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THERMAL ACCEPTABILITY

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ABSTRACT

The effects on occupants from temperatures that deviate from those of optimum comfort can be predicted by various methods (PPD, percent comfortable, percent thermally acceptable). Though the various acceptability criteria are different, the results are quite similar. A generalization is that a 2.5° C temperature deviation from optimum where acceptability is about 95% will decrease acceptability to about 80%. The optimum temperature for office spaces away from perimeter areas is mainly a function of the occupant's clothing which is influenced by or chosen for the season and outside conditions.

INTRODUCTION

For purposes of energy and cost savings it is sometimes necessary to control environments to conditions that deviate from those of optimum thermal comfort. How these deviations affect the building's population is important to the building designer, owner and operator. Fortunately, as a result of extensive experimental testing, primarily at Kansas State University, the Pierce Foundation Laboratories and the Technical University of Denmark, the relationship between a person's thermal sensations and environmental parameters is fairly well defined. A typical thermal sensation scale is listed in Table 1. Equations have been developed to relate the thermal sensations experienced under test conditions of sedentary and active subjects to the thermal conditions (1, 2). Further, through various thermal physiological modeling techniques the experimental thermal sensation results can be extended and applied over a rather wide range of conditions (3).

TABLE 1. A Standard Thermal Sensation Scale

thermal sensation	numerical code
hot	+3
warm	+2
slightly warm	+1
neutral	0
slightly cool	-1
cool	-2
cold	-3

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Perhaps more important than thermal sensation is the question of how an alteration in the environment will affect the thermal acceptability of the space or change the percentage of persons dissatisfied with the environment. A person feeling slightly cool or warm may not be dissatisfied or uncomfortable and the environment may still be thermally acceptable. Therefore, procedures to quantify and predict or assess these more integrated feelings of occupants have been investigated. It is the purpose of this paper to compare the recent methods for quantifying the acceptability of an environment.

PREDICTED PERCENT DISSATISFIED - FANGER

Working with the thermal sensation responses from 1300 Kansas State University (KSU) and Danish subjects, Fanger developed a method to predict the percentage of persons dissatisfied with an environment (4). It has become the most widely used method of estimating occupant acceptability.

Fanger reasoned that an individual whose thermal sensation is warmer than slightly warm (+1) or cooler than slightly cool (-1) will be dissatisfied with the environment and be likely to complain. For every test group he determined the average thermal sensation and the percentage of subjects in that group that had thermal sensations beyond ± 1. The final results are illustrated in Fig. 1. Thus from knowing or being able to predict the mean thermal sensation of an environment, one is able to estimate the percentage expected to be dissatisfied (PPD). Fanger, with his Comfort Equation, had previously developed a method of predicting the mean thermal sensation, called Predicted Mean Vote (PMV), from environmental parameters. At a PMV of neutral the PPD reaches a minimum of 5% dissatisfied. As the environment deviates from this condition of optimum thermal comfort the dissatisfaction increases. At a group mean sensation of slightly warm or slightly cool the PPD is 27% and when the mean sensation has reached warm (+2) or cool (-2) the predicted percent dissatisfied is about 77%.

PREDICTED PERCENT DISSATISFIED - ROHLES

Using the dissatisfaction criteria of Fanger and similar methods, Rohles et al. (5) determined the predicted percent dissatisfied relationship for 1600 subjects exposed in groups of 10 for 3 h to 20 air temperatures and 8 humidities. Rohles chose to display the PPD results (Fig. 2) in terms of the new effective temperature scale (ET*) or the temperature of a 50% RH environment whose air movement is equal to or less than 0.15 m/s. The subjects wore a standard uniform of a long sleeved shirt and trousers (0.6 clo). Between 20 and 32° C, mean thermal sensations (TS) can be determined for this environment by the following regression equation

$$TS = 0.325\ ET^* - 8.444 \qquad (1)$$

In Fig. 2, the minimum PPD is 4% at 25.3° C where the regression equation predicts a thermal sensation of -0.2 or very close to neutral. At temperatures less than this, PPD increases faster than for temperatures above 25.3°C. Using the regression equation to determine ET* for slightly warm (29°C) and slightly cool (22.9°C) sensations, the corresponding PPD's are 30 and 26%. When the mean thermal sensation is warm (33°C) and cool (18.9°C) the PPD is 80 and 90%. Thus the PPD relationship determined independently by Rohles compares closely to Fanger's.

