10514

4052

A Field Study of Office Thermal Comfort Using Questionnaire Software

Guy R. Newsham, Ph.D. **Dale K. Tiller, D.Phil.**

ABSTRACT

Custom software to automatically administer questionnaires on computer screens was installed on computers in four open-plan offices. Five questions related to thermal comfort were presented twice per day for three months. Results indicate that this new method of subjective data collection was successful and efficient: the participants had few complaints about the method of questionnaire delivery, and a substantial literature review demonstrates that our results are comparable with results from other field studies of thermal comfort conducted using different methods. Participants responded to the questionnaire 29% of the occasions on which it could have been presented and took an average of 45 seconds to answer the five questions. Overall, the number of thermal sensation votes indicating thermal acceptability were as predicted by the ANSI/ASHRAE Standard and by the comfort theory on which this standard was based. However, our results indicate a greater sensitivity to temperatures away from the neutral temperature than theory predicts. Only 11% of the variance in thermal sensation vote was explained by indoor air temperature. Approximately 15% of the people modified their clothing in the hour prior to the appearance of the questionnaire, suggesting that clothing modification may be an important mechanism for achieving thermal comfort.

INTRODUCTION

A Brief Summary of Thermal Comfort Research

In post-occupancy studies, the thermal environment is frequently rated as one of the most important aspects of a healthy, pleasing, and productive workplace (Baillie et al. 1988; de Dear et al. 1993; Jaakkola et al. 1989; Rohles et al. 1989). Many studies have been performed to elucidate the relationship between human thermal sensation and the physical environment. The principal goal of such research is to determine what physical parameters provide a comfortable and productive indoor environment and how best to deliver those physical parameters.

Past research has included both laboratory and field studies. In laboratory studies, participants typically sit in climate chambers wearing fixed clothing ensembles and remain sedentary while experiencing thermal environments chosen by the experimenters or adjusting the thermal environment (normally air temperature) themselves in order to achieve an optimum environment. Most codes and standards are based on laboratory studies of this type, particularly the seminal work of Fanger (1970). Fanger found that in climate chamber studies the mean reported thermal sensation of a group of people exposed to the same thermal environment was a function of four physical parameters (air temperature, mean radiant temperature, humidity, and air speed) and two personal parameters (clothing and metabolic rate).

While the laboratory affords the advantages of being able to manipulate and measure the stimuli exactly, there have been numerous criticisms of laboratory studies of thermal comfort. The criticisms can generally be grouped under the heading of "external validity," that is, how well do the results translate to the real world where they will be applied. First, climate chambers tend to be stark, sterile spaces, not aesthetically similar to most real-world interiors. Second, the participants do not perform tasks representative of real-world tasks. Third, many of the parameters held constant in laboratory studies are not constant in the real world—clothing, for example. Fourth, the participants in laboratory studies are usually college students, not very representative of the real-world population.

In field studies, participants typically report their thermal sensations in situ while all important parameters are recorded at their prevailing values. The results are often compared to the predictions made from the results of laboratory studies in order to test the validity of the laboratory studies; in many cases, the data collected in field studies have proven incompatible with the laboratory studies. However, these comparisons are complicated by the difficulty of precisely defining the relevant parameters in

Guy R. Newsham and **Dale K. Tiller** are research officers at the National Research Council Canada, Ottawa, Ontario.

the field. For example, in the context of Fanger's equation, accurately determining an individual's clothing insulation and metabolic rate in a practical manner in the field is extremely difficult. There has been a considerable and ongoing effort to conduct field studies on many different populations in many different geographical locations. The data collected in our study add to this body of work, and comparisons to prior research, particularly to other field studies, will be made throughout this paper.

Transient Conditions and the Need for Longitudinal Studies

The vast majority of laboratory studies have examined thermal comfort under fixed thermal conditions. Those laboratory studies that have looked at transient conditions (Purcell and Thorne 1987) have done so in a mechanistic way, with the changes being provided by a climate control system invisible to the participants and according to regular mathematical functions. Baillie et al. (1988), Hensen (1990), and Oseland and Humphreys (1994) called for an investigation of the effect of more realistic changes in the thermal environment, such as those caused by solar radiation.

The only way to capture this kind of information in a field study is to conduct a longitudinal (or time-series) study, in which opinions (e.g., thermal sensation votes) are surveyed many times over the study period. In this way, the investigator can observe how participants' reactions change in response to a changing physical environment, observe how past experience influences reactions, and avoid the possibility that a snapshot survey captured atypical information (Cena et al. 1990; Humphreys 1994; Nicol and Humphreys 1973).

However, conducting longitudinal surveys in the field using the traditional method of paper questionnaires would be disruptive, expensive, and labor intensive. Recognizing this, Humphreys and Nicol (1970) and Fishman and Pimbert (1982) developed voting box hardware to collect thermal sensation votes automatically. Each participant in each study had a box about the size of a telephone placed on his or her desk. At regular intervals the box used an audible tone to cue the participant to vote. The participant voted by pressing one of seven buttons on the box, each button corresponding to a response on a thermal comfort scale. Sensors attached to the box simultaneously recorded various physical parameters of the thermal environment. These systems worked reliably, collecting much valuable data. However, the number of participants was limited (presumably by the cost of manufacturing the boxes), and the number and variety of responses were limited by the arrangement of buttons on the box.

We sought to build on the success of these longitudinal studies by embodying the voting box principle in software. We developed software to automatically administer questionnaires on computer users' screens at predetermined dates and times. Software provides a great deal more flexibility than hardware in the number of questions that can be asked and the variety of responses offered. Further, because the cost of reproducing software is negligible, larger sample sizes can be entertained. Software embodiment also allows the delivery of questionnaires on any predetermined, regular or irregular, schedule and automatic rescheduling of questionnaires if there is no response. All data are accurately time-stamped for comparison to physical data records, and the time to complete a questionnaire can also be recorded. In addition, all data are generated in an electronic format that is easily read by analysis software, reducing data translation errors and facilitating data analysis.

MATERIALS AND METHODS

Study Sites and Participants

Data collection took place from October 1994 to January 1995. The study was carried out at four sites. All sites were federal government facilities in Ottawa, Ontario, Canada (latitude 45° 19' N, longitude 75° 40' W); office layouts were predominantly open-plan.

At each site we met with each staff member face-to-face, explained the project to them, and invited them to participate. Those who agreed to participate were asked to sign a consent form and were given some written information on the project. They were told that the software would be installed on their computer within a week and that it would be installed outside of normal working hours. All written information was supplied in either English or French, according to the participant's preference. In addition, the on-screen questionnaire was delivered in the language of the participant's preference.

TABLE 1
Participant Demographic Information

Age	Sex		S
	Female	Male	
20-29	8	1	9
30-39	5	13	18
40-49	7	11	18
50-59	1	3	4
60-69	0	1	1
S	21	29	50

The software was installed on more than 60 computers at the four sites. At the conclusion of the study period, useful data were recovered from 55 participants. Of these 55 participants, 50 returned the basic demographic information shown in Table 1.

Measurement of Outdoor and Indoor Climate

Outdoor climate data were recorded at an electronic weather station located close to one of the sites. The data recorded at this station were used for all sites, though some local differences may have occurred. Mean relative humidity, mean air temperature, and total solar radiation on a horizontal plane were recorded hourly during the study period. Total solar radiation on a horizontal plane was converted to total solar radiation on a vertical plane in each of the four cardinal directions using correlation equations (Barakat 1983; Orgill and Hollands 1977).

Indoor air temperature and relative humidity were measured at the four sites using stand-alone dataloggers. Climate chamber tests confirmed the factory calibration and claimed accuracy of the loggers' sensors (air temperature ±0.4°C [±0.7°F], relative humidity ±4%). The dataloggers were programmed to record both indoor air temperature and relative humidity every 20 minutes for the duration of the study period.

