Title

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

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Thermal sensation and comfort models for non-uniform and transient environments:
Part I: local sensation 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 the 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 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 I describes thermal sensation models representing 19 individual local body parts. The models' structure and coefficients were derived by regression of skin and core temperatures against thermal sensation votes obtained in the chamber experiments. The sensation for each local body part is predicted by a logistic function with four inputs: local skin temperature, mean skin temperature presenting the whole body thermal state, and the time derivatives of skin and core temperatures representing the response to transients. These inputs can be obtained from thermophysiological computer programs that treat the body as multiple segments.

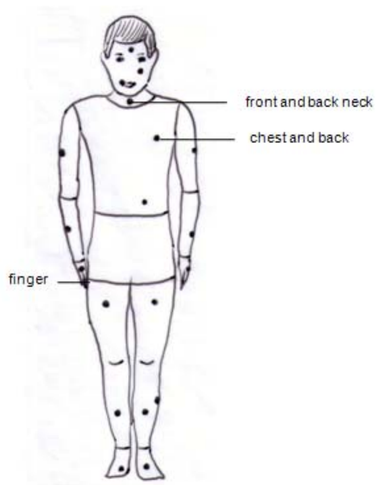
Keywords: Sensation, skin temperature, mean skin temperature, skin temperature derivative, sensation overshoot, logistic function

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.

Environmental conditioning systems can use non-uniformity and transient operation to reduce the energy needed to provide an acceptable environment. It is also possible that environmental asymmetry can be *more* pleasurable than the conventional optimum of neutrality or uniformity [1-3]. People's reaction to asymmetrical environments depends on the thermal sensations of their local body parts, not just those of their whole body [4,5]. There is no existing sensation model capable of predicting these local effects.

The most commonly used thermal sensation-predicting model is the PMV model, developed in uniform and steady-state experimental conditions [6]. It treats the body as a whole, in terms of physiological averages and sensations, and cannot predict transient responses. More advanced models developed in recent years [7-12] can predict transient behavior, and also calculate physiological responses for multiple (six to twenty) body parts. However, they can only predict sensation at the whole-body level, and therefore have limited value for evaluating non-uniform environments.

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 [13].



a. Thermocouple locations and body segment boundaries

b. back cooling or heating

c. head cooling or heating

Figure 1. Body segments, skin temperature measurement locations, and examples of the apparatus for conditioning segment skin temperatures.

The tests were designed to force local skin temperatures through a range of values. 22 measurement points were used to represent 19 body segments[1] (Figure 1a). 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 1b and c). Within each segment, skin temperatures were measured by at least one thermocouple, positioned at standard locations (Figure 1a). Mean skin temperature was calculated using the seven locations in DuBois and Hardy's method [14]. The subjects wore a leotard (0.32 clo) in order to fasten the edges of the sleeves, hold the thermocouple harness in place, and eliminate any

[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

sensation of air movement within the air-sleeves [13, 3, 4]. Skin temperatures were measured every 5 seconds, and core temperatures every 20 seconds using an ingestible radio-thermometer pill.

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. 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. Separate three-hour-long tests under neutral conditions were done to obtain segment setpoint temperatures.

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 resulting thermal transient, 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 visible change), all body parts were surveyed for sensation and comfort.

The questionnaire's sensation scale 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 2 shows an example for the left arm.

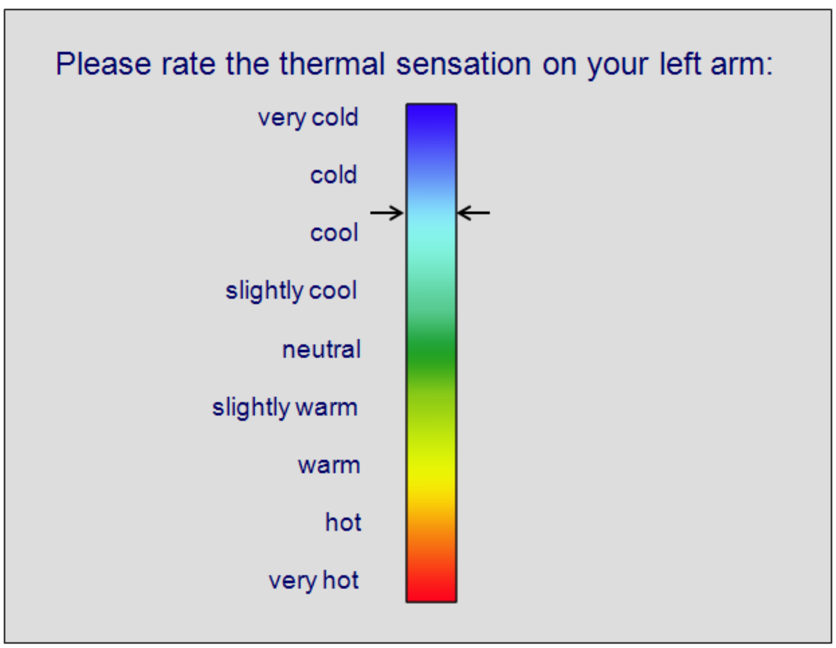


Figure 2. Thermal sensation scale

The 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.

