called arteriovenous anastomosis (AVA) action [7]. This pattern was seen in some of the *cold* condition tests and a few of the *slightly cool* condition tests. We do not know why the pattern occurred irregularly among the subjects.

This example gives an opportunity to examine whether  $T_{\text{finger}}$  or  $T_{\text{gradient}}$  might predict a whole-body cooling transient, perhaps before it was perceived by the subject. Both skin and core temperatures were decreasing, with the core dropping 0.05°C and the forehead temperature dropping 0.71°C during the hour-long test. Around the time (35<sup>th</sup> minute) that the finger temperature became cooler than that of the forearm and hand (at finger temperature 30.4°C, finger-forearm temperature gradient was 0°C), the subject began to consistently vote thermal sensation below -0.5. The comfort votes became neutral or negative about 5 minutes later. This phenomenon occurred in both of these gradual- cooling tests (the crossing temperature of other test was 30.6°C).

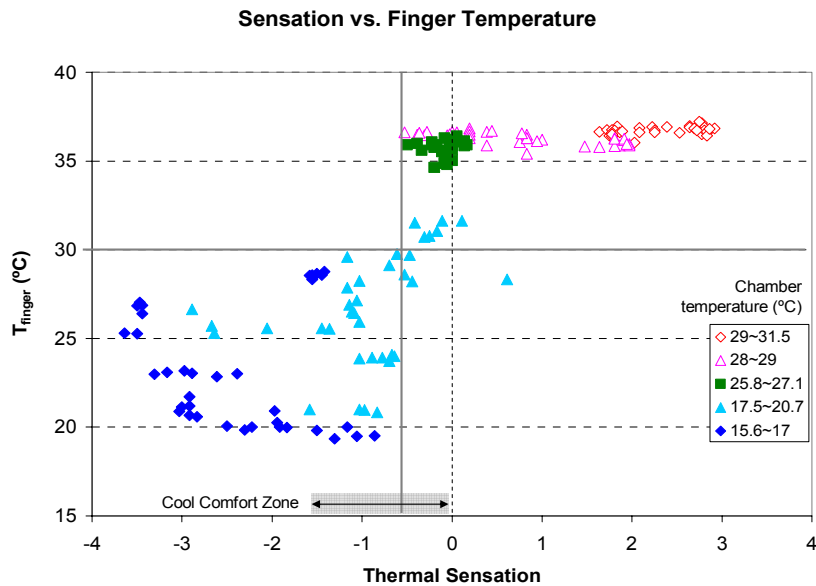


*Cold:* In cold conditions (Figure 9) the finger was now consistently colder than all the other skin temperatures, and was clearly vasoconstricted. Finger temperature was around 22°C (note the change in scale on this figure) and was consistently colder than the hand (24.7°C), forearm (30.5°C), and forehead (33.5°C) with differences of -2.7, -8.5, and -1.5°C respectively. This particular example did not exhibit an AVA pattern as in Figure 8. The overall thermal sensation averaged -2.27.

#### **b) Correlations of overall thermal sensation and skin temperature gradients between finger, hand, and forearm**

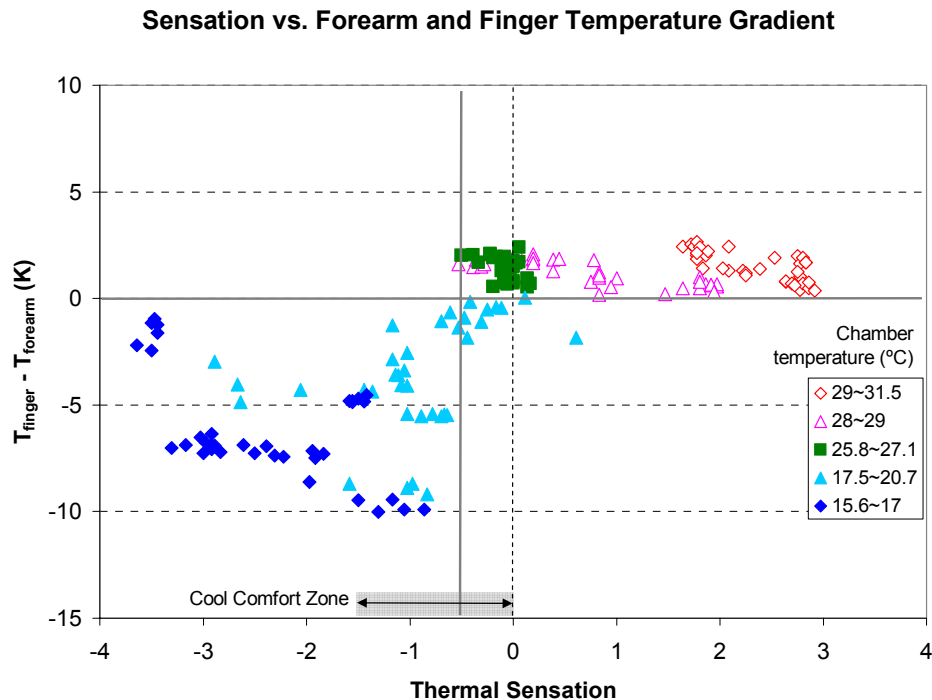
*Observations:* Figure 10 presents subjects' overall thermal sensation votes and corresponding finger temperatures obtained during the final 10 minutes of the 23 hour-long stable condition tests. The chamber air temperatures were fixed, from 15.6 in the coldest tests to 31.5°C in the warmest. Each subject registered 6 votes.

