Thermal sensation and comfort models for non-uniform and transient environments:
Part III: whole-body sensation and comfort

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Abstract

A three-part series presents the development of models for predicting the local thermal sensation (Part I) and local thermal comfort (Part II) of different parts of the human body, and also the whole-body sensation and comfort (Part III) that result from combinations of local sensation and comfort. The models apply to sedentary activities in a range of environments: uniform and non-uniform, stable and transient. They are based on diverse findings from the literature and from body-part-specific human subject tests in a climate chamber. They were validated against a test of automobile passengers. The series is intended to present the models' rationale, structure, and coefficients, so that others can test them and develop them further as additional empirical data becomes available.

A) The whole-body (overall) *sensation* model has two forms, depending on whether all of the body's segments have sensations effectively in the same direction (e.g warm or cool), or whether some segments have sensations opposite to those of the rest of the body. For each, individual body parts have different weights for warm versus cool sensations, and strong local sensations dominate the overall sensation. If all sensations are near neutral, the overall sensation is close to the average of all body sensations.

B) The overall *comfort* model also has two forms. Under stable conditions, people evaluate their overall comfort by a complaint-driven process, meaning that when two body parts are strongly uncomfortable, no matter how comfortable the other body parts might be, the overall comfort will be near the discomfort level of the two most uncomfortable parts. When the environmental conditions are transient, or people have control over their environments, overall comfort is better than that of the two most uncomfortable body parts. This can be accounted for by adding the most comfortable vote to the two most uncomfortable ones.

Keywords: whole-body, overall, thermal sensation, thermal comfort, predictive model

1. Introduction

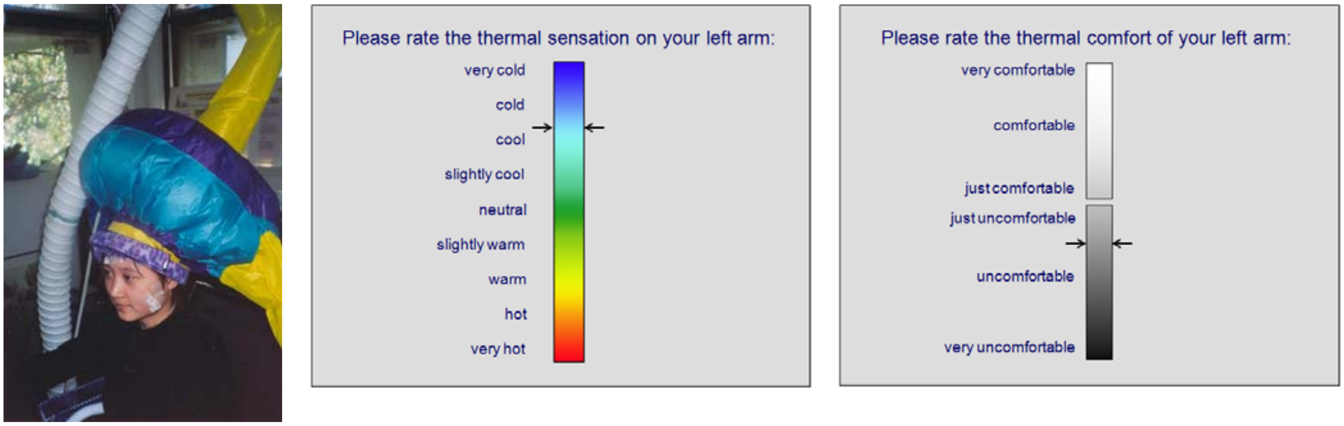
In both uniform and non-uniform environments, thermal sensation differs across the segments of the body. The differences may depend on many factors: how the body's local thermoregulatory mechanisms respond to the body's overall thermal state, asymmetry in clothing insulation and environment conditions around the body, the rate of change in the body's skin and core temperatures, and on the thermal sensitivity of the different parts involved. Although the thermosensitivity of individual body parts has been investigated in the past (e.g., [1,2]), there have been no studies of how people integrate the sensations from all their body parts when judging their whole-body thermal sensation.

Similarly, local comfort varies across the body, depending on the thermal state of the rest of the body. A cool head can be evaluated as either comfortable or uncomfortable based whether other body parts are warm or cool, or whether the body is warming or cooling. Other body parts (e.g. hand or back) will respond differently from the head. With different levels of comfort/discomfort experienced in different body parts, how do people feel overall? Is it based on the levels of local comfort or discomfort, or the number of body parts experiencing comfort or discomfort, or something else? There is almost no literature on how comfort is integrated in people's minds.

Nomenclature

S_{local}	thermal sensation for a local body part
$S_{overall}$	thermal sensation for whole-body
Interval	steps in sensation scale for judging influence of S_{local} on $S_{overall}$
$S_{overall\ bigger\ group}$	sensation of the bigger group of local warm (or cool) body parts
$S_{local,max}$	the warmest local body thermal sensation
$S_{local,third\ max}$	third-warmest local body thermal sensation
$S_{local,min}$	the coolest local body thermal sensation
$S_{local,third\ min}$	third-coolest local body thermal sensation
$S_{local,opposite}$	local sensation opposite (warm or cool) to a reference sensation
delta S_{local}	local thermal sensation difference from a reference value
$S_{overall,modifier}$	individual part's modification of the overall sensation
force (individual or combined)	effect of opposite local sensations on the sensation of the bigger group
a, b, c	regression coefficients

In 2001-2003 the authors conducted an extensive set of climate-chamber tests in which subjects had their local skin temperatures individually changed, while their local skin temperatures were measured and they were surveyed repeatedly for their local- and whole-body thermal sensation and comfort levels [3].



a. body-segment cooling or heating

b. thermal sensation scale

c. thermal comfort scale

Figure 1. Example apparatus for conditioning segment skin temperatures; survey scales.

The tests were designed to force local skin temperatures through a range of values. 19 body segments were tested[1]. The entire surface of a body segment was cooled or heated by using a sleeve of conditioned air that enclosed the segment (the head sleeve is shown in Figure 1a). Most of the tests involved cooling a body part under warm overall conditions, and then removing the sleeve and allowing the local part to warm up to its initial temperature. A smaller number of tests warmed a body part under cool conditions, followed by cooling recovery. Both types of tests produced data for analyzing cooling and warming transient responses. Measurements taken before and after the transient tests were used to analyze steady-state responses.

During the tests, the subjects occupied themselves with computer activities. Thermal sensation and comfort questionnaires appeared on the computer screen in intervals from 1 to 5 minutes after a local temperature was applied. During the transient in skin temperature, sensation and comfort was surveyed for the whole-body, the body part experiencing the transient, and a randomly selected second body part. The random part was surveyed so that subjects would not focus excessively on the part that was experiencing cooling or heating. When the part's local sensation reached a steady-state value (no further change), all body parts were surveyed for sensation and comfort.

The sensation scale (Figure 1b) is an extended ASHRAE 7-point scale, adding "very hot" and "very cold" to accommodate extreme environments: 4-"very hot", 3-"hot", 2-"warm", 1-"slightly warm", 0-"neutral", -1-"slightly cool", -2-"cool", -3-"cold", -4-"very cold". Figure 1c shows the two-sided comfort scale, in which the discomfort scale is balanced by an equivalent scale for comfort.

[1] head, face, neck, breathing zone, chest, back, pelvis, left and right upper arms, left and right lower arms, left and right hands, left and right thighs, left and right lower legs, left and right feet

The climate-chamber test program produced 347 sets of data representing steady-state conditions, and 3568 representing transients. Each data set contains physiological data (skin and core temperatures) and subjective responses.

An additional 1600 transient datasets were obtained from validation tests done in an automobile test facility. A car was positioned in a cold or hot wind tunnel to simulate winter or summer conditions (-23 to 43ºC). Instrumented subjects got into the car, voted their sensation and comfort for local parts and the whole-body, and then turned on the heater or air-conditioner while voting their sensation and comfort every 2 minutes for 40 minutes. The measurement locations and survey scales were the same as those used in the climate chamber tests, but the subjects wore normal winter and summer clothing.

The methods and experimental results of these tests have been previously published: the physiological responses to local heating and cooling [4,5], thermal sensation and comfort under uniform conditions [6], and thermal sensation and comfort under non-uniform conditions [7]. This present series of papers (Parts I, II and III) completes the project by describing the predictive models that were developed from the experimental results. Part III contains two sections: (A) for the whole-body sensation model, and (B) for the whole-body comfort model. Note that only the subjective responses in the datasets (local and overall sensation and comfort) are used in developing these models.