The methods and experimental results of these tests have been previously published: the physiological responses to local heating and cooling [13,15], 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.

2. Development of the local sensation model

This paper describes the development of local *sensation* models for the 19 body parts, applicable to both non-uniform and transient conditions. The models are intended to be rational in form, with an explanatory physical basis for each of the mathematical terms, so that others can test and modify them as new data become available.

Nomenclature

T_{skin}	skin temperature (ºC)	$\frac{dT_{skin,i}}{dt}$	derivative of body part '*i*' skin temperature (ºC)
$T_{skin,i}$	body part '*i*' skin temperature (ºC)	$\frac{dT_{core}}{dt}$	derivative of core temperature (ºC)
$\overline{T}_{skin}$	mean skin temperature (ºC)	i	body part i, ranges from 1 - 19
T_{core}	core temperature (ºC)	$Sensation_i$	local sensation for body part i
$T_{skin,,i,set}$	body part '*i*' skin temperature (ºC) setpoint	C1 – C3	regression coefficients for slope of logistic curve
$\overline{T}_{skin,set}$	mean skin temperature (ºC) setpoint	K1	factor for effect of whole-body temperature on local thermal sensation
$T_{core,set}$	core temperature (ºC) setpoint		
t	time		

2.1. Inputs of the local sensation model

Humans only sense the warmth or coolness of an environment through thermoreceptors located in the skin and core [16]. The thermoreceptors sense the tissue temperatures surrounding them and send signals to the brain to interpret the environment as thermal sensation. Around neutral, at least, the feelings are independent of the modes of heat exchange with the environment, whether by convection or by radiation [17].

The characteristics of thermoreceptors determine thermal sensation responses. A thermoreceptor adapts to the rate of change of temperature. When it is subjected to an abrupt change in temperature, it is strongly stimulated at first, but then the stimulation fades quite rapidly, decreasing asymptotically until it reaches a steady response rate [18]. Thermoreceptors respond to steady temperature states at this lower rate. As a result, a person feels colder when the temperature of the skin is actively falling than when the temperature remains at the same level. The strong sensation response during transients has been termed "overshoot" [19] or "anticipation" [20]. The more advanced physiological models mentioned earlier implement derivatives of skin and core temperatures, or of heat storage in skin, to capture the dynamic response of thermal sensation under transient conditions.

We propose a local sensation model of the form in Eq. (1). The local sensation, in units as in Figure 2, is a function of local skin and mean skin (or core) temperatures and their rates of change. The local- and mean-skin temperatures represent the response to stable conditions, and the derivatives of skin temperature and core temperature represent response to transients. In the static part of the model, local skin temperature represents local skin thermal state, and mean skin temperature represents the whole-body thermal state. Core temperature might be an alternative way to represent whole-body state, but it is hard to fix the value of the body's neutral setpoint using core temperature because its inter- and intra-personal variability is greater than its variability in response to temperature. This disadvantage disappears when the objective is to characterize whole-body temperature changes over short time periods. Because core temperature can be measured with better resolution than mean skin temperature, it is used for the dynamic part of the model.

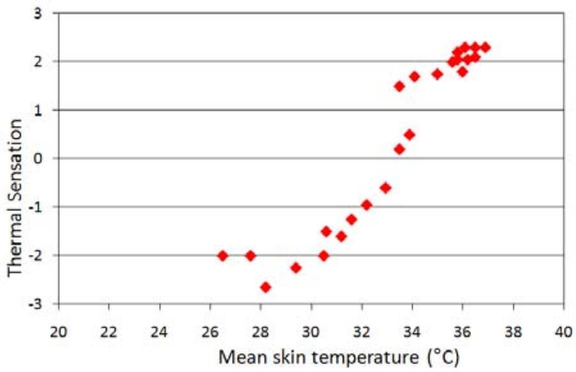
$$Local\ Sensation = f\left(T_{skin,i}, \frac{dT_{skin,i}}{dt}, \overline{T}_{skin}, \frac{dT_{core}}{dt}\right) \qquad \text{Eq. (1)}$$

Note that the local sensation prediction is based entirely on physiological data, not on environmental parameters such as the air temperatures surrounding the body. There is a distinct model for each body part, so that in combination they capture the asymmetrical features of any environment.