When subjects felt warm or hot (their overall sensation between 0.5 and 2.8), their finger temperatures can be seen to be closely bunched between 35 and 37°C, close to the core temperature. The lack of variation in finger temperature in warmer-than-neutral conditions suggests that measuring finger temperature will not predict the onset of warm sensations and discomfort. On the cool- to cold side (overall sensation cooler than -0.5), finger temperature ranged widely between 20-30°C. In the middle (-0.5 to +0.5) there are two regimes: from -0.5 to 0 there is a large variation from 28 to 35°C, while from 0 to +0.5 the finger temperature has almost no variation. The variation occurs almost entirely in the cool half of the typical (-1.5 to +1.5) comfort zone, as shown in Figure 11. Inspecting the data in cooler-than-neutral conditions reveals a prominent threshold in finger temperature that might be used to detect the onset of cool sensations and discomfort.



**Fig 10. Sensation and finger temperature**

Whenever finger temperature was *above* 30°C, the overall sensation was above  $-0.5$  (one-sample t-test,  $p < 0.001$ ) (the lower boundary of the neutral sensation zone), and there was therefore no possibility of cool discomfort. When finger temperature was *below* 30°C, whole-body sensation was (with the exception of very few data points) below  $-0.5$  ( $p < 0.001$ ), and therefore, cool discomfort was a possibility. 30°C is a clear threshold separating warm from cool, and it is associated with an overall thermal sensation of  $-0.5$ . All the actual cool discomfort votes occurred below 28.5°C (if one makes the common assumption that cool discomfort is represented by overall thermal sensation  $< -1.5$ ).



**Fig 11. Sensations and finger-forearm temperature gradient**

In Figure 11, thermal sensation is plotted against the finger-forearm skin temperature gradient. As with the finger temperatures, a threshold is prominently visible: a gradient of 0°C had the same effect of separating warm from cool sensations as the 30°C finger temperature did in Figure 10. When this gradient was above zero, overall sensation was above -0.5 (one-sample t-test,  $p < 0.001$ ) and no cool discomfort happened. When the gradient was less than zero, most of the overall sensation votes were below -0.5 ( $p < 0.001$ ), and therefore cool discomfort was a possibility.

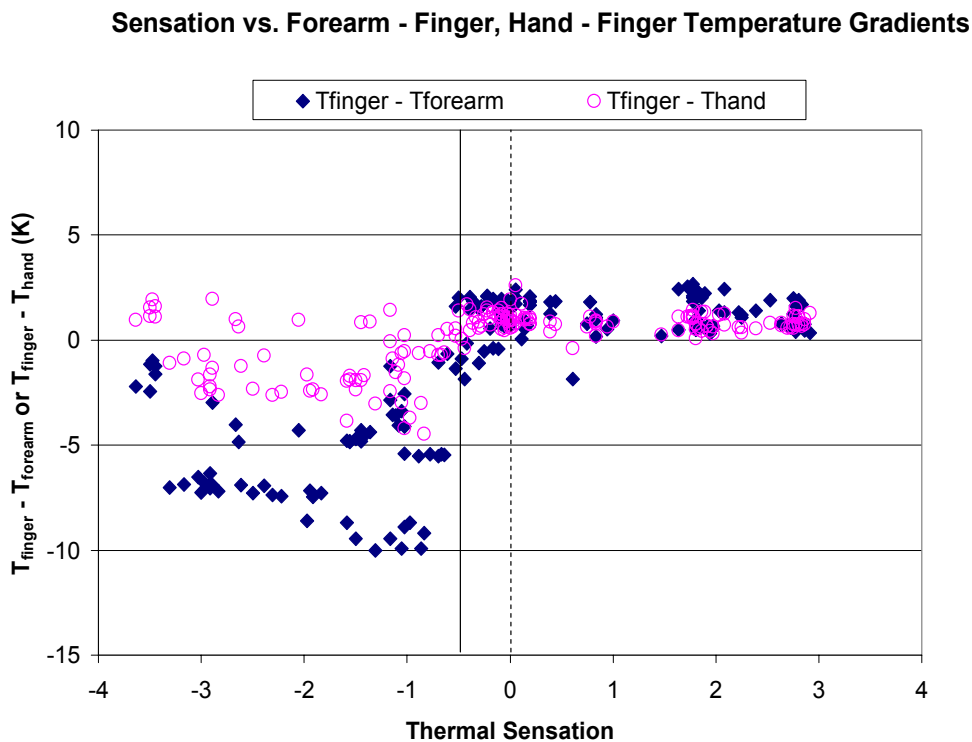
Note that these thresholds coincide with the time-series data shown in Figure 8, where the three extremity skin temperatures became identical at 30.4°C (finger-forearm gradient equal to zero), and thermal sensation was at -0.5 and decreasing.