A: Whole-body sensation model

2. Background

Most of the existing research on thermal sensation was conducted in uniform thermal conditions [8,9,10,11], so most predictive models apply to uniform environments [10,12,13,14]. Fiala's whole-body thermal sensation model [14] is obtained from analysis of experiments in the literature. It addresses both stable and transient conditions, but not non-uniform environments.

Hagino and Hara [15] obtained subjects' thermal sensation votes for the head, upper arm, thigh, and foot in stable automobile environments under several combinations of air-conditioner discharge temperature and solar load. They determined the weights of the local sensation votes in predicting overall sensation. The weights are specific to their particular combinations of tests. There have been no other studies on how the body determines whole-body sensation based on local sensations.

3. Experimental basis for the model

By examining all the individual datasets, patterns could be identified that could serve as the basis for models. Models were tested and modified to reduce residuals in the predictions. The models based on observed psychophysical effects and some posited explanations for them. The experimental basis for the model is presented below, first for uniform and stable environments and second for environments with local body cooling/heating.

3.1 Uniform tests

These tests are described in [3,6]. The subjects were exposed to uniform thermal environments, but because clothing and physiology are inherently non-uniform across the body, there are significant differences in sensations among the subjects' local body parts. Overall sensation tends to be close to the most stressful (cold or hot) local sensations, following a "complaint" pattern.

Table 1 gives results for 5 thermal conditions. The circles show the warmest local sensations in warm environments (normally the head and hands), and the coldest local sensations in cool environments (normally the hands, arms, and feet). The overall sensations (also circled) follow the local extreme sensations, which might be seen as a complaint pattern where complaints dominate the overall sensation. Under a neutral environment, the overall sensation does not follow the complaint pattern. It is noteworthy that the head region (breathing zone, head, neck, and face) has the lowest cool perception in the cold environment.

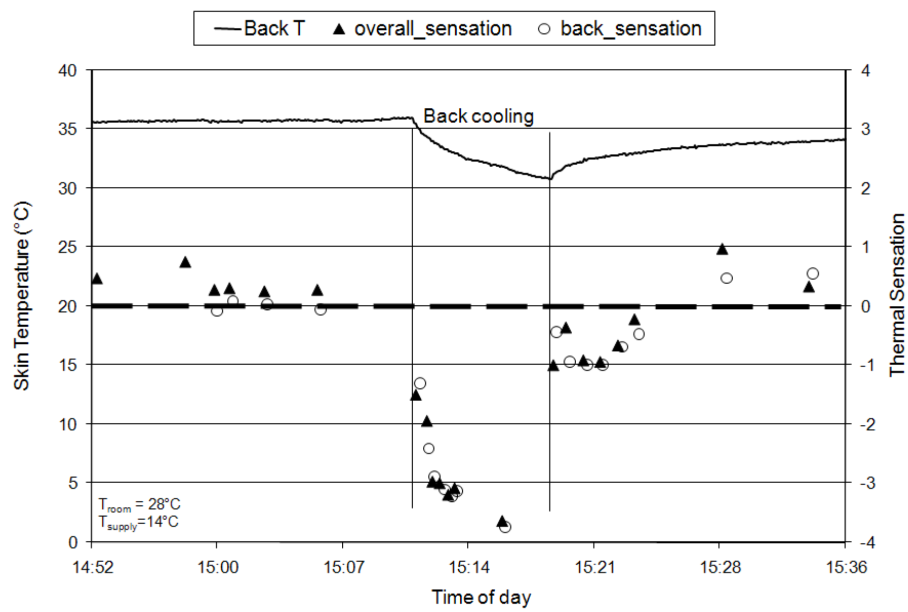
Table 1. Local and overall thermal sensations

	cold (5 tests)	sl. cool (6 tests)	neutral (8 tests)	sl. warm (3 tests)	hot (10 tests)
overall	-3.1	-1.0	-0.1	1.0	2.5
head	-1.4	-0.7	0.1	0.9	2.3
face	-1.4	-0.6	0.4	0.9	2.3
breath	-0.7	-0.1	0.2	0.5	1.6
neck	-1.1	-0.6	0.0	0.8	1.9
chest	-2.2	-0.6	-0.1	0.8	1.8
back	-1.6	-0.9	-0.1	0.7	1.4
pelvis	-1.7	-0.6	0.0	0.5	1.3
arm	-3.3	-0.8	0.2	0.7	1.6
hand	-3.5	-0.6	0.3	0.7	1.9
leg	-2.6	-1.1	0.0	0.6	1.7
foot	-3.3	-1.7	-0.8	0.5	0.8

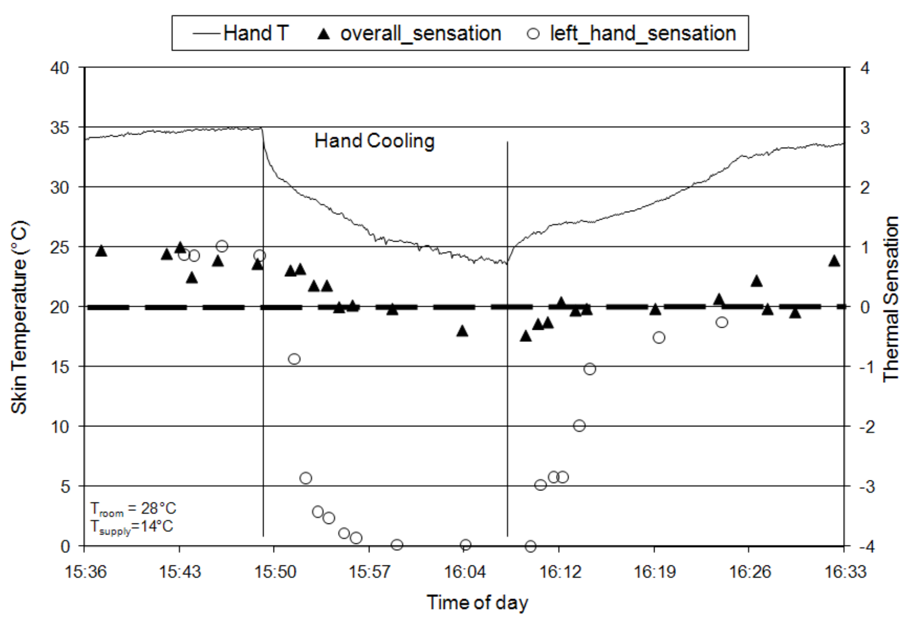
3.2. Non-uniform tests.

Non-uniform tests and results are described in [3-5,7]. To experimentally simulate non-uniform environments, we cooled/heated various body parts while the whole body was exposed to warm or cool environments. Figure 2 shows the time series of two such tests, in which the back and the hand were first cooled and then allowed to recover. The two tests differ in the effect this treatment has on the whole body thermal sensation. In Figure 2a, the overall sensation closely followed the local back sensation during both cooling and recovery. The hands (Figure 2b) and feet have much less impact on overall sensation even though the level of cooling, as measured by local sensation, is the same. During hand cooling and recovery, the hand itself felt very cold while the overall sensation only dropped from slightly warm to neutral.

From examining all the tests, we found that the back is one of three 'dominant' body parts (back, chest, and pelvis) that strongly influence overall thermal sensation. The brain appears to pay more attention to cooling changes in these parts near the body core than to changes in parts that can be physiologically isolated (the extremities), and/or are commonly exposed to environmental changes due to lack of clothing (face and hands). This distinction proved important in developing the prediction model.



a. Back cooling and recovery



b. Hand cooling and recovery

Figure 2. Overall and local sensations during local body part cooling and recovery

During the transient part of the tests, the value of local sensation is affected by the rate of temperature change, as described in [3,7]. Our local sensation model (described in Part I of this series) predicts sensation using skin and core temperatures and their time derivatives. To avoid double counting transient effects, we did not include a local-sensation time derivative as an input to the overall sensation model. Validation tests with the highly transient data from the automotive tests appear to support that the model works for both stable and transient conditions (described below in the model validation section).

4. Development of the overall sensation model

The model addresses two different conditions separately. When there is *no* body part that feels *significantly* opposite to the other body parts (e.g. one body part feels cold while other body parts feel warm) we call it, for lack of an equally exact alternative term, the 'no-opposite-sensation' condition. When there are body parts that feel significantly opposite to the rest of the body parts, we call it the "opposite-sensation" condition.