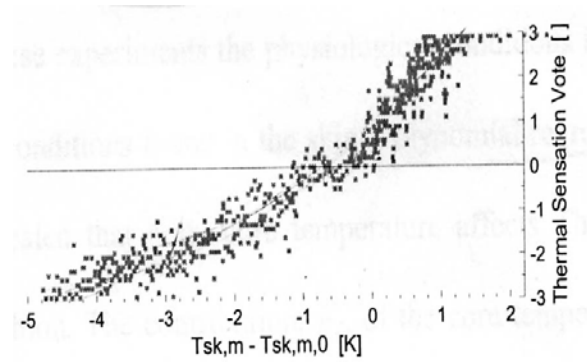
The following section describes the stepwise development of the model, using results from both our experiments and those from the literature.

2.2. Basic logistic function for local skin temperature and sensation

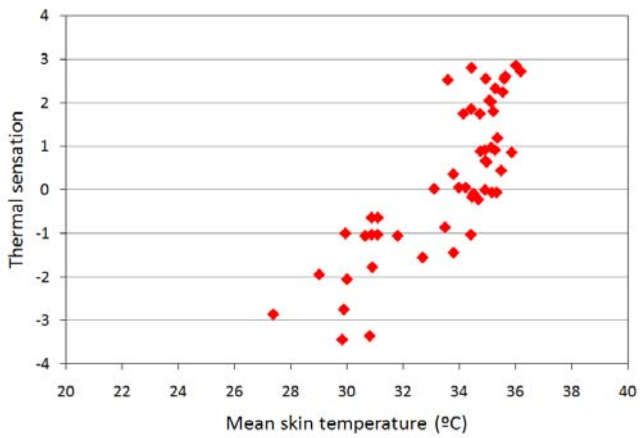
When the skin temperature is in a middle range between very low and very high, the correlation between skin temperature and thermal sensation is close to linear. Figure 3 shows that overall sensation is roughly a linear function of mean skin temperature between 29 and 34°C (Figure 3a,c), or of a difference (ranging from –3 and 1K) between the mean skin temperature and a set point (Figure 3b). As skin temperature moves above or below the middle range, the linear relationship disappears, and thermal sensation levels off.



a. Sensation as a function of mean skin temperature (transcribed from a figure by McIntyre [16] using data from Gagge [20])



b. Sensation as a function of skin temperature difference from set point [9]



c. Sensation as a function of skin temperature (our test data)

Figure 3. Relationship between mean skin temperature and overall thermal sensation

To cover the full range of skin temperature change, we propose that local sensation is a logistic function of local skin temperature, as represented by the difference between local skin temperature and its set point. The set point for a body part is its local skin temperature when the sensation for the body part is neutral (zero). The logistic function is presented in Eq. (2). It exhibits the features shown in Figure 3, a linear relationship in the middle that levels off as the skin temperature goes high or low.

$$\text{Local Sensation } = 4\left(\frac{2}{1+e^{-C1(T_{skin,i}-T_{skin,i,set})}}-1\right) \qquad \text{Eq. (2)}$$

In this equation, the number “4” defines the sensation range, from very cold (-4) to very hot (+4). When local skin temperature ($T_{skin,i}$) is much lower than its set point ($T_{skin,i,set}$), the exponential term $e^{-C1(T_{skin,i}-T_{skin,i,set})}$ is large and the term $\frac{2}{1+e^{-C1(T_{skin,i}-T_{skin,i,set})}}$ approaches zero. Therefore, the local sensation approaches its lower limit of –4 (very cold). When the skin temperature is much higher than its set point, the exponential term $e^{-C1(T_{skin,i}-T_{skin,i,set})}$ is close to zero and the term $\frac{2}{1+e^{-C1(T_{skin,i}-T_{skin,i,set})}}$ approaches a value of 2. The corresponding local sensation approaches its high limit, +4 (very hot). The term $-C1(T_{skin,i}-T_{skin,i,set})$ determines the slope of the logistic function. C1 is the coefficient for steady state conditions (C2 and C3 will apply to transient conditions described later). When C1 is larger, the logistic curve is steeper. C1 is different for different body parts. For some body parts (such as chest and back), a small skin temperature decrease induces a large cooling sensation, so the slope is steep, and C1 has a large value. For body parts like the hand, the skin temperature change range is quite large, and the slope is therefore much more gradual, so C1 is smaller. Figure 4 shows the logistic curves for two example C1 values: 1 and 0.5.