PERCENT COMFORTABLE

More recently Gagge et al. (6) completed a survey of a New York City high rise office building for the FEA and obtained data relating the comfort judgment to air temperature and thermal sensation under actual working conditions. During the winter of 1975, comfort observations from 492 of the building's working occupants were obtained as well as measurements of the thermal properties of their microenvironments and estimates of their clothing insulation and activity levels. The occupant questionnaire included the standard thermal sensation scale and a comfort scale with categories: comfortable, slightly uncomfortable, uncomfortable and very uncomfortable. In the analysis, the comfortable and slightly uncomfortable responses were lumped together to determine the percent comfortable of all responses. The clothing insulation averaged 0.85 clo as determined by the Sprague-Munson technique (7). A regression analysis of the thermal sensations yielded the following correlation of thermal sensation to air temperature.

$$TS = 0.48T_a - 12.1 \tag{2}$$

The percent comfortable data is plotted against air temperature in Fig. 3. The maximum percent comfortable for this study from Fig. 3 is about 93% and occurs when the mean thermal sensation is - 0.6 or slightly to the cool side of neutral. The minimum PPD found by Rohles also occurred on the cool side of neutral.

THERMAL ACCEPTABILITY

In the studies of occupant responses to slow temperature drifts, Berglund and Gonzalez (8, 9) employed a ballot with the standard thermal sensation scale and the question:

Is the present environment thermally acceptable?

_______ yes

_______ no

An example of the results for subjects wearing typical clothing is presented in Fig. 4, where it can be seen that minimum discomfort corresponds to maximum thermal acceptability and to a neutral temperature sensation. Furthermore, there is a region near neutral in which thermal acceptability is rather insensitive to air temperature. The mean thermal acceptability and thermal sensation data from all of the drift experiments are presented in Fig. 5. A best fit 3rd degree polynomial equation derived from the data is also drawn on Fig. 5. The acceptability is not completely symmetrical to neutral as thermal acceptability decreases faster on the cool side of neutral than on the warm. The multiple linear regression equation from this study that relates the mean thermal sensation to clothing level and temperature is:

$$TS = 0.305\,T + .996\ clo - 8.08 \tag{3}$$

The equation has a multiple correlation coefficient (R) of 0.95.

COMPARISON

The conditions of the various tests described were different but the investigators all used the same thermal sensation scale for subject responses. Therefore, thermal sensation is a convenient parameter with which to compare the acceptability measures. In Fig. 6, PPD by Fanger, PPD by Rohles, percent comfortable and the best fit equation for percent thermally acceptable are all plotted against thermal sensation. For the plotting of Fig. 6, the ET* or T_a scales of Fig. 2 and 3 were converted to thermal sensation by the respective investigators' thermal sensation regression equations.

The PPD curves developed independently by Fanger and Rohles are very similar with only small differences near neutral and on the warm side. Both investigations were done in test chambers and the subjects were not asked if they were dissatisfied with the environment. Instead, the investigators reasoned that individual votes beyond ± 1 represented dissatisfied people.

However, in the percent comfortable relationship of Gagge, the office workers were asked to indicate their comfort as well as thermal sensation. The shape of this curve is similar to those for PPD, but it is displaced slightly to the cool region. The percent thermally acceptable curve was also determined by actually asking subjects if the environment is thermally acceptable or not. This curve is the least sensitive of the various acceptability measures to thermal sensation near neutral.

Table 2 compares in tabular form the thermal sensations at the 80 and 90% satisfaction levels indicated by the various scales.