*Skin temperatures and overall sensation in the cool comfortable zone (between thermal sensation levels 0 and -1.5):* The onset of cool discomfort generally occurs between the sensation levels -1 and -2, with -1.5 often set as the threshold for discomfort in laboratory and field comfort studies [14]. It is useful to correlate skin temperatures in the 'cool-but-comfortable' zone with their corresponding overall thermal sensations to see whether it would be possible to use it to predict the crossing of this threshold of cold-discomfort using skin (and air) temperature measurements. We correlated overall sensation with both finger temperature, and with finger-forearm skin temperature gradient, in the zone from thermal

sensation 0 (neutral) to  $-1.5$ . We can see in Figures 10 and 11 that both finger temperature, and the finger-forearm skin temperature gradient, varied greatly in this zone.

Within this zone, the correlation coefficient between overall sensation with chamber air temperature is 0.78 ( $r^2=0.61$ ), with finger temperature 0.78 ( $r^2=0.60$ ), with finger-forearm temperature gradient 0.80 ( $r^2=0.64$ ). Adding air temperature to the prediction of overall sensation by finger temperature, or by finger-forearm temperature gradient raises the correlations to 0.81 ( $r^2=0.66$ ,  $p = 0.05$ ) and 0.84 ( $r^2=0.70$ ,  $p = 0.005$ ) respectively. This is consistent with Humphreys' conclusion that adding finger temperature to air temperature will improve the correlation with thermal sensation.

*Comparison of finger-forearm and finger-hand temperature gradients:* The temperature gradient between *finger and hand* was significantly smaller than the gradient between *finger and forearm* (paired t-test,  $p<0.001$ , Figure 12).



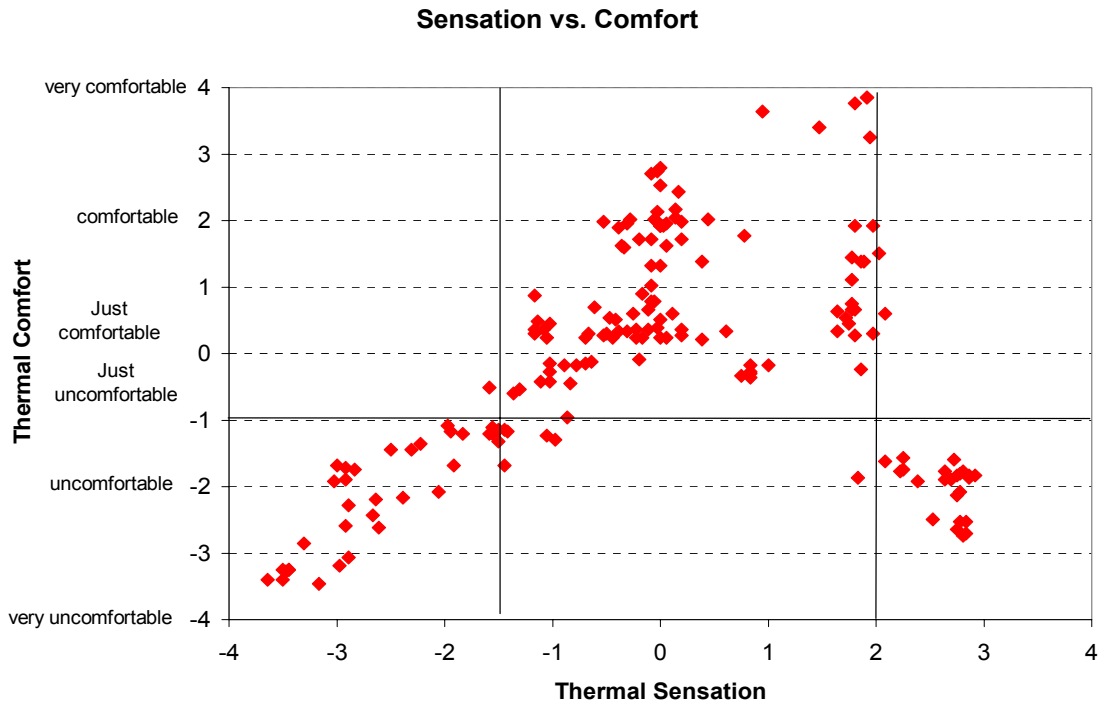
**Fig 12. Sensation and finger-to-hand and finger-to-forearm-temperature gradients**

When the subject felt warm to hot, the *finger-to-hand* gradient covered a range from 0 to  $1.7^{\circ}\text{C}$ , without any clear trend. Near the neutral zone, it ranges from  $-0.4$  to  $2.6^{\circ}\text{C}$ . When cold, it changes from  $-4.5$  to  $2^{\circ}\text{C}$ , again without a trend. Although the *finger-to-forearm* gradient is only slightly greater than the *finger-hand* gradient in neutral and warm conditions ( $-2$  to  $2.7^{\circ}\text{C}$  versus  $-0.4$  to  $2.6^{\circ}\text{C}$ ) it is much greater in cold conditions ( $-10$  to  $-1^{\circ}\text{C}$ , solid diamond in Figure 12) than the latter ( $-4.5$  to  $1.7^{\circ}\text{C}$ , open circle in Figure 12). Both gradients

show a diminishing trend in very cold conditions: as the hand and forearm are chilled in these conditions, they begin to approach the cold finger temperature.

