3371 (RP-462)

4729

A COMPARISON OF MEASURED AND PREDICTED COMFORT IN OFFICE BUILDINGS

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ABSTRACT

The objective of this paper is to determine the extent to which theoretical and laboratory-based equations accurately predict workers' thermal responses in existing office buildings. It also compares both direct and indirect assessments of comfort in these buildings to examine the validity of associating thermal comfort with thermal neutrality. Measured data are based on ASHRAE RP-462, a field study of 10 San Francisco Bay Area office buildings in which physical measurements and subjective responses were collected during 2342 visits to workers. Thermal sensation predictions are based on several models referenced in the literature, including PMV as cited in Fanger (1970) and in ISO Standard 7730 (ISO 1984), another version of Fanger's PMV as cited in Gagge et al. (1986), and TSENS as cited in Pierce (1987) and Doherty and Arens (1988). The ASHRAE RP-462 data are also compared to measurements from other field studies, including Gagge and Nevins (1976), Fishman and Pimbert (1978), Howell and Kennedy (1979), Howell and Stramler (1981), and Dedear and Auliciems (1985). The best agreement between measured and predicted thermal sensation was in the region near neutral, while predictions consistently underestimated the warm thermal sensations. Neutral temperatures and optimum acceptability were both lower in the office environments when compared to laboratory measurements. Results also suggest that workers voting within the extreme thermal sensations were not always simultaneously dissatisfied, and that feelings of discomfort were more often associated with a sense of warmth as compared to coolness.

INTRODUCTION

Approximately one-third of the United States' energy use is consumed by buildings, with a majority of that energy due to the costs of mechanically heating, cooling, and lighting the interior environments. Although modifying the conditions at which we maintain the indoor thermal environment may result in both energy and cost savings, it is not always clear how deviations from optimum thermal conditions may affect the occupants' comfort, health, or productivity. The effect of the thermal environment on worker productivity becomes a particularly important issue when one recognizes that the total salaries of workers in office buildings are one to two orders of magnitude higher than the energy operating costs.

Thermal comfort is a particularly complex issue in the office environment, where trends in office design and environmental control systems raise important questions regarding potential conflicts with individual needs of the occupants. Several surveys of worker comfort in the office environment have received attention during recent years (Harris 1978, 1980; Brill 1984; BOMA 1985; Trane 1985). These studies produced a range of interesting findings, and all of them identified lack of temperature control as one of the most important complaints in existing office buildings. These studies were limited, however, because they did not include physical measurements of the thermal environments in the buildings during the time of the surveys. Humphreys (1976) gives a worldwide summary of a large number of thermal comfort field studies performed over many years, all combining physical measurements and subjective questionnaires. Gagge and Nevins (1976), Fishman and Pimbert (1978), Howell and Stramler (1981), Dedear and Auliciems (1985), and Schiller et al. (1988) report on several of the largest recent studies of this type.

Standards for maintaining comfortable indoor thermal environments have been developed by ASHRAE and the International Standards Organization (ISO). ASHRAE's Standard 55-81 (ASHRAE 1981) and ISO's Standard 7730 (ISO 1984) are both based on a strong foundation of extensive research in laboratory facilities. Equations have been developed, based on these experiments, to predict the average thermal sensation felt by a large group of people exposed to a given set of thermal conditions. The mathematical models for predicting thermal sensation use a combination of theoretical and empirical equations describing (1) the heat exchange between the human body and the environment, (2) the physiological thermoregulation mechanisms of the body, and (3) the relationship between people's thermal sensation (a psychological response) and the physiological thermal strain on the body due to environmental and personal conditions. The expressions predicting the average thermal sensation felt by a large group of people are based on experiments conducted in carefully controlled laboratory conditions. In these experiments, clothing and activity are typically constrained to selected values, the key thermal variables (air tem-

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perature, humidity, air velocity, mean radiant temperature) are either held constant or varied over a specified range, and the subjects report their thermal sensation and other responses on commonly used scales.

In addition to estimating a group of people's average response to a given thermal environment, the acceptability of that environment is often described in terms of the percentage of people expressing dissatisfaction. A common approach involves an *indirect* assessment of acceptability by assuming that certain votes on the thermal sensation scale (slightly cool, neutral, slightly warm) correspond to satisfaction, while others (cold, cool, warm, hot) correspond to dissatisfaction (Fanger 1970). Both ASHRAE Standard 55-81 and ISO Standard 7730 are based on this assumption, which implies that a "neutral" thermal sensation is considered to be the optimum. However, it is possible that, for some people, sensations outside the range of the three central categories may also be considered to be "comfortable."

The primary advantages of laboratory experiments such as those used as the basis of the standards is the ability to provide consistent, precisely controlled, and easily measured thermal conditions. However, one of the major shortcomings of laboratory studies is the artificiality of the conditions under which the data are collected. Laboratory subjects are not in their familiar surroundings or engaged in their usual work activities during the period of testing. As a result, they may perceive and accept the thermal environment atypically, influencing the study's results. A field study avoids this potential problem by investigating people's thermal response in their normal working conditions.

ASHRAE recently sponsored a research project (RP-462) in which an interdisciplinary research team developed procedures for assessing thermal environments and occupant comfort in existing office buildings and conducted a field study in 10 San Francisco Bay Area office buildings during the winter and summer seasons of 1987 (Schiller et al. 1988). This paper compares the data collected in these office buildings to comfort predictions cited in the literature and to data from other field studies. The objective of this paper is to determine the extent to which theoretical and laboratory-based equations accurately predict workers' responses in real office buildings. It also compares both direct and indirect assessments of comfort in these buildings to examine the extent to which thermal comfort is associated with thermal neutrality.

METHODS

Data Collection Procedures

The 10 buildings used in this study were chosen to obtain a varied, but representative, sample of existing office buildings in the San Francisco Bay Area. After obtaining permission from the building manager at each site to conduct the study, volunteers were recruited through a written invitation circulated by a contact person in the office. Each building was measured for a week during the 1987 winter season and again the following summer. A total of 2342 visits (1308—winter, 1034—summer) to 304 participants in the 10 buildings were made during the two seasons. The subjects comprised 187 females (62%) and 117 males (38%). Of the 261 participants who provided detailed demographic data, 76% were within 20 to 40 years of age, and 81% were Caucasian.

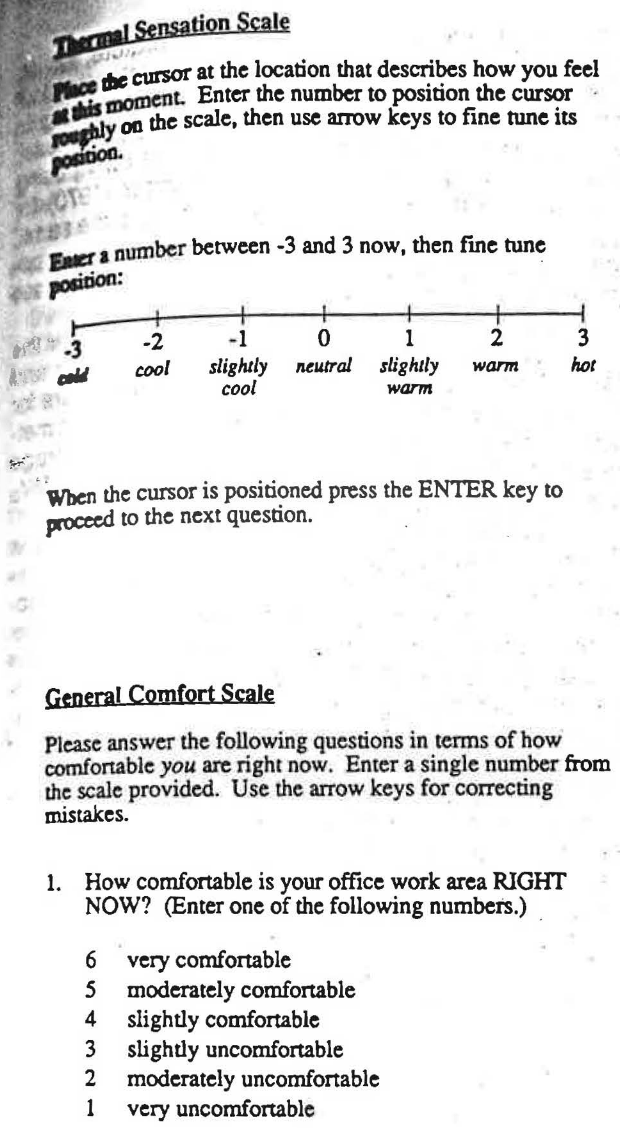
The volunteers first filled out a background survey, including 135 fields of data addressing demographic information, health characteristics, environmental sensitivity, characteristic emotions, personal vs. comparative comfort, office description, work area satisfaction, and job satisfaction. Each participant was then visited at his or her desk five to seven times during the course of the measurement week. At each visit, the worker completed a thermal assessment survey, administered through an interactive program run on a battery-powered laptop microcomputer. The computer-based survey included 53 fields of data addressing thermal sensation, thermal preference, comfort, mood, clothing, and activity.