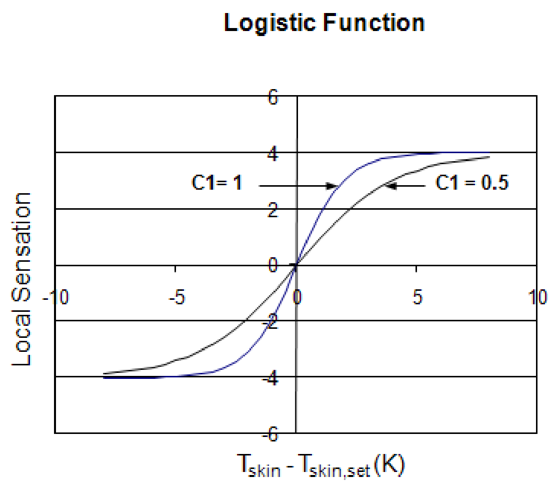


Figure 4. Slope and upper and lower limits of logistic functions

2.3. Impact of whole-body thermal state on the (local skin temperature / sensation) function

2.3.1. Observations from this experiment

Local sensation is influenced not only by the local skin area's temperature but also by overall thermal state. Figure 5 shows examples of this phenomenon. The solid circles in the graphs are from cold-condition tests when room air temperature was between 16 and 20°C and the whole body was cold (the leotard provided only 0.32 clo). The open triangles are data from warm-condition tests when the room air temperature was between 28 and 32°C and the whole body was warm. Each data point is from the end of a particular local cooling or heating test, when the body's thermal state had become stable.

We see a clear separation of local sensation in relation to warm or cold whole-body thermal states. For body parts with the same skin temperature, local sensation is much warmer during the cold tests when the whole body is cold, and much colder during the warm tests when the whole body is warm.

When $T_{skin,i} - T_{skin,i,set} < 0$, we see a change in local sensation as skin temperature gets colder. This phenomenon is more evident in the head region and trunk regions and less evident in the extremities. (notice that the solid circles diverge from the triangles on the cold side).

When $T_{skin,i} - T_{skin,i,set} > 0$ the effect is not as clear. Because our project was focused on cooling in warm environments, we performed only a few local heating tests when the body was cold. Therefore, the number of solid circles on the warm side of the figure is small. Most of our warming data was obtained by surveying the subjects after the removal of local cooling in warm environments. The open triangles on the warm side represent such data. They do not show a clear pattern, but one can see that the skin temperature range is limited on the warm side.

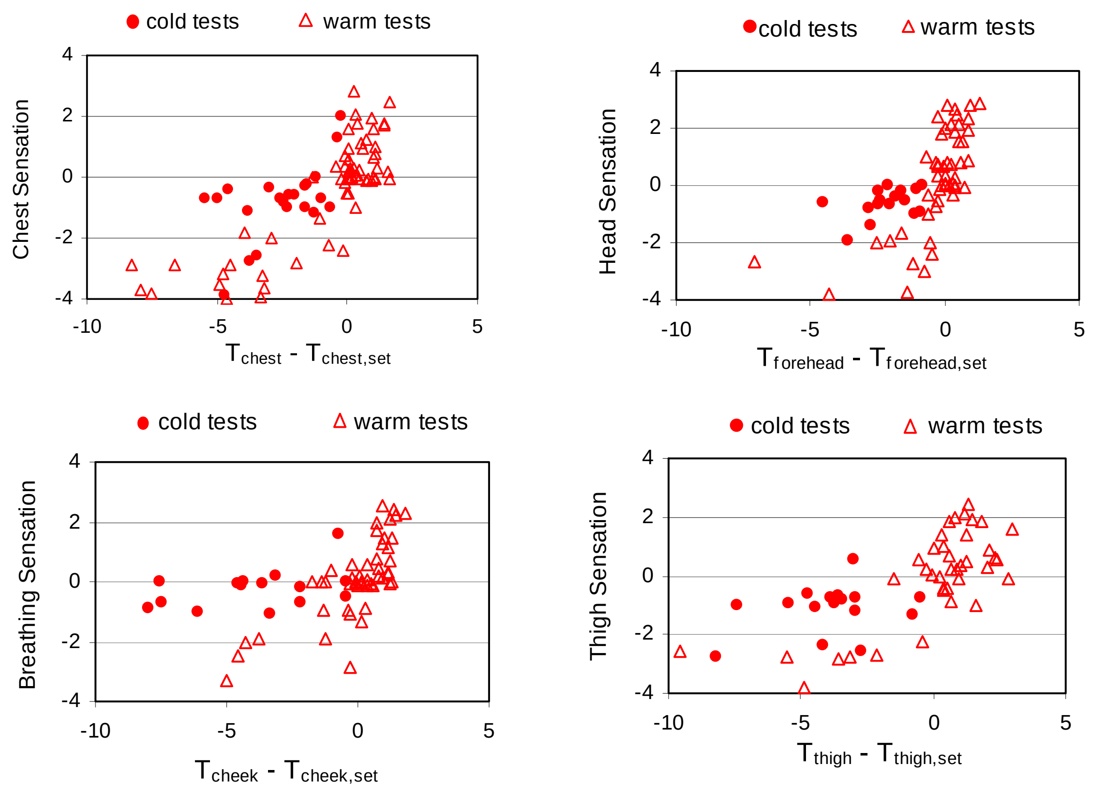
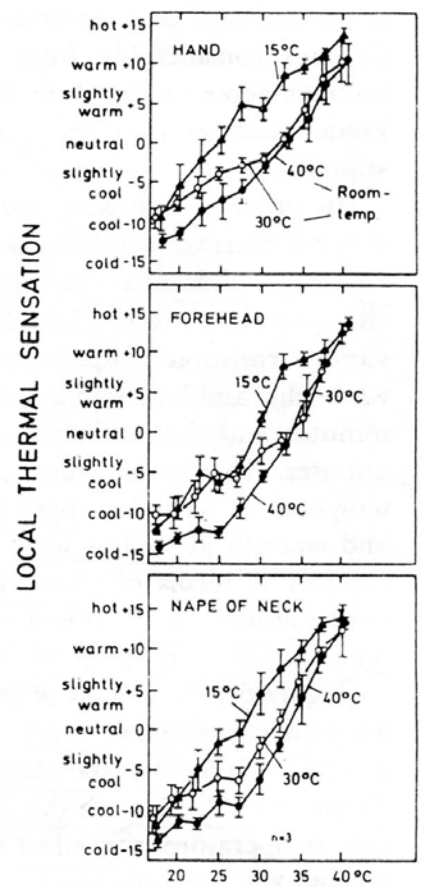


