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Thermal sensation and comfort models for non-uniform and transient environments: Part II: local comfort of individual body parts

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Publication Date
2009-07-01

Peer reviewed

Thermal sensation and comfort models for non-uniform and transient environments:
Part II: local comfort of individual body parts

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Abstract
A three-part series presents the development of models for predicting the local thermal sensation (Part I) and local comfort (Part II) of different parts of the human body, and also the whole-body sensation and comfort responses (Part III). The models predict these subjective responses to the environment from thermophysiological measurements or predictions (skin and core temperatures). The models apply to a range of environments: uniform and non-uniform, transient and stable. They are based on diverse results from literature and from body-part-specific human subject tests in a climate chamber. They were validated against a test of passengers in automobiles. This series is intended to present the rationale, structure, and coefficients for these models so that others can test them and develop them further as additional empirical data becomes available. The experimental methods and some measured results from the climate chamber tests have been published previously.

Part II describes a thermal comfort model with coefficients representing 19 individual local body parts. For each part, its local comfort is predicted from local and whole-body thermal sensations. These inputs are obtained from the sensation models described in Part I and III, or from measurements.

Keywords: Local thermal comfort, local thermal sensation, whole-body thermal sensation, predictive model, logistic function.

1. Introduction
Thermal environments are often asymmetrical, meaning either spatially non-uniform or transient--changing over time. There are many examples of such environments: rooms with cold/hot surfaces, solar gain, or temperature stratification; workstations or vehicles conditioned by local air movement, or with heated or cooled seats, and adjacent spaces with different temperatures that people move between.

Asymmetrical environments may require less energy to produce than uniform ones, while being equally comfortable to the inhabitants. In some cases environmental asymmetry can be *more* comfortable than the usual optimum of neutrality or uniformity [1-3]. However, the positive side of asymmetry has rarely been addressed in conventional building design and operation, largely because comfort in asymmetrical environments has been difficult to quantify. People's response to such environments depends on the comfort of their local body parts, not just the comfort of their whole body [4]. There has been no model for quantifying and predicting local comfort effects.

Local comfort has been previously addressed by the Equivalent Homogeneous Temperature (EHT) [5-7], which defines the comfort range for each body part when measuring environments with a thermal manikin. The EHT ranges are not associated with the body's physiological parameters such as skin and core temperatures, and apply only to a specific combination of metabolic and clothing levels. EHT does not indicate levels of comfort, and does not address the combined effect of body parts exposed to different temperatures.

Some thermal physiology models predict whole-body comfort. It is done indirectly, via a prediction of thermal sensation of the entire body [8-13]. In uniform environments, sensation and comfort correlate quite well: a neutral sensation corresponds to the best comfort; warmer or cooler sensations correspond to reduced comfort [14]. In non-uniform or transient environments, however, the relationship between sensation and comfort becomes more complex: for example, the identical cool face sensation may be perceived as comfortable when the whole body is warm, or uncomfortable when the whole body is cold.

Psychophysiological research [1,15,16] has shown that when a thermal stimulus applied to a local body part (e.g. hand, head) serves to reduce whole-body thermal stress, perceived comfort is 'very pleasant', ie., better than 'pleasant'. Such results indicate that asymmetrical and transient environments may not necessarily be less desirable than thermal neutrality, but might actually produce better comfort than a uniform neutral condition. This type of research has not received attention in the thermal comfort field partially because it has been typically conducted under extreme environmental conditions, with hyper- and hypo-thermic subjects.

In addition, past comfort scales used in research have been unidirectional, ranging only downward: 'comfortable', 'slightly uncomfortable', 'uncomfortable', 'very uncomfortable'. This scale actually evaluates the degree of discomfort, with no provision for the types of pleasant effects noted in [1]. To evaluate comfort properly, a balanced scale is needed that also measures the degree of positive comfortable perceptions (from 'just comfortable' to 'comfortable' to 'very comfortable').

In 2001-2003 the authors conducted an extensive set of 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 [17].

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 (examples shown in Figure 1a and b). Most of the tests involved cooling a body part under warm conditions, and then removing the sleeve and allowing the local part to warm up to its initial temperature.

[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

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. The comfort scale used was bi-directional (Figure 1c). While the skin temperature was changing, sensation and comfort questions were asked about 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 visible change), all body parts were surveyed for sensation and comfort.

a. arm cooling or heating

b. pelvis cooling or heating

c. thermal comfort scale

Figure 1. Local body parts cooling and heating

The test program produced 347 sets of data representing steady-state conditions. Each data set contains physiological data (skin and core temperatures) and subjective responses for a single subject and test condition. The subjective responses are the only data needed to predict local comfort, so the test conditions are not presented here.

The methods and experimental results of these tests have been previously published: the physiological responses to local heating and cooling [18,19], thermal sensation and comfort under uniform conditions [4], and thermal sensation and comfort under non-uniform conditions [3]. This present series of papers completes the project by describing the predictive models that were developed from the experimental results.

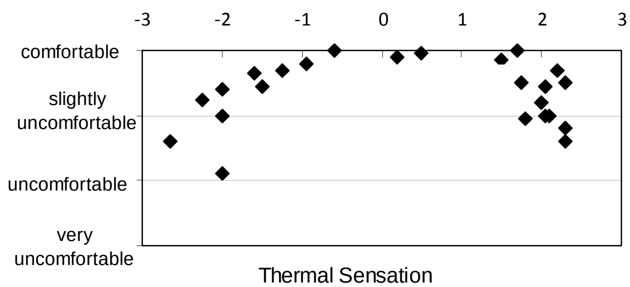
Nomenclature	
S_l	thermal sensation for a local body part
S_o	whole-body thermal sensation
C1 – C8	regression coefficients
a,b,c	intermediate variables of the logistic function
- *offset*	local sensation at which maximum comfort occurs

maxcomfort	maximum comfort when local sensation equals to the -offset
right slope	slope to the right of the offset
left slope	slope to the left of the offset
n	exponent for modifying logistic-adapted linear equation

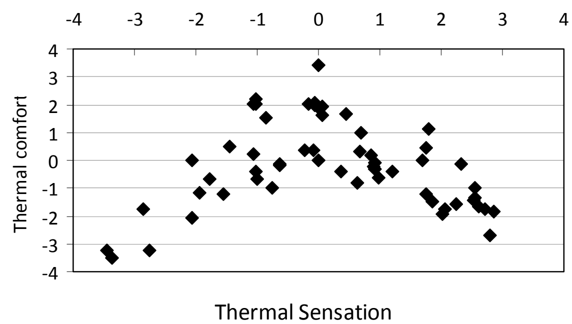
2. Development of the local comfort model

The model is based on effects seen in the experimental literature as well as in our data. It is intended to be rational in form, with an explanatory physical basis for each of the mathematical terms, so that others can test and manipulate them as additional data become available. The stepwise development of the comfort model is described below.