Ideally, physical measures would have been taken at each of the participants' workstations. However, only a limited number of dataloggers were available. Therefore, we placed the loggers at representative points at the four sites. Sites 1, 2, 4, and the ninth floor of site 3, where the office spaces were predominantly on a single facade, received one logger each. Five loggers were placed on the seventh floor of site 3, where there were offices on four facades and in a core area. Care was taken not to place the loggers in unrepresentative locations, such as places where they would be exposed to direct sunlight or close to other sources of internal heat gain.

Recording Participants' Reactions and Personal Information

Subjective reactions to the indoor thermal environment and other participant responses were collected using questionnaire software developed by the authors. Questions can be created with one of three response types:

1. A list of responses from which the participant may pick only one.
2. A list of responses from which the participant may pick as many as apply.
3. A sliding scale labeled with descriptors: the participant places a pointer on the scale at a position that best describes his or her response.

Once created, the questions can then be administered in any order, at dates and times specified by the experimenter in a data file. When administered, the questionnaire takes the form of a "window" that appears over the user's other open applications. The responses to the questions are stored on the host computer's hard disk for collection at the end of the study by the experimenter.

The questions asked using the software were divided into two types: demographic questions and recurring questions. Demographic questions were asked only once because answers were not expected to change with time. These questions concerned sex, age, office orientation, and office occupancy. Recurring questions are questions that are asked many times. Answers to these questions were expected to change with time. Recurring questions were asked twice per day, once before 1300 hours and once after 1300 hours. The times at which the questions appeared and the order in which they appeared followed a pseudo-random but predefined schedule. Each participant followed the same schedule. The recurring questions concerned thermal sensation (ASHRAE scale), thermal preference (McIntyre scale), clothing worn, clothing modification, and window blind use. Figure 1 shows the on-screen appearance of the ASHRAE thermal sensation question.

At the end of the study period, the authors asked the participants to complete a paper-based questionnaire to evaluate the performance of the questionnaire software and to invite any suggestions for improvements.

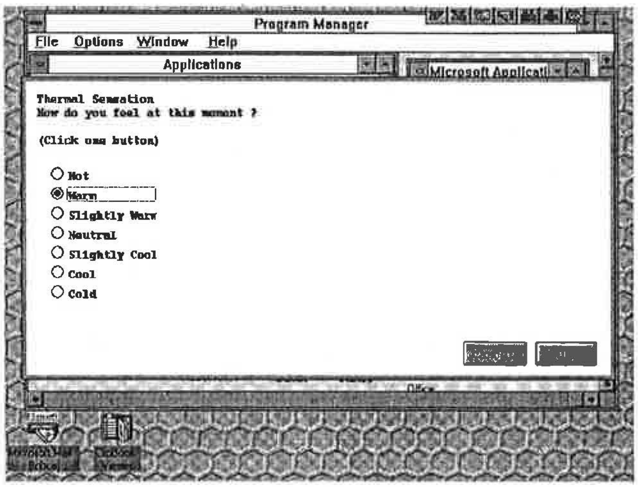

Figure 1 *The on-screen appearance of the ASHRAE thermal sensation question.*

RESULTS

Data are presented for the 10-week period of October 15, 1994, to December 23, 1994. This paper contains only a subset of the data and analyses generated by this study; for more details, see Newsham and Tiller (1995).

Response Rate and Response Time

Each recurring question could have been answered a maximum of 100 times over the 10-week period. The mean response rate to the ASHRAE thermal sensation question (Figure 1) was 29.1% (n=55), s.d. = 12.7, which represents 1,600 data points. In other words, each participant answered the ASHRAE thermal sensation question an average of 29 times during the 10-week period (the response rate to other questions differed). The minimum response rate was 2% and the maximum response rate was 62%.

When participants responded, it took an average of 45.3 seconds (n= 1600), s.d. = 32.6, to answer all five questions. The minimum mean response time was 29.6 seconds, and the maximum mean response time was 100.7 seconds.

Aggregate Frequency Data

Table 2 shows the frequency of responses to the ASHRAE thermal sensation question; the response frequencies form a normal distribution. Figure 2 shows the frequency of votes in the central category (0) and the central three categories (-1, 0, and +1) of the ASHRAE thermal sensation scale at each measured indoor air temperature. In this figure the ASHRAE votes were binned according to the corresponding indoor air temperature,

TABLE 2
Frequency of Response to ASHRAE Thermal Sensation Question

Scale Descriptor	'Numerical' Vote Value	Frequency	%
Cold	-3	25	1.6
Cool	-2	62	3.9
Slightly Cool	-1	309	19.3
Neutral	0	821	51.3
Slightly Warm	1	268	16.8
Warm	2	94	5.9
Hot	3	21	1.3
		1600	

TABLE 3
Frequency of Response to McIntyre Thermal Preference Question

Scale Descriptor	'Numerical' Vote Value	Frequency	%
Cooler	-1	197	12.3
No Change	0	1113	69.6
Warmer	1	289	18.1
		1599	

and the mean vote of each bin was plotted vs. the mean temperature of the bin. The peak for both curves occurs for the temperature bin 23.1°C-24°C, with a mean bin temperature of 23.4°C.

Table 3 shows the frequency of responses to the McIntyre thermal preference question. Figure 3 shows the frequency of votes in each of the McIntyre thermal preference categories at each indoor air temperature; Figure 3 was constructed in the same way as Figure 2. The peak for the "no change" curve occurs for the temperature bin 23.1°C-24°C, with a mean bin temperature of 23.4°C.

A great deal of uncertainty was associated with our estimate of clothing insulation worn. Participants were asked to complete a checklist of clothing items to answer the question: "What clothing were you wearing when you arrived at work today?" We converted the responses into an equivalent clothing insulation value using the insulation values from ASHRAE Standard 55-1992 (ASHRAE 1992). Following ASHRAE 55-1992, we assumed that the total insulation of the clothing ensemble equaled the sum of the insulation values for the individual garments. Because we were administering the clothing checklist on a frequent basis, we did not want the checklist to be too cumbersome. As a result, our clothing checklist was very generic. For example, we chose a single, average value for a sweater of 0.34 clo, taking no account of the variety of garments that might be included by the participants under this descriptor.

Figure 4 shows the frequency of responses to the question regarding clothing insulation worn at the start of the working day.

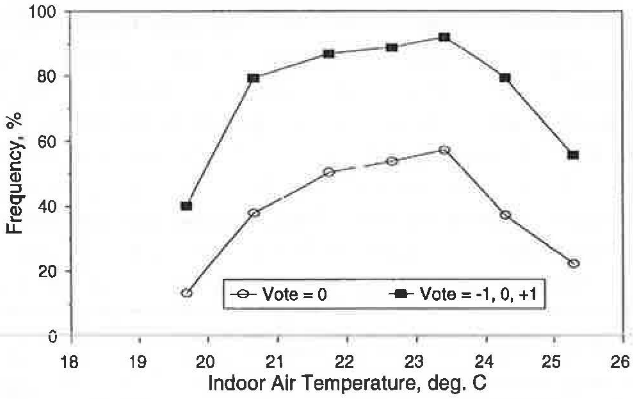

Figure 2 Frequency of response to the ASHRAE thermal sensation question vs. indoor air temperature, at all sites. The lower curve shows the frequency of 0 (neutral) votes; the upper curve shows the frequency of votes in the central three categories, -1, 0, +1 (slightly cool, neutral, slightly warm).

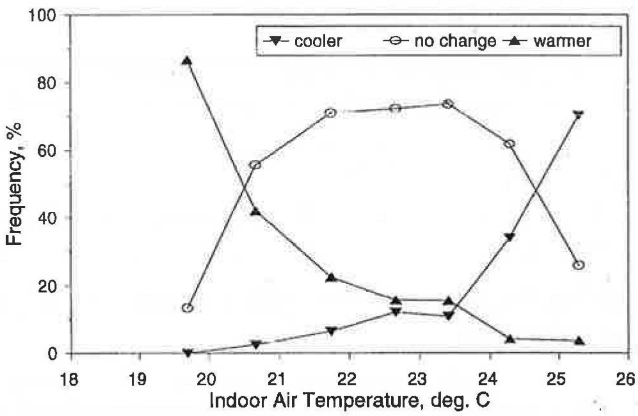

Figure 3 Frequency of response to the McIntye thermal preference question vs. indoor air temperature, at all sites.