After completing the survey, the worker stepped away from the desk and a mobile measurement cart was placed directly at the workstation, replacing the chair on which he or she had been sitting. Instruments on the cart were located at three heights (representing ankle, mid-body, and head/neck), and measurements included air temperature, dew point temperature, globe temperature, air velocity, radiant temperature asymmetry, and illuminance. Mean radiant temperature was calculated for each visit based on these measurements.

Detailed descriptions of the data collection methods, surveys, and instrumentation are presented by Schiller et al. (1988) and Benton et al. (1990). This paper will describe only the survey questions and physical measurements used in the analyses reported here.

Thermal Assessment Survey

The seven-point ASHRAE Thermal Sensation Scale, which has been widely used in comfort research to assess thermal sensation, asks the subjects to rate their current feelings of warmth using graded categories ranging from cold to neutral to hot. We used a continuous form of this scale showing both numbers and their associated adjectives (Figure 1). The subject could move a computer cursor between −3 and +3, the selected position being encoded in 0.1 increments. In this paper, measured values of thermal sensation based on the ASHRAE scale are termed TS. In using the ASHRAE Thermal Sensation Scale to assess thermal comfort, we adopted the conventional approach of regarding the central three categories of the scale (slightly cool, neutral, and slightly warm) as indicating a comfortable state. It was then assumed that only people voting outside these central categories (cold, cool, warm, hot) were dissatisfied with their thermal state. Because we used a continuous form of the Thermal Sensation Scale, percent dissatisfaction was calculated by counting the number of votes where



Thermal Sensation Scale

Place the cursor at the location that describes how you feel at this moment. Enter the number to position the cursor roughly on the scale, then use arrow keys to fine tune its position.

Enter a number between -3 and 3 now, then fine tune position:

-3	-2	-1	0	1	2	3
cold	*cool*	*slightly cool*	*neutral*	*slightly warm*	*warm*	*hot*

When the cursor is positioned press the ENTER key to proceed to the next question.

General Comfort Scale

Please answer the following questions in terms of how comfortable *you* are right now. Enter a single number from the scale provided. Use the arrow keys for correcting mistakes.

1. How comfortable is your office work area RIGHT NOW? (Enter one of the following numbers.)

6	very comfortable
5	moderately comfortable
4	slightly comfortable
3	slightly uncomfortable
2	moderately uncomfortable
1	very uncomfortable

Figure 1 *Thermal sensation and general comfort scales*

TS > 1.5. This approach was first proposed by Fanger (1970) and has been used in a wide variety of studies.

In addition to the commonly used Thermal Sensation Scale, the survey also collected direct comfort judgments using a six-point general comfort scale (1, 2, 3 = very, moderately, and slightly uncomfortable, and 4, 5, 6 = slightly, moderately, and very comfortable, respectively). The general comfort scale is shown in Figure 1. These data allow a comparison of both direct and indirect assessments of comfort to examine the appropriateness of the neutrality assumption in the office buildings studied.

A person's thermal response to a given set of environmental conditions is strongly influenced by clothing and activity. The thermal assessment survey included male and female versions of a clothing checklist, presenting an itemized list of garments and a four-point rating scale indicating the relative weight of each. An activity checklist also inquired about the worker's physical activity prior to taking the survey. Based on the responses to these questions, both total (ensemble) intrinsic clothing insulation (clo) and metabolic rate (met) were computed using procedures outlined in the ASHRAE Handbook of Fundamentals (ASHRAE 1985)[1].

Effective Temperature—ET*

The task of describing the thermal environment in terms of its effect on comfort is often simplified by using environmental indices combining two or more parameters into a single variable. In comfort research, effective temperature (ET*) is widely used as the independent variable describing the thermal environment, combining the effects of air temperature, humidity, and mean radiant temperature. It is useful because values of equal ET* represent constant physiological strain and thermal sensation, so that two environments having the same ET* should evoke the same thermal response. As such, it facilitates the comparison of results from studies conducted under different thermal conditions. ET* is defined as the uniform temperature of a radiantly black enclosure at 50% relative humidity, in which an occupant would experience the same comfort, physiological strain, and heat exchange from the skin as is actually occurring (Gagge et al. 1971). Values of ET* in the analyses presented in this paper were calculated based on a 60-minute exposure using a BASIC version of a Fortran program (Pierce 1987) described by Gagge et al. (1986).

Two methods were used for calculating ET*, each applicable to the different kinds of analyses presented here. For each of the 2342 visits to the office workers in this study, the computer program calculated ET* based on the *actual* measured physical parameters (air temperature, humidity, velocity, and mean radiant temperature) and the subject's clothing and activity levels obtained from the thermal assessment survey *for each individual.* In addition, the computer model was used to perform parametric calculations of predicted comfort indices for a range of ET* values. The range of ET* values was obtained by fixing values of vapor pressure (P_a) = 10.1 torr, velocity (V) = 0.1 m/s, and mean radiant temperature (MRT) = air temperature (T_a). These values are consistent with the *averages* of the data measured in the office buildings. Values of T_a were then varied to obtain the range of ET* values found in the office buildings (18° to 28°C).

Thermal Sensation Predictions

Thermal sensation predictions analyzed in this paper are based on several models cited in the literature. These models are formulated to predict the average response of a large group of people, rather than a single response from an individual. The comfort in-

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[1] Clo was calculated using Table 1C, and met was calculated using Table 4A, both in Chapter 8 of the 1985 *ASHRAE Handbook of Fundamentals* (ASHRAE 1985). Clo can also be calculated in exactly the same way using Table 2 in ASHRAE (1981) or Table 3 in Annex C of ISO (1984).

dices, and the models from which they came, are summarized as follows:

1. The original PMV and PPD, cited in Fanger (1970) and calculated using algorithms presented in ISO (1984);
2. A modified version of PMV (noted in this paper as PMV_G), cited in Gagge et al. (1986) and calculated using a computer program (Pierce 1987);
3. TSENS, cited in Gagge et al. (1986) and Doherty and Arens (1988), and calculated using the same computer program (Pierce 1987).

Descriptions and comparisons of the models and indices are given by Fanger (1970), Gagge et al. (1972, 1986), Berglund (1978), ISO (1984), and Doherty and Arens (1988). A brief description of the thermal sensation indices calculated in this paper is presented here.

PMV and PPD The most commonly used predictive indices of thermal sensation and acceptability are Fanger's Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD). Fanger (1970) developed the PMV model based on responses from 1300 subjects at universities in the United States and Denmark, combined with a steady-state heat balance model of the human body. PMV is an index that predicts the mean vote (thermal sensation) of a large group of people exposed to the same thermal conditions. The vote is based on the seven-point ASHRAE Thermal Sensation Scale shown in Figure 1. PMV is a function of the difference between the body's metabolic heat production and the body's heat loss, calculated with the skin temperature and evaporative sweat rate constrained to values corresponding to neutral thermal sensations at the given activity level. PPD is the predicted percentage of people expressing dissatisfaction with a given thermal environment, based on the assumption that thermal sensation votes of "warm" or "hot" (vote = 2, 3) or "cool" or "cold" (vote = −2, −3) imply dissatisfaction. When the PMV value has been determined for a given set of conditions, PPD can be calculated directly as a function of PMV, using an empirical equation developed by Fanger (1970).