4.1. 'No-opposite-sensation' model

This model applies in the conditions (i) uniform sensations, (ii) local body part warming when the whole body feels warm, (iii) local body part cooling when the whole body feels cool, or (iv) slight feeling of local cool/warm when the rest of the body parts feel warm/cool. It does *not* address the conditions (v) significant local warming while the whole body is cold, or (vi) significant local cooling while the whole body is warm.

Defining n^- to represent the number of local body parts with negative sensations (cool side of the thermal sensation scale), n^+ to represent the number of local body parts with positive sensations (warm side of the thermal sensation scale), and 1 or –1 as the thresholds for "significant", the 'no opposite-sensation' condition is determined by one of the following four conditions ($n^- + n^+$ = total number of body parts):

$n^- = 0$ (a)
$n^+ = 0$ (b)
$n^- > n^+$ and $S_{local,\,max} \leq 1$ (c)
$n^+ > n^-$ and $S_{local,\,min} \geq -1$ (d)

Table 1 shows that integration of local sensations into overall sensation is different near the neutral zone than it is warmer or cooler than the neutral zone, defined as $|S_{local}| \geq 2$. The following sections describe the modeling of these two zones separately.

4.1.1. High levels of thermal sensation (complaint model, outside of shaded zone in Figure 3)

Local sensations beyond neutral ($|S_{local}| \geq 2$) on the sensation scale generate the equivalent of a complaint in the mind, strongly influencing the whole-body sensation. Through trial and error we found that a weighted average of the most extreme sensation plus the third-most-extreme sensation effectively determines $S_{overall}$ for both the warm and the cold sides. The regression results are given in Eq. (1) and (2), and the actual votes vs. predicted votes are shown in Figure 3 (at the upper and lower ends of the un-shaded section).

- *Warm side*: Use the third-most-extreme thermal sensation as the determining criterion. When $S_{local\ third\ max} \geq 2$ (meaning there are at least three local sensations above 2)

$$S_{overall} = 0.5\ S_{local,max} + 0.5\ S_{local,third\ max} \qquad \text{Eq. (1)}$$

- *Cool side:* When $S_{local\ third\ min} \leq -2$ (meaning there are at least three local sensations below –2)

$$S_{overall} = 0.38\ S_{local,min} + 0.62\ S_{local,third\ min} \qquad \text{Eq. (2)}$$

When the most extreme body parts include two hands or two feet, only one hand or one foot is counted.

4.1.2. Low levels of thermal sensation (gradual model, shaded zone in Figure 3)
As local sensations move towards neutral, extreme sensations begin to lose their strong influence on overall sensation. The complaint-driven process becomes less obvious, and the overall sensation approaches the mean of all local sensations. In order to avoid a discontinuity between the two methods (complaint-based or mean-based), we gradually add increasingly less-extreme local body sensations to the extreme ones to obtain an average that becomes the overall sensation. This is termed the 'gradual model', defined below for the warm and cool sides. A counting interval is used to determine how many less-extreme local sensations should be included.

- *Slightly warm sensations:*

When $S_{local\ third\ max} < 2$, first rank the local sensations in descending order:

$$i=0,1,2,\ldots n^{+}, \quad S_{local,0,max} > S_{local,1,max} > S_{local,2\ max},\ldots > S_{local,i\ max}\ldots$$

Dividing the sensation scale from ($S_{local} = 2$) to ($S_{local} = 0$) into equal intervals by the number of body parts (counting hands and feet as only two body parts):

Interval = 2 /(total body parts – 2) (in sensation scale units)

If $S_{local,i,max} > 2 - \text{Interval} \times (i-2)$

$$S_{overall} = \text{average}\ (S_{local,0,max},\ S_{local,1,max},\ S_{local,2,max},\ldots\ S_{local,i\ max}) \qquad \text{Eq. (3)}$$

- *Slightly cool sensations:*

When $S_{local\ third\ min} > -2$, first rank the local sensations in ascending order:

$$i=0,1,2,\ldots n^{-}, \quad S_{local,0,min} < S_{local,1,min} < S_{local,2,min},\ldots < S_{local,i\ min}\ldots$$

Interval = 2 /(total body parts – 2) (in sensation scale units)

If $S_{local,i,min} < -2 + \text{Interval} \times (i-2)$

$$S_{overall} = \text{average}\ (S_{local,0,min},\ S_{local,1,min},\ S_{local,2,min}, \ldots\ S_{local,i\ min}) \qquad \text{Eq. (4)}$$

The actual votes of 'no opposite-sensation' situations are compared with predictions of the three-piece model in Figure 3. The model is effective, with an overall R^2 of 0.94.

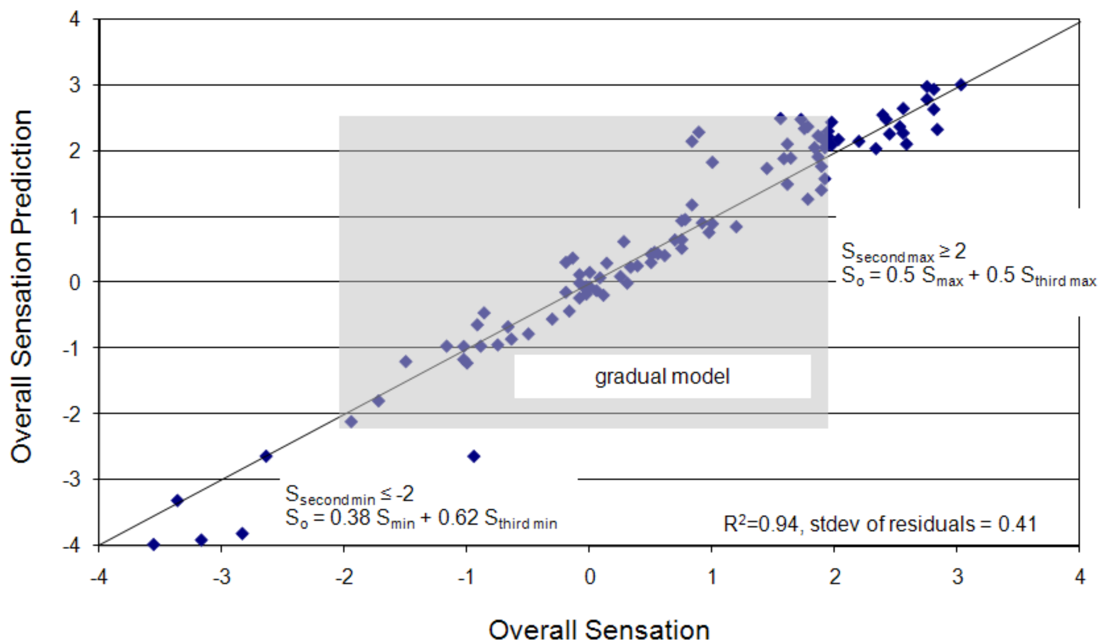


Figure 3. Overall sensation model - no opposite-sensation

4.2. 'Opposite-sensation' model (asymmetrical conditions)

When one or more body parts experience local cooling when the whole body feels warm, or local heating when the whole body feels cool, we consider these local sensations as 'opposite sensations'. The opposite sensation needs to be strong enough to create an impact on the whole-body sensation. The threshold is ±1. A body part has an 'opposite sensation' if its $|S_{local}|$ is greater than one. There is one exception: when one of the three dominant parts (chest, back, and pelvis) is slightly cool, then the S_{local} threshold is either less than *or* equal to -1. This distinction becomes important when sensation input data is in integer format, as in the surveys used in the tests done to validate this model (described later).

The model creates two groups for warm and cool sensations. Whichever group has more body parts ('bigger group') represents the sensation for the whole body, and the smaller group represents the 'opposite' sensation. To obtain the sensation for the bigger group, we use the 'no-opposite sensation' model as above. Body parts with sensations = 0 belong to the bigger group, and if the two groups have identical size, the positive sensation group is considered the bigger group.

The smaller group of 'opposite-sensation' body parts acts to pull the bigger group's sensation towards them. Each body part of the opposite-sensation group can be envisioned as creating an 'individual force', the largest one or two of which comprise a 'combined force' that is used to modify the bigger group's overall sensation.

The following two sections describe a) how to calculate each individual force, and b) how to combine them.