TABLE 2. Thermal Sensations Corresponding To The Various Measures of Acceptability

	90%		80%	
	cool	warm	cool	warm
% thermally acceptable	-0.8	+1.	-1.2	+1.35
% comfortable	-0.9	-0.4	-1.4	+0.15
100 - PPD (Fanger)	-0.5	+0.5	-0.8	+0.8
100 - PPD (Rohles)	-0.55	+0.3	-0.85	+0.7
Average of above	-0.69	+0.35	-1.06	+0.75

The percent thermally acceptable and percent comfortable functions are quite similar for cool sensations. Of all the acceptability measures, the percent thermally acceptable permits the largest variations in thermal sensation.

What then are the temperature ranges for a given level of thermal environmental satisfaction? In a given environment a person's thermal sensation is determined by his clothing and activity as well as by humidity, temperature, thermal radiation and air velocity. The air movement indoors is typically 0.15 m/s or less and small variations about this point are inconsequential. In nonperimeter areas of an office the mean radiant temperature is very close to air temperature. Humidity also has only a small effect in the comfort region. The activity level of indoor occupants is near sedentary for most situations. But clothing is an important modifier of the environment and people's dress is influenced by the outside weather and season of the year (6). Using clothing insulation levels of typical office workers in the summer (0.5 clo), spring-fall (0.7 clo) and winter (0.9 clo), the temperature ranges for 80% acceptance can be determined by each method. These are given in Table 3. The neutral sensation for these clothing levels and conditions occurs at about 24.9, 24.2 and 23.5° C (10). The Fanger and Rohles functions are so similar only the PPD by Fanger is presented in Table 3.

The temperature limits for the percent thermally acceptable criteria are the widest of the three in Table 3 as would be expected from Fig. 6 and Table 2. This may be partly because the data were gathered during slowly drifting temperatures rather than during static conditions as with the other measures. In these studies, Berglund and Gonzalez (8) observed response lags during the first hour of the drift experiments. The lagging may account for some of the differences between methods and one should be cautious in using the thermal acceptability limits determined during temperature drifts for static conditions.

SUMMARY

The effects on occupants from temperatures that deviate from those of optimum comfort can be predicted by various methods. Though the various acceptability criteria described are different, the results are quite similar. A generalization from Table 3 is that a 2.5° C temperature deviation from optimum where acceptability is about 95% will decrease acceptability to about 80%. The optimum temperature for office spaces is mainly a function of the occupant's clothing which is influenced by or chosen for the season and outside conditions.

TABLE 3. Seasonal Temperature Limits For 80% Acceptance In Office Spaces By The Various Methods

Season	Method	Temperature range for acceptance ≧ 80%
Summer ≈ 0.5 clo*	% thermally acceptable	22.2 - 29
	% comfortable	23.5 27
	PPD	23.8 28.2
	Average	23.2 28
Spring-Fall ≈ 0.7 clo*	% thermally acceptable	21.7 28.5
	% comfortable	22.9 26.2
	PPD	22.2 27.5
	Average	22.2 27.4
Winter ≈ 0.9 clo*	% thermally acceptable	20.2 27.9
	% comfortable	20.9 24.2
	PPD	20.7 26.7
	Average	20.6 26.3

* by Sprague-Munson technique (7).

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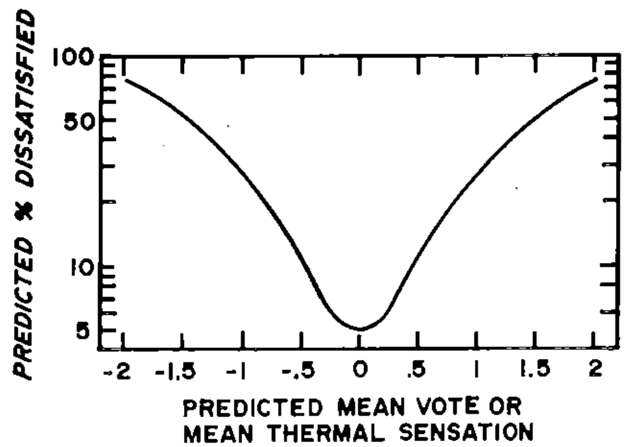