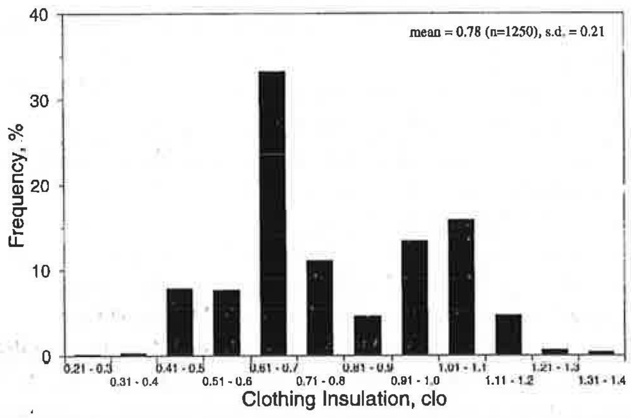

Figure 4 Frequency of response to the question regarding clothing insulation worn to work, at all sites.

TABLE 4
Frequency of Response to Clothing Modification Question, "How Have You Modified Your Clothing in the Last Hour?"

Scale Descriptor	'Numerical' Vote Value	Frequency	%
Major Decrease	-2	95	5.9
Minor Decrease	-1	57	3.6
No Change	0	1365	85.3
Minor Increase	1	31	1.9
Major Increase	2	53	3.3
		1601	

In Figure 4, clothing insulation was sorted into 0.1-clo bins. The mean clothing insulation worn was 0.78 ($n = 1250$), s.d. = 0.21. The frequency distribution is bimodal. The first peak occurs for clothing insulation of 0.61 to 0.7 clo, the second at 1.01 to 1.1 clo. Table 4 shows the frequency of responses to the question regarding clothing modification.

Correlations Between Data

We performed a number of correlations between individual parameters; only a subset of the resulting correlation coefficients are reported in this paper. The correlation between the two thermal acceptability measures, ASHRAE thermal sensation votes and McIntyre thermal preference votes, was strong and significant ($r = -0.712$, $n = 1544$, $p < 0.01$). The correlation between clothing modification and indoor air temperature was also highly significant ($r = -0.189$, $n = 1544$, $p < 0.01$); however, the correlation between clothing insulation worn and indoor air temperature was not significant.

Regressions Between Participant Responses and Physical Measures

Figure 5 shows a bubble plot of all the individual responses to the ASHRAE thermal sensation question vs. the corresponding indoor air temperature. A bubble plot is a variation on a scatter plot in which the size of the bubble is proportional to the number of data points at a particular location on the plot. A regression line is drawn through the data and has the equation:

$$\mathrm{TS} = -7.69 + 0.34 T_{ia} \; (n = 1600, r^2 = 0.11, p < 0.001) \quad (1)$$

where

TS = ASHRAE thermal sensation vote

T_{ia} = indoor air temperature (°C).

Figure 6 shows a more traditional plot of the same data. In this figure the ASHRAE votes were grouped according to the corresponding indoor air temperature bin, and the mean vote of each bin was plotted vs. the mean temperature of the bin. Also shown in the figure are the number of data points in each bin, the standard deviations in the ASHRAE votes for each bin (represented by the error bars), and a regression line. The regression line is weighted according to the number of observations associated with each mean and has the equation:

$$\mathrm{TS} = -7.56 + 0.33 T_{ia} \; (n = 1600, r^2 = 0.77, p < 0.001). \quad (2)$$

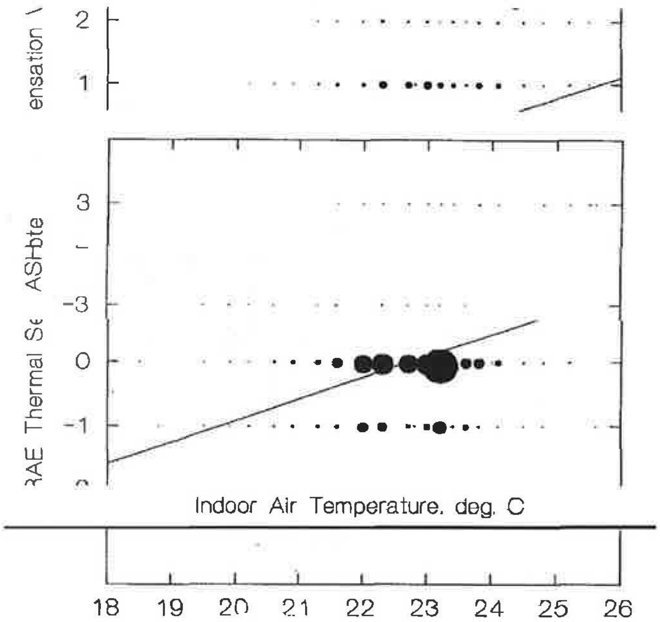

Figure 5 *A bubble plot of ASHRAE thermal sensation vote vs. indoor air temperature at all sites. The bubble size is proportional to the number of votes at the particular ASHRAE vote/air temperature combination.*

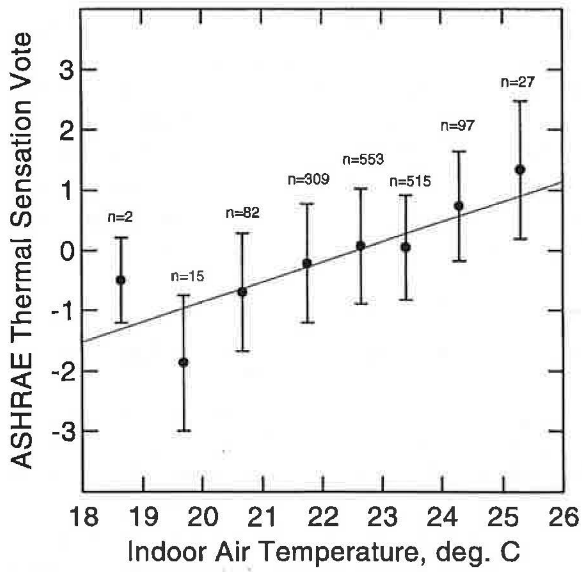

Figure 6 *Mean ASHRAE thermal sensation vote per temperature bin vs. mean temperature in the bin, data from all sites. The number of votes per bin is shown; error bars indicate standard deviations.*

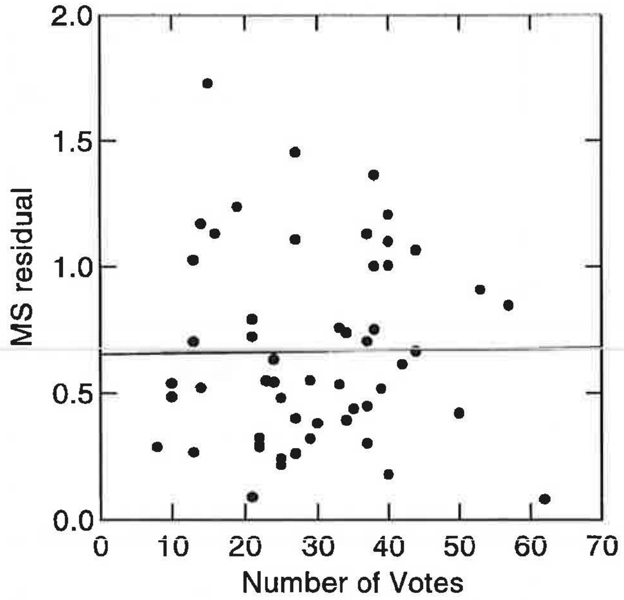

Figure 7 Variance in ASHRAE thermal sensation vote not due to indoor air temperature (MS residual) for each participant vs. total number of votes made by the participant.