**c) The relationship between thermal sensation and comfort**

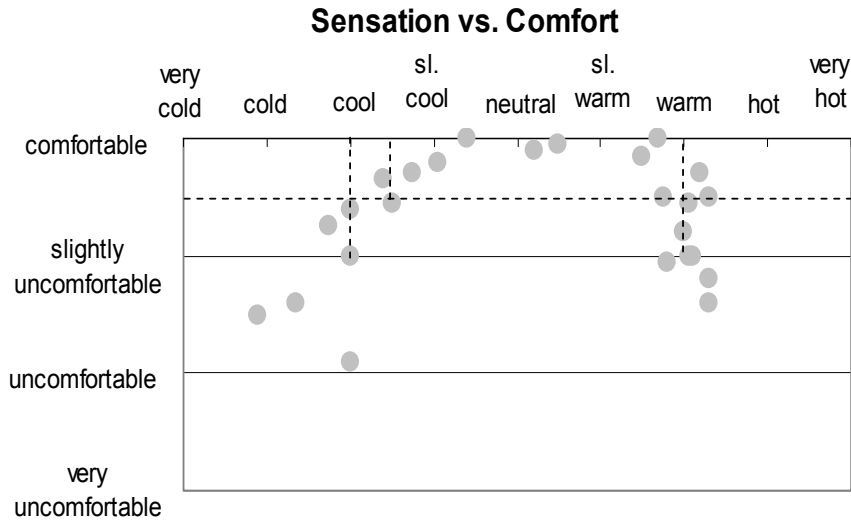
Since both sensation and comfort votes were collected during each survey, it is possible to determine the threshold levels in thermal sensation above and below which warm and cold discomfort are likely to occur. In Figure 13 we use a value of -1 on the comfort scale to indicate the onset of discomfort. -1 is half way between ‘just uncomfortable’ (-0.1) and ‘uncomfortable’ (-2). When sensation votes were between -1.5 and 2, the comfort votes were above -1 (one-sample t-test,  $p < 0.001$ ). When sensation votes were cooler than -1.5, comfort votes were below -1 ( $p < 0.001$ ). A similar strong division occurred on the warm side, but at sensation scale value 2.0. When sensation votes were above 2, most comfort votes were below -1 ( $p < 0.05$ ).



**Fig 13. Overall sensation and comfort (UCB data)**

This relationship can be examined in data collected by Gagge et al. [14, 15] (rearranged in Figure 14). They also used the ASHRAE thermal sensation scale, but their comfort scale differs in not extending symmetrically in the positive direction. Their results appear quite similar to our data. On the cold side, depending on whether one draws the discomfort boundary at -0.5 or -1.0 (‘slightly uncomfortable’), thermal sensations of -1.5 (halfway between ‘slightly cool’ and ‘cool’) and -2 (‘cool’) are good indicators of comfort and discomfort. The two scales are roughly correlated with a 45° slope. On the warm side,

comfort votes decrease very abruptly around thermal sensation +2 ('warm'), which can be taken to be the boundary between comfort and discomfort. The slopes of their data match ours closely on both the cold and warm sides of neutral.



**Fig 14. Overall sensation and comfort (data reformatted from Gagge et al 1967): effects of hand heating**

**d) Sensation and comfort resulting from heating and cooling the hand**

In the local segment tests, the hand (including fingers) was exposed to hot and cold air, while the forearm was at ambient chamber temperature. These tests allow us to detect how active heating and cooling of the extremity might affect overall sensation and comfort. In these cases, the gradient from finger/hand to forearm is not meaningful, because the extremity skin temperatures were only partially due to the body's own thermoregulation, being driven by the rather strong heating and cooling that we applied and then removed. The gradient between finger and hand does reflect local thermoregulation.