Fig. 1 Relationship between predicted percent dissatisfied and predicted mean vote by Fanger (4)

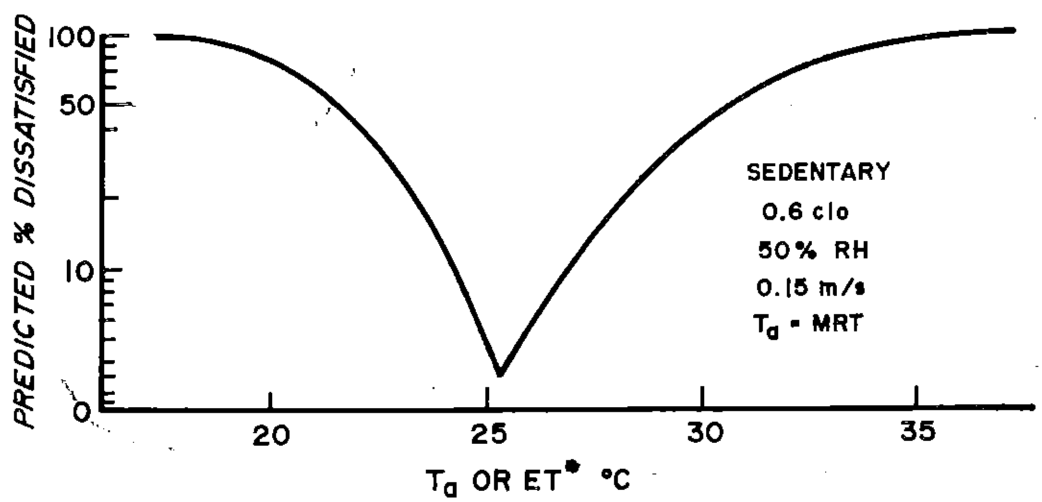

Fig. 2 Predicted percent disatisfied relationship to temperature by Rohles et al. (5)

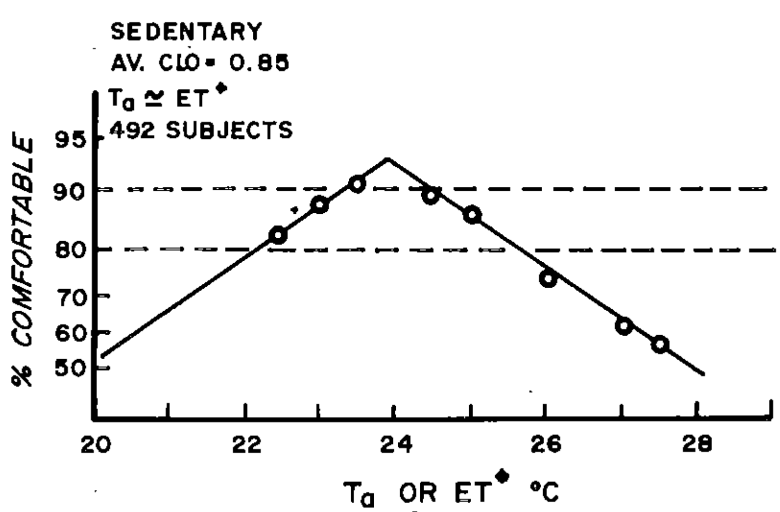

Fig. 3 Percent comfortable results from survey of a New York City high-rise office building