4.2.1. Calculation of individual forces

Individual forces are calculated using Eq. (5). The coefficients a, b, and c are from regression using our measured data (Table 2).

$$\textit{Individual force} = S_{overall,modifier} = a\,(\textit{delta}\ S_{local} - c) + b \qquad \text{Eq. (5)}$$

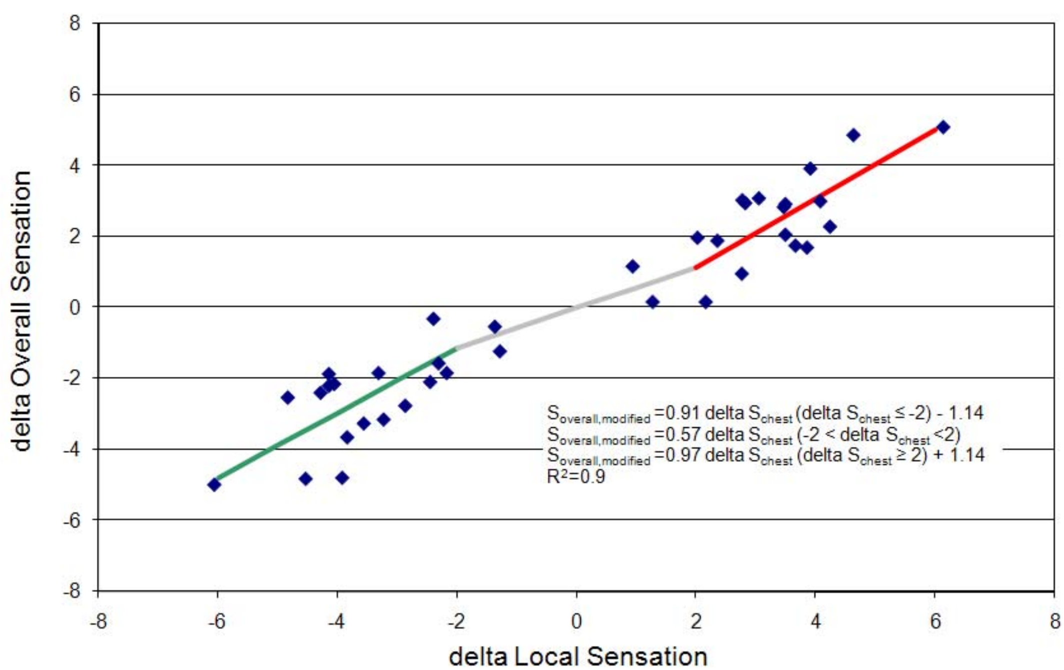
delta S_{local} is the difference in local sensation from the beginning to end of a local cooling/heating application, and $S_{overall,modifier}$ is the effect of that local sensation change on overall sensation. The slope coefficient "a" quantifies the ability of each body part to influence overall sensation, and 'b' and 'c' are linear regression coefficients. The influence of local sensation change on overall sensation change is shown by three examples in Figure 4, and the Equation 5 coefficients for all body parts are presented in Table 2.

Comparing people's thermal sensation responses, we found three features common for all body parts:

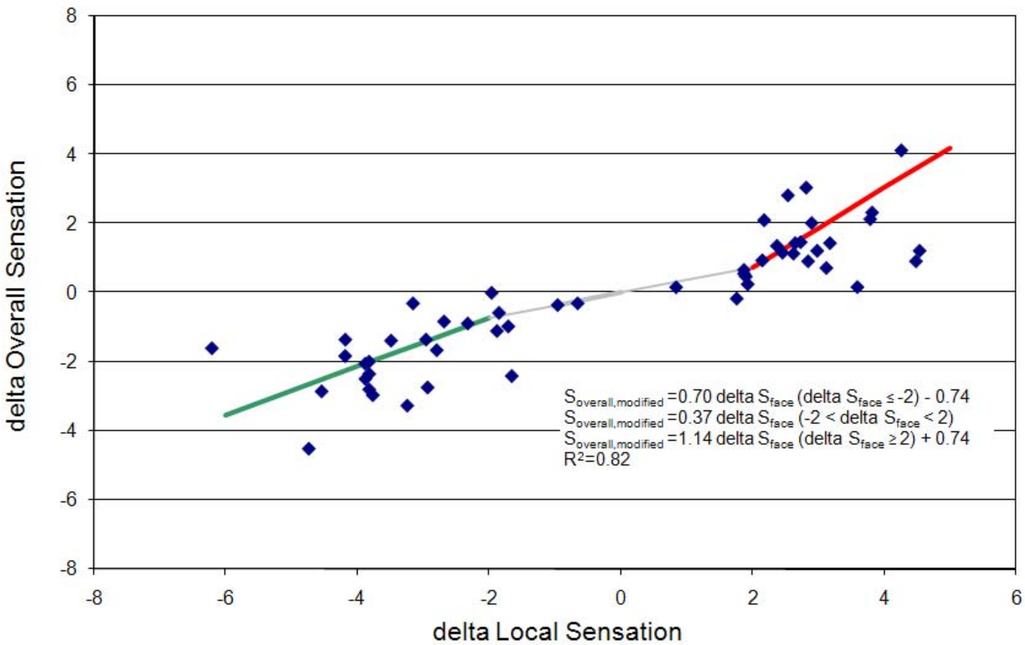
- Heating or cooling the dominant body parts *chest*, *back*, and *pelvis* has more effect on overall sensation than heating or cooling the hands and feet. This is seen in Table 2 and Figure 4a and 4c by the bigger slope 'a' for the chest than the hand.
- Some body parts differ in their warm and cool thermal sensitivity. For example, the *face* in Figure 4b and Table 2 has a bigger slope 'a' for warming than for cooling.
- The magnitude of the (local-overall) sensation difference affects the impact on overall sensation. Piecewise regression picks this up, allowing us to assign larger coefficients for more extreme opposite local sensations ($|\textit{delta}\ S_{local}| > 2$). In Figure 4, the slope in the middle is less steep than the slopes of the two end pieces. This is true for all the body parts in Table 2, seen in the smaller regression coefficient 'a' in the middle section than the other two sections.

Table 2. Single-body-part 'opposite-sensation' model coefficients a, b, c for Equation (5), obtained by 3-piece regression.

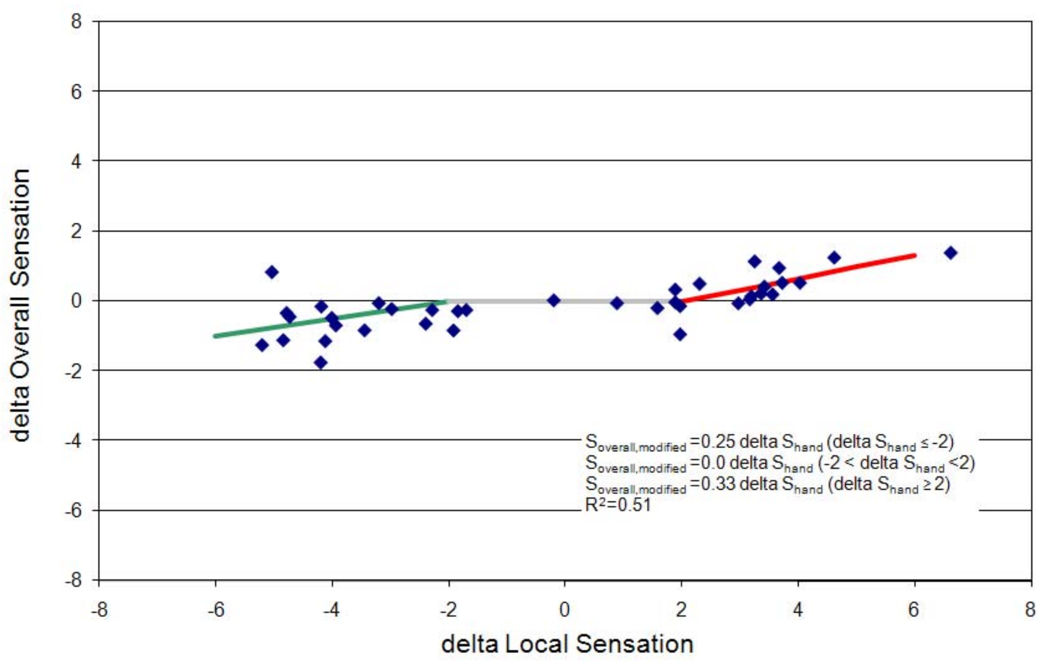
body part	*delta* $S_{local} \leq -2$			$-2 <$ *delta* $S_{local} < 2$			*delta* $S_{local} \geq 2$			R^2
	a	b	c	a	b	c	a	b	c	
head	0.54	-1.1	-2	0.50	0	0	0.4	1.1	2	0.89
face	0.70	-0.74	-2	0.37	0	0	1.14	0.74	2	0.82
breath	0.27	-1	-2	0.51	0	0	0.39	1	2	0.78
neck	0.65	-0.92	-2	0.46	0	0	0.63	0.92	2	0.81
chest	0.91	-1.14	-2	0.57	0	0	0.4	1.14	2	0.90
back	0.91	-0.92	-2	0.46	0	0	0.2	0.92	2	0.62
pelvis	0.94	-0.64	-2	0.32	0	0	0.6	0.64	2	0.89
upper arm	0.43	-0.56	-2	0.28	0	0	0.4	0.56	2	0.73
lower arm	0.37	-0.73	-2	0.38	0	0	0.3	0.73	2	0.67
hand	0.25	0	-2	0	0	0	0.1	0	2	0.51
thigh	0.81	-0.6	-2	0.3	0	0	0.4	0.6	2	0.73
leg	0.7	-0.59	-2	0.29	0	0	0.4	0.59	2	0.71
foot	0.50	0	-2	0	0	0	0.6	0	2	0.45



a. Chest



b. Face



c. Hand

Figure 4. Piecewise regressions for chest, face, and hand showing change in overall sensation due to change in local sensation