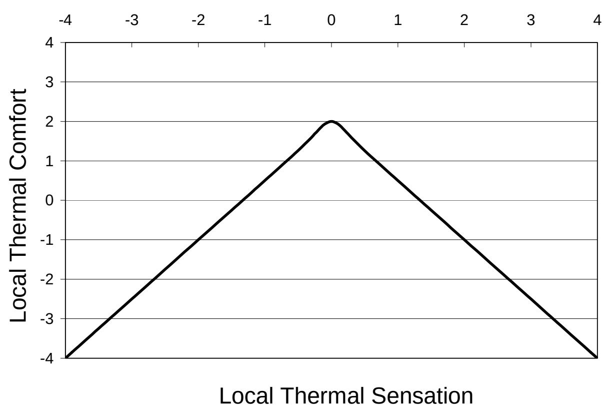
In a uniform environment, as sensation moves away from neutral, comfort level decreases. Figure 2a is transcribed from a figure in [19] using data from Gagge [14], and 2b is from our study. Drawing from these whole-body results, we hypothesize a linear model to represent local comfort as a function of local sensation in uniform conditions. Note that the model is centered on the neutral thermal sensation.



a. Overall sensation vs. comfort (Gagge data)



b. Overall sensation vs. comfort (current study)

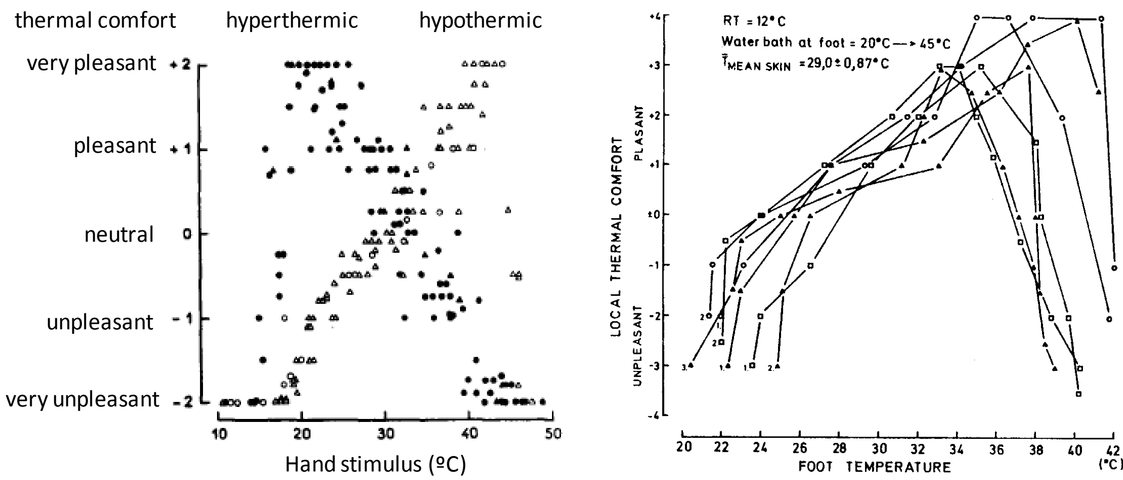


c. Initial linear local comfort model

Sensation scale:
-4 very cold, -3 cold, -2 cool, -1 slightly cool, 0 neutral, 1 slightly warm, 2 warm, 3 hot, 4 very hot

Figure 2. Local comfort model under uniform environments

When the whole-body thermal state is different from that of a local thermal state, the comfort assessment of the local part is affected. Cabanac [1] systematically changed the core temperature of human subjects by immersing them in baths of various temperatures (Figure 3a). When the subjects were hypothermic, warm stimuli applied to the hand were perceived as pleasant and cold stimuli were perceived as unpleasant. (Cabanac uses the term ‘pleasantness’ interchangeably with ‘comfortable’.) The opposite responses were observed in hyperthermic subjects. However, there are limits to this rule. At some point, regardless of how warm the body may be, an increasingly cold local sensation will become uncomfortable when it approaches the pain threshold. This limit is seen in Figure 3a on both the warm and cold sides. It is also seen in Figure 3b, for a cool body in which feet were warmed [20]. The two tests differ in that Cabanac tests were highly transient while Issing and Hensel’s test conditions were steady-state.