A multiple regression of the individual ASHRAE thermal sensation votes on the following variables—clothing insulation, measured indoor air temperature, indoor relative humidity, outdoor air temperature, outdoor relative humidity, total horizontal solar radiation, calculated vertical solar radiation on the relevant orientation, and forecast temperature (outdoor air temperature at 8 a.m. each morning, a temperature that might have influenced morning clothing choice)—did not substantially increase r^2 over using indoor air temperature alone ($r^2 = 0.14$ vs. $r^2 = 0.11$; see Equation 1).

The Effect of Response Rate on Regressions

In the above correlations and regressions we grouped all responses into a single data set. However, as noted earlier, each participant voted a different number of times. Is it appropriate to group the data given that the participants with a greater response rate will be more represented in the data set than the participants who voted less frequently?

To address this issue we regressed the ASHRAE vote on indoor air temperature for each participant. We then plotted, for each participant, the mean square residual, $MS_{Residual}$ (variance in ASHRAE vote not accounted for by indoor air temperature) vs. the number of responses; this graph is shown in Figure 7. There is no correlation between $MS_{Residual}$ and response rate ($F = 0.008$, $n = 54$, $r^2 < 0.001$, $p = 0.93$). Since response rate appears to have no significant effect on the ASHRAE vote, we conclude that it was appropriate to group all the response data for the purposes of the above correlations and regressions.

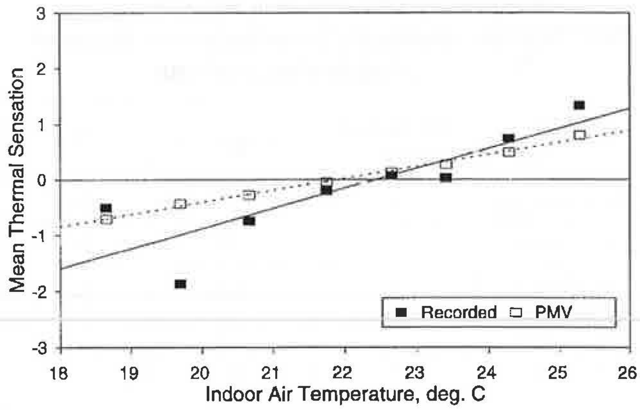

Figure 8 A comparison of the recorded mean ASHRAE thermal sensation vote and Predicted Mean Vote (PMV) vs. indoor air temperature, data from all sites.

Neutral and Preferred Temperatures

The neutral temperature (T_n) is the indoor air temperature most likely to produce the response "0" or "neutral" on the ASHRAE thermal sensation scale. T_n can be derived in two ways, first, from the regression of Equations 1 and 2, and second, from the frequency distribution of Figure 2. Inserting the value TS = 0 into Equations 1 and 2 yields a T_n of 22.7°C (72.8°F) and 22.9°C (73.2°F), respectively. Figure 2 shows that the temperature bin with the highest frequency of "neutral" responses was 23.1°C-24°C.

Comparison with Predicted Mean Vote (PMV)

The PMV is the mean thermal sensation vote for a population as predicted from Fanger's thermal comfort equations (Fanger 1970). We calculated the PMV associated with each questionnaire response using a simplification of Fanger's equations (Sherman 1985). As inputs to the equations, we used the measured values of indoor temperature, humidity, and reported clothing (with the addition of 0.15 clo to account for the insulative value of an office chair, as recommended in Brager et al. 1994; de Dear and Fountain 1994; McCullough et al. 1994; Palonen et al. 1993) and assumed a mean radiant temperature equal to air temperature, an air velocity of 0.1 ms^{-1}, and an activity of 1.2 met. These are all common assumptions for the office environment but clearly introduce uncertainty into the calculation of PMV.

Figure 8 compares our reported mean ASHRAE vote and mean PMV in each temperature bin. Also shown in Figure 8 are regression lines through the two sets of points.

Longitudinal Data

Figure 9 shows the weekly mean response to the ASHRAE thermal sensation question for all four sites. The standard deviation in the weekly data is indicated by the error bars. There may be a slight tendency for mean response to decrease with time (as

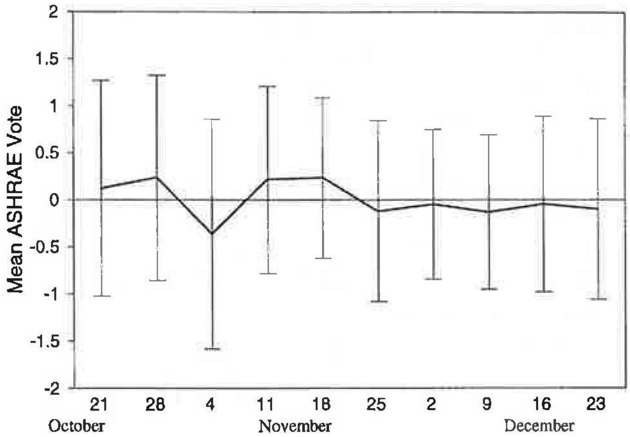

Figure 9 *Mean weekly ASHRAE thermal sensation vote, data from all sites. Error bars indicate standard deviations.*

the outdoor climate gets colder), although the week ending November 4 is an obvious exception to this. We tested this tendency by collapsing the ASHRAE votes into two subsets: those of the first five weeks of the study (mean = 0.09, $n = 854$) and those from the second half (mean = -0.09, $n = 746$). These means are significantly different ($n = 1600$, $F = 13.0$, $p < 0.001$).

Figure 10 shows the mean response to the ASHRAE thermal sensation question in the morning and afternoon for each orientation at site 3 (the only site with participants in offices with windows facing the four cardinal directions). The differences in the means in the morning and afternoon were not significant, except for the south orientation ($n = 185$, $F = 8.1$, $p = 0.005$).

Analysis of Final Evaluation Questionnaire

When asked "Did this method of automatic questionnaire administration distract you from your work?" only 11% of respondents voted 3 or 4 on the 5-point scale (0 = "not at all," 5 = "very much"). When asked about the number of questions asked at each scheduled time, 79% of respondents found the number of questions "acceptable," whereas 19% thought "too many" questions were asked each time. When asked if the questionnaire appeared too often, only 6% of respondents said "yes."

DISCUSSION

Comparison of Frequency Data with Thermal Comfort Standards

ASHRAE (1992) and ISO (1984) standards have requirements for acceptable indoor thermal comfort conditions. The goal of these standards is that 80% of the occupants should be satisfied. Satisfaction is defined as being a vote in the central three categories ("slightly cool," "neutral," "slightly warm") of the ASHRAE thermal sensation scale. The standards use Fanger's PMV model (1970) to derive acceptable operative temperature ranges, given assumptions for the other environmental and personal variables required by Fanger's model. Table 5 shows the required temperature ranges, and assumptions, by season. Note that Table 5 quotes the required temperature ranges for 10% dissatisfaction, whereas the overall goal of the standard is to achieve the less stringent 20% dissatisfaction.

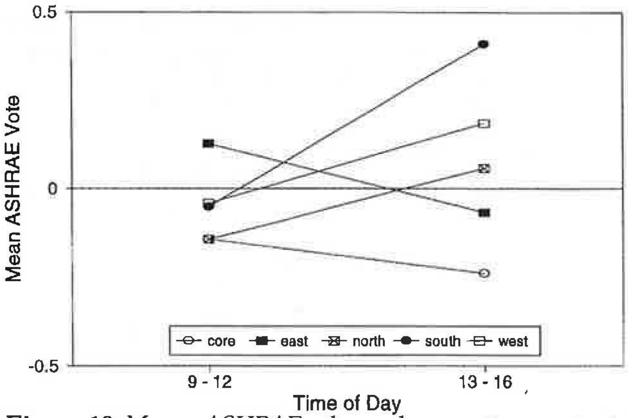

Figure 10 *Mean ASHRAE thermal sensation vote in morning and afternoon, by orientation, for site 3 only.*

Table 2 shows that in our study, 87% of responses to the ASHRAE thermal sensation question were within the central three categories. This indicates that, according to ASHRAE and ISO standards, the sites as a whole exhibited acceptable thermal comfort. But was this acceptable thermal comfort achieved by adhering to the temperature ranges specified in the standards? Our measured clothing insulation and indoor relative humidity differed from the winter assumptions in the standards. The standards offer a method for deriving temperature ranges in such cases. Using these methods, we derived an acceptable temperature range of 21.5°C to 25.0°C (70.7°F to 77°F). The standard's assumptions regarding activity and air speed are consistent with our assumptions. Note that the standards specify operative temperature, whereas we measured air temperature. If air temperature and MRT are equal, a valid assumption in most offices, air temperature and operative temperature are identical. For the purposes of this comparison, we shall make this assumption.