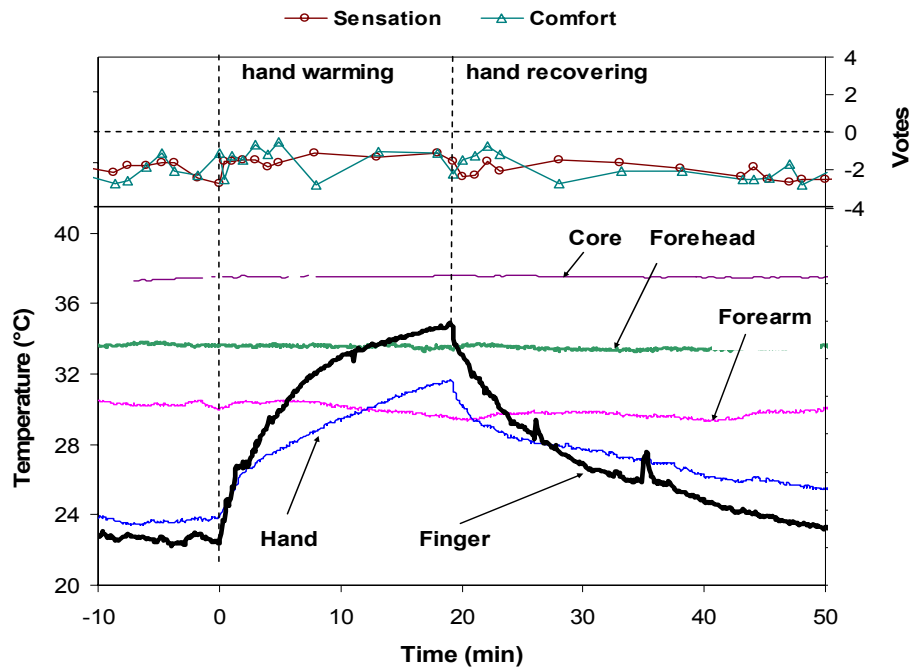


Fig. 15. Hand heating and recovery test ( $T_{\text{chamber}}=19^{\circ}\text{C}$ )

### Hand heating

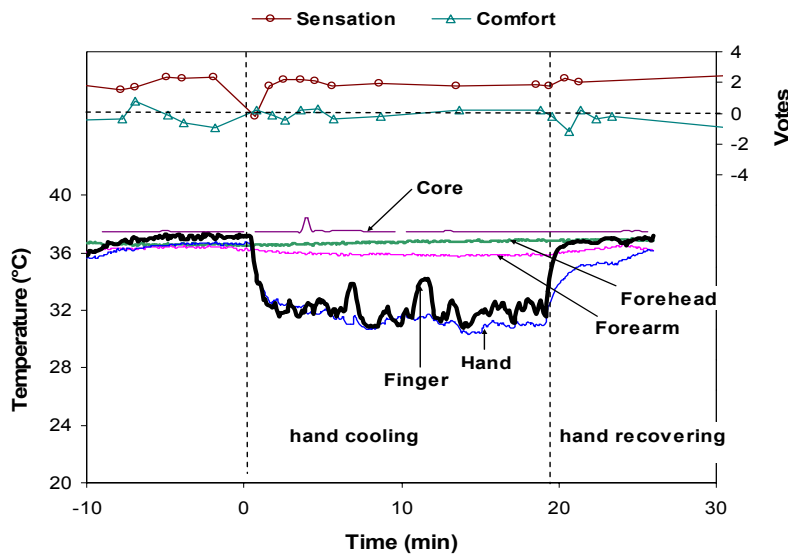
Figure 15 shows the temperature measurements and thermal sensations of a subject under a *cool* condition in which *hot* air was locally supplied to the left hand. The chamber temperature was  $19.0^{\circ}\text{C}$  and the local supply air temperature was  $36^{\circ}\text{C}$ . Initially the finger was cooler than hand and forearm. The finger temperature rose most rapidly and went above that of the hand and forearm. The heat was then removed (at the 20<sup>th</sup> minute), and the finger cooled most rapidly. The finger and forearm temperatures became identical 5 minutes after the heat was removed, at a cross-over point of  $29.7^{\circ}\text{C}$ . During the hand warming, the sensation warmed up from  $-2.7$  to  $-1.1$ , 1.6 scale, and comfort improved 2 scale units from  $-2.5$  to  $-0.5$  in 5 minutes, and then reduced a little to  $-1$  (with the exception of one point at  $-2.8$ ). Because the body was cold in this test, warming the hand alone was not able to bring the overall comfort to a positive level (the comfortable side in the comfort scale). Upon removing hand-warming, there was an overshoot in overall sensation, where sensation dropped from  $-1.1$  to  $-2.3$  for 2 minutes, then went up to  $-1.5$  and gradually back down to  $-2.7$ . The comfort votes during this period also showed an overshoot, from  $-2.2$  to  $-0.8$ , subsequently going back to  $-2.7$  and gradually stabilizing at  $-2.5$ . The subject in this test attributed the comfort increase that occurred after hand warming was removed to relief from the high supply air temperature ( $36^{\circ}\text{C}$ ) used for warming. Prior to hand warming removal, the

subject's left hand sensation was 'very hot' (3.6) and 'uncomfortable' (-2.6) (data not shown in this figure).

Unlike the results shown in Figure 8 where the skin temperatures were a result of the chamber environment, the reversal of the temperature gradients from finger to forearm under the active hand-heating here did not correspond to a significant change in overall sensation.