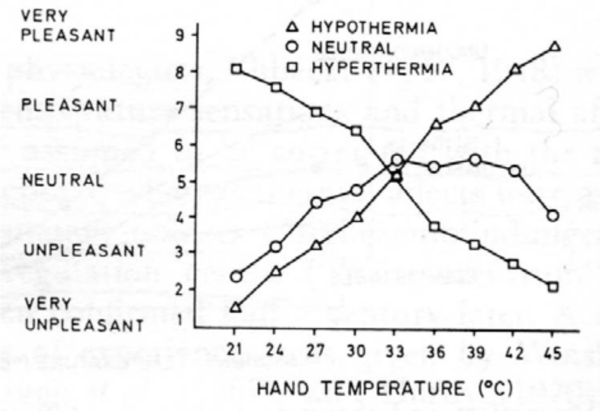


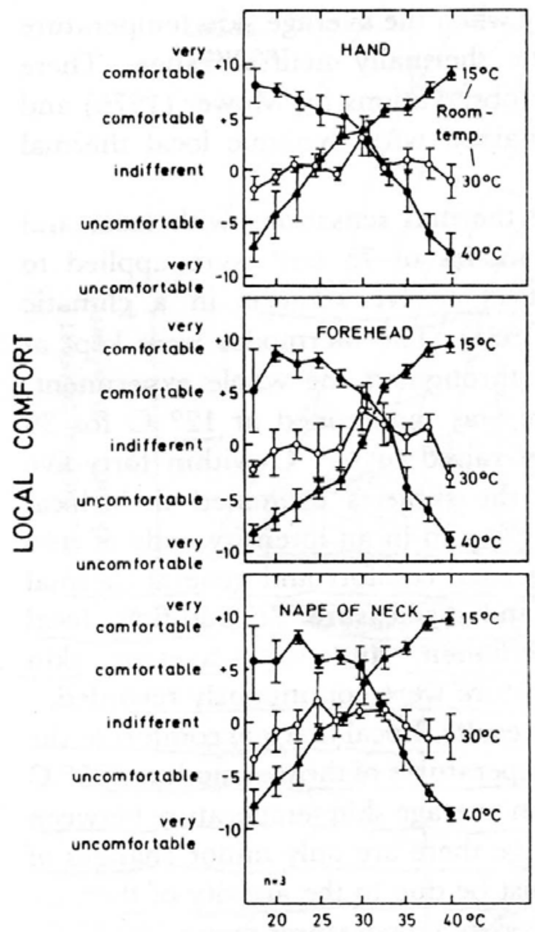
a. Hand, adapted from Cabanac [1]

b. Foot, from Issing and Hensel [20]

Figure 3. Comfort of a local body part when the whole body is cold or warm.

Mower [15] and Attia [21] added neutral subjects to those who were hypothermic and hyperthermic (Figures 4a,b). They too found ‘very pleasant’ sensations for stimuli opposite to the whole-body temperature when subjects were cold or hot. For neutral subjects, the stimuli were never perceived as ‘very pleasant’. As noted by Cabanac and Kuno [1, 22], the magnitude of pleasantness at neutral is not as great as when the thermal stimuli act to remove heat stress or relieve discomfort. This fits a general adaptive principle: when an action satisfies a need, the action is perceived as pleasurable. Cabanac coined “alliesthesia” [23] to describe how a given stimulus can arouse pleasure or displeasure according to the internal state of the body. Because the primary goal of mammalian thermoregulation is to keep core temperature constant, it is beneficial to the organism that an action (e.g., putting a hand in warm water) can be perceived as either comfortable or uncomfortable depending on the body’s thermal state.





a. Hand, from Mower [15]

b. Hand, forehead, neck, from Attia [21]

Figure 4. Local body comfort for cold, warm, and for the neutral whole body

Figure 5 shows examples (chest, hand, and foot) from our tests. The data are the last vote of a local cooling and heating application, when conditions were stable (for details, see [17]). The correlation between local sensation and comfort is similar to that found in the studies cited above: maximum comfort shifts to the left or right based on the whole-body thermal state, and maximum comfort is higher than comfort in the neutral condition when local sensation is zero. The examples also show that when the whole body is cold, heating an individual body part creates comfort (triangles) and cooling an individual body part produces only discomfort (open circles), as shown in the figures for hand and foot. We did not apply heat to individual body parts when the entire body was hot, so the right side of the figure is less populated than in the studies described above.

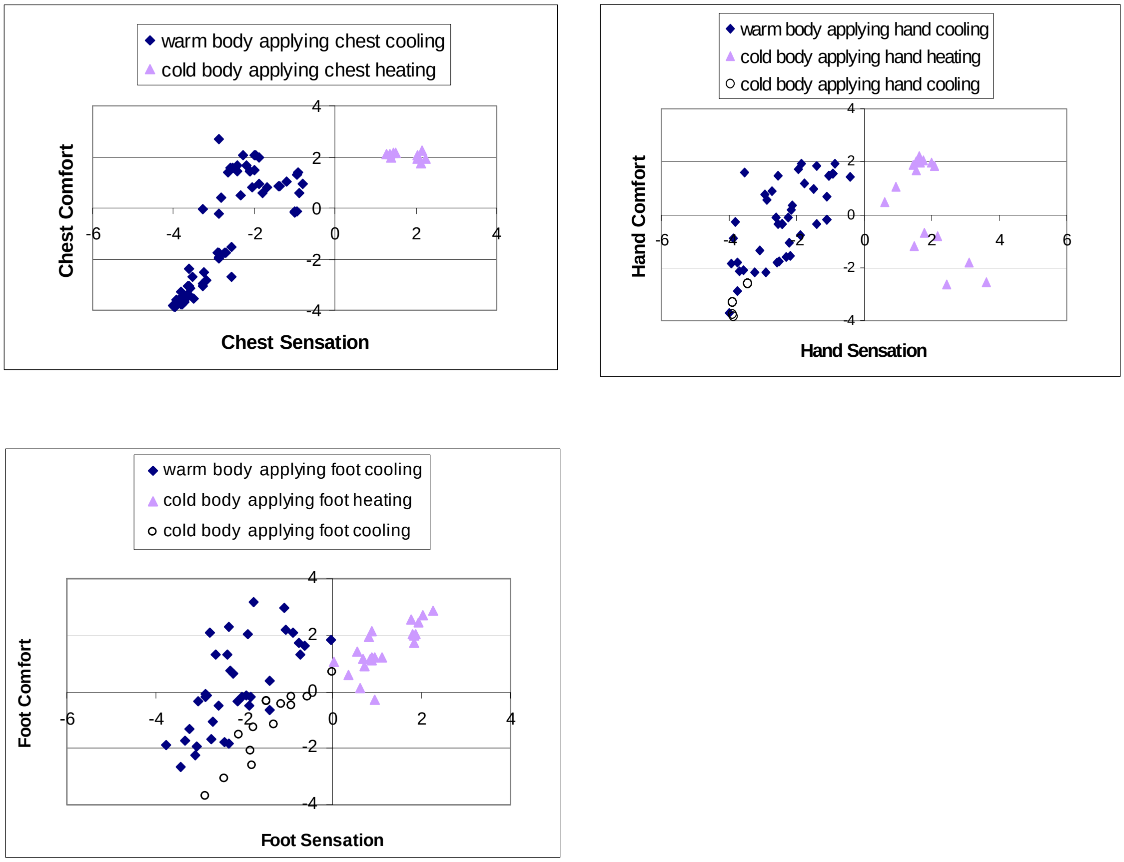


Figure 5 Local comfort vs. local sensation and whole body thermal states

Following all these results, we modify the Figure 2c model to the form in Figure 6. The magnitude of maximum comfort increases when overall thermal status is warm or cold. In addition, the warm and cold maxima may not be the same for some body parts. For example, a warm pelvis is perceived as very comfortable when the body is cold, but people do not find a cold pelvis comfortable even when the body is warm. This asymmetry in relation to overall sensation is visible.