Figure 5 shows that although a large majority of responses fall within the required limits of temperature and thermal sensation, there are both acceptable thermal sensation votes at temper-

TABLE 5
ANSI/ASHRAE and ISO Standard Acceptable Operative Temperatures for Thermal Comfort, by Season (ANSI/ASHRAE 1992; ISO 1984)

Season	Optimum Temperature, °C	Range for 10% Dissatisfaction, °C	Assumptions
Winter	22.0	20.0 to 23.5	RH=50%, mean air speed £ 0.15 ms^{-1}, 1.2 met, 0.9 clo
Summer	24.5	23.0 to 26.0	RH=50%, mean air speed £ 0.15 ms^{-1}, 1.2 met, 0.5 clo

TABLE 6
Frequency of Responses According to Various Criteria
Acceptable Thermal Sensation Equals Central Three Categories of the ASHRAE Scale, and Temperature Limits Equal 21.5 °C to 25.0 °C (as Suggested by ANSI/ASHRAE and ISO Standards)

Acceptable Thermal Sensation?	Within Temperature Limits?		
	Yes	No	Σ
Yes	79%	8%	87%
No	10%	3%	13%
S	89%	11%	100%

atures outside the recommended range and unacceptable thermal sensation votes at temperatures within the recommended range. Table 6 shows the frequency of observations according to various criteria. Table 6 shows that 89% of the observed temperatures were within the temperature limits suggested by the standards, though we were unable to ascertain whether the building managers were expressly following the standards. For the thermal sensation votes cast when the observed temperature was within the required limits, only 11% (10/89) were outside the central three categories of the scale. This is very close to the goal criterion (10%) from which the temperature limits were derived. Therefore, our observations in the field seem to support the thermal comfort theory on which the standards were based.

Correlations Between Parameters

We observed a strong correlation between responses to the ASHRAE and McIntyre scales ($r = -0.71$). A strong correlation would certainly be expected, and similar results have been reported by Busch (1990) ($r = -0.69$) and Schiller et al. (1988a) (in summer, $r = -0.66$; in winter, $r = -0.45$).

Busch (1990) also reports a small but significant correlation between clothing insulation and indoor temperature ($r = -0.16$). Schiller et al. (1988a) report a larger, significant correlation for their winter survey (males: $r = -0.32$ females; $r = -0.24$) but no significant correlation in the summer. Comparisons with our study are harder to make since our reported clothing insulation level was based on clothing worn at the start of the working day and is therefore unlikely to be influenced by the indoor air temperature prevailing when the questionnaire was presented. More relevant in the context of our study is the correlation between reported clothing modification and indoor air temperature. We observed a significant ($p < 0.01$) correlation between clothing modification and indoor air temperature. Interestingly, this correlation is of about the same magnitude ($r = -0.19$) as the correlations between clothing insulation and temperature reported by Busch and Schiller et al.

Effect of Response Rate

A number of field studies have collected multiple thermal comfort votes from each of their participants (Ballantyne et al. 1977; Black 1954; Fishman and Pimbert 1982; Hindmarsh and Macpherson 1962; Humphreys and Nicol 1970; Palonen et al. 1993; Rowley et al. 1947; Schiller et al. 1988a). Inevitably, a different number of votes were collected from each participant in these studies. Generally, these studies grouped all the data together for analysis, with little reference to the fact that some participants would thus be overrepresented in the grouped data and other participants underrepresented. Statistically, one might desire an equal number of votes from each participant. However, if our aim is to produce better indoor thermal environments, perhaps it is advantageous from a practical point of view to bias the data set toward the responses of those subjects most frequently in the indoor environment in question. This practical consideration might justify analysis of grouped data irrespective of the biases that might be introduced. In fact, our analysis showed that the ASHRAE vote was not significantly correlated to frequency of response.

Overall Satisfaction

Table 7 presents a comparison of frequency responses to the ASHRAE thermal sensation scale and McIntyre thermal preference scale from various field studies in office or office-like environments. The level of thermal satisfaction according to responses on the ASHRAE scale in our study is similar to that reported in previous studies.

When comparing votes in the central category of the McIntyre scale, we find that the level of satisfaction reported in our study is substantially higher than in other studies. The reason for the high degree of satisfaction expressed in our study is not known. However, we did observe temperatures in the space in close agreement with those required by standards for thermal comfort.

Regressing Thermal Sensation on Temperature

Many authors have used field study data to derive a regression of thermal sensation vote on room temperature with the goal of generating a predictive equation. Such an equation can then be used, at the very least, to derive T_n for the studied population. Table 8 shows the regression coefficients, along with several other relevant observed and derived parameters, for a number of field studies in office or office-like environments (for example, college lecture theaters have also been included). The regression coefficients stated in Table 8 all refer to an equation of the form:

$$\text{TS} = a + b \times T. \quad (3)$$

Note that in some cases the thermal sensation response was made on the ASHRAE scale and in others on a Bedford Scale.[1] Note further that the temperature parameter was, variously, air temperature, operative temperature, environmental temperature, or some other composite temperature. However,

1. The Bedford Scale is another seven-point scale, with the following descriptors: "much too warm," "too warm," "comfortably warm," "comfortable," "comfortably cool," "too cool," "much too cool." Whereas the ASHRAE scale deals solely with thermal sensation, the Bedford scale combines thermal sensation and comfort.

TABLE 7
Thermal Acceptability Recorded by Various Field Studies

Field Study	ASHRAE Thermal Sensation		McIntyre Thermal Preference
	3 central categories (-1, 0, +1)	Central category only (0)	Central category (no change)
Auliciems and de Dear (1986a, 1986b)			
Darwin "Buildup season"	82%		
Darwin "Dry season"	76%		
Brisbane	84%		
Melbourne	85%		
Auliciems (1977)			
Adelaide	84%		
Melbourne	73%		
Armidale	85%		
Perth	80%		
Brisbane	86%		
Boonlualohr (1989)	~ 80%		
Busch (1992)	88%	43%	51%
de Dear et al. (1991)	78%		
de Dear and Fountain (1994)			
"Dry season"	76%	61%	
"Wet season"	74%	55%	
Hindmarsh and Macpherson (1962)	93%	62%	
Howell and Kennedy (1979)	72%	24%	
Humphreys and Nicol (1970), Humphreys (1976)	95%	50%	
Paciuk (1989)	77%	47%	
Schiller et al. (1988a), Schiller and Arens (1988)			
Winter	82%	41%	53%
Summer	84%	43%	52%
Wong (1967)			
Summer	87%	39%	
Winter	68%	32%	
Newsham and Tiller (1995)	**87%**	**51%**	**70%**

in most cases, the authors (and others) have observed that the performance of the two response scales, and the various temperature parameters, are very similar, and so it seems reasonable to present these various field studies side by side. In some studies certain of the values presented were not explicitly stated by the author. Where appropriate, we have used published data to derive approximate values for certain parameters.

As indicated in Table 8, the results of our field study, conducted using a new and original method for collecting participant responses (questionnaire software), compare well with those of other field studies. The similarity to the results of Schiller et al. (1988a, 1988b) is remarkable. Although Schiller et al. conducted their study in a different climatic zone (San Francisco Bay area), the buildings studied were similar to ours, being largely typical North American air-conditioned offices populated with professional/government workers. One limita-

TABLE 8
Regression Coefficients for Thermal Sensation vs. Temperature for Various Field Studies

(Other Relevant Parameters are Also Listed. Proportion of Variance in Thermal Sensation Vote Accounted for by Temperature (r^2) is Only Shown When the Regression was Done with Individual Data Points and Not with Binned Data. # Indicates an Approximate Value Derived from Publish d Data.)