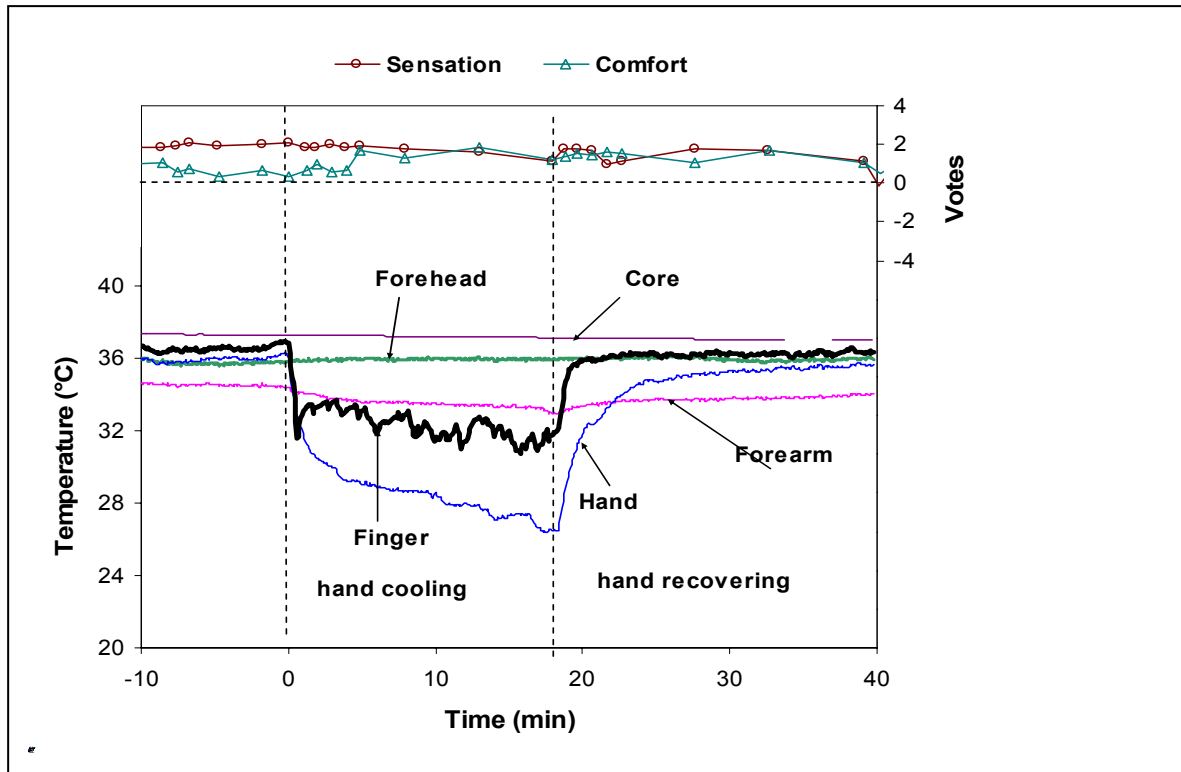
### Hand cooling

Figure 16-18 show the temperature measurements and thermal sensations at three successively cooler levels (chamber temperatures 31, 29.4, and 28.4°C), when *cold* air (14.0°C) was locally supplied to the left hand. Figure 16 is when the room air temperature was warm (31°C) and the person felt warm (2.3 sensation scale) before hand cooling was applied. Adding hand cooling reduced the warm feeling 0.6 scale units, from 2.4 to 1.8. Comfort was enhanced by 1.2 scale units, from -0.9 to 0.3, and switched from negative to positive. Upon the removal of hand cooling, the whole body sensation showed a small overshoot, from 1.9 to 2.3, then went back to 2. The comfort vote showed a larger overshoot, from -0.2 to -1.2, then falling back to about -0.2. The finger and hand skin temperature were quite close with each other, reduced from 37 and 36.7°C to 32 and 31°C, about a 5°C reduction. The forearm slowly reduced slightly, from 36.6 to 35.9°C. As in the steady-state neutral test in Figure 7, the finger showed a significant fluctuation, the biggest one about 2.5°C.



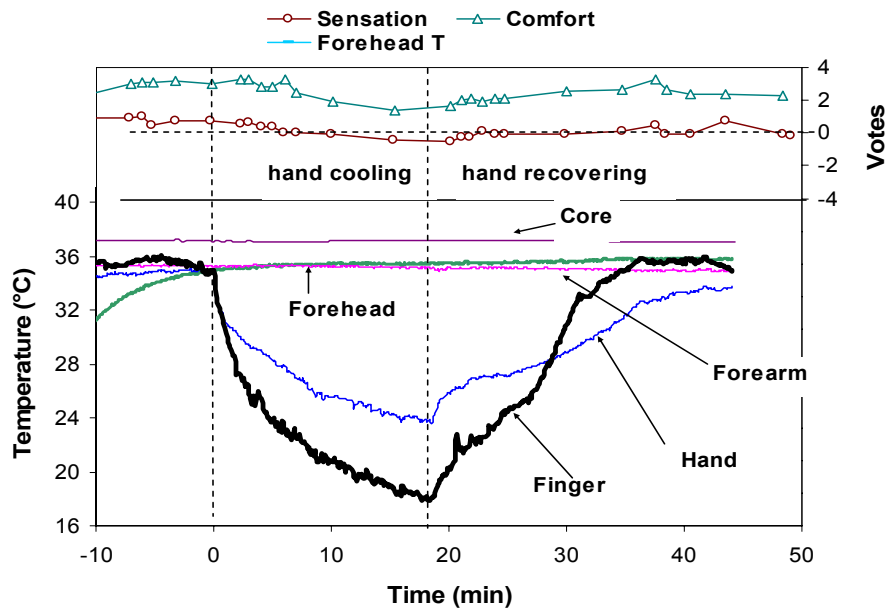
**Fig 16. Hand cooling and recovery test ( $T_{\text{chamber}} = 31^{\circ}\text{C}$ )**