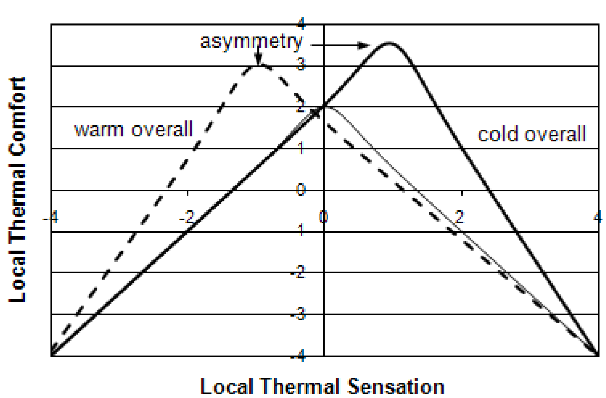


Figure 6. Local thermal comfort model.

The curves in Figure 6 represent three whole-body thermal states. To approximate a continuum of whole body states, we refer to an unpublished study from Issing and Hensel [20], who applied thermodes of 75 cm^2 to forehead, abdomen, and foot of twelve subjects, keeping them at several constant temperatures (Figure 7). Their test chamber was first set at 12°C for 30 minutes and then ramped up to 45°C over 45 minutes, producing a range of transient whole-body average skin temperatures and steady-state local thermal sensations.

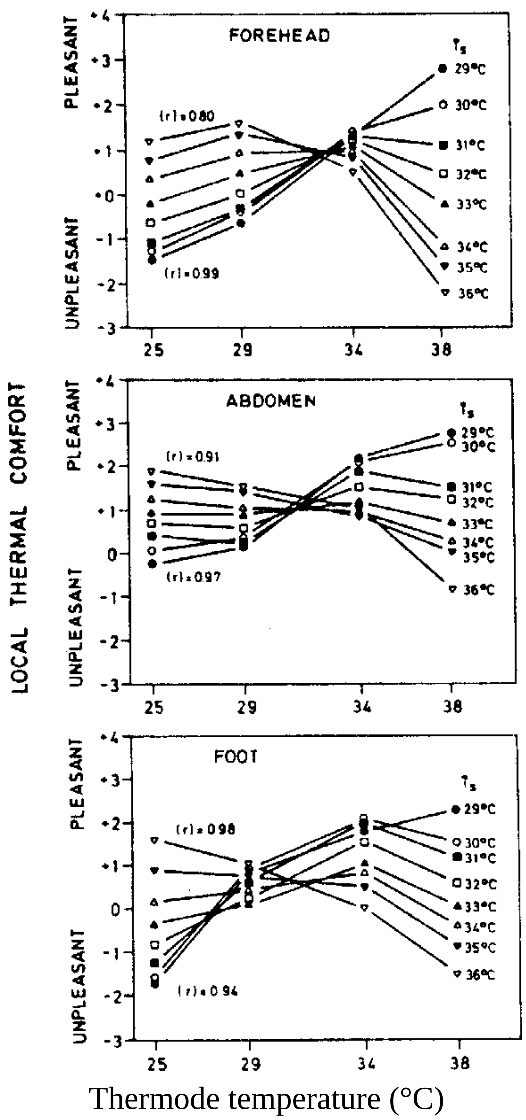


Figure 7. Local comfort as a function of local temperatures of forehead, abdomen, and foot, for various average skin temperatures (T_S) [20].

The horizontal axis is the thermode (local skin) temperature. The lines inside the figure show equal whole-body average skin temperatures, representing the overall thermal state. It is obvious that with the same thermode temperature (i.e. 38°C), the local comfort is highly dependent on average skin temperature. Figure 8 shows the final local comfort model, using a family of curves to represent such results.

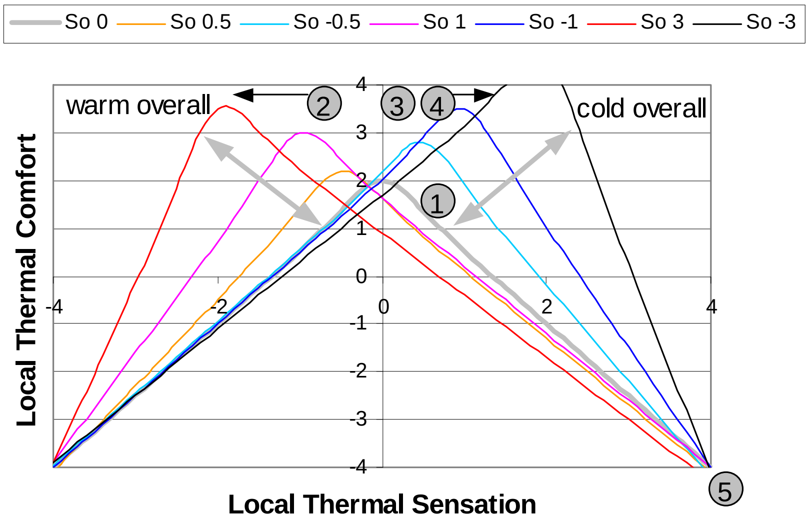


Figure 8. The local thermal comfort model

The model is now a saddle-shaped set of curves representing a range of overall whole body thermal states. Marked on the figure are five key requirements derived from the experimental observations:

1. Local thermal comfort is a two-part linear function of local thermal sensation. As local sensation moves from neutral toward very hot (+4) and very cold (–4), local comfort moves toward very uncomfortable (–4). (Figure 2).

2. The local sensation at which maximum comfort is felt shifts with the body's overall sensation. The warmer (or cooler) the overall sensation, the cooler (or warmer) the local sensation associated with maximum local comfort. (Figures 3,4,5).

3. Maximum comfort is a function of overall sensation. The warmer (or cooler) the overall sensation, the greater the comfort in response to local cooling or heating. Maximum comfort levels are higher than comfort under the neutral condition. (Figure 4).

4. Maximum comfort levels may be asymmetrical (Figure 7) on the cool and warm sides. Some body parts (e.g., pelvis) feel comfortable when warmed while the

overall sensation is cool, but do not feel comfortable when cooled while the overall sensation is warm. Conversely cooling of the breath intake air feels pleasant when subjects feel warm overall, but warming of breath intake air does not feel comfortable in any of our tests.