Study	Regression coefficients			Neutral temperature, T_n		Mean clothing worn	Mean TS	Mean environmental parameters		Notes
	a	b	r^2	obs.	pred.	clo		T_{air}, °C	RH,%	
Auliciems and de Dear (1986a, 1986b), de Dear and Auliciems (1985)										T_n from Probit
Darwin "Buildup"	-9.65#	0.40#	0.27#	24.1	25.3	0.43	-0.43	23.7±0.14	56	
Darwin "Dry"	-10.53#	0.44#	0.25#	24.0	24.7	0.49	-0.16	23.3±0.07	47	
Brisbane				23.8	25.1	0.48	0.03	23.8±0.05		
Melbourne				22.6	24.8	0.55	0.25	23.4±0.11		
Auliciems (1977)										TS=Bedford
Adelaide	-4.56	0.22	0.11	20.6			-0.30±1.07	19.5±1.7		
Melbourne	-6.75	0.33	0.32	20.5			-0.04±1.22	20.4±2.1		
Armidale	-6.33	0.30	0.24	21.3			0.31±1.09	22.4±1.8		
Perth	-4.52	0.29	0.08	21.9			-0.47±1.18	19.6±1.5		
Brisbane	-5.03	0.22	0.20	23.1			-0.10±1.03	22.6±2.2		
Auliciems and Parlow (1975)							0.17±0.88			TS=Bedford
Ballantyne et al. (1977)										T_n from Probit
Summer				22.7		0.67		22.8		
Winter				21.3		1.03		20.7		
Gagge and Nevins (Berglund 1979)	-12.10	0.48		25.2		0.85				
Boolualohr										
Winter			0.08			0.66±0.15	0.14±1.06	22.8±1.1	34.0±2.0	
Summer			0.10			0.48±0.09	-0.02±0.91	23.3±1.1	73.1±3.0	
Fall			0.27			0.67±0.17	0.63±1.12	23.5±1.0	36.9±14.6	
Brager et al. (1994)	-6.40	0.29		22.4	22.6					$T=T_{operative}$
Busch (1990)	-8.09	0.33	0.20	24.8						T=ET
Cena et al. (1990)										
Philadelphia						0.60±0.10	0.2±1.2	23.8±3.0		
Perth						0.37±0.05	1.2±1.3	27.2±2.8		
Croome et al. (1992)	-10.01	0.46	0.53	21.8	22.7			24.0	45.5	
de Dear et al. (1991)	-9.68#	0.40#	0.18#	24.2		0.44±0.10	-0.34±1.2#	22.9±1.3	55.5±7.6	T_n from Probit, $T=T_{operative}$
de Dear and Fountain (1994)										
"Dry"	-12.31#	0.51#	0.18#	24.2		0.54±0.19	-0.4±1.1	23.3±0.9	51±9	T_n from Probit
"Wet"	-13.75#	0.57#	0.23#	24.6		0.44±0.13	-0.3±1.1	23.6±1.0	56±6	

TABLE 8 (Continued)

Regression Coefficients for Thermal Sensation vs. Temperature for Various Field Studies

(Other Relevant Parameters are Also Listed. Proportion of Variance in Thermal Sensation Vote Accounted for by Temperature (r^2) is Only Shown When the Regression was Done with Individual Data Points and Not with Binned Data. # Indicates an Approximate Value Derived from Publish d Data.)

Fishman and Pimbert (1982)		0.24		22.0	22.6					$T=T_{globe}$
Grivel and Barth (1982)	-3.47	0.18	0.04	19.6		0.76±0.19	0.00	22.5±1.3	49±7	
Grivel and Barth (1980)						0.78	0.82	22.8		
Hindmarsh and Macpherson (1962)	-3.69#	0.16#	0.42#				0.06±0.80#	22.9±3.2#		TS=Bedford
Howell and Kennedy (1979)							-0.59	23.2		
Humphreys and Nicol (1970), Humphreys (1976)		0.20		20.3			0.24			T_n from Probit, TS=Bedford
Kakhonen et al. (1990)	-7.68#	0.36#		21.1#		0.63±0.10	0.66±0.63#	22.9±1.4#	30±3#	
Markee White (1986)										
Summer				24.9		0.60±0.11		24.0±0.9	52±4	
Winter				23.4		0.81±0.17		22.8±0.8	29±8	
Oseland (1994)	-4.57	0.21	0.40	21.8		0.8	-0.5	20.7	41	$T=T_{operative}$
Paciuk (1989)		0.30	0.14	21.7	23.4	0.66±0.12	0.41±1.17	21.7±1.4	58±10	$T=T_{operative}$
Schiller et al. (1988a, 1988b)										T=ET*
Winter	-7.20	0.33	0.09	22.0		0.58	0.18	22.8±1.2		
Summer	-7.04	0.31	0.13	22.6		0.52	0.23	23.3±1.3		
Wong (1967)										
Summer							-0.09	23.2		
Winter							0.11	21.2		
Newsham and Tiller (1995)	**-7.69**	**0.34**	**0.11**	**22.7**	**21.9**	**0.78±0.21**	**0.01±1.00**	**22.7±1.0**	**28.3±8.6**	

tion of our study is that we did not measure temperature and humidity at every participant's desk; our paucity of datalogging equipment required us to choose a single measurement point for each building orientation. This might be expected to reduce the correlation between temperature and thermal sensation votes. However, Table 8 shows that the proportion of variance in individual thermal sensation votes accounted for by indoor air temperature (r^2) we observed is similar to that observed by Schiller et al., who made detailed environmental measurements at every workstation when thermal sensation votes were gathered. Schiller et al.'s study was arguably the most rigorously conducted study of its kind at the time, and their procedure was adopted as a model by ASHRAE and was recently replicated by de Dear and Fountain (1994) in northeastern Australia.

The proportion of variance in individual thermal sensation votes accounted for by indoor air temperature in our study is small ($r^2 = 0.11$) but within the range of variance explained by temperature reported by other field studies. Even when we regress thermal sensation on a wider range of measured physical and personal parameters (clothing insulation, measured indoor air temperature, indoor relative humidity, outdoor air temperature, outdoor relative humidity, total horizontal solar radiation, vertical solar radiation on the relevant orientation, and forecast temperature), the proportion of variance explained only rises to 0.14. Similar observations have been made by other authors (Grivel and Barth 1982; Schiller et al. 1988b; Paciuk 1989).

One reason why r^2 is so small is that in most offices, particularly air-conditioned offices, the range of temperatures to which the participants are exposed is small compared to the range of temperatures the human body can physiologically accommodate. A narrow stimulus range is a fundamental cause of low correlation (Howell and Kennedy 1979; Markee White 1986; McIntyre 1978). Nevertheless, we are faced with the fact that the traditional physical and personal parameters are not very good predictors of individual thermal comfort votes in the field.

Comparison with PMV

We noted earlier that the data from our study seemed in good agreement with the ASHRAE and ISO standards for thermal comfort. These standards are based on Fanger's theory. Figure 8 compares the mean observed ASHRAE votes vs. temperature and PMV vs. temperature. Since PMV predicts the mean response of large populations, it is appropriate to make comparisons between the mean responses of grouped data and not between the responses of individuals at specific times.

The mean response data from our study fit the PMV values quite well. The fit around the neutral temperature (temperature at which the mean thermal sensation = 0) is close, within 1°C (1.8°F). However, the field data show a tendency to diverge toward more extreme responses both above and below T_n, indicating that our participants were more sensitive to temperature deviations away from T_n than would have been predicted by Fanger's theory. However, this comparison is clouded by the assumptions and estimations made for input variables to the PMV equation that were not measured. Perhaps chief among these is the estimation of clothing insulation.