4.2.2. Adding individual forces to the bigger-group overall sensation to get the final overall sensation

For cooling, if one or more of the multiple parts having an opposite sensation is a dominant body part (chest, back, and pelvis), the overall sensation $S_{overall}$ will be the local sensation of the part with the largest absolute value (the strongest cool sensation).

For heating, or for cooling if there is no dominant body part among the multiple body parts, we obtain the 'individual force' which will modify the opposite sensation of the bigger group as follows. Use Table 2 to obtain the strongest and the second strongest individual forces of all the body parts. Combine these as follows to get the 'combined force':

$$[\textit{combined force}] = [\max S_{overall,modifier} + 10\% \text{ of second max } S_{overall,modifier}] \quad \text{Eq. (6)}$$

We obtained the 10% weight for the second most extreme body part by trial and error using both the UCB and automotive data sets. If there is no second opposite body part, the second maximum $S_{overall,modifier}$ is zero.

We then obtain the sensation of the bigger group, $S_{overall,bigger\text{-}group}$, from the 'no-opposite-sensation' model (Figure 3). This bigger group sensation is added to the [combined force] to yield the final overall sensation:

$$S_{overall} = S_{overall,bigger\text{-}group} + [\textit{combined force}] \quad \text{Eq. (7)}$$

5. Summary of the overall sensation model

This section summarizes the three steps of the overall sensation model, and provides a flow chart for computer programming.

Step 1. Determine whether there are opposite sensations

Separately sum the numbers of body parts with negative local sensations (n^-) and positive local sensations (n^+). The group with more body parts is termed the bigger group, and the other is termed the smaller group. Body parts with sensations = 0 belong to the bigger group. If the two groups have identical size, the positive sensation group is considered as the bigger group.

If the smaller group is zero (n^-=0 or n^+=0), 'no opposite sensation' exists. *Go to step 2* to calculate overall sensation for the condition 'no opposite sensation' as seen in Figure 3.

If both are not zero, check the local sensations in the smaller group of (n^-) and (n^+). When the absolute values of all local sensations in the smaller group are less and equal to *one* ($|S_{local\ opposite}| \leq 1$), *and* greater than one ($S_{local\ opposite} > -1$) for cooling any of the three dominant body parts (chest, back, and pelvis), 'no opposite sensation' exists. *Go to step 2* to calculate the overall sensation based on the 'no-opposite-sensation' model.

Otherwise, 'opposite sensation' exists. *Go to step 3* to calculate the overall sensation based on the 'opposite-sensation' model.

Step 2. Overall sensation when there is 'no opposite sensation'

The model is presented in Figure 3 and in Section 1 above. If the most extreme sensations (first, second, and third extremes) include two hands or two feet, only one hand or foot is counted, and the next extreme is considered.

Step 3. Overall sensation when there are 'opposite sensations'

A. Consider the bigger group as a group with 'no opposite sensation', apply step 2 (above) to it to get the overall sensation for this bigger group, $S_{overall,\ bigger\text{-}group}$. .

B. Add the local opposite forces from the smaller group to the overall sensation of the bigger group, $S_{overall,\ bigger\text{-}group}$ as follows:

If any of the dominant body parts has a sensation ≤ -1 (is cool or cold), then the whole-body sensation equals the local sensation of the coldest dominant body part: $S_{overall} = S_{local}$.

Otherwise, individually calculate local 'opposite sensation' forces ($S_{overall,modifier}$) for all the 'opposite sensation' body parts, using regression coefficients in Table 2. Use Eq. 6 to get the *combined force*.

Next add the *combined force* to the bigger group overall sensation to get the whole-body sensation. Figure 5 is a flow diagram of this three-step process.

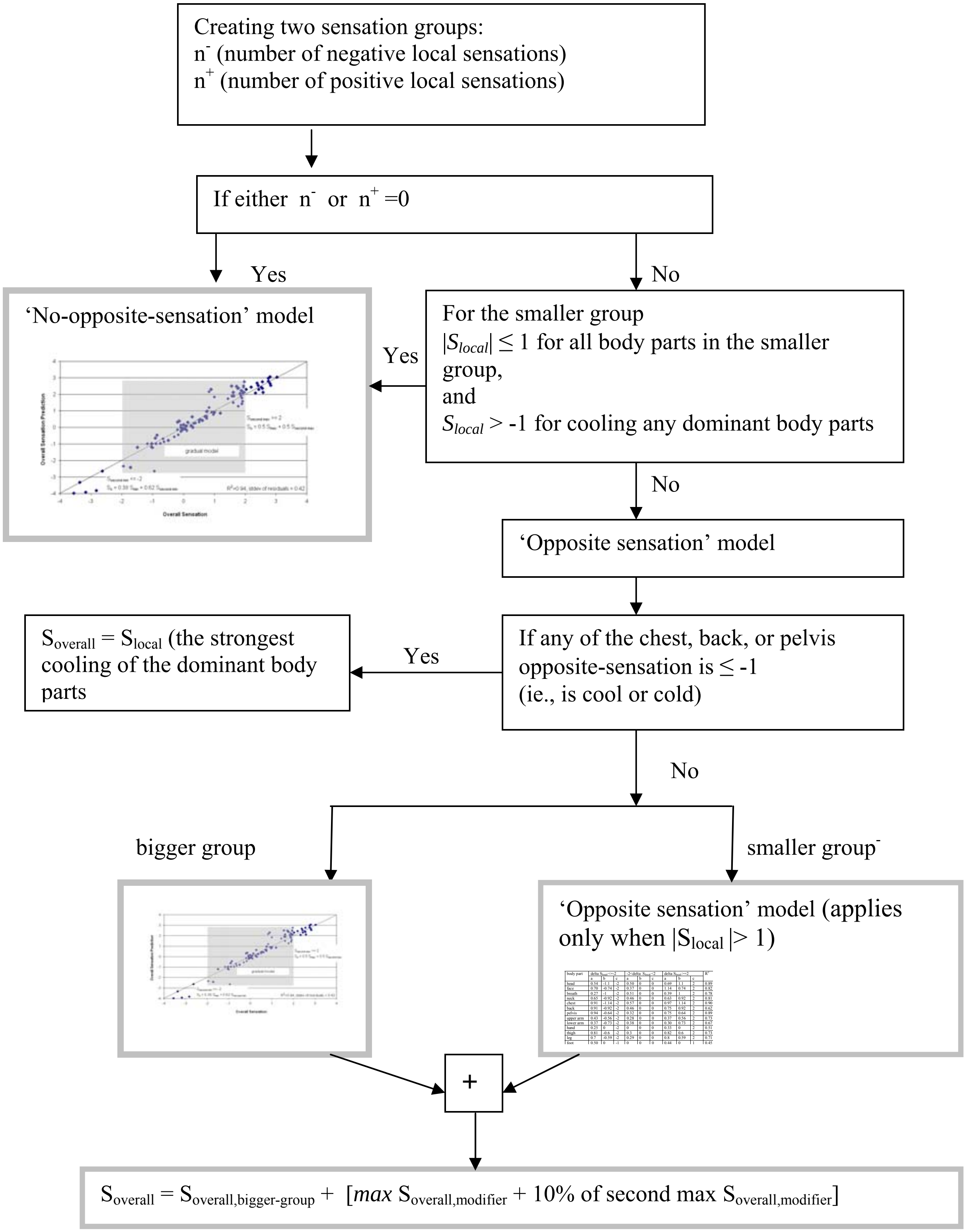


Figure 5. Flow-chart of the whole-body sensation model

6. Overall sensation model validation

The overall sensation model is validated by experimental data from the automobile company tests. These validation data are divided into two groups representing uniform and non-uniform environments.