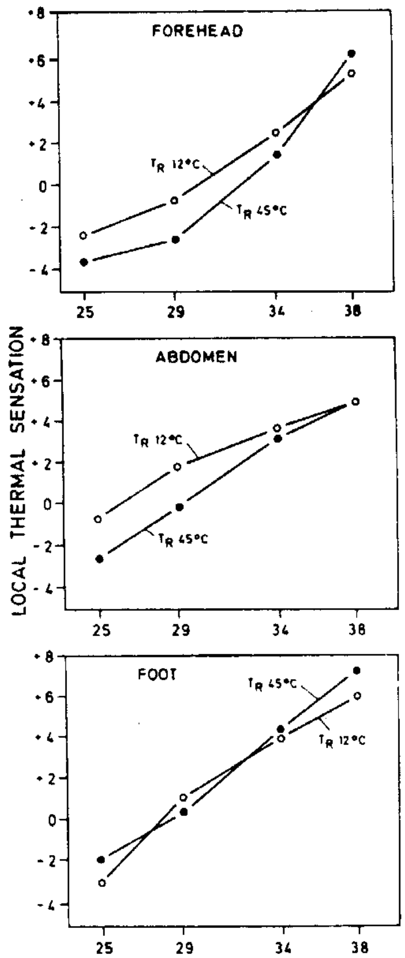
Figure 5. Local sensation, local skin temperature, and cold or warm whole-body state.

2.3.2. Experimental observations from other research

The research shown in Figure 6a (Hildebrandt et al. [21]) and 6b (Issing and Hensel, unpublished, from [18]) support the observations in Figure 5. The room air temperatures indicated in the figures represents the overall body thermal state; high room temperature indicates a warm overall state and low room temperature indicates a cold overall state. The horizontal axis is the temperature of the thermode, a conductive surface used in this test to force the local skin temperature beneath it. One can see that, at the same skin temperature, the local sensation is warmer when the air is cold (12°C or 15°C) than it is when the air is hot (40°C or 45°C). The two figures also show that within a certain local skin temperature range, local sensation and skin temperature exhibit a nearly linear relationship. The linear relationship seems to cover a larger local skin temperature range here than in Figure 5. This might be expected in that the local skin areas affected by the thermodes are much smaller than the entire body parts being heated or cooled in Figure 5.



a: (from [21])



b: (from [18])

Figure 6. Whole body thermal state influence on local sensation (horizontal axis is the thermode temperature, which represents local skin temperature)

