#4773

THERMAL RESPONSES TO THE THAI OFFICE ENVIRONMENT

J.F. Busch
Student Member ASHRAE

ABSTRACT

This paper reports on a field study of more than 1100 Thai office workers in which a questionnaire survey and simultaneous physical measurements were taken. Both air-conditioned and non-air-conditioned buildings were included. The data are compared to those from other field studies from both temperate and tropical climates. Thai subjective responses were analyzed on the ASHRAE, McIntyre, and other rating scales, relating them to effective temperature, demographics, and to rational indices of warmth such as PMV and TSENS. Selected results are as follows: the neutral temperature of the whole sample was 25°C and in rough agreement with several empirical model predictions; the ASHRAE Scale category widths, determined through probit analysis, exceed by several degrees previously published findings; Thai conditions of thermal acceptability exist over a broad range of effective temperature, from 22°C to 30.5°C, pushing the summer comfort zone outward by 4°C. These findings suggest that, without sacrificing comfort, significant energy conservation opportunities exist through the relaxation of upper space temperature limits.

INTRODUCTION

To date the majority of studies of human response to the thermal environment in building interiors have been carried out in the temperate climates of industrialized countries. In this paper, findings of a field study of thermal comfort in offices in Bangkok, Thailand, are presented. The field study is part of a larger study of energy conservation potential in Thai commercial buildings.

It is important to examine thermal comfort in the context of tropical developing countries because of the concentration of world population and growth there. Currently, air-conditioned buildings in the tropics and elsewhere are designed according to criteria based on comfort studies of white, male, college-age respondents from the West. Because the conditions are so different in most developing countries in terms of race, age distribution, climatic experience, and perhaps expectation, these criteria may be inappropriate. Specifically, there may be opportunities to save energy and capital investment in air-conditioning equipment should there be a preference or higher tolerance of thermal environmental factors such as temperature, humidity, and air flow.

The objectives here are to place the data collected in Thai offices in context by comparison with results of other researchers, particularly those from tropical countries, and to contrast the results from different subgroupings of the data, such as between seasons, between conditioned and unconditioned buildings, between men and women, and other comparisons where appropriate. Ultimately the goal of this thermal comfort research is to define the limits of tolerance or acceptability of conditions for the purpose of determining energy conservation potential in buildings. The rest of the paper contains a section on the methods used for gathering and processing the data, followed by discussion of the results and conclusions.

METHODOLOGY

In the following section we describe the buildings and how we chose them, followed by our methods for conducting the field survey and carrying out the analysis.

Building Selection

The criteria for selecting buildings for the field study were as follows:

1. located in Bangkok, the capital city of Thailand, where the majority of commercial buildings are,
2. modern buildings not more than 10 years old,
3. both air-conditioned (AC) and non-air-conditioned or naturally ventilated (NV) buildings,
4. regular office desk work of a majority of the building occupants,
5. a variety of ages and sexes.

Building Descriptions

The two air-conditioned buildings are of modern high-rise design, one a head office for a bank, the other a multiple-client building. The two naturally ventilated buildings are contemporary medium-rise government buildings housing ministerial and departmental offices. All buildings are located within 10 kilometers (km) of one another in downtown Bangkok.

John F. Busch is a doctoral candidate in the Energy and Resources Group, University of California, Berkeley, and research assistant at Lawrence Berkeley Laboratory, Berkeley, CA.

Subjective Rating Scales Used in Thai Thermal Comfort Study

ASHRAE Scale: "Rate how you feel at this moment"

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

McIntyre Scale: "I would like to be ..."

Warmer
No Change
Cooler

Humidity Scale: "Rate the immediate environment at this moment in terms of humidity"

-3	-2	-1	0	1	2	3
much too dry	too dry	slightly dry	just right	slightly humid	too humid	much too humid

Air Flow Scale: "Rate the immediate environment at this moment in terms of air movement"

-3	-2	-1	0	1	2	3
much too still	too still	slightly still	just right	slightly breezy	too breezy	much too breezy

Figure 1

Data Collection

Thailand experiences three distinct seasons in a year. The studies reported in this paper were carried out in each of two seasons: during the hot season (in April) and the wet season (in July) of 1988. Each of the four buildings mentioned above was visited in both seasons. Data were typically collected over one work week at each site per season.