6.1 When there is no opposite sensation

Data for this were collected in the automotive tests after the subjects went inside the car and before they turned on its air-conditioning system. At this time in the tests, the environment was uniform, so there were no strong opposite sensations. The test data provide local sensations for individual body parts, and the coincident whole-body sensation. Figures 6 compares these data to the overall sensation model predictions.

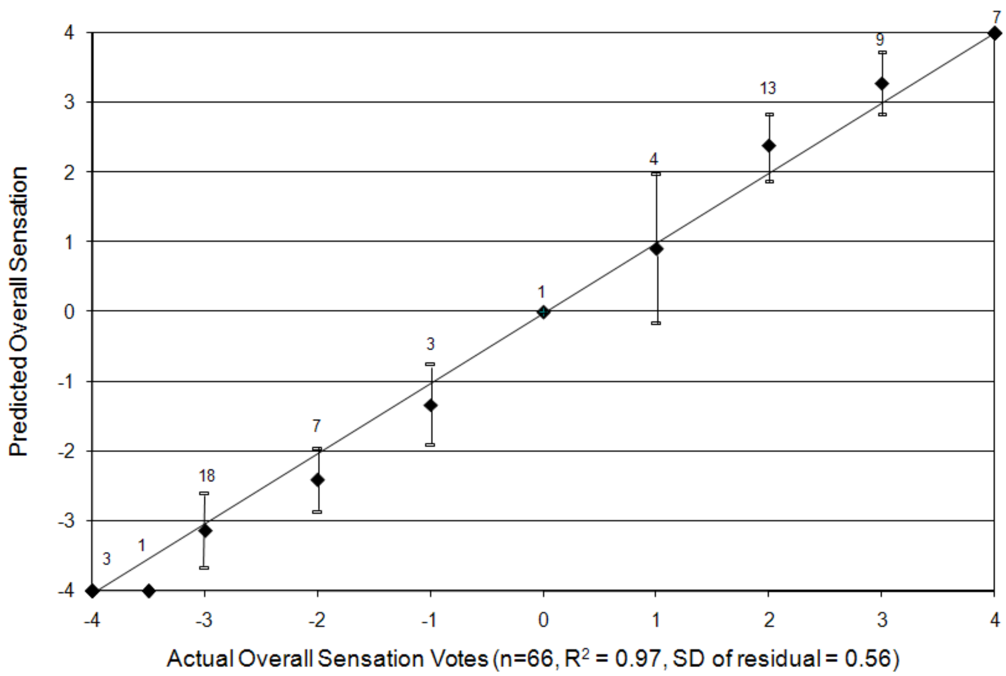


Figure 6. Measured vs. predicted overall sensation under uniform ('no-opposite sensation') environments (data from automobile tests, obtained before the subjects turned on the air-conditioning in the car). Numbers indicate number of votes.

6.2 When there are opposite sensations

These local- and whole body sensation votes were obtained after the subjects started the air-conditioning in the car to warm or cool themselves. So the data were obtained during highly asymmetrical conditions, and there were body parts with opposing sensations. The validation results below compare the model's overall sensation predictions with the measured data. The summer condition (after the subjects turned on the cooling system in the car) is presented in Figure 7, and the winter condition (after the subjects turned on the heater in the car) is presented in Figure 8.

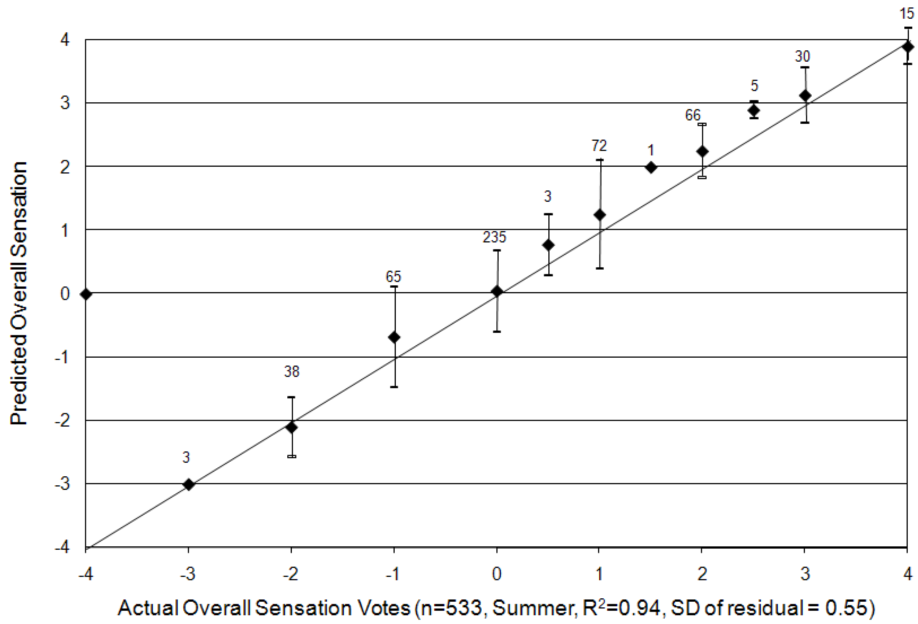


Figure 7. Actual overall sensation votes vs. predictions in non-uniform ('opposite-sensation') environments (data from automotive summer condition tests, obtained after the subjects started the cooling in the car)

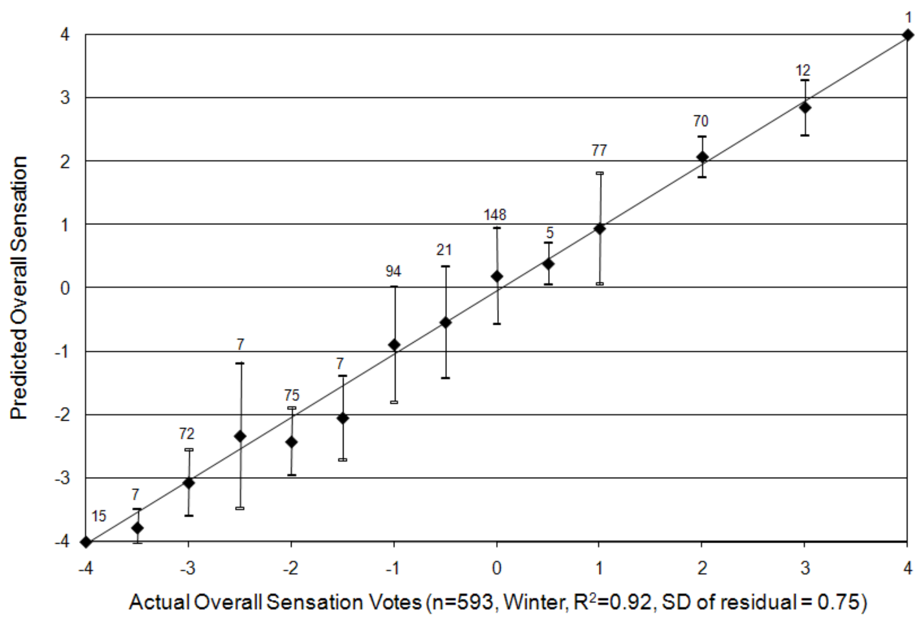


Figure 8. Actual overall sensation votes vs. predictions in non-uniform ('opposite-sensation') environments (data from automotive winter condition tests, obtained after the subjects started the heater in the car)

The opposite-sensation model predicts the actual votes well. Because the automotive data were obtained under highly transient conditions, the validation suggests that the comfort model applies to both transient and asymmetric (spatially non-uniform) conditions.

7 Further validations

Yu [16] tested subjects under stable (20, 23, 26ºC) and thermally stratified environments (1, 3, 5K). The local sensations of the body parts vary substantially (Table 3). As in the UCB tests from which the overall sensation model was developed, the overall sensation is close to that of the extreme body parts (circled) in non- neutral environments. The extreme parts are the hands and feet in cool environments, and the trunk in warm environments.