**Fig 17 Hand cooling and recovery test ( $T_{\text{chamber}}=29.4^{\circ}\text{C}$ )**

When the room air temperature was less warm ( $29.4^{\circ}\text{C}$ , Figure 17) and the subject also felt warm (1.9 on the sensation scale), adding hand cooling reduced the warm sensation from 1.9 to 1.1, a difference of 0.8 scale units. Comfort increased 1.5 scale units, from 0.3 to 1.8. Upon removing hand cooling, the sensation overshoot from 1.2 to 1.8 for 3 minutes, then gradually varied between these values in the following 20 minutes. Comfort increased from 1.2 to 1.6. Finger temperature dropped from 37 to  $31^{\circ}\text{C}$ . Hand temperature dropped much more, from  $36.3$  to  $26.5^{\circ}\text{C}$ . As in the previous condition, the forearm gradually cooled from  $34.4$  to  $33^{\circ}\text{C}$ , and there was considerable finger temperature fluctuation during the hand cooling (about  $1^{\circ}\text{C}$ ). In both examples, the finger crossed forearm temperature very soon after the hand cooling was applied and was removed, so it is hard to tell whether the cross-over points were related with any overall sensation change, because the sensation changes corresponded to the local cooling and removal actions.



**Fig 18 Hand cooling and recovery test ( $T_{\text{chamber}}=28.4^{\circ}\text{C}$ )**

Figure 18 represents the coolest example shown. The finger temperature was now lower than that of the hand. Finger fluctuation is no longer visible; suggesting that the hand was well vasoconstricted. Overall thermal sensation did not change while the hand was cooled, however 4.5 minutes after local cooling was supplied, overall thermal comfort did drop a small amount (the subject remained comfortable). As soon as local cooling was removed, the subject's comfort went up again. This is because starting at neutral, cooling the hand made it locally too cool. Unlike the previous two examples, the subject did not feel warm at the outset. Adding hand cooling created significant hand vasoconstriction, and finger temperature decreased 19 K, from 35.6 to 16.7°C. Finger temperature became 7 K lower than the hand temperature, which decreased from 35.2 to 24°C. This affected overall comfort. Very much like the previous two tests, the forearm skin temperature only decreased slightly and gradually during the cooling, from 34.6 to 34°C. Finally, as with the hand warming test (Figure 15), we did not see a sensation change corresponding to the reversal of the skin temperature gradient.

In all these hand cooling tests (Figure 16 – 18), the changes in overall sensation and comfort are smaller than the changes in hand warming (Figure 15).

#### 4. DISCUSSION

The prediction of overall sensation based on finger temperature from our data is much higher ( $r^2 = 0.6$ ) than the prediction presented by Humphreys et al. ( $r^2 = 0.19$ , 1999). This is primarily because our data is from a laboratory study of 23 subjects in standard clothing, while Humphreys' data is from a field study of 200 office workers whose self-selected

clothing was variable. Humphreys observed finger temperature had two peaks with a strong peak around 35°C, and a weak peak around 26°C. When occupants felt cold, the predominant finger temperature was around 26°C; when occupants felt anywhere in the range of warm to hot, the predominant finger temperature was around 35°C. In our study, we found that when people were warm, the finger temperature is within 36 – 37°C. When cold, their finger temperature was between 20 – 27°C, with the majority below 25°C. Our finger temperatures may have been lower than Humphreys' when people felt cool because we measured our finger temperature on the dorsal side of the 4<sup>th</sup> finger (Figure 3), while the Humphreys' finger temperatures was measured between the pads of the thumb and the forefinger, and in addition the sensor was enclosed by fingers on both sides. On the warm side, our higher temperatures may have been due to the more extreme chamber temperatures producing the warm/hot sensations—these were appropriate for people in the 0.32 clo leotard, but because of them our subjects' hand surfaces were exposed to a warmer air temperature than Humphrey's. Humphreys' subjects were more heavily- and variably clothed, and during the course of their office work were probably experiencing close-to-neutral sensations.