ISO (1984) includes a computer algorithm for calculating PMV and PPD based on Fanger's equations, and it was used to calculate the values of PMV and PPD presented in this paper. The ISO program was used to perform parametric calculations of PMV and PPD over the range of ET* values found in the office buildings; the program does not itself calculate or use ET* directly. However, by using the same values of P_a, V, and MRT as used in the Pierce model runs, and varying T_a over the same values, the PMV and PPD calculations were matched to the ET* values. All calculations are for an ensemble clothing insulation of 0.55 clo and a metabolic rate of 1.12 met, corresponding to the average values measured in our study.

PMV_G and PPD_G A modified version of PMV was recently cited by Gagge et al. (1986), and is called PMV_G for the purpose of this paper. Although PMV_G uses the same algebraic form as Fanger's original PMV, the major difference is that dry heat transfer from the skin is calculated using skin temperature, T_{sk}, as calculated from Gagge's two-node model instead of Fanger's empirical equation for T_{sk} corresponding to neutral thermal sensation at the given activity level. PPD_G is then calculated as a function of PMV_G using the same equation developed by Fanger (1970) for calculating PPD from PMV. The equation is the same, but by using PMV_G as the input, the resulting calculation is also given the "G" subscript for the purposes of distinguishing it in this paper.

Both PMV_G and PPD_G were calculated over the range of ET* values found in the office buildings and for a 60-minute exposure time. All calculations are for an ensemble clothing insulation of 0.55 clo and a metabolic rate of 1.12 met, corresponding to the average values measured in our study. A description of PMV_G can be found in Gagge et al. (1986).

TSENS Another index of thermal sensation is TSENS, developed by Gagge et al. (1972) using responses from 1000 subjects tested in a university laboratory, and a two-node transient heat balance model of the body. According to the definition given in that paper, values of TSENS represent loci of constant temperature sensation, as observed after one hour's exposure. Several different empirical relationships for TSENS can be found in the literature. Some of the earlier equations calculate TSENS as a function of standard effective temperature (SET) and saturated vapor pressure at SET (P_{SET}*). Calculations in this paper used more recent equations, in which TSENS is calculated as a function of mean body temperature (Gagge et al. 1986; Pierce 1987; Doherty and Arens 1988). As for the previous indices, the Pierce model was used to calculate TSENS over a range of ET* values for 0.55 clo and 1.12 met.

RESULTS

Many different kinds of analyses were performed to compare measured and predicted comfort, and to examine the extent to which thermal comfort is associated with thermal neutrality. The methods used to calculate the predicted indices were presented in the previous section. To guide the reader through the discussion of results, the analyses that follow are summarized below:

Mean Thermal Sensation vs. ET—Measured vs. Predicted*

- measured and predicted mean thermal sensation as a function of the thermal environment, plotted as mean TS, PMV, PMV_G, and TSENS vs. ET*;

Thermal Acceptability vs. ET—Measured vs. Predicted*

- measured and predicted thermal acceptability as functions of the thermal environment, plotted as the measured percent dissatisfied, PPD, and PPD_G vs. ET*;

Thermal Acceptability vs. Mean Thermal Sensation—Measured vs. Predicted

- measured and predicted thermal acceptability as functions of mean thermal sensation, plotted as the measured percent dissatisfied and PPD vs. mean TS (or PMV);

Neutral Temperature—Measured vs. Predicted

- calculated values of neutral temperature for winter and summer using the measured regressions of TS vs. ET*, the PMV and PMV_G models, and acclimatization equations based on more than 50 field studies;

Thermal Sensation at Each Visit—Measured vs. Predicted

- correlations of workers' subjective judgments of thermal sensation (TS) to the calculated values of PMV_G and TSENS for each visit;
- coincident distributions of measured (TS) and predicted (PMV_G) thermal sensation using a frequency matrix;
- scatter plot and regression of mean TS vs. predicted PMV_G.

Thermal Sensation and Comfort—Examining the Neutrality Assumption

- frequency matrix of responses to both the thermal sensation and general comfort scales (*indirect* and *direct* assessments of comfort, respectively).
- average comfort votes for groups of people experiencing the same thermal sensation.

Mean Thermal Sensation vs. ET*—Measured vs. Predicted

A primary use of the predicted comfort indices is to examine how the average thermal sensation felt by a large group of people will change as the thermal environment varies. As such, it is useful to compare how both the *measured* mean sensation and *predicted* mean sensation each vary with changes in ET*.

The average clo and met of the occupants in the office buildings were similar in both seasons, and values are given below:

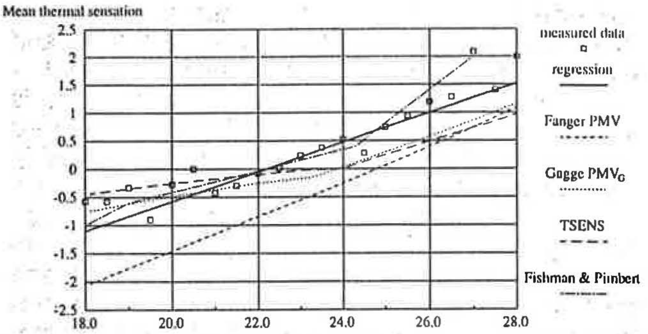
TABLE A

	Winter	Summer	Combined
mean clo	.58	.52	.55
mean met	1.12	1.13	1.12

Separate regressions for winter and summer were presented in Schiller et al. (1988) and were not significantly different between seasons. Because of the similarity of the seasonal clothing, activity levels, and the corresponding regression equations, a regression of mean thermal sensation vs. ET* was made here for the seasonal data combined. The mean TS as a function of thermal conditions was obtained by grouping all people experiencing the same ET*, and calculating the average of all TS votes in that group. The linear regression was weighted by the number of observations for each value of ET*. Mean TS for the combined winter and summer seasons can be described by the following regression equation:

$$mean\ TS = -5.83 + 0.26\ ET^* \quad (R^2 = .86) \qquad (1)$$

The regression line from the measured data is shown in Figure 2. The results of the ISO calculations of PMV and the Pierce model's calculations of PMV_G and TSENS are also shown in Figure 2, in addition to a curve from data collected in an office building by Fishman and Pimbert (1978).



Measured data is for a total of 2342 observations, with averages of 0.55 clo and 1.12 met. Regression is weighted by number of observations at each temperature. PMV, PMV_G, and TSENS calculations were also based on 0.55 clo and 1.12 met. ET*, PMV_G, and TSENS calculations were based on a 60-minute exposure time. Variations in ET* for the predicted curves were calculated by setting P_a = 10.1 torr, MRT = T_a, and V = still air, and varying T_a. Fishman & Pimbert curve is based on an analysis into proportions of median vote, as a function of globe temperature instead of ET*.

Figure 2 *Thermal sensation vs. ET**

Discussion The neutral temperature, T_n, is the temperature at which the mean thermal sensation of a large group of people is neutral (or a mean vote = 0 based on the ASHRAE Thermal Sensation Scale). Neutral temperatures can be determined by this graph at the point where the curves cross the neutral thermal sensation line, and are summarized below:

TABLE B

	T_n (°C)
measured regression	22.4
TSENS	23.8
Gagge PMV_G	23.9
Fanger PMV	24.8

Measured neutral temperatures were cooler than predicted by all of the indices, by 1.4° to 2.4°C. In an analysis presented later in this paper, measured and predicted neutral temperatures will be examined in more detail for winter and summer separately, and the potential effect of clothing and activity differences will be estimated.