Clothing Modification

Table 4 shows that 14.7% of participants had modified their clothing in the hour prior to the appearance of the questionnaire. Although we didn't ask why modifications were made, it is likely that improving thermal comfort was the principal reason. In the context of trying to produce a thermal environment dissatisfactory to only 20% of occupants (according to ANSI/ASHRAE and ISO standards), the fact that up to 14.7% of participants used clothing modification to achieve improved thermal comfort becomes important.

Longitudinal Data

Humphreys' well-known meta-analysis (1978) found a strong relationship between monthly mean outdoor air temperature and thermal comfort indoors, even in air-conditioned buildings ($r^2 = 0.5$ to 0.6). However, studies carried out between seasons in the same location have found little variation in thermal comfort data that could not be explained by seasonal clothing changes (Auliciems and de Dear 1986a, 1986b; Fishman and Pimbert 1982; Markee White 1986; Schiller et al. 1988a; Hindmarsh and Macpherson [1962] is an exception). In our study, the tendency for the mean ASHRAE vote to vary with the week (Figure 9) is in the expected direction, but small. Though our study covered only 10 weeks, mean daily outdoor air temperature changed substantially (by about 20°C [36°F]) over the period.

A number of laboratory studies have found no effect of time of day on thermal sensation (Fanger et al. 1973; Griffiths and McIntyre 1973; Rohles 1980). In these studies the thermal conditions were maintained constant or were manipulated toward thermal neutrality by the participants; what they were essentially looking for was whether diurnal changes in human internal body temperature affected thermal preference (Boolualohr 1989; Hensen 1990; Purcell and Thorne 1987). In a field study, the effect of time of day is confounded by many other factors that also change systematically with time: solar radiation, work schedule, and caffeine intake, for example. From a practical point of view, systematic variations in thermal comfort with time could have important implications for building controls technology, whatever their cause.

Observed differences in mean thermal sensation between morning and afternoon at site 3 were small and not statistically significant, with the exception of the south orientation where the difference was 0.46 on the ASHRAE scale. Nevertheless, the differences in the mean response are in the expected directions: the east orientation is warmer than neutral during the morning and on the cold side of neutral during the afternoon; whereas the opposite tendency is apparent for the west and south orientations. These relationships would be worth pursuing in a more focused study.

Final Evaluation Questionnaire

The principal aim of the final evaluation questionnaire was to evaluate the acceptability to participants of the computer-based questionnaire method and to solicit suggestions for improvements. Results generally indicate that the respondents found the questionnaire software method acceptable. While no direct comparisons to paper-based questionnaires were made, it seems unlikely that a paper-based questionnaire, administered as frequently as the questionnaire was administered in our study, would have produced the same low ratings of distraction. Cena et al. (1990) suggest that minimum disruption is an important consideration because normal work practices are maintained and the results are likely more valid. Some have argued (e.g., Fanger 1992) that the stress of being interviewed can increase metabolic rate and thus bias thermal sensation ratings; the computer-based questionnaire, which eliminates the interviewer-interviewee relationship, might serve to reduce these biases.

Questionnaire Success

Given the results of the final evaluation questionnaire and the measures of response rate and response time, we can conclude that the questionnaire software was successful in achieving its goals of being an effective way of administering questionnaires in longitudinal studies. Further, the results of our study were consistent with the results of other field studies of thermal comfort conducted using more traditional methods, as well as obtaining additional data (longitudinal) that would have been extremely hard to gather using traditional methods.

Since completion of this study, we have further developed the computer-based questionnaire. An additional response type, open-ended text entry, has been added. Questions can now be enhanced with color and graphics and even sound and video clips. Further, the software is now network compatible, so that all questionnaire files and responses can be recorded in a single location on a network drive. We continue to employ the computer-based questionnaire in several of our ongoing indoor environment research projects.

CONCLUSIONS

This section presents the major conclusions of the study. This study had two aims: to field test the questionnaire software to assess its usefulness as a survey tool and to examine the relationship between the thermal environment in open-plan office spaces and the thermal comfort of its occupants. The conclusions are presented according to these aims.

- The vast majority of participants (89%) said that the computer-based questionnaire did not distract them significantly from their work, only 6% said the questionnaire appeared too often, and 19% said the number of questions asked each time was too many.
- The five thermal-comfort-related questions in the questionnaire took an average of only 45 seconds to answer.
- Each participant answered the questionnaire an average of 29 times; the questions were presented a maximum of 100 times.
- The results of the thermal comfort study were consistent with the results of prior field studies of thermal comfort conducted using more traditional survey methods.
- Thermal sensation votes were normally distributed. Fifty-one percent of votes were in the central category ("neutral"); 87% were in the central three categories ("slightly cool" to "slightly warm").
- Thermal preference votes were normally distributed. Seventy percent of votes were in the central category ("no change").
- Fifteen percent of respondents indicated a clothing modification during the hour before questionnaire administration. Incidences of clothing removal outweighed those of clothing addition 2:1.
- An individual's frequency of response and his/her ASHRAE thermal sensation vote were not significantly correlated, which allowed us to group data for statistical analysis.
- Eleven percent of the variance in individual ASHRAE thermal sensation votes was explained by indoor air temperature.
- By regressing the ASHRAE vote on air temperature, we derived a neutral temperature (T_n) of 22.7°C (72.8°F). The temperature bin with the highest frequency of "neutral" responses to the ASHRAE thermal sensation question was 23.1°C-24°C.
- The measured data on mean thermal sensation compare quite well with PMV around the neutral temperature. However, the PMV vs. indoor air temperature curve has a lower gradient than the measured thermal sensation data.
- The mean response to the ASHRAE thermal sensation question varied little from week to week despite a dramatic change in outdoor climate over the period of the study.
- The mean response to the ASHRAE thermal sensation question varied little from hour to hour. However, when the data were subdivided by orientation, variations with time of day were revealed. Although the differences were for the most part insignificant, they were in the expected direction.
- Eighty-nine percent of the observed temperatures were within the temperature limits suggested by the standards. When the observed temperature was within the suggested limits, only 11% of the thermal sensation votes were outside the central three categories of the ASHRAE thermal sensation scale. This corresponded well with the goal criterion from which the temperature limits were derived.

Further analyses are available in Newsham and Tiller (1995).

ACKNOWLEDGMENTS

The authors have many people to thank for the successful completion of this project: Sequence Electronics for development of the version of the questionnaire software used in this study; Dr. Jennifer Veitch for her help in the statistical analysis of the data; and all the people who agreed to participate in this thermal comfort study, in particular Tony Fisher, Albert Joseph, Ian Beausoleil-Morrison, and Scott Mellon, who acted as local coordinators at each of the study sites. We would also like to acknowledge the financial support of Public Works and Government Services Canada in the development of the questionnaire software package.

REFERENCES

ASHRAE. 1992. *ANSI/ASHRAE Standard 55-1992, Thermal environmental conditions for human occupancy.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Auliciems, A. 1977. Thermal comfort criteria for indoor design temperatures in the Australian winter. *Architectural Science Review*, December, pp. 86-90.

Auliciems, A., and R. de Dear. 1986a. Air conditioning in Australia I—Human thermal factors. *Architectural Science Review* 29(9): 67-75.

Auliciems, A., and R. de Dear. 1986b. Air conditioning in a tropical climate: Impacts upon European residents in Darwin, Australia. *International Journal of Biometeorology* 30(3): 259-282.

Auliciems, A., and J. Parlow. 1975. Thermal comfort and personality. *Building Services Engineer* 43(8): 94-97.

Baillie, A.P., I.D. Griffiths, and J.W. Huber. 1988. Thermal comfort assessment: A new approach to comfort criteria in buildings. ETSU Report No. S-1177.

Ballantyne, E.R., R.K. Hill, and J.W. Spencer. 1977. Probit analysis of thermal sensation assessments. *International Journal of Biometeorology* 21(1): 29-43.

Barakat, S.A. 1983. Comparison of models for calculating solar radiation on tilted surfaces. *Proceedings of 4th International Symposium on the Use of Computers for Environmental Engineering Related to Buildings*, Tokyo, Japan, pp. 317-322.