5. When local sensation equals either 4 (very hot) or –4 (very cold), local comfort will be –4 (very uncomfortable). (Figures 3,5).

We investigated the zero local sensation point, the crossover between warm and cold. We wondered whether the neutral overall contour (So = 0) should be above or below the contours for warm or cold overall body at this crossing point (e.g., might asymmetric conditions always be better than neutral?). Mower (Figure 4a) has local comfort slightly higher in the neutral condition than in hyper- or hypo-thermic states, while Attia (Figure 4b) has neutral slightly lower. In general, they are quite close. In our proposed model (Figure 8), the local comfort contours in the middle near the crossing point are also close, with some higher and some lower than the neutral condition's local comfort.

The following subsection explains the mathematical definition of the local comfort model shown in Figure 8.

3. Mathematical description

The primary challenge is finding a mathematical description of the two-part linear model that changes slope and magnitude at a location depending on overall sensation. This requirement can be satisfied by a logistic function that provides values for the two slopes, with a transition range in between. The following example shows how the logistic function acts on the linear model.

Assume the following basic logistic function with arbitrary constants:

$$y = \frac{a}{e^{c(x+offset)}+1} - b \qquad \text{Eq. (1)}$$

When the exponential term (x) is very large, y equals –b. The value –b is the right-hand side linear model slope (*right slope = -b*). When x is negative and very small, the exponential term is near zero and y is found by: (a – b). The value (a – b) is the left-hand side linear model slope (positive slope). The logistic function not only allows the sign to switch (positive vs. negative), but also provides two different values, which correspond to the different slopes (steeper vs. gradual) for the two linear functions on the left and right sides. 'a' must be larger than 'b' to assure a positive slope on left side of the curve. The exponent 'c' controls the speed of the slope transition from –b to (a – b) and allows the two curves to meet in a curve rather than a sharp angle. We chose c = 25 which makes the transition almost a step-change. Another variable ('n', to be described below) also affects the curvature between the two slopes.

Thus, the proposed model is a linear model modified by a logistic function, or a logistic-adapted linear model. The logistic function provides two different slopes for the linear model.

$$Local\ Comfort = LogisticFunction(S_l + offset) + maxcomfort \qquad \text{Eq. (2)}$$

$$Local\ Comfort = \left(\frac{a}{e^{25(S_l+offset)}+1} + right\ slope\right)(S_l + offset) + maxcomfort \qquad \text{Eq. (3)}$$

S_l represents local sensation.

Changing the 'offset' value shifts the maximum comfort left or right. Changing 'maxcomfort' alters the maximum value up or down. Changing the 'right slope' and 'a' values alters the right- and left-side (a + *right slope*) slopes of local sensation. Figure 9 shows how the logistic function modifies the linear function. The continuous lines represent a case centered on neutral. The left-shifted logistic curve with larger magnitude (dotted line) shifts the local sensation predictions toward cold, increases the local comfort levels on the left side, and slightly decreases comfort predictions on the right side (represented by + and – signs in the figure).

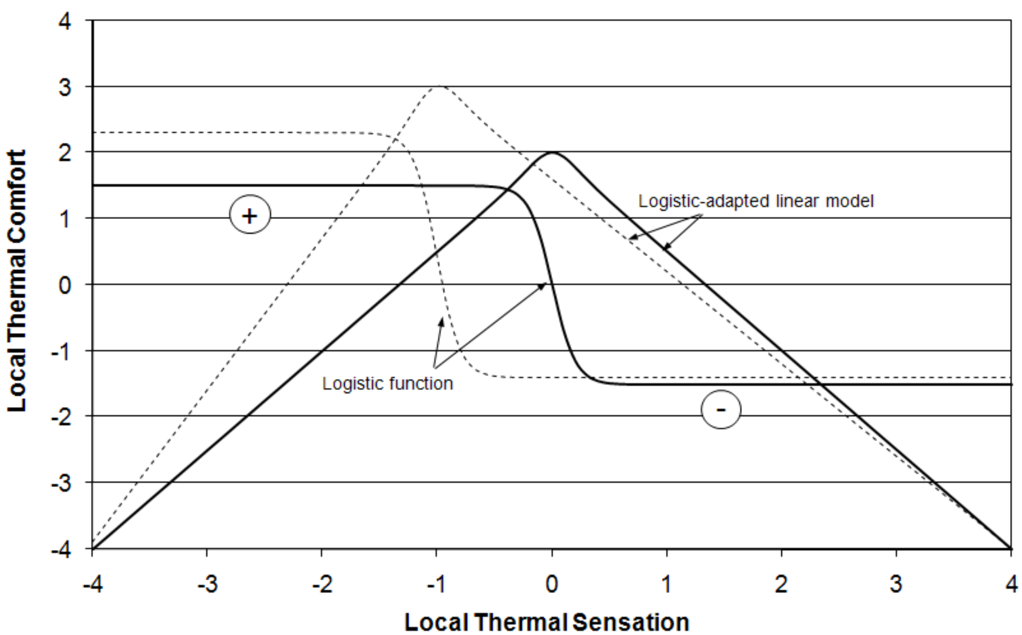


Figure 9. Logistic function acting on the linear function

The variable *offset* is predicted by the linear relationship (offset = C3 S_o), where S_o represents whole-body (overall) sensation.

"maxcomfort" is also a linear relationship: *maxcomfort* = C6 + C7 abs (S_o). Since the magnitudes are asymmetrical for warm and cool overall sensations (Requirement 4 above), separate coefficients are needed: *maxcomfort* = C6 + C71 abs (S_o^-)+ C72 abs (S_o^+). All three coefficients (C6, C71, and C72) should be positive. The maximum comfort happens at an offset of (-C3 S_o).