Fanger's PMV consistently underpredicted thermal sensation by 0.5 to 1.0 units, with the difference being strongest at the cooler temperatures. The best agreement between our measured data and the prediction indices PMV_G and TSENS was found between 20°C and 23°C, the region near and slightly below the measured neutral temperatures. As conditions moved away from optimum, PMV_G and TSENS predictions were more conservative and office workers were voting at more extremes than predicted. This is particularly true above the neutral temperature, where PMV, PMV_G, and TSENS all underestimate warm thermal sensation. Gagge's PMV_G and TSENS were quite close to each other, particularly for the warmer temperatures, and both underpredicted thermal sensation by up to 0.5 units for temperatures of ET* above 24°C.

The slopes of TS, PMV, PMV_G, and TSENS are all fairly similar on the warm side of neutral, indicating that the workers' sensitivity to *changes* in the warm thermal environment was the same as predicted. Because there were relatively few observations on the cool side of neutral, it is difficult to assess whether the measured TS curves might begin to flatten out and follow the PMV_G and TSENS curves more closely.[2]

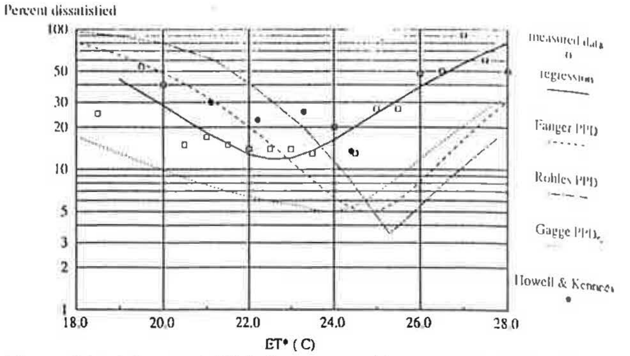
The slope of our measured regression line is slightly lower than the values of 0.30 to 0.33 obtained in other studies by Berglund (1979), Auliciems (1977), and Rohles et al. (1975). Our measured data are also in rough agreement with data collected in the office building study of Fishman and Pimbert (1978), although their curve does not allow an accurate and direct comparison. It is based on an analysis into proportions of median votes (instead of mean) as a function of globe temperature (instead of ET*). Although they did not report an average value for clothing insulation, their paper includes a scatter plot of mean clo vs. air temperature that indicates their average clothing was significantly higher than ours.

Thermal Acceptability vs. ET*—Measured vs. Predicted

When a large group of people are exposed to the same environment, they will experience a range of thermal sensations distributed around the mean value. The percentage of people who are satisfied with that environment is called the thermal acceptability. The most widely used method of estimating thermal acceptability has been to regard the central three categories of the thermal sensation scale (−1, 0, +1) as indicating a comfortable state and to assume that only people voting outside these central categories (±2, ±3) are dissatisfied and likely to complain. This approach was first proposed by Fanger (1970) in developing the concept of Predicted Percent Dissatisfied (PPD).

For the combined winter and summer measured data, the percent dissatisfied as a function of thermal conditions was obtained by calculating the percentage of people experiencing the same ET* who voted a TS of ±2 or ±3. (Because we used a continuous form of the scale, this corresponds to votes of $TS > 1.5$). A second-order polynomial was fit to the data, weighted by the number of observations for each value of ET*. This curve, shown in Figure 3, represents the relationship found in the office buildings for an average clothing insulation of 0.55 clo and a metabolic rate of 1.12 met.

In addition to our measured data, Figure 3 includes three other curves. Two of these are PPD vs. ET* and PPD_G vs. ET*, based on the calculations described previously under "Methods." Figure 3 also includes a PPD vs. ET* curve developed by Rohles et al. (1975), based on a probit analysis of data from a laboratory study of 1600 subjects. The curve represents subjects wearing 0.6 clo with sedentary activity (1.0 to 1.2 met). These conditions are nearly identical to the average values measured in the office buildings in the study reported here, with clothing insulation being only slightly higher. The curve also represents standard conditions of 50% RH, MRT = T_a, and still air at $V = 0.15$ m/s. The values of these parameters that existed in the laboratory study are also consistent with the average values measured in the office buildings. Berglund (1979) showed that this PPD relationship, determined independently by Rohles, compares closely with Fanger's.



Measured data is for a total of 2342 observations, with averages of 0.55 clo and 1.12 met. Regression is weighted by number of observations at each temperature. Fanger PPD and Gagge PPD_G calculations were also based on 0.55 clo and 1.12 met. ET and PPD_G calculations were based on a 60-minute exposure time. Variations in ET* for the predicted curves were calculated by setting $P_a = 10.1$ torr, MRT = T_a, and V = still air, and varying T_a. The Rohles PPD curve is based on experimental data with 0.6 clo, 1-1.2 met, 50% RH, MRT = T_a, and $V = 0.15$ m/s.*

Figure 3 *Percent dissatisfied vs. ET**

Discussion Three significant trends are evident from a comparison of the field measurements and laboratory-based predictions. These observations concern comparisons of the percent dissatisfied, the temperatures at which optimum conditions occur, and the rates at which acceptability changes.

First, the *minimum* rate of dissatisfaction in the office buildings, as a function of ET*, is approximately 12%; this is substantially higher than the optimum of 5% predicted by PPD and PPD_G. (Although Rohles' probit analysis of the data shows an even lower optimum of 3.5% dissatisfaction.) Since our measurements indicated there was negligible radiant asymmetry and, on average, very low air velocities in the office buildings, it is unlikely that draught or radiant effects can account for the difference in measured and predicted acceptability.

It is possible, however, that the wider *range* of clothing worn in the offices in any given thermal environment, as compared to the standard uniforms in the laboratory experiments, could account for some of the discrepancy. (The PPD curve is based on a single clo value corresponding to the *average* clothing worn.) For the group of workers exposed to values of ET* around 22.5°C (the approximate optimum temperature for our study), *average* clothing insulation was 0.55 clo, while the *range* of clothing worn by that group varied from 0.23 to 1.14 clo. This wide range might explain the higher rate of dissatisfaction found in the office buildings at the given value of ET*.[3]

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[2] The measured regression was a linear fit, based on the number of observations at each value of ET*. Perhaps a third-degree polynomial fit would generate a curve that more closely followed the changing slopes of PMV_G and TSENS.

[3] Clo values were calculated from the clothing survey form filled out by the workers. It is likely that the low value of 0.23 clo comes from a form filled out erroneously, and that this value is underestimated

Looking at predicted acceptability beyond the optimum, PPD and PPD_G calculations compare well to each other in the warm regime, but the differences between them become significantly greater as temperatures become cooler than optimum. At temperatures above 24°C, predicted dissatisfied consistently underestimates measured values, with the measured data showing that 10% to 50% of the people are dissatisfied *beyond* the amount predicted by either PPD or PPD_G. At temperatures below the measured optimum of 22.5°C, measured thermal acceptability falls between the two predictions made by PPD and PPD_G. Fanger's PPD *overestimates* dissatisfaction by up to approximately 20% dissatisfied, while Gagge's PPD_G *underestimates* it by up to 30% dissatisfied.

A second observation concerns the difference between measured and predicted optimum temperature, determined by the value of ET* at which the lowest rate of dissatisfaction occurs (note that this may not always be equivalent to neutral temperature, particularly for field data). Optimum temperatures based on Figure 3 are summarized below:

TABLE C

	$T_{optimum}$ (°C)
measured regression	22.5
Gagge PPD_G	23.9
Fanger PPD	24.8
Rohles PPD	25.3

Optimum temperature in the office buildings was only 0.1°C higher than the neutral temperature, so the relationships between measured and predicted optimum temperatures are the same as shown in Figure 2 for neutral temperature. Measured optimum temperature was approximately 2.3°C cooler than that determined by Fanger's PPD vs. ET* and 1.4°C cooler than predicted by PPD_G. A later discussion of measured and predicted neutral temperatures examines whether this discrepancy could be explained by underestimations of clothing or activity in the field study.