2.3.3. Mathematical description

The above examples show that local sensation is modified by the whole-body thermal state, and that this needs to be incorporated into Eq. (2). As described above, the mean skin temperature difference from setpoint is more effective for defining stable thermal states than body core temperature. Since the exponent in Eq. (2), $-C1(T_{skin,i} - T_{skin,i,set})$, controls the slope of the logistic function, the whole-body modification needs to go into this part of the equation. The difference between the local and the whole-body thermal states is described as $(T_{skin,i} - T_{skin,i,set}) - (\overline{T}_{skin} - \overline{T}_{skin,set})$, so we modify the exponent as follows:

$$\text{Local Sensation}_{\text{static}} = 4\left(\frac{2}{1+e^{-C1(T_{skin,i}-T_{skin,i,set})-K1\left[(T_{skin,i}-T_{skin,i,set})-(\overline{T}_{skin}-\overline{T}_{skin,set})\right]}}-1\right) \qquad \text{Eq. (3)}$$

where the term $-K1[(T_{skin,i} - T_{skin,i,set}) - (\overline{T}_{skin} - \overline{T}_{skin,set})]$ (alternatively written as $-K1[(T_{skin,i} - \overline{T}_{skin}) - (T_{skin,i,set} - \overline{T}_{skin,set})]$) represents the modifying effect of whole-body thermal status on local sensation. When the difference between local and mean skin temperatures equals the difference of their set points ($T_{skin,i} - \overline{T}_{skin} = T_{skin,i,set} - \overline{T}_{skin,set}$), then the contribution from whole-body thermal sensation is zero. When the term is not zero, the curve will be shifted up or down. The positive sign of the whole-body term: $K1(\overline{T}_{skin} - \overline{T}_{skin,set})$, counteracts the local temperature difference from its setpoint: $-C1(T_{skin,i} - T_{skin,i,set})$. A warmer whole-body sensation produces a cooler local sensation at any given local skin temperature.

The coefficient K1 is specific for each body part. It is different for the warm and cold sides of neutral, as described below.

2.4. Impact of warm-cold asymmetry in the (local sensation / skin temperature) function
Figures 3 and 5 show that the range of skin temperature change on the cold side of neutral is much greater than that on the warm side. This is expected. When a hand is vasoconstricted in a cold environment, the skin temperature can be 20K below its set point (~33ºC). In a hot environment, hand skin temperature will only increase via vasodilation to 37ºC, close to the core temperature. Sweating will keep the skin and core temperatures from increasing beyond this. Therefore, there should be two equations for the cold and warm sides, with different coefficients of C1 and K1 to capture the asymmetrical temperature ranges.

Figure 7 shows the form of the model, for a range of whole-body states. Since the cold curves are inherently more distinct, the curves should be generated by stepwise logistic regression from the cold to the warm side, fitting the origin of the warm curves so that they equal the neutral endpoints of the cold curves.

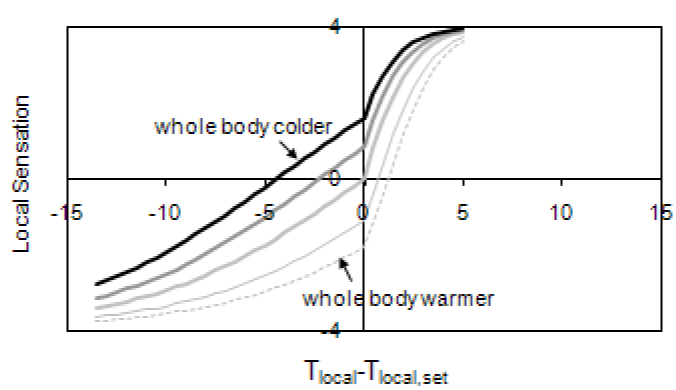


Figure 7. Final steady-state local sensation model

2.5. Coefficients for the static part of the model

Fitting Equation 3 with our data, we obtained separate regression coefficients C1 and K1 for the left (local cooling, $T_{skin,i}$ - $T_{skin,i,set}$<0) and right (local warming, $T_{skin,i}$ - $T_{skin,i,set}$>0) sides of Figure 7. The results are shown in Table 1. The coefficients (C1 and K1) are listed separately for local skin temperatures higher or lower than their set points. The different K1 values for cool (left) and warm (right) sides are responsible for the different degrees of steepness on the two sides as seen in Figures 3 and 7. The R^2 and N for the combined cool and warm regression fits are included.

Table 1. Regression coefficients for Eq. (3) – steady-state model of local sensation in asymmetrical environments