Putting the above relations into Eq. (3), we get:

$$Local\ Comfort = \left(\frac{a}{e^{25(S_l + C3 S_o)} + 1} + right\ slope\right)(S_l + C3\,S_o) + \left(\ C6 + C71\left|S_o^{\,-}\right| + C72\left|S_o^{\,+}\right|\ \right)$$

Eq. (4)

In addition, the right and left slopes must pass through two points (4, -4) and (-4, -4) to meet Requirement 5. The maximum discomfort/sensation limits are implemented by inserting 4 and –4 into Eq. 4:

$$right\ slope = \frac{C6 + C71\left|S_o^{\,-}\right| + C72\left|S_o^{\,+}\right| + 4}{-C3\,S_o - 4}$$ Eq. (5)

$$left\ slope = \frac{C6 + C71\left|S_o^{\,-}\right| + C72\left|S_o^{\,+}\right| + 4}{-C3\,S_o + 4}$$ Eq. (6)

As mentioned earlier, *left slope = a + right slope*. Putting the above two equations, we get "*a*" as a function of C6, C71, C72, and C3:

$$a = left\ \ slope - right\ slope$$

$$= \frac{C6 + C71\left|S_o^{\,-}\right| + C72\left|S_o^{\,+}\right| + 4}{-C3\,S_o + 4} - \frac{C6 + C71\left|S_o^{\,-}\right| + C72\left|S_o^{\,+}\right| + 4}{-C3\,S_o - 4}$$

$$= \frac{(C6 + C71\left|S_o^{\,-}\right| + C72\left|S_o^{\,+}\right| + 4)(-8)}{(-C3\,S_o + 4)(-C3 S_o - 4)}$$

Eq (7)

Putting equations 5 - 7 into the original equation 4, we have:

$$Local\ Comfort = \left[\frac{(C6 + C71\left|S_o^{\,-}\right| + C72\left|S_o^{\,+}\right| + 4)(-8)}{(-C3\,S_o + 4)(-C3\,S_o - 4)(e^{25(S_l + C3 S_o)} + 1)} + \frac{C6 + C71\left|S_o^{\,-}\right| + C72\left|S_o^{\,+}\right| + 4}{-C3\,S_o - 4}\right] *$$
$$\left[\ (S_l + C3\,S_o)\ \right] + \left(\ C6 + C71\left|S_o^{\,-}\right| + C72\left|S_o^{\,+}\right|\ \right)$$

Eq. (8)

At this stage, there are four parameters to define: C3 determines the offset of the maximum comfort (this should be a positive value, as noted above); C6 should be a positive value because it is the maximum comfort value; and C71 and C72 should be positive values because as overall sensation moves in the direction of cooler or warmer, the maximum comfort is higher.

There are two additional adjustments, required only for certain body parts:

1. Warming versus cool asymmetry. By adding a constant value (C8) to the local sensation offset portion, the local sensation can be shifted when overall sensation is neutral (the offset becomes C8 + C3 So). We further replace coefficient C3 with C31 and C32 in order to address the asymmetrical shifts in local sensation caused by non-neutral overall sensations (Eq. 9).

2. Curvature in the saddle shape. The linear model is highly responsive near the maximum comfort point. Examination of scatter plots of local sensation and local comfort for different body parts suggests that for some body parts, a quadratic or exponential shape may better represent the relationship. We therefore provided for three possible models, linear (n=1), exponential (n=1.5), and quadratic- (n=2) (Figure 10). .

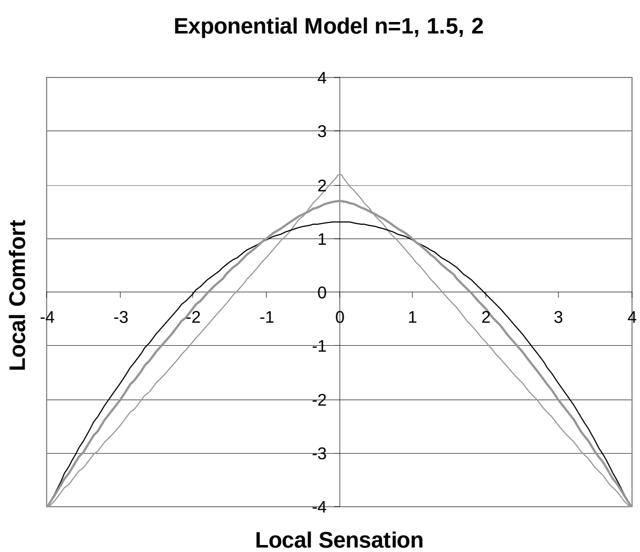


Figure 10. Three possible shapes for the relationship between local sensation and local comfort.

Regressions using the general equation form in Eq. (9) with the three values (n=1, 1.5, 2) for each body part did not generally change the R^2. However, the distribution of the residuals changed. By comparing R^2 and the residual distribution with the three regressions for each body part, we chose one value of n for each segment (Table 1).

$$Local\ Comfort = \left[\frac{ \dfrac{-4-(C6+C71|S_o^-|+C72|S_o^+|)}{\left|(-4+C31|S_o^-|+C32|S_o^+|+C8)\right|^n} - \dfrac{-4-(C6+C71|S_o^-|+C72|S_o^+|)}{\left|(4+C31|S_o^-|+C32|S_o^+|+C8)\right|^n} }{ e^{25(S_l+C31|S_o^-|+C32|S_o^+|+C8)}+1 } + \frac{-4-(C6+C71|S_o^-|+C72|S_o^+|)}{\left|(4+C31|S_o^-|+C32|S_o^+|+C8)\right|^n} \right]$$

$$*\left[\ (S_l + C31|S_o^-| + C32|S_o^+| + C8)^n\ \right] + \left(\ C6 + C71|S_o^-| + C72|S_o^+|\ \right)$$

Eq. (9)

Eq. (9) is the final form of the local comfort model, producing the asymmetrical saddle shape. The form allows us to change the shape of the saddle (linear vs. curved), to adjust shifts toward cold or warm local sensation, and to determine maximum comfort values separately for warm and cold overall thermal states. These adjustments are all functions of local and overall thermal sensation.

4. Regression coefficients

The coefficients for all body parts are shown in Table 1. The coefficients C6 and C8 represent the maximum local comfort and the offset in local sensation at neutral overall sensation. As overall sensation gets colder or warmer, maximum local comfort is felt at warmer or colder local sensations, and becomes greater than the maximum local comfort felt with neutral overall sensation. The coefficient C31 represents the shift in local sensation toward the warm direction as overall sensation gets colder, and the coefficient C32 represents the shift in local sensation toward the cold direction when overall sensation is warm. Larger coefficients represent bigger shifts. The coefficients C71 and C72 correspond to heightening of maximum comfort: larger values indicate higher levels of maximum comfort. A positive value indicates a cool preference, and a negative value indicates a warm preference. The regression value n represents the shape of the curve relating local sensation and local comfort, with n=1 providing greater sensitivity near maximum comfort (Figure 10).