A third observation is that the office workers' sensitivity to *changes* in temperature was relatively flat, or at least broadly curved, over a 2° to 3°C range near the optimum. (This is shown more strongly in the measured data, as compared to the second-degree polynomial fitted curve.) This is compared to a stronger peak shown in the PPD curves from Rohles and Fanger, where people's responses changed fairly rapidly as conditions deviated from neutral. In contrast, the shape of Gagge's PMV_G is quite similar to the shape of that found from the measured data and is even broader than the curve fitted to the data points. The rate of dissatisfaction changes quite slowly near neutral, with the slopes increasing at a similar rate at the more extreme temperatures.

Figure 3 also includes four points from data collected by Howell and Kennedy (1979) for office employees and students. Their data primarily fall between our office building data and the PPD curve. Similar to our measured data, Howell's subjects were more comfortable in the cooler conditions than were the laboratory subjects.

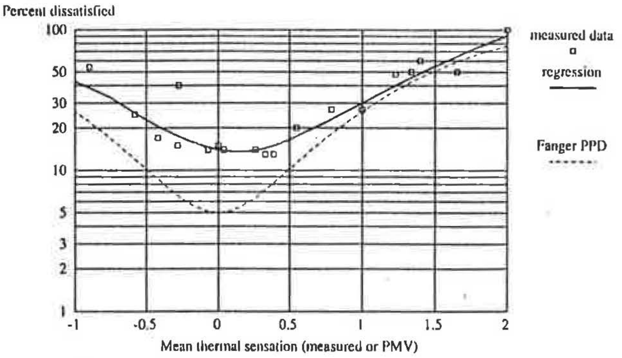
Thermal Acceptability vs. Mean Thermal Sensation—Measured vs. Predicted

Measured thermal acceptability vs. thermal sensation is shown in Figure 4, where each data point represents calculations for a group of people experiencing the same ET*. For each group, the mean thermal sensation and the percent dissatisfied were calculated. A second-order polynomial was fit to the data of dissatisfaction vs. mean thermal sensation, weighted by the number of observations for each corresponding value of ET*. This curve, as in Figure 3, is for an average clothing insulation of 0.55 clo and a metabolic rate of 1.12 met.

The calculations of PMV as a function of ET* were described earlier. For each value of ET*, PPD was calculated as a function of PMV using Fanger's equation. PPD vs. PMV could then be plotted, with each point representing calculations for a given ET*.

Discussion Since there is a unique relationship between mean thermal sensation (measured or as PMV) and ET*, Figure 4 is actually a combination of the information provided in Figures 2 and 3. However, since Fanger's PPD vs. PMV curve is a classic relationship and widely recognized, it is therefore useful to present the measured data in a similar format.

As in Figure 3, the optimum acceptability found in the office buildings is less than that predicted by Fanger based on his laboratory studies. The PPD vs. PMV relationship underpredicted the percent dissatisfied, especially on the cool side of neutral. However, the rate at which the office workers' dissatisfaction increased with higher mean TS is in rough agreement with the rate shown in the PPD vs. PMV curve. Also similar to the relationship shown in Figure 3, the percent of office workers dissatisfied with the thermal environment changed only gradually when mean thermal sensation deviated around neutral. This is compared to a steeper curve based on laboratory subjects, where people's responses changed fairly rapidly as thermal sensation deviated from neutral.



Measured data is for a total of 2342 observations, with averages of 0.55 clo and 1.12 met. Regression is weighted by number of observations at each temperature. Fanger PMV and PPD calculations were also based on 0.55 clo and 1.12 met. Each point represents a group of people experiencing the same ET.*

Figure 4 *Percent dissatisfied vs. mean thermal sensation*

It is interesting to compare the PMV and PPD relationships provided in Figures 2, 3, and 4. On all the graphs, each point represents a group of people exposed to the same ET*. For warm temperatures, PPD significantly underestimated the measured percent dissatisfied (Figure 3), while at the same time PMV underestimated the mean thermal sensation (Figure 2). As a result, when the PPD vs. ET* data (Figure 3) are translated into PPD vs. PMV (Figure 4), the curve shifts to the left in relation to the measured data. The curves of measured percent dissatisfied vs. mean thermal sensation, and PPD vs. PMV, then become quite close in the regime of warm sensations. This implies that Fanger's equation for PPD predicts thermal acceptability quite accurately if a group's mean thermal sensation is known and is on the warm side of neutral. However, these predictions compared less well to the measured data in the office buildings when starting from the physical parameters of the thermal environment, or ET*.

Neutral Temperatures—Measured vs. Predicted

Neutral temperatures, T_n, can be determined by either measured data or predicted relationships. Table 1 compares measured values of T_n to predicted values based on (1) the Pierce model calculation of PMV_G, (2) the ISO algorithm for PMV, and (3) an acclimatization equation developed by Auliciems (1984).

Measured T_n Separate regression equations for winter and summer data were given in Schiller et al. (1988). Measured neutral temperatures were calculated from the winter and summer measured data by solving these regression equations for TS = 0.

PMV_G-Predicted T_n Neutral temperatures were predicted with the Pierce model, based on a 60-minute exposure time, by iterating the program through changes in ET* until PMV_G equaled zero. The PMV_G calculations were done separately for winter and summer, with input values determined from measured averages of clothing, activity, humidity, air velocity, and mean radiant temperature. (These values are also summarized in Table 1.)

TABLE 1
Neutral Temperature: Measured and Predicted

	Winter	Summer
Neutral Temperatures (ET*)		
Measured	22.0°C	22.6°C
PMV-Predicted	24.4°C	25.0°C
PMV_G-Predicted	23.6°C	24.0°C
Acclimatization-Predicted	22.1°C	22.4°C
Measured averages used for predictions		
Air Temperature	22.8°C	23.3°C
Mean Radiant Temperature	23.0°C	23.6°C
Velocity	0.06 m/s	0.10 m/s
Clothing	0.58 clo	0.52 clo
Activity	1.12 met	1.14 met
Values required to match PMV-predicted and measured neutral temperatures.		
Clothing	0.80 clo	0.72 clo
Activity	1.75 met	1.75 met

PMV-Predicted T_n Neutral temperatures were predicted with the ISO algorithm using the same method just described for PMV_G. By varying T_a and using the same values of the input parameters as used in the Pierce model runs, the neutral air temperature from the ISO model was matched to an ET* value from the Pierce model calculations.

Acclimatization-Predicted T_n Using data from more than 30 field studies, Humphreys (1976) demonstrated that acclimatization can affect the temperature required for thermal neutrality, and developed a regression equation predicting the neutral temperature from the mean indoor air temperature. Auliciems (1984) reanalyzed these data to restrict them to office work, giving the equation:

$$T_n = 5.41 + 0.73\ T_m \tag{2}$$

where T_m is the mean indoor air temperature. It is useful to apply this equation to data collected in field studies, to assess the degree to which acclimatization to the indoor environment might be occurring.

Discussion In addition to the measured and predicted values of T_n, Table 1 summarizes the seasonal averages of air temperature used as input to Auliciems' equation and the other comfort variables used as input to the PMV and PMV_G models. Both PMV and PMV_G overpredicted neutral temperatures. PMV predictions were higher than the measured T_n by 2.4°C in both seasons, while PMV_G predictions were higher by 1.4° to 1.6°C. The table shows that the measured neutral temperatures were closer to those predicted by regression equations based on the findings of 50 years of field surveys, as compared to predictions of both the PMV and PMV_G models. A similar result was found by Dedear and Auliciems (1985) in examining data from six Australian office buildings. These results are important because they suggest that the prevailing thermal environments in the buildings affect workers' expectations and preferences and influence their degree of discomfort as conditions deviate from these preferred conditions.