Table 3. Local and overall thermal sensations, ASHRAE 7-point scale (Yu [16])

	cool (20ºC, 0.73 – 0.77 clo) air temperature stratification K			neutral (23ºC, 0.89 - 0.9 clo) air temperature stratification K	warm (26ºC, 0.8 – 0.85 clo) air temperature stratification K		
	1	3	5	1	1	3	5
overall	-2.3	-2.1	-2.0	-0.3	1.1	1.2	1.3
head	-1.2	-0.9	-0.8	-0.1	0.3	0.5	0.5
chest	-1.5	-1.1	-0.8	0.0	0.8	1.0	1.2
back	-1.5	-1.0	-0.9	0.1	0.9	1.0	1.3
stomach	-1.1	-1.0	-0.8	-0.1	0.8	1.0	1.1
r. arm	-1.9	-1.7	-1.7	0.0	0.8	0.8	0.8
l. arm	-1.8	-1.7	-1.7	0.0	0.8	0.8	0.8
r. hand	-2.5	-2.3	-2.1	-0.5	0.3	0.5	0.5
l. hand	-2.4	-2.2	-2.1	-0.5	0.3	0.5	0.5
r. thigh	-1.5	-1.2	-1.1	-0.2	0.6	0.9	1.0
l. thigh	-1.5	-1.2	-1.1	-0.2	0.6	0.9	1.0
r. calf	-2.0	-1.8	-1.8	-0.8	0.5	0.5	0.5
l. calf	-2.0	-1.7	-1.7	-0.8	0.6	0.6	0.6
r. foot	-2.3	-2.2	-2.2	-1.0	0.6	0.6	0.6
l. foot	-2.3	-2.2	-2.2	-1.0	0.6	0.6	0.6

The overall sensation model was validated using all of Yu's 15 tests. The low residuals indicate that the model predicts the data very well (Table 4).

Table 4. Comparison of overall sensation votes, model versus Yu's actual votes.

	air temperature stratification K	actual votes	model predictions	residual
Neutral (obtained by subjects adjusting clothing)	1	-0.50	-0.48	0.02
	3 (20ºC)	-0.60	-0.52	0.08
	5	-0.45	-0.49	-0.04
	1	-0.40	-0.48	-0.08
	3 (23ºC)	-0.46	-0.42	0.04
	5	-0.26	-0.34	-0.08

	1	0.02	-0.03	0.05
	3 (26ºC)	0.01	0.15	-0.05
	5	0.10	0.10	0.00
cool	1	-2.30	-2.30	0.00
	3 (20ºC)	-2.20	-2.05	-0.15
	5	-2.10	-1.85	-0.25
warm	1º	1.14	0.85	0.29
	3 (26ºC)	1.20	1.24	-0.04
	5	1.10	0.99	0.11

8. Discussion

The initial 2003 version of this model [3] underpredicted overall sensation when conditions were far from neutral. The model here has been changed in two ways: 1) instead of calculating the overall sensation based on weighting factors from every body part, now only the two most extreme body parts used when local body sensations are far from neutral. 2) The 2-section piecewise linear regressions used for the previous model are now replaced by 3-piecewise linear regressions for calculating the weighting factors, increasing the coefficients when the difference between local sensation and overall sensation is great, as shown in Figures 4 a, b, c.

B: Whole-body comfort model

9. Background

Overall comfort has traditionally been quantified using thermal sensation. ASHRAE Standard 55 [17] and ISO Standard 7730 [18] define dissatisfaction, or discomfort, as sensation votes outside of –1 'slightly cool' and +1 'slightly warm'. This approach does not apply to local body segments, or to asymmetrical or transient thermal environments. For these, the link of sensation to comfort depends in a complex way on the state of all body segments.

The link between local comfort votes and overall comfort is more direct. For stable asymmetrical environments near thermal neutrality, Pellerin et al. [19] found a significant link between the number of uncomfortable local body parts and overall discomfort, or dissatisfaction with the thermal environment. They found that as long as no more than 2 body parts felt uncomfortable, less than 30% of their subjects were uncomfortable or dissatisfied. They did not quantify the levels of overall comfort, either as associated with the number of body parts or with levels of local comfort. They suggest that overall cold discomfort is driven by discomfort of local parts, while warm discomfort is whole-body in origin.

10. Development of the overall comfort model

As with the whole-body sensation model, the approach to developing the model was to closely examine individual responses observed in our human subject tests. Reference [3] gives numerous examples of such effects and suggests explanations for them. Rule-based models seemed to work better for comfort and starting from that, the process was to try variations of the rules and observe the residuals. The initial model was developed using the chamber study results. We found we could base overall comfort on local comfort only, without needing to include local sensation information. We then applied our model to the automotive test results, which had been obtained using the same measurements and scales but in considerably different conditions. The automotive residuals suggested two more modifications that were adopted in the final model. Validations followed using both datasets, plus a third study from the literature.

10.1. Comfort complaint-driven feature.

Table 5 shows the averages of local and overall comfort for each of the five sensation categories shown in Table 1 (neutral, slightly warm, slightly cool, hot, cold) from the UC Berkeley tests.

Table 5. Local and overall thermal comfort

	cold (5 datasets)	sl, cool (6 datasets)	neutral (8 datasets)	sl. warm (3 datasets)	hot (10 datasets)
overall	-2.8	-0.1	1.6	-0.4	-1.4
head	0.5	0.4	1.1	-0.3	-1.7
face	0.6	0.4	-0.3	-0.3	-1.7
breath	1.4	0.5	0.2	0.4	-0.7
neck	0.5	0.4	1.1	-0.3	-1.3
chest	-0.3	0.4	1.2	0.6	-1.3
back	-0.7	0.2	1.1	0.5	-1.0
pelvis	-0.3	0.2	1.2	0.7	-0.7
arm	-2.5	0.3	1.0	0.3	-1.2
hand	-3.0	0.5	1.3	-0.5	-1.2
leg	-1.7	0.5	1.3	0.5	-0.9
foot	-2.4	-0.1	0.0	1.0	-0.3

Overall comfort and the two or three most uncomfortable votes are circled in each case. From these circled data, we see that the overall comfort is close to the most uncomfortable vote (or the most uncomfortable two votes), although there may be other local comfort votes less comfortable or on the comfortable side. This complaint—driven feature also appeared in the more extreme portions of the overall sensation model (outside the gray region in Figures 3 and 4). The least comfortable local votes have the most significant influence, and we found that for the UCB data, averaging the two least comfortable votes gave the best prediction. As with the sensation model, two cold feet or two cold hands are counted as one.

10.2. Higher comfort in transient environments and with personal control

When we applied this proposed model to the automotive test data, the subjects perceived higher overall comfort levels than our predictions (one example is shown in Figure 9).

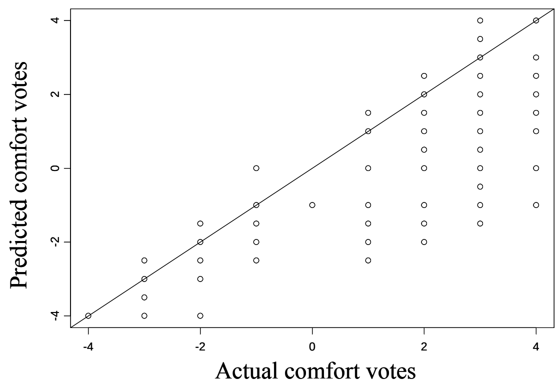


Figure 9. Under-estimation for Automotive data

We propose two causes for the differences: (1) automotive subjects had control over their thermal environments by adjusting the air-conditioner inside the vehicle, while the UC Berkeley subjects experienced local and chamber temperatures imposed by a researcher. Being able to control their own thermal environments may make the automotive subjects feel more positive about their overall thermal comfort, an effect observed in other research [20,21]. (2) The car environments in the automotive tests were transient because the subjects adjusted the air-conditioning as needed during the entire tests, while the UCB data were from stable condition tests. Under a stable condition, any local discomfort is felt constantly. In a transient condition, the uncomfortable body parts and the levels of the discomfort vary, so the feeling of local discomfort may be less definite. In addition, as the transient swings from too warm to too cold, the two types of discomfort may overcome each other.

In order to accommodate the more comfortable votes from automotive test data, we add the *best* comfort vote, together with the two most uncomfortable votes, to calculate the overall comfort during transients and when people have control over their environments. The best comfort vote is used because under asymmetrical environments or during transient processes, the most comfortable feeling might be the most recognizable, and thus influence the overall outlook.

This idea is related to an idea from Cabanac [22]: "the maximization of pleasure, and the minimization of displeasure, not only leads to useful behavior, but is also the answer to motivation conflicts". The idea is experimentally supported in psychological research [23]. If the most extreme feelings on both sides are important in making a decision, perhaps both the worst and the best comfortable feelings combine in judging overall comfort.