Table 1. Regression coefficients for local thermal comfort models

	C31	C32	C6	C71	C72	C8	n	R^2
Head	-0.35	0.35	2.17	0.28	0.40	0.50	2	0.55
Face	-0.11	0.11	2.02	0	0.40	0.41	1.5	0.44
Breath	0	0.62	1.95	0	0.79	1.10	1.5	0.33
Neck	0	0	1.96	0	0	-0.19	1	0.43
Back	-0.45	0.45	2.10	0.96	0	0	1	0.74
Upper back	-0.30	0	2.05	0	0	0	1	0.45
Lower Back	-0.23	0	2.20	0	0	0	1	0.69
Chest	-0.66	0.66	2.10	1.39	0.9	0	2	0.68
Pelvis	-0.59	0	2.06	0.50	0	-0.51	1	0.74

Upper Arm	-0.30	0.35	2.14	0	0	-0.40	1	0.70
Lower Arm	-0.23	0.23	2.0	0	1.71	-0.68	1	0.77
Hand	-0.80	0.80	1.98	0.48	0.48	0	1	0.60
Thigh	0	0	1.98	0	0	0	1	0.59
Lower Leg	-0.2	0.61	2.0	1.67	0	0	1.5	0.68
Foot	-0.91	0.40	2.13	0.50	0.30	0	2	0.55

5. Discussion

5.1 Analysis of the regression results

The regression coefficients reflect a wide range of local comfort features observed in the literature, and quantified in our tests. Below, we demonstrate how the model predicts these features for body parts that represent features such as asymmetry, torso-versus-extremity, and cool and warm preference (*breathing intake air, head region, foot, pelvis, back, chest, and hand*).

Breathing intake air: In our tests, cool breathing air was experienced as comfortable, and warm air as uncomfortable. In Table 1, we see a positive coefficient (1.10) for C8. This indicates that with a neutral overall sensation, maximum comfort is felt at a breathing sensation near slightly cool (–1.1, Figure 11). As the overall body becomes warmer (So = 1, 2, 3), maximum comfort occurs at local sensations that are 0.62 units (C32) cooler for each unit of overall sensation increase. The magnitude of maximum local comfort increases 0.79 units (C72) per unit overall sensation increase. The warm-side offset (C31) and max-comfort coefficients (C71) are zero, indicating that people don’t like breathing warm air, even when the body is cold.

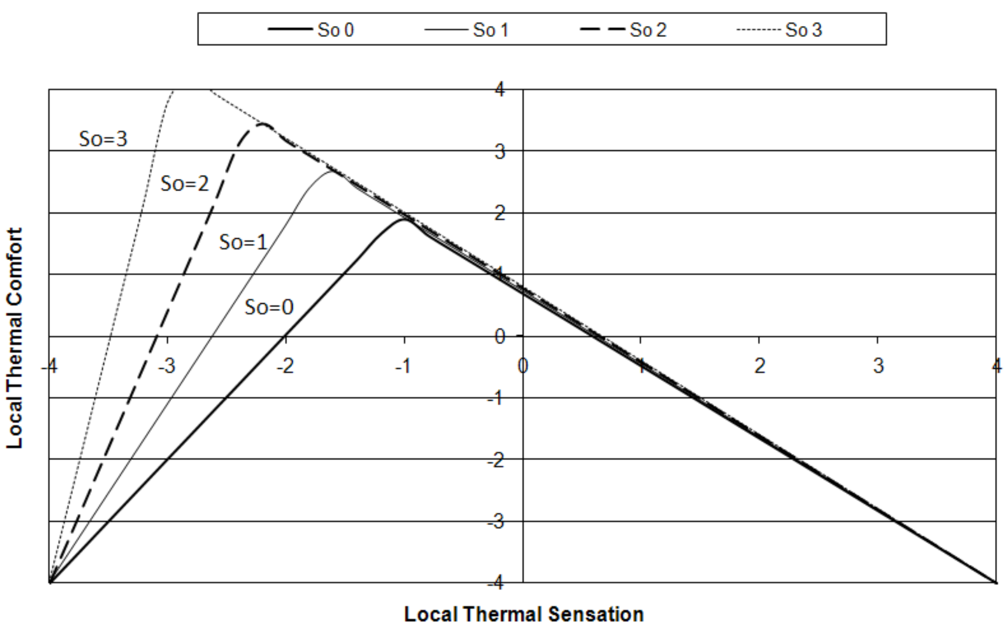


Figure 11. Local thermal comfort model for breathing

Head region: Subjects were generally more comfortable with a cool head region. The regression results show three of the four C8 coefficients (for head, neck, face, breathing) to be positive, indicating maximum comfort at a negative local sensation when overall sensation is neutral. The C8 for neck is -0.19, indicating a slight preference for warmth when overall sensation is neutral. As with breathing, the C31 and C71 coefficients for face, and neck are zero or slightly negative, showing no shift in the location of maximum comfort in the warm direction. The value of n is 1 only for the neck, showing that of the four head parts (head, face, breath, neck), the neck is the most sensitive.

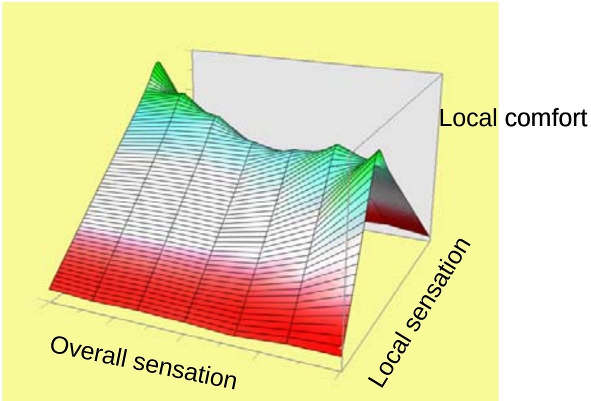
Foot: Subjects were most comfortable with warm feet. The shift in the warm direction (C 31 = -0.91) for a cold overall sensation is much larger than the shift in the cold direction for a warm sensation (C32 = 0.40), indicating that people prefer to have very warm feet when whole body feels cold. The increase in maximum comfort for the warm local shift with a cold body is also higher (C71 = 0.50) than for the cold local shift with a warm body (C72 = 0.30). That means warming feet in cool environment enhances comfort more than cooling feet in warm environments.