It was considered that the differences between measured T_n and PMV- or PMV_G-predicted values for T_n could be accounted for if measured clothing or activity were perhaps underestimated based on the checklist responses in the field study questionnaire. To examine this possibility, the Pierce PMV_G model was iterated for winter and summer conditions, first independently increasing clo, then setting clo back to its measured average and increasing met, until the model predicted a T_n equivalent to the measured value for that season. This analysis allows one to examine the extent to which clo or met would have had to be underestimated to account for the discrepancy between measured and predicted T_n. These results, shown in Table 1, indicate that actual clothing levels would have had to be 0.80 clo (winter) and 0.72 clo (summer), or activity level 1.75 mets (both seasons) in order for measured and PMV_G-predicted values of T_n to coincide. Since the ISO model for Fanger PMV overpredicted neutral temperatures by a greater amount, clothing and activity levels would have had to be even higher for the measured and PMV-predicted values to match. Both these values of clo and met are unreasonably high compared to conditions that existed in these office buildings, indicating that the overprediction of neutral temperatures actually reflected the workers' preference for cooler conditions, rather than the experimenters' underprediction of clothing or activity levels.

Thermal Sensation at Each Visit—Measured vs. Predicted

Thermal sensation was measured at each visit using the seven-point ASHRAE Thermal Sensation Scale previously described. The measured physical parameters and clothing and activity levels from each visit were used as input to the Pierce program to calculate ET*, PMV$_G$, and TSENS.[4] Measured thermal sensation (TS) and predicted thermal sensation (PMV$_G$ and TSENS) for each individual are compared separately for the winter and summer seasons by examining the correlation coefficients, a cross-frequency matrix, and a scatter plot of mean TS vs. PMV$_G$.

Correlation Coefficients The winter and summer correlations between individuals' TS, PMV$_G$, TSENS, and ET* are given in Table 2. As expected, PMV$_G$ and TSENS are strongly related (.88 and .94). Correlations between ET* and both PMV$_G$ and TSENS are higher for the summer (.78 and .74, respectively) than for the winter (.59 and .48). This is most likely due to the wider range of clothing worn by the office workers in the winter, since clothing variations are not included in the calculation of ET*. In comparison to the relationship with predicted thermal sensation, correlations between ET* and measured TS are much lower (at .30 for both seasons).

Correlations between TS and PMV$_G$ and between TS and TSENS are quite similar. Correlations for both pairs were higher for the summer (.33 and .32, respectively) than for the winter (.23 and .20). The stronger correlations for the summer were most likely due to the wider range of thermal conditions in that season, where a greater number of observations fell above the neutral zone. The relatively low correlations for both are due to the fact that measured thermal sensation judgments covered the full range of −3 to +3, while calculated values of PMV$_G$ and TSENS covered a relatively narrow range. It is important to note the distinction that TS is a vote by one person, while PMV$_G$ is the predicted average sensation of a large group of people subjected to the same thermal conditions. As a result, one would expect to get a wider spread of TS and relatively low correlations between individual TS votes and PMV$_G$. The spread of TS votes and PMV$_G$ calculations is described below in the frequency matrix.

TABLE 2
Correlations between Measured and Predicted Thermal Sensation

	Thermal Sensation	PMV	TSENS	ET*
Thermal Sensation		.33	.32	.30
PMV	.23		.94	.78
TSENS	.20	.88		.74
ET*	.30	.59	.48	

WINTER (1308 observations)

a: correlation coefficients significant beyond .001

Although the correlations between measured and predicted thermal sensation are low, the fact that they are comparable to the correlations between TS and ET*—and that *both* correlations are low—suggests that factors other than the primary variables used in the prediction models are influencing people's responses. The contribution of psychological factors has been discussed in studies by Rohles (1980) and Howell and Stramler (1981). Our results also compare well with those of Howell and Kennedy (1979), where a correlation of .24 between measured TS and Fanger's PMV was determined from a study of 521 employees and students.

Frequency Matrix Cross-frequency matrices of measured TS vs. PMV$_G$ for each visit in the winter and summer are presented in Tables 3a and 3b, respectively. In this analysis, both TS and PMV$_G$ are binned into integer values. Physical conditions in the buildings were fairly moderate in both seasons, resulting in 95% to 96% of the PMV$_G$ values falling within ±0.5 (binned as zero). However, TS votes covered the full range of −3 to +3, with only 37% to 40% voting neutral and 17% to 19% voting at the extremes of ±2 and ±3. The wide discrepancy in the distributions of TS and PMV$_G$ helps to explain the low correlations found between them. As noted previously, the discrepancy is to be expected since PMV$_G$ represents mean, not individual, sensation. However, the frequency matrix is still useful for examining the symmetry of warm and cool votes.

Tables 3a and 3b suggest that people generally felt warmer than predicted more often than they felt cooler. This trend occurred during both seasons. Of the people with a neutral PMV$_G$ (0), 37% to 38% voted warmer than neutral ($TS > 0$), compared to 23% to 25% voting cooler ($TS < 0$). When PMV$_G$ was slightly warm (+1), everyone voted either neutral or on the warm side of neutral, with no one feeling cooler than neutral. During the summer, when PMV$_G$ was slightly cool (−1), a significant number of people (36%) still felt warm or hot ($TS = 2, 3$).

Regression of Mean TS vs. PMV$_G$ The previous correlation and frequency matrix analyses were based on a point-by-point comparison. Since PMV$_G$ is used to predict the *average* thermal sensation of a large group of people, it is useful to compare this predictive index to the mean value of the measured TS. PMV$_G$ can be used as the control variable for this comparison, since it is assumed that the same mean physiological strain and thermal sensation will exist in

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[4] At the time of this writing, the ISO model has only been used to perform the *parametric* calculations described earlier, and Fanger's PMV values are not available for each individual visit.

TABLE 3a — Winter
Thermal Sensation: Measured and Predicted

Measured Thermal Sensation		Predicted Mean Vote (PMV_G) −1 cool	0 neutral	1 warm	Row Total (col. %)
2,3 Warm,Hot	# people	3	153	6	162
	col. %	**9**	**12**	**35**	**12**
1 Slightly Warm	# people	2	322	5	329
	col. %	**6**	**26**	**29**	**25**
0 Neutral	# people	15	464	6	485
	col. %	**44**	**37**	**35**	**37**
−1 Slightly Cool	# people	9	226	0	235
	col. %	**26**	**18**	**0**	**18**
−2, −3 Warm,Hot	# people	5	91	0	96
	col. %	**15**	**7**	**0**	**7**
Column Total	# people	34	1256	17	1307
	col. %	**3**	**96**	**1**	**100**

TABLE 3b — Summer
Thermal Sensation: Measured and Predicted

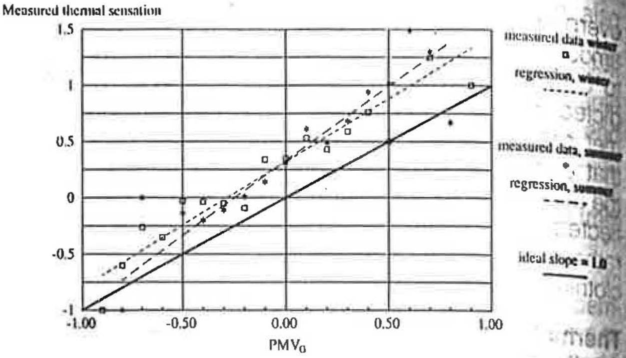
Measured Thermal Sensation		Predicted Mean Vote (PMV_G) −1 cool	0 neutral	1 warm	Row Total (col. %)
2,3 Warm,Hot	# people	4	111	23	138
	col. %	**36**	**11**	**52**	**13**
1 Slightly Warm	# people	0	250	12	262
	col. %	**0**	**26**	**27**	**25**
0 Neutral	# people	3	401	9	413
	col. %	**27**	**41**	**20**	**40**
−1 Slightly Cool	# people	4	172	0	176
	col. %	**36**	**18**	**0**	**17**
−2, −3 Warm,Hot	# people	0	44	0	44
	col. %	**0**	**5**	**0**	**4**
Column Total	# people	11	978	44	1033
	col. %	**1**	**95**	**4**	**100**

different environments, as long as the value of the PMV_G index is the same.