Finger temperatures vary between individuals because their thermoregulatory setpoints differ. That is probably part of the reason that Humphreys' 200 office workers showed such a large variation in finger temperature for the same sensation. We hypothesized that for field studies it would be better to measure the finger-forearm gradient instead of the fingertip temperature, because there would be less variation in this measure among a group of individuals. However, our data show that the gradient only improves the prediction a small and insignificant amount over using the finger temperature alone. This may be due to the relatively small number of subjects and test conditions in our experiment.

These results might be useful for the following types of uses:

- Occupant surveys for evaluating building performance, or for thermal comfort research. Consistent with Humphreys' finding, adding finger temperature to air temperature measurement improves the correlation with thermal sensation and may explain the variation seen in survey results among individuals.
- Real time monitoring and prediction of occupant thermal state for environmental control purposes. The extremities are exposed and sensitive indicators of body thermal state. It may be possible to devise models for predicting the time that discomfort might occur, based on observed traverses through the (0 to-1.5) and (0 to 1.5) thermal sensation bands. Such models may involve detecting the reversal of finger-to-hand or finger-to-forearm gradients, or detecting the onset and cessation of finger temperature fluctuations. We have not developed these prediction models here because our observations came out of an experiment designed for other purposes, and do not provide a balanced data set for this purpose. Developing the models would require a further, focused investigation in which the variables of interest were tested systematically.

## 5. CONCLUSIONS

In this observational study, we have noted a number of effects which may be useful for various purposes:

- 1) Under warm conditions skin temperatures remain in a very narrow range of 35-37°C. Under cool conditions, skin temperatures are in a wide range. Finger skin temperature measurement is therefore a more sensitive indicator of body thermal state, thermal sensation, and comfort in the cooling region.
- 2) Finger temperature (30°C) and finger-forearm temperature gradient (0°C) are significant thresholds for overall thermal sensation. Above these values, the overall sensation is above -0.5 and cool-discomfort is not likely to happen. Below these values, the overall sensation is cooler than -0.5 and cool-discomfort becomes a possibility. These values might be helpful when operating HVAC or local environmental control systems to provide comfort. Because the gradient of finger-forearm is larger than the gradient of finger-hand, using the former promises to provide more accurate results than the latter.
- 3) When people are warm or hot, we saw a modest positive (fingers warmer) finger-forearm skin temperature gradient. The forehead-to-extremity gradient is a more sensitive indicator of warm or hot sensations, if the forehead measurement is available, as in [6].
- 4) When people feel cold, we saw a negative gradient. Under stable conditions, using the finger-forearm skin temperature gradient to predict overall thermal sensation does not significantly improve the prediction comparing using the finger temperature alone. However the crossover of the gradient may indicate a cooling of the overall body just below thermal neutrality. This crossover occurred around 30.4°C during cooling trends exemplified in Figure 8.
- 5) When a person's whole-body thermal sensation is near neutral (from -0.5 to 0.5), the finger temperature occurs in a wide range (28 to 36°C), and the finger-forearm temperature gradient between -2 to 2°C. This is in part due to the 1 to 2 K fluctuations in finger skin temperature occurring over time periods of a few minutes (2-5) caused by vasoregulation. It is also due to people's different thermoregulatory setpoints ranging around neutral. This means that under neutral conditions, both finger temperature and the finger-forearm temperature may not be good indicators of overall sensation. Fortunately environmental control action is usually not needed within the neutral range. The challenge is to detect a transition occurring out of this range. The strong correlation between thermal sensation and comfort within the range of thermal sensation 0 to -1.5 might be useful for this.
- 6) A changing temperature gradient from finger to forearm might reveal that a subject was currently feeling neutral but imperceptibly in the process of becoming cold.
- 7) Similarly, observing the onset or cessation of thermoregulatory fluctuations in skin temperatures may be a way of detecting whether the finger is within the thermoregulatory range where hand cooling can have an effect.
- 8) In our cool-environment tests, warming one hand brought about substantial improvement in thermal sensation, but was not sufficient to bring the overall comfort vote to a positive level. Hands are relatively small and when vasoconstricted cannot transfer an appreciable amount of heat to the body.

However, our tests represented fairly extreme environments as found in automobiles. It is likely that under milder conditions hand-warming might have had a more positive effect. For example, in an office environment, the level of body cooling is often small enough that only the extremities become cold, a situation that is exacerbated by their vasoconstriction. So the hands (and feet) may be the person's only sources of discomfort. In such a situation, warming the hand could directly remove the body's only source of discomfort and therefore have a strong effect on overall sensation and comfort. In our tests, we had few conditions that were sufficiently mild for us to observe this. This requires further investigation.

- 9) The improvement in overall sensation and comfort is larger for hand warming in cool environment (Figure 15) than for hand cooling in warm environment (Figure 16 – 18). The smaller effect is partially due to vasoconstriction of hands during our cooling tests, caused by the tests' rather cold (14°C) supply air. In our tests vasoconstriction set in quickly and reduced the subsequent cooling effect. For hand cooling to work, vasoconstriction must be carefully limited, and the cooling system must be designed to not induce hand vasoconstriction.

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