Pelvis: Under neutral whole-body conditions, the pelvis shows a preference for a warm local sensation (C8 = -0.51). With a cold whole body, the shift of maximum comfort toward a warmer local sensation is larger (C31 = -0.59) than the shift toward a cold local sensation when the whole body is warm (C32 = 0). Local maximum comfort increases (C71 = 0.5) with the shift toward warm local sensation when the overall whole body is cold. Maximum comfort des not increase as local sensation shifts toward cold (C72= 0), even when the overall body is warm. Adding cooling to the pelvis cannot create a comfort level higher than under the neutral condition.

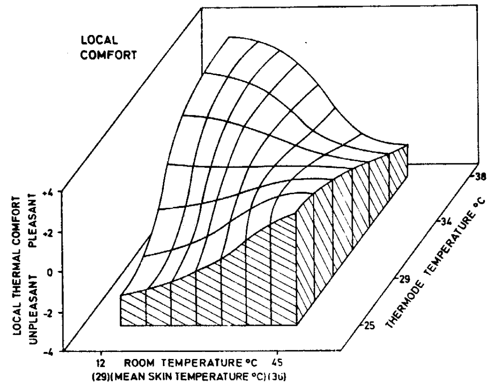
Back, chest: The back is similar to the pelvis, with a preference for warmth. However, chest cooling does increase comfort when the body is warm.

Hand: The hand does not show any preference in the neutral condition, so C8 =0. The hand is also symmetrical for local cooling and heating when the whole body is warm or cold (C31 = -C32, C71 = C72).

Figure 12 shows a 3-D comparison of our saddle model (for the foot) and a model proposed by Issing and Hensel (unpublished, from [20]) for unspecified body parts. In our figure, the x and y axis represent overall and local sensation. In Issing and Hensel's figure, the x and y axes are the temperatures of the room (representing the overall whole body thermal state) and the thermode (representing the local skin temperature). The two figures show similar results, in that they both have a saddle with its ridge passing from the left rear to the right front, and that the peak at the left rear is higher. For these body parts a warm local sensation applied to a cool body produces the highest comfort response (the preference for warm local sensation noted in the previous section).



Our model, for foot



Issing and Hensel, for unspecified body parts

Figure 12. 3-D presentations of our saddle model and the model proposed by Issing and Hensel (unpublished, copied from [20]).

5.2 Limitations to the model

The model is structured to predict the full range of effects seen in the literature as well as in our test data. The regression coefficients however represent only the range of testing and test conditions in our experiments. The number of warm tests where a local part underwent local cooling and recovery greatly exceeded the number of cold tests with local heating and recovery. This may affect our coefficients for certain applications. In both the chamber tests and the validation tests described below, the highest temperatures were sufficient for the subjects to sweat moderately, so the model coefficients should apply to some wet skin conditions as well as dry.

Our coefficients may also have deficiencies because we did not explore a sufficiently wide range of cooling rates in our tests. For example, when we cooled the back of warm subjects using a large volume of relatively cold air, we did not see an increase in maximum local comfort (C72 = 0). They may have been uncomfortably overcooled, and if we had cooled them more gradually, our results might have found a maximum.

These examples suggest that our coefficients could be improved in the future if more data become available.

The skin and core temperatures used in the model could be caused by a number of means, including contact, convection, and radiation. The model should also apply to smaller surface areas within a body segment (since thermode data show the same patterns), but its coefficients would be different.

6. Validation of the local thermal comfort model in an automobile setting

The local thermal comfort model (equation 9 with coefficients from Table 1) was applied to data gathered from tests performed in an automobile industry wind tunnel. In 64 tests, subjects answered detailed questions about their local sensation and comfort shortly after they entered a car in the wind tunnel. The car interior was at a range of temperatures, having been exposed for 60-90 minutes in wind tunnel temperatures between –23ºC and 43ºC, with and without solar heating. The subjects stood in the wind tunnel environment for 5 – 10 minutes before entering the car. The thermal sensation and comfort surveys used the same scales as the human subject tests at UC Berkeley, except that the surveys were done in paper, with sensation and comfort scales in integer increments. For a detailed description of the automotive human subject test, see Zhang [17].

The tests provided both steady and transient conditions. Each record includes sensation and comfort for overall and all the local body parts (12 local body parts: face, chest, back, right lower arm, right foot, right calf, right hand, left upper arm, left foot, left thigh, left hand, pelvis). Table 2 presents the prediction R^2, and the standard deviation of the residuals (SD).

The predictions explain between 51% (right foot) and 76% of the variance (right hand), with most of the predictions around 70%. The poorest fit was for feet; the automotive test subjects did not show the preference for warm feet predicted in our model.

Table 2. Validation for automotive tests (driver only; 160 datasets)

Body part	R^2	SD
Face	0.69	0.81
Chest	0.59	0.97
Back	0.70	1.00
Pelvis	0.70	1.04
Upper arm	0.68	1.16
Lower arm	0.67	0.74
Left hand	0.73	0.80
Right hand	0.76	0.75
Thigh	0.53	1.13
Lower leg	0.69	1.01
Left foot	0.55	1.36
Right foot	0.51	1.40

7. Conclusion

This paper describes a new model of local comfort on the body, together with coefficients for 19 individual body parts. Local comfort is a function of both local and overall (whole-body) thermal sensation. The model is based on a rational mathematical structure capable of reflecting features observed in the literature and from our own human subject tests. We used our test data to develop the coefficients, and validated the individual models using separate tests in an automobile testing facility. The final model reproduces all the major effects that we have observed about human thermal comfort responses to thermal environments: the relationship between local comfort to local sensation and the whole-body thermal state; effects of non-uniform environments; asymmetric local comfort maxima that are higher than found in neutral uniform conditions; and differences in individual body parts' preference for cooling and warming.

The coefficients of the model may be improved as more test data becomes available, especially for comfort responses to local body part warming, which had received less emphasis in our experimental test program, and for responses at lower rates of cooling.

Acknowledgments
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 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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