Examining the winter and summer data separately, the mean of TS votes was calculated for each group of people experiencing the same PMV_G *based on the individual data*. The regression of mean TS was then weighted by the number of observations for each value of PMV_G. The results of this analysis are shown in Figure 5, and the regression equations are:

$$\text{winter} \quad \text{mean TS} = 0.32 + 1.12\, PMV_G \quad (3a)$$
$$(R^2 = .79) \quad (3b)$$
$$\text{summer} \quad \text{mean TS} = 0.33 + 1.33\, PMV_G$$
$$(R^2 = .76)$$

Mean thermal sensations were warmer than predicted by PMV_G. Within the range of optimum predicted thermal sensation (PMV_G within ±0.5), PMV_G underpredicted the mean thermal sensation felt by office workers by 0.2 to 0.5 units, with the discrepancy being larger for warmer sensations as opposed to cooler ones. In another study of office workers, Fishman and Pimbert (1978) obtained closer agreement between actual and predicted results, with Fanger's PMV underpredicting thermal sensation by approximately 0.15 units within this same neutral zone.



Winter data based on 1308 observations. Summer data based on 1034 observations. Gagge PMV_G calculations are based on measured thermal environment, clothing, and activity at each observation. Regressions are weighted by number of observations at each values of PMV_G.

Figure 5 *Measured thermal sensation vs.* PMV_G

The discrepancies between measured and predicted thermal sensation might be accounted for if measured clothing or activity had been underestimated from the checklist responses. A previous analysis of measured and predicted neutral temperatures calculated the extent to which clothing and metabolic rate would have to increase for these values to be equivalent. Results showed that it is unlikely that underestimations of clothing and activity could account for these differences. Mean thermal sensations that are warmer than predicted may imply that workers, on average, simply prefer slightly cooler conditions than expected based on the comfort models. This is supported by analysis presented by Schiller et al. (1988).

Thermal Sensation and Comfort—Examining the Neutrality Assumption

The assumption of associating thermal comfort with thermal neutrality was examined by comparing a *direct* assessment of comfort using responses to the general comfort scale (COMF) and an *indirect* assessment based on responses to the thermal sensation scale (TS). As noted earlier, the thermal sensation and comfort scales are shown in Figure 1. Note that this analysis is based only on measured data and does not use any of the predicted comfort indices.

Frequency Matrix Tables 4a and 4b are cross-frequency matrices of thermal sensation and comfort responses for winter and summer, respectively. For simplicity, the central three categories of the thermal sensation scale (the *indirect* comfort assessment) will be referred to as "neutral comfort" to distinguish them from the *direct* assessment of comfort using the general comfort scale. It is important to remember that, in this discussion, the phrase "neutral comfort"

TABLE 4a — Winter
Thermal Sensation and Comfort

Thermal Sensation Scale		General Comfort Scale				
		1,2 mod.-very uncomfortable	3 slightly uncomfortable	4 slightly comfortable	5,6 mod.-very comfortable	Row Total (col. %)
2,3 Warm,Hot	# people	53	40	15	30	138
	row. %	**38**	**29**	**11**	**22**	**11**
1,0,−1 Neutral,Slightly Warm/Cool	# people	22	179	214	659	1074
	row. %	**2**	**17**	**20**	**61**	**82**
−2,−3 Cool,Cold	# people	27	32	21	16	96
	row. %	**28**	**33**	**22**	**17**	**7**
Column Total	# people	102	251	250	705	1308
	row. %	**8**	**19**	**19**	**54**	**100**

TABLE 4a — Summer
Thermal Sensation and Comfort

Thermal Sensation Scale		General Comfort Scale				
		1,2 mod.-very uncomfortable	3 slightly uncomfortable	4 slightly comfortable	5,6 mod.-very comfortable	Row Total (col. %)
2,3 Warm,Hot	# people	52	33	14	18	117
	row. %	**44**	**28**	**12**	**15**	**11**
1,0,−1 Neutral,Slightly Warm/Cool	# people	22	165	146	540	873
	row. %	**2**	**19**	**17**	**62**	**84**
−2,−3 Cool,Cold	# people	14	13	2	15	44
	row. %	**32**	**30**	**5**	**34**	**4**
Column Total	# people	88	211	162	573	1034
	row. %	**9**	**20**	**16**	**55**	**100**

from "neutral thermal sensation" and actually refers to an *assumption* of comfort based on thermal sensation responses. Also, for simplicity, the total votes in the upper three categories of the general comfort scale (4, 5, 6) will be called "comfortable," with the combined votes in the upper two categories (5, 6) referred to as "decidedly comfortable."

The overall distribution of responses to both the thermal sensation and general comfort scales were similar between the two seasons: 82% to 84% of the people voted in the central three "neutral comfort" categories (TS = −1, 0, +1); 71% to 73% of the people voted in the upper three comfort categories (COMF = 4 to 6), with more than half the people decidedly comfortable (COMF = 5, 6).

The first approach to examining the data in Tables 4a and 4b is based on percentages on a row basis (e.g., for a group voting in a specified thermal sensation category, look at the percentages that are comfortable or uncomfortable). Of the group of people voting neutral comfort based on the thermal sensation scale, a strong 79% to 81% simultaneously voted that they were comfortable, with 61% to 62% decidedly comfortable. Although 19% to 21% of the people in the neutral comfort category simultaneously said they were uncomfortable, the majority of these were only slightly uncomfortable and may not be likely to complain about their thermal environment. Although these results initially appear to roughly validate the assumption that the three central categories are equated with comfort, it is of interest to now examine responses at the more extreme thermal sensation categories.

Of the people voting in the extremely cold categories (TS = −2, −3), 39% of the people in both seasons felt this was comfortable (voting COMF = 4 to 6), although these cold sensations were viewed as more decidedly comfortable (COMF = 5, 6) during the summer. Of the people voting in the extremely hot categories (TS = 2, 3), 33% felt this was comfortable in the winter, compared to only 27% finding hot sensations comfortable in the summer.

These results appear to conflict with the assumption that people voting ±2, 3 on the thermal sensation scale will be uncomfortable. Although the data indicate that the central three thermal sensation categories can roughly be considered as comfortable, people voting within the extreme sensations are not necessarily dissatisfied. The concept of "comfort" covered a broader range of thermal sensations for the participants in our study, suggesting that the thermal acceptability of the office environments studied may actually be higher than suggested by the previous analysis using Fanger's "neutral comfort" assumption.

A second approach to using Tables 4a and 4b for examining the relative comfort or discomfort of hot vs. cold sensations is based on percentages on a column basis (e.g., for a group voting in a specified comfort category, look at the percentages experiencing different thermal sensations). Note that these numbers are not directly shown in the table. Of the people who were decidedly uncomfortable (voting COMF = 1, 2), the majority (52% to 59%) associated their feelings with an extreme sense of warmth (TS = 2, 3), compared to 16% to 26% feeling extreme coolness (TS = −2, −3). These percentages roughly compare with those found by Gagge and Nevins (1976) in a New York City office building, where 59% of the people voting "uncomfortable" expressed a sense of warmth and 32% expressed coolness.

Average Comfort by Thermal Sensation The average vote on the general comfort scale was calculated for each group of people experiencing the same thermal sensation, and results for winter and summer are shown in Table 5. In each season, average comfort is asymmetric for equal deviations away from neutral, with a cool sensation being rated as slightly more comfortable than a warm one. (This trend is stronger in summer than in winter and is consistent except for extremely cold responses in summer.) These results are consistent with those shown in Tables 4a and 4b, where a greater percentage of people voting cool felt that this was comfortable, as compared to those simultaneously voting warm and comfortable.

Comparing seasonal responses for a given thermal sensation, the data indicate that warm and slightly

TABLE 5
Average Comfort by Thermal Sensation

Thermal Sensation	Average Comfort	
	Winter	Summer
3	2.5	2.6
2	3.2	3.0
1	4.1	3.9
0	5.0	5.0
−1	4.4	4.6
−2	3.4	3.8
−3	2.6	1.9

warm sensations are more comfortable in the winter than in the summer, and cool and slightly cool sensations are more comfortable in the summer than in the winter. However, this trend is not particularly strong and is not consistent for votes of ±3.