Berglund, L.G. 1979. Thermal acceptability. *ASHRAE Transactions* 85(2): 825-834.

Black, F.W. 1954. Desirable temperatures in offices. *Journal of the Institution of Heating and Ventilating Engineers* 22(11): 319-328.

Boonlualohr, P. 1989. The effect of radiant heat exchange on thermal comfort in the workplace. Ph.D. thesis, University of Michigan.

Brager, G.S., M.E. Fountain, C.C. Benton, A.E. Arens, and F.S. Bauman. 1994. A comparison of methods for assessing thermal sensation and acceptability in the field. *Proceedings of Thermal Comfort: Past, Present and Future*, Garston, U.K., pp. 17-39.

Busch, J.F. 1990. Thermal responses to the Thai office environment. *ASHRAE Transactions* 96(1): 859-872.

Busch, J.F. 1992. A tale of two populations: Thermal comfort in air-conditioned and naturally ventilated offices in Thailand. *Energy and Buildings* 18: 235-249.

Cena, K.M., P.G. Ladd, and J.R. Spotila. 1990. A practical approach to thermal comfort surveys in homes and offices: Discussion of methods and concerns. *ASHRAE Transactions* 96(1): 853-858.

Croome, D.J., G. Gan, and H.B. Awbi. 1992. Field evaluation of the indoor environment of naturally ventilated offices. *Proceedings of 13th AIVC Conference*, Nice, France, pp. 333-342.

de Dear, R.J., and A. Auliciems. 1985. Validation of the predicted mean vote model of thermal comfort in six Australian field studies. *ASHRAE Transactions* 91(2B): 452-468.

de Dear, R.J., and M.E. Fountain. 1994. Field experiments on occupant comfort and office thermal environments in a hot humid climate. *ASHRAE Transactions* 100(2): 457-475.

de Dear, R., M. Fountain, S. Popovic, S. Watkins, G. Brager, E. Arens, and C. Benton. 1993. A field study of occupant comfort and office thermal environments in a hot-humid climate. ASHRAE Report No. RP-702. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

de Dear, R.J., K.G. Leow, and S.C. Foo. 1991. Thermal comfort in the humid tropics: Field experiments in air conditioned and naturally ventilated buildings in Singapore. *International Journal of Biometeorology* 34: 259-265.

Fanger, P.O. 1970. *Thermal comfort*. Copenhagen: Danish Technical Press.

Fanger, P.O. 1992. *Building Services*, November, p. 15.

Fanger, P.O., J. Hojbjerre, and J.O.B. Thomsen. 1973. Man's preferred ambient temperature during the day. *Archives des Sciences Physiologiques* 27: A395-A402.

Fishman, P.S., and S.L. Pimbert. 1982. The thermal environment in offices. *Energy and Buildings* 5(1): 109-116.

Griffiths, I.D., and D.A. McIntyre. 1973. Subjective response to relative humidity at two air temperatures. *Archives des Sciences Physiologiques* 27: A459-A466.

Grivel, F., and M. Barth. 1980. Thermal comfort in office spaces: Predictions and observations. *Proceedings of Building Energy Management*, Povoa de Varzim, Portugal, pp. 681-693.

Grivel, F., and M. Barth. 1982. Personal characteristics related to interpersonal differences of thermal comfort expressed in office spaces. *Proceedings of Persons Not People*, CIB, Chester, U.K., pp. 8.1-8.12.

Hensen, J.L.M. 1990. Literature review on thermal comfort in transient conditions. *Building and Environment* 25(4): 309-316.

Hindmarsh, M.E., and R.K. Macpherson. 1962. Thermal comfort in Australia. *Australian Journal of Science* 24(8): 335-339.

Howell, W.C., and P.A. Kennedy. 1979. Field validation of the Fanger thermal comfort model. *Human Factors* 21(2): 229-239.

Humphreys, M.A. 1976. Field studies of thermal comfort compared and applied. *Building Services Engineer* 44(4): 5-27.

Humphreys, M.A. 1978. Outdoor temperature and comfort indoors. *Building Research and Practice* (Apr): 92-105.

Humphreys, M.A. 1994. Field studies and climate chamber experiments in thermal comfort research. *Proceedings of Thermal Comfort: Past, Present and Future*, Garston, U.K., pp. 52-72.

Humphreys, M.A., and J.F. Nicol. 1970. Thermal comfort of office workers. *Journal of the Institution of Heating and Ventilating Engineers* 38(11): 181-189.

ISO. 1984. International Standard 7730, Moderate thermal environments—Determination of the PMV and PPD indices and specification of the conditions for thermal comfort. Geneva: International Organisation for Standardization.

Jaakkola, J.J.K., O.P. Heinonen, and O. Seppanen. 1989. Sick building syndrome, sensation of dryness and thermal comfort in relation to room temperature in an office building: Need for individual control of temperature. *Environment International* 15: 163-168.

Markee White, N.L. 1986. Quantification of factors influencing thermal comfort in an office environment: Implications for energy conservation. Ph.D. thesis, University of California, Davis.

McCullough, E.A., B.W. Olesen, and S. Hong. 1994. Thermal insulation provided by chairs. *ASHRAE Transactions* 100(1): 795-802.

McIntyre, D.A. 1978. Seven point scales of warmth. *Building Services Engineer* 45(3): 215-226.

Newsham, G.R., and D.K. Tiller. 1995. A field study of office thermal comfort using questionnaire software. IRC Internal Report No. 708. Ottawa, Canada: National Research Council.

Nicol, J.F., and M.A. Humphreys. 1973. Thermal comfort as part of a self-regulating system. *Proceedings of Thermal*

Comfort and Moderate Heat Stress, Garston, U.K., pp. 263-274.

Orgill, J.F., and K.G.T. Hollands. 1977. Correlation equation for hourly diffuse radiation on a horizontal surface. *Solar Energy* 19: 357-359.

Oseland, N. 1994. Predicted and reported thermal sensation in climate chambers, offices and homes. *Energy and Buildings* 23: 105-115.

Oseland, N.A., and M.A. Humphreys. 1994. Trends in thermal comfort research. BRE Report BR 266. Garston, U.K.: Building Research Establishment.

Paciuk, M.T. 1989. The role of personal control of the environment in thermal comfort and satisfaction in the workplace. Ph.D. thesis, University of Wisconsin.

Palonen, J., O. Seppanen, and J.J.K. Jaakkola. 1993. The effects of air temperature and relative humidity on thermal comfort in the office environment. *Indoor Air* 3: 391-397.

Purcell, A.T., and R.H. Thorne. 1987. The thermal environment and level of arousal: Field studies to ascertain the effects of air-conditioned environments on office workers. *Architectural Science Review* 30(4): 91-116.

Rohles, F.H. 1980. Temperature or temperament: A psychologist looks at thermal comfort. *ASHRAE Transactions* 86(1): 541-551.

Rohles, F.H., J.E. Woods, and P.R. Morey. 1989. Indoor environment acceptability: The developing of a rating scale. *ASHRAE Transactions* 95(1): 23-27.

Rowley, F.B., R.C. Jordan, and W.E. Snyder. 1947. Comfort reactions of workers during occupancy of air conditioned offices. *ASHVE Transactions* 53: 357-368.

Schiller, G.E., and E.A. Arens. 1988. Thermal comfort in office buildings. *ASHRAE Journal* (Oct): 26-32.

Schiller, G.E., E.A. Arens, F.S. Bauman, C. Benton, M. Fountain, and T. Doherty. 1988a. A field study of thermal environments and comfort in office buildings. *ASHRAE Transactions* 94(2): 280-308.

Schiller, G.E., E.A. Arens, F.S. Bauman, C. Benton, M. Fountain, and T. Doherty. 1988b. A field study of thermal environments and comfort in office buildings. ASHRAE Report No. 462-RP. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Sherman, M. 1985. A simplified model of thermal comfort. *Energy and Buildings* 8: 37-50.

Wong, F.M. 1967. The significance of work comfort in architecture. *Architectural Science Review* 10(12): 119-130.