Our final proposed rule-based overall thermal comfort model is presented in Table 6. The comfort model is calculated either by the two minimum local comfort votes (Rule 1), or from the average of the two minimum votes and the maximum comfort vote (Rule 2).

Table 6. Overall thermal comfort model

Rule 1:	Overall comfort is the average of the two minimum local comfort votes unless Rule 2 applies.
Rule 2:	If either of the following criteria are met: a). the subject has some control over his/her thermal environment b). the thermal conditions are transient then overall comfort is the average of the two minimum votes and the maximum comfort vote.
Note: if both hands or both feet comprise the two most uncomfortable body parts, ignore the second lowest hand or foot comfort value, and use the third lowest local comfort vote as the second lowest vote in Rule 1 and Rule 2.	

11. Validation of overall comfort model

We applied this overall comfort model to both the UCB and the automotive datasets. Because our rule-based model had not been developed by regression but by visual inspection of individual datasets, it is possible to use these data to validate the model's performance. We further validated the model using experimental data from [16].

Rule 1 was applied to the averaged comfort votes in the UCB steady-state datasets, in which the subjects did not have control over their environments (Table 5). The prediction is shown in Table 7.

Table 7. Validation of overall comfort using UCB steady-state test data

Test condition	Overall comfort (measured)	Overall comfort (predicted)
a. overall sensation near –3, 5 datasets	-2.8	-2.75
b. overall sensation between 2 and 3, 10 datasets	-1.4	-1.65
c. overall sensation near –1, 6 datasets	-0.1	0.05
d. overall sensation near 1, 3 datasets	-0.4	-0.44

Rule 2 is used to predict the transient and user-controlled automotive test data. The real votes and the predictions are shown in Figure 10. These are improved over the initial predictions using Rule 1 (Figure 9).

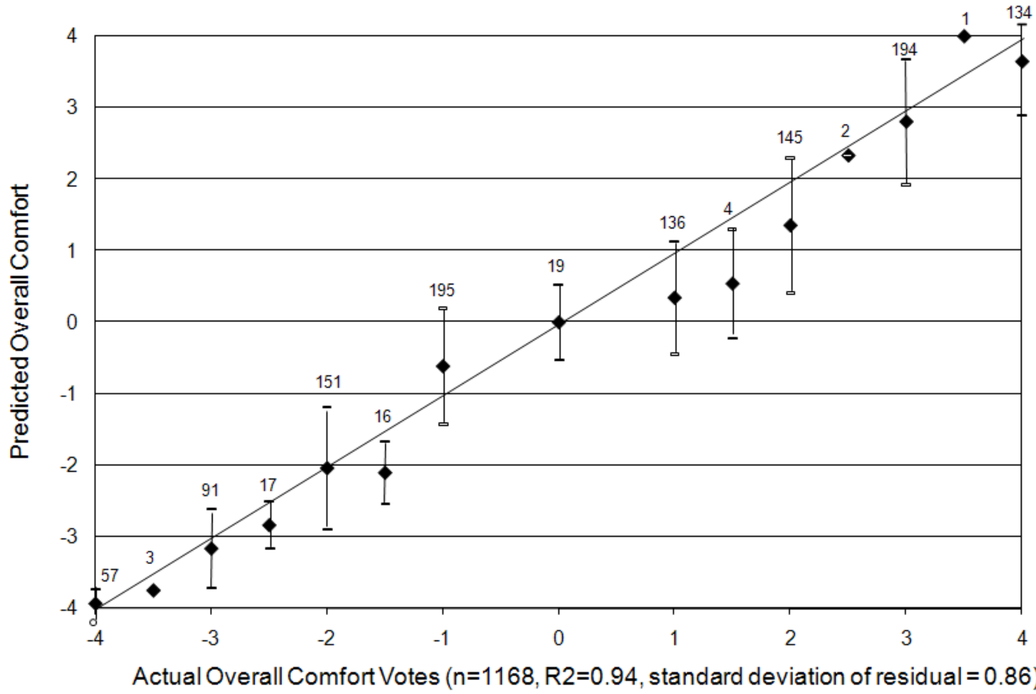


Figure 10. Actual overall comfort votes vs. predictions in non-uniform environments (data from automotive winter and summer condition tests, obtained after the subjects started the heater or air-conditioner in the car)

The subjects in the automotive tests experienced very complex sets of sensations and comfort perceptions. Body parts could be both comfortable and uncomfortable, and the discomfort would come from both warmth and cooling, i.e., an uncomfortably hot back and a slightly uncomfortable or comfortable cooled chest. The validation results show that the comfort integration model gives good prediction results.

We also validated the comfort model with data from Yu [16]. In his thermally stratified environments, the subjects' local comfort was less complex than in the automotive tests, with their body parts being either all warm or all cool. He measured comfort using the Bedford Scale (-3 much too cool, -2 too cool -1 comfortably cool, 0 comfortable (and neither cool nor warm), 1 comfortably warm, 2 too warm, 3 much too warm). Unlike the comfort scale used in the UCB and automotive tests, positive votes can be uncomfortable in the Bedford scale. The greatest discomfort votes have the highest absolute values.

In Yu's experiment, clothing under warm and cool conditions was fixed for half the tests, and adjustable by the subjects to make them comfortable in the other half. When clothing could not be adjusted, Rule 1 applies, and subjects were warm or cool. When subjects had control over adjusting their clothing, Rule 2 applies (grey area in the Table 8), and subjects were comfortable.

The comparison is shown in Table 8. The measured votes and the predictions are very close. Although the comfort model was developed from UCB tests using a balanced two-sided scale (ranging from 'very uncomfortable' to 'very comfortable'), the model appears to apply to one-sided scales as well. The Bedford Scale is essentially a pair of one-sided comfort scales (ranging from either 'too warm' or 'too cool', to 'comfortable').

Table 8. Validation using Yu's human subject tests, whole-body thermal comfort [16]

	air temperature stratification (K)	actual votes	model predictions	residual
neutral (adjusted clothing; Rule 2 applies)	1	-0.47	-0.70	-0.23
	3 (20ºC)	-0.60	-0.65	-0.05
	5	-0.50	-0.73	-0.23
	1	-0.50	-0.57	-0.07
	3 (23ºC)	-0.53	-0.54	-0.01
	5	-0.37	-0.57	-0.20
	1	-0.10	-0.05	0.05
	3 (26ºC)	0.13	0.20	0.07
	5	0.07	0.15	0.08
cool (Rule 1 applied)	1	-2.10	-2.28	-0.18
	3 (20ºC)	-1.97	-2.13	-0.16
	5	-1.73	-2.06	-0.34
warm (Rule 1 applied)	1	0.80	0.76	-0.04
	3 (26ºC)	1.00	1.10	0.10
	5	0.97	0.97	0.00

12. Conclusions

The main conclusion from the overall comfort model is that in order to keep the whole body comfortable, eliminating the most uncomfortable local votes has the highest priority.

There may also be benefit in providing personal control over an environmental feature capable of providing a local pleasurable sensation. The pleasurable sensation can offset some discomfort on other parts of the body.

The UCB and automotive tests were not designed to investigate the difference between control vs. non-control over the thermal environment, or between transient vs. steady-state conditions. We are encouraged that the overall comfort model predicts these two datasets well, as well as Yu's study which includes both control and non-control tests.

Skin wettedness above 20% may cause discomfort through a tactile sensation of stickiness [24]. The model was developed and validated using tests that included sweating in warm conditions. We did not measure skin wettedness because, with our leotard/air sleeve method, the stickiness sensation would differ from that with normal clothing which tends to cling when wet. We cannot quantify how the model works for predicting such tactile discomfort, but are encouraged by its good performance in the automotive validations where the clothing was normal.

This is a first attempt to understand and model overall comfort based on local comfort. There is much more that could be done, especially with additional experimental datasets. More validation is needed for the two conditions specified in Rule 2, transience and user control, and for other types of environmental conditions.

Acknowledgements

The experimental work was supported through the National Renewable Energy Laboratory (NREL) by U.S. DOE's Office of FreedomCAR and Vehicle Technologies (OFCVT). The authors appreciate the support of NREL project team members Rom McGuffin, John Rugh and Rob Farrington. Delphi Harrison contributed in-kind support to make the automotive testing possible. We wish to thank Taeyoung Han, Lin-Jie Huang, Greg Germaine and the volunteer subjects from Delphi Harrison.

We are grateful to UC Berkeley's Center for Information Technology in the Interest of Society (CITRIS) for supporting the data analysis, through the NSF ITR Grant # EIA-0122599. We are also very grateful to General Motors Corporation, for providing support to complete these publications.

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