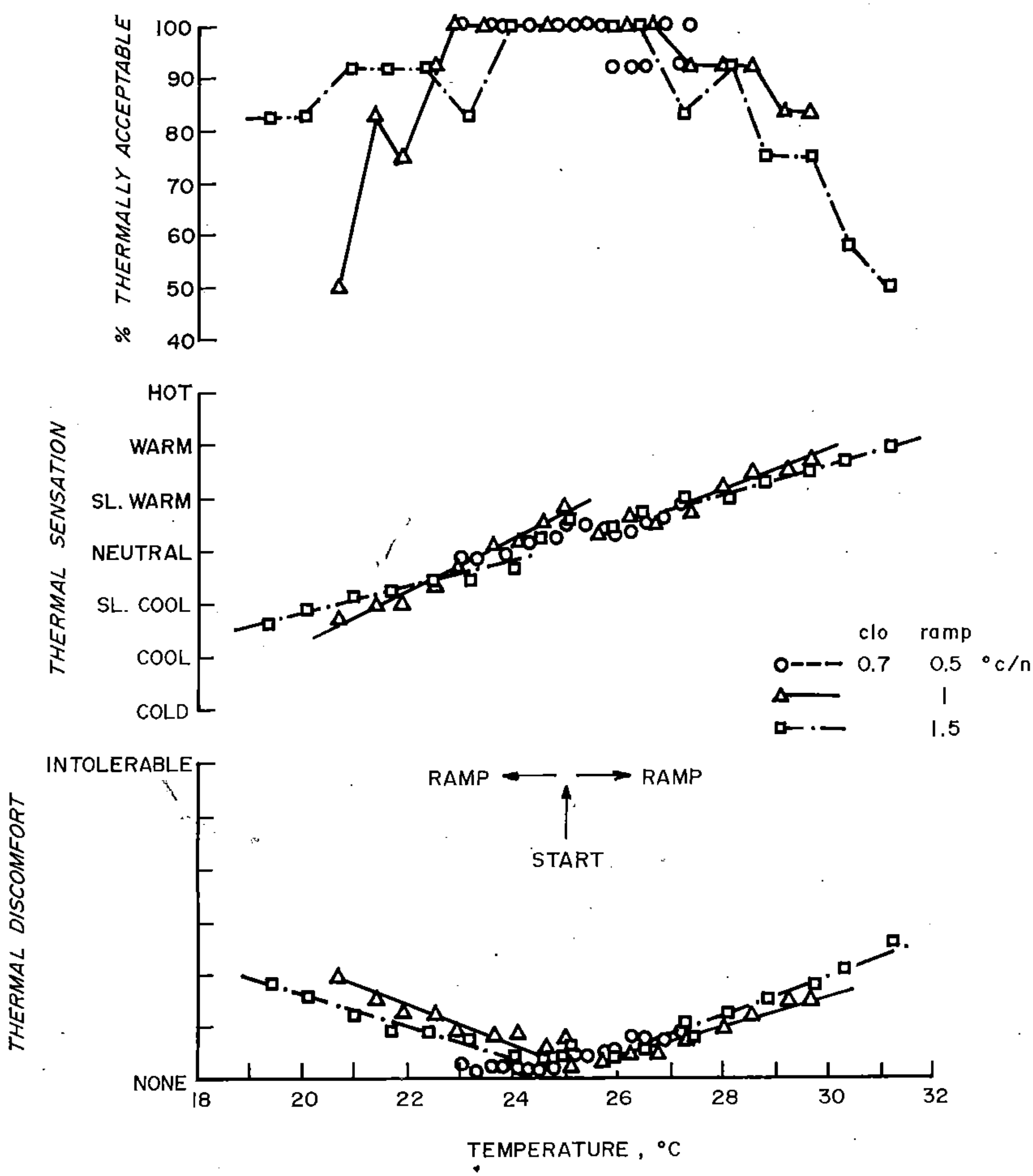

Fig. 4 Mean responses of subjects wearing normal office clothing

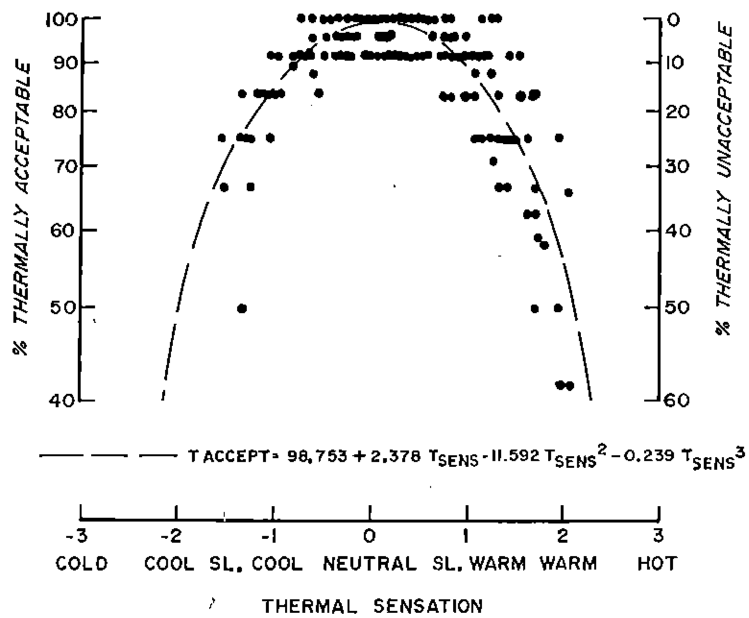

Fig. 5 Mean thermal acceptability and thermal sensation votes

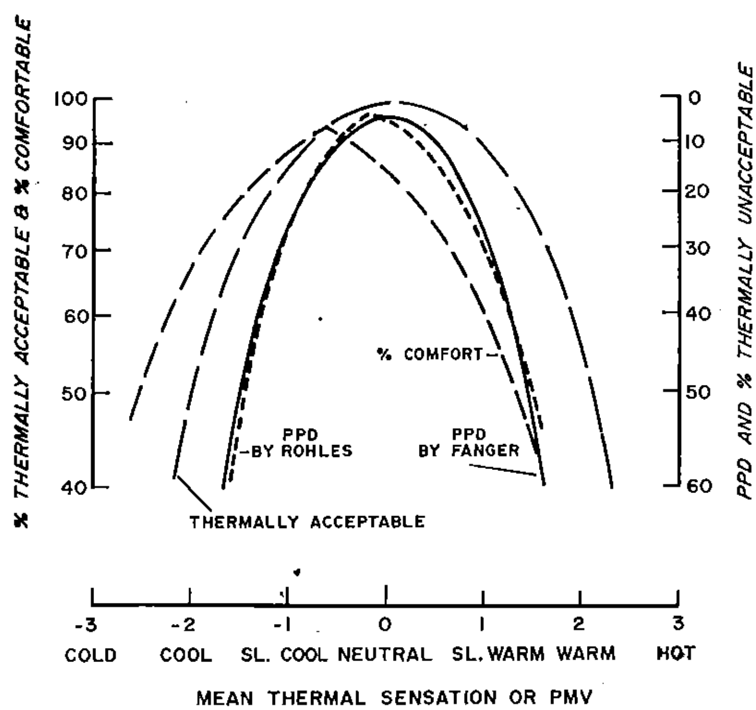

Fig. 6 Comparison of the various acceptability measures

DISCUSSION

P.O. FANGER, Prof., Technical Univ. of Denmark, Lyngby, Denmark: Dr. Berglund should be complimented for establishing a useful comparison between different studies on thermal comfort and acceptability.

As stated by the author, the wider range of acceptable temperatures found by Berglund and Gonzalez may be casued by the steadily increasing or decreasing temperatures in their experiments compared to the steady-state conditions in the other studies. Further studies relating acceptability to thermal sensation during steady-state conditions would be useful.

The present paper discussed the acceptability of different ambient temperature levels. But it should be remembered that a thermal environment may be unacceptable although the temperature level in the space is right. An environment may be unacceptable if the body somewhere is exposed to an uncomfortable local heating or cooling. This may be caused by a too high local velocity (draft), by a too warm or cool floor, by a too asymmetric radiant environment, or by a too large vertical air temperature gradient. In practice these factors should be considered as well as the ambient temperature level.

L.G. BERGLUND: Thank you for the comment. The thermal sensation and thermal acceptability results discussed in this paper were obtained in thermally uniform environments. Non-uniform conditions, as you point out, can cause local discomfort and detract from the level of thermal acceptability in the space. Thus, if asymmetric radiation, draft or temperature gradients are present the temperature ranges for 80% acceptability would be expected to be narrower than those presented here.