CONCLUSIONS

This paper compared both measured and predicted comfort responses in existing office buildings and examined the extent to which the workers' sense of comfort was associated with thermal neutrality. The analysis was based on data collected from 2342 visits to 304 participants in 10 buildings in the San Francisco Bay Area during the winter and summer seasons of 1987. Predictions were based on Fanger's PMV and PPD, Gagge's modified version of PMV and PPD (called PMV_G and PPD_G in this paper), and TSENS. Predicted indices were calculated using values of P_a, V, MRT, clo, and met consistent with the averages of the measured data in the buildings, and T_a was varied to obtain the range of values of ET* found in the office buildings.

The range of thermal environments that existed in the office buildings during the measurement periods was fairly narrow, although the thermal sensation votes covered the full range of the seven-point ASHRAE Thermal Sensation Scale. Fanger's PMV consistently underpredicted measured thermal sensation (TS) by 0.5 to 1.0 units, with the difference being strongest at the cooler temperatures. The best agreement between TS and PMV_G was in the region near neutral. As conditions moved away from optimum, predictions were more conservative and office workers voted at more extremes than predicted by PMV_G, particularly for the warmer temperatures. Gagge's PMV_G and TSENS were comparable, particularly for the warmer temperatures.

Neutral temperatures in the buildings were lower than predicted from the laboratory-based comfort models. Measured T_n was 2.4°C cooler than predicted by Fanger's PMV and 1.4°C cooler than predicted by Gagge's PMV_G. Further analysis revealed that lower neutral temperatures measured in the office buildings reflected workers' preference for cooler conditions, rather than the experimenters' underprediction of clothing or activity levels.

Optimum acceptability in the office environments was 12% dissatisfied, compared to a predicted minimum of 5% based on experiments in laboratory conditions. This could be explained by either the wider range of clothing worn by office workers at any given ET*, compared to the standard uniforms in the laboratory experiments, or by the range of people's thermal expectations and preferences. For temperatures above 24°C, PPD and PPD_G were similar, but both significantly underestimated the measured percent dissatisfied. The low levels of acceptability, and the range of workers' comfort requirements due to clothing, activity, or thermal preference, suggest that centralized, autonomous environmental control systems have inherent limitations to their effectiveness.

Correlations between TS and ET* and between TS and PMV were low but comparable, suggesting that factors other than the primary variable used in the prediction models influence people's responses.

A comparison of both direct and indirect assessments of comfort suggested that a strong majority of people voting within the three central categories of the thermal sensation scale were simultaneously comfortable. However, up to one-third of the people voting within the four extreme categories of the thermal sensation scale (±2, 3) also felt these conditions were comfortable. These results suggest that the concept of "comfort" covered a broader range of thermal sensations than commonly assumed and that people voting within the extreme sensations are not necessarily dissatisfied. This is somewhat in contrast to the assumption commonly used to relate thermal sensation to comfort. Utilizing more direct assessments of thermal comfort and satisfaction in future surveys would allow a more thorough investigation of the relationship between thermal sensation and acceptability.

The comparison of thermal sensation and comfort responses further indicated that the majority of people who were decidedly uncomfortable associated their feelings with an extreme sense of warmth, rather than coolness. Comfort was also asymmetric for equal deviations away from neutral, particularly in the summer, with a cool sensation being rated as slightly more comfortable than a warm one.

These results suggest that current standards and practices for maintaining comfortable thermal environments in office buildings need to be reexamined, supplementing laboratory data with information obtained in field studies. Based on the findings presented in this paper, recommendations for future research include repeating field studies in more extreme climatic zones, conducting laboratory experiments in more realistic and familiar settings, utilizing direct assessments of comfort and satisfaction, and investigating the effectiveness of demand-controlled environmental control systems for increasing worker satisfaction.

ACKNOWLEDGMENTS

The author gratefully acknowledges the assistance of ASHRAE, Inc., and the IBM DACE Grant Program for providing funds and computer equipment for this research. Special recognition goes to Edward Arens, Charles Benton, Fred Bauman, Marc Fountain, and Tammy Doherty, the research team for ASHRAE RP-462, and to Nora Watanabe, Administrator for the Center for Environmental Design Research, for taking care of details throughout the project. Professor Kenneth Craik of the Institute of Personality Assessment Research, U.C. Berkeley, and his research assistant Karl Dake, contributed to the survey development. Thanks also go to Qiufang Ren and to Savitha Sridharan for their assistance in the statistical analyses and graphics prepared for this paper. I am especially grateful to Marc Fountain for being there in a pinch and working beyond the call of duty.

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DISCUSSION

F. Mills, Building Design Partnership, Manchester, England: Has your research been extended to cover major circulation spaces such as atrium areas and, if so, what has your comparison concluded?

G.E. Schiller: Our research concerned only the immediate surroundings of the workers and has not yet been extended to cover atrium areas or other circulation spaces.

D.P. Wyon, S/B, Gävle, Sweden: The equations used to predict thermal comfort assume that the seat has no thermal insulation. Fanger's subjects sat in string chairs that compressed clothing and actually reduced insulation. A real seat insulates 20% to 25% of body surface area, hence the discrepancy.

Schiller: I am grateful to Dr. Wyon for his insightful observation, initially made during my presentation in Atlanta. Clothing insulation was calculated based on a checklist filled out by the worker, and the insulating value of the chair was not accounted for. As Table 1 indicates, average insulation of the workers participating in this study would have had to be 0.20 to 0.22 clo higher than estimated by the checklist to fully account for the discrepancy between measured and predicted neutral temperatures. Although we do not know the exact insulating value of a typical office chair, the extent to which it contributes to the overall thermal insulation of a seated worker may be significant enough to account for part, if not all, of the discrepancy.

P.O. Fanger, Professor, Technical University of Denmark, Lyngby: The author should be complimented for her excellent research in the field and the present careful analysis of the results. It is essential to learn how well models based on labaoratory studies of human beings are able to predict how environments in real buildings are perceived by their occupants.

But no model is better than the data fed into the model by the user. In this case, the critical data are the clothing and activity of the occupants in the investigated buildings. The author discusses this carefully, and I am sure she has rigorously followed guidelines given for these estimates in existing standards. I just wonder whether these guidelines are adequate.

For clothing, no additional insulation is provided for the chair. The original lab studies with 1300 subjects were done in wooden chairs or string chairs. Modern upholstered office furniture may very well add an additional 0.1 to 0.2 clo to the clothing insulation. In the original lab studies, the subjects' thermal sensation votes were collected at an activity around 1 met after people had been resting in a sedentary position for two to three hours in the environmental chamber. Compared to this, the assumed activity in the office buildings of 1.12 met seems low.

ISO 7730 recommends 1.2 met for offices, but this is an estimate based on rather old data. In a modern office with stressful work, the activity may very well be 1.3 met. My point is that these moderate changes in your assumptions are sufficient to explain the observed difference in preferred temperature between the present 300 office workers and the 1300 people studied in test chambers and forming the basis for the PMV and PPD models.

Further studies on activities and clo values of furniture occurring in modern office buildings should be encouraged. Besides the 2°C difference, I think that there is a surprisingly good agreement between models and real life in this very fine study.

Schiller: Dr. Fanger has made a number of valuable comments, and I appreciate his complimentary remarks regarding this study. While the methods available for calculating clothing and activity rates are based on rigorous research, the guidelines available for applying them to occupants in real buildings may, indeed, be inadequate. For example, current comfort standards are based on assumptions regarding seasonal clothing worn by workers and do not themselves account for the additional insulating value of the chair.

I would like to comment briefly on the data used as input to the predictive models, specifically the clothing and activity levels of the buildings' occupants. First, it is entirely likely that the effect of the chair's thermal insulation may very well account for some, if not all, of the discrepancy between measured and predicted comfort. (This was discussed above in response to Dr. Wyon's comment.)