Body part *(thermocouple measurement location)*	$T_{skin,i} - T_{skin,i,set} <0$ (local body part cool)		$T_{skin,i} - T_{skin,i,set} >=0$ (local body part warm)		R^2	N
	C1	K1	C1	K1		
Head *(forehead)*	0.4	0.2	3.9	0.2	0.55	136
Face *(cheek)*	0.15	0.1	0.7	0.1	0.70	192
Breath *(cheek)*	0.1	0.2	0.6	0.2	0.58	136
Neck *(front neck)*	0.4	0.15	1.25	0.15	0.63	136
Chest *(upper left chest)*	0.35	0.1	1.0	0.1	0.67	172
Back *(upper left back)*	0.3	0.1	1.0	0.1	0.66	164
Pelvis *(front upper thigh)*	0.2	0.15	0.4	0.15	0.50	124
Upper arm *(lateral side of upper arm)*	0.3	0.1	0.4	0.1	0.72	124
Lower arm *(lateral side of lower arm)*	0.3	0.1	0.7	0.1	0.81	124
Hand *(back of hand)*	0.2	0.15	0.45	0.15	0.74	166
Thigh *(front upper thigh)*	0.2	0.1	0.3	0.1	0.50	142
Lower leg *(shin)*	0.3	0.1	0.4	0.1	0.62	142
Foot *(top of foot)*	0.25	0.15	0.25	0.15	0.76	180

2.6. Dynamic model for local sensation in transient conditions

The steady model described so far represents steady-state sensation, but underestimates the sensations observed when skin temperatures are rising or falling. For this a dynamic term is needed.

A typical example of sensation during cooling and rewarming is shown in Figure 8. Instead of following the logistic curve, votes (diamonds) jumped as cooling was first applied and then removed, due to the higher rate of signals from thermoreceptors experiencing change. The sensation is a function of the rate of skin warming or cooling.

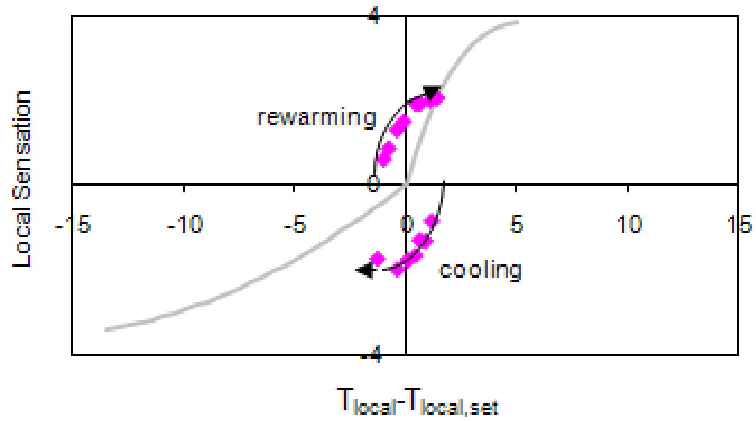


Figure 8. Dynamic local sensation

The transient local sensation model is:

Local Sensation = $Sensation_{static}$ + $Sensation_{dynamic}$ Eq. (4)

The static portion ($Sensation_{static}$) is the steady-state model as presented in Eq. (3). A dynamic portion ($Sensation_{dynamic} = C2\ dT_{skin,i}/dt + C3\ dT_{core}/dt$) is added to predict local sensation in transient conditions. As described above, the derivative of core temperature is better for calculating the dynamic term for local sensation than the derivative of mean skin temperature.

Table 2 shows the dynamic model for each body part. The regressions were performed separately for negative and positive derivatives of skin temperature, represented by two coefficients C21 and C22 respectively. A positive derivative means that the body part is experiencing local heating, and a negative derivative means that the body part is experiencing local cooling. In Table 2, $dT_{i\ skin}/dt^{(+)}$ is used when $dT_{i\ skin}/dt \geq 0$, meaning the local skin temperature is increasing, and $dT_{i\ skin}/dt^{(-)}$ is used when $dT_{i\ skin}/dt \leq 0$, meaning the local skin temperature is decreasing.

When the derivative of skin and core temperature is zero, the body is in a steady-state condition. The dynamic portion of the model is zero, and the local sensation is predicted by the steady- state model (Eq. 3).

The tests show that the core temperature immediately increases when certain influential body parts (chest, back, and pelvis, and face) are cooled [13, 15]. The increase is reflected in the negative coefficients for the derivative of the core temperature. For other segments, the influence of the core temperature derivative is not significant and the coefficients are zero.

Table 2. Dynamic model as a function of the derivatives of skin and core temperatures ($Sensation_{dynamic} = C21\ dT_{skin,i}/dt^{(-)} + C22\ dT_{skin,i}/dt^{(+)} + C3\ dT_c/dt$)

Body part *(thermocouple measurement location)*	C21	C22	C3	R^2	N
Head *(forehead)*	543	90	0	0.64	260
Face *(cheek)*	37	105	-2289	0.74	500
Breath *(cheek)*	68	741	0	0.92	220
Neck *(front neck)*	173	217	0	0.80	260
Chest *(upper left chest)*	39	136	-2135	0.61	340
Back *(upper left back)*	88	192	-4054	0.73	300
Pelvis *(front upper thigh)*	75	137	-5053	0.86	260
Upper arm (lateral side of upper arm)	156	167	0	0.74	240
Lower arm (lateral side of lower arm)	144	125	0	0.77	240
Hand (back of hand)	19	46	0	0.90	340
Thigh (front upper thigh)	151	263	0	0.94	200
Lower leg (front shin)	206	212	0	0.85	200
Foot (top of foot)	109	162	0	0.55	360

During sudden environmental changes, skin temperature derivatives can be very large. Examples of physiological changes seen in this project may be seen in [15], and the resulting dynamic overshooting of local sensation responses may be seen in [3].

2.7. The complete local thermal sensation model

Equation 5 combines the steady state and dynamic local thermal sensation models. There is one of these for each body part.

$$Sensation_i = 4\left(\frac{2}{1+e^{-C1(T_{skin,i}-T_{skin,i,set})-K1\left[\left(T_{skin,i}-\dddot{T}_{skin}\right)-\left(T_{skin,i,set}-\dddot{T}_{skin,set}\right)\right]}}-1\right) + C2_i\frac{dT_{skin,i}}{dt} + C3_i\frac{dT_{core}}{dt} \qquad \text{Eq. (5)}$$

3. Validation of the local thermal sensation model

Validation was done against an entirely separate set of 64 tests in a real vehicle situated in an automobile company wind tunnel facility (Figure 9). The vehicle interior environments were highly asymmetrical and transient, and therefore appropriate for validation. The wind tunnel was conditioned to summer and winter conditions, ranging from -7 to 43°C, with and without solar radiation. The subjects wore summer and winter clothing (approximately 0.5 and 1.0 clo). After 5 – 10 minutes outside the car, they sat inside for 45 minutes. During that time, they could adjust the air-conditioner according to their preferences, meanwhile answering every 2 minutes thermal questions similar to those used to develop the model in the Berkeley chamber tests. The local skin temperature (Figure 1) and core temperature measurements (radio pill) were also the same as in the chamber tests, but there was only one measurement representing the head.

Figure 9. Subjects in a car in the automotive wind tunnel

The validations for summer and winter tests are presented in Table 3. The validation R^2 and the standard deviation of residuals (SD, in thermal sensation scale units) are also included. In total, there are 160 data sets used in the validation of each of the ten body parts.

Table 3. Validation for automotive tests (driver)

Body part	summer		winter	
	R^2	SD	R^2	SD
Face	0.70	0.58	0.40	0.62
Chest	0.65	0.63	0.36	0.75
Back	0.34	0.68	0.32	0.61
Pelvis	0.30	0.70	0.69	0.38
Upper arm	0.65	0.61	0.60	0.54
Lower arm	0.65	0.57	0.58	0.62
Hand	0.55	0.58	0.65	0.61
Thigh	0.76	0.59	0.36	0.60
Lower leg	0.74	0.45	0.53	0.57
Foot	0.66	0.55	0.30	0.65

In laboratory and field studies, the intrapersonal variation in measured thermal sensation is about one scale unit, so these prediction results seem reasonable.

4. Discussion

The model was developed from human subject tests in which air was used to cool or heat each body part. However, the model can be applied for other modes of heat transfer because it correlates sensation to skin and core temperatures, not to the environmental surroundings. This is appropriate in that the body's thermoreceptors detect tissue temperature, not the temperature of the surrounding environment.

It requires a huge number of tests to cover a full range of test conditions for each body part. In this project, we could only carry out a subset of possible test conditions, focusing more on cooling the local body in warm environments than on warming it in cool environments. The experiments were done with cooling supply air temperatures that produced fairly rapid rates of skin temperature change. In the future it would be desirable to perform additional tests of warming in cool environments, and of cooling at more gradual rates than were done here.

The model was developed and validated with data from sedentary subjects. We cannot judge its applicability at higher activity levels. The subjects did sweat when warm, so the effects of sweating are included in the model's coefficients, and the validation shows the model may be applied when there is some degree of sweating.

If this sensation model is incorporated into a computer model of thermal physiology, the skin and core temperatures and their setpoints may all be calculated values. We have observed that with our physiology model, accurate setpoint determination requires running a neutral condition for a minimum of five hours.

The model structure is rationally based in that its components explain the processes involved. Its coefficients may be readily tested and modified to represent a wide range of possible environmental conditions, without changing the model form. We hope people will do this as more data become available in the future.

5. Conclusion

This paper describes a model of local sensation, together with coefficients representing in total 19 individual body parts. Local sensation is a function of both local and overall (whole-body) skin temperature, and the rate of change over time of local skin temperature and body core temperature. 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 these test data to develop the coefficients, and validated the model using separate tests in an automobile testing facility. The final model reproduces each of the major effects that we have observed about human thermal sensation responses to thermal environments.

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