Questionnaire The questionnaire consisted of a section of subjective ratings on a variety of thermal scales, followed by a section on recent food and beverage consumption, then separate clothing lists for men and women, and concluded with a section on demographic factors. Subjective ratings employed the seven-point ASHRAE Thermal Sensation Scale shown in Figure 1. Respondents were asked to mark the scale at any one of the seven points or the mid-points in between them (i.e., at any "tick mark"). Another seven-point scale, the Bedford Scale, was not used in this study because, though semantically different from the ASHRAE Scale, earlier studies using both produced similar results. The respondents were also asked the question, "I would like to be . . . warmer (1), no change (0), cooler (−1)," otherwise known as the three-point McIntyre Scale. Two further seven-point scales specifically addressing perceptions of airflow and humidity conditions were also used. The questionnaire was translated into the Thai language and scrutinized for semantic accuracy by Thai social scientists with facility in both English and Thai.

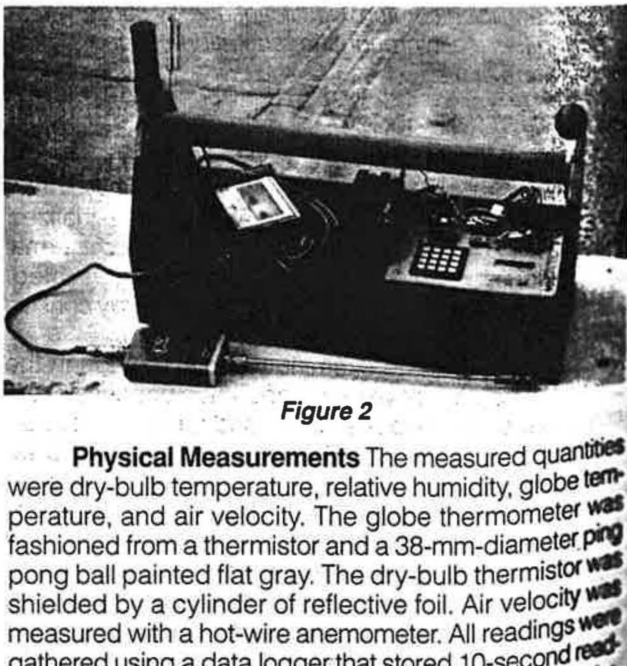

Figure 2

Physical Measurements The measured quantities were dry-bulb temperature, relative humidity, globe temperature, and air velocity. The globe thermometer was fashioned from a thermistor and a 38-mm-diameter ping pong ball painted flat gray. The dry-bulb thermistor was shielded by a cylinder of reflective foil. Air velocity was measured with a hot-wire anemometer. All readings were gathered using a data logger that stored 10-second readings on magnetic tape. The data logger, tape recorder, and battery (for the hot-wire anemometer) were all contained within, and the temperature and humidity sensors were attached to a wooden box with a handle, similar in size and shape to a standard tool box (see Figure 2). The hot-wire anemometer was detached from the "tool box" but connected by a two-meter cord. As is evident from Figure 2, the sensors were attached vertically to maximize exposure to room air and far enough apart to minimize interference with each other. Data for outdoor weather conditions were gathered from measurements made in the city center by the Royal Thai Meteorological Department.

Conduct of the Survey

Teams of two or three typically carried out the survey with one member taking the physical measurements and one or two handing out and collecting the questionnaire survey forms. The latter would approach prospective respondents and ask if they had been seated at that spot for at least 15 minutes; those who replied affirmatively received the form, the others did not. The questionnaire came with a cover letter explaining the project and the auspices under which it was being carried out, along with general directions for filling out the form. Confidentiality was confirmed and disclosure of a respondent's name was optional. An attempt was made not to gather multiple responses from the same individual in a given season, but there was no corresponding effort to exclude people from participating in both seasons. Survey teams sought participation from a roughly equal proportion of men and women in a range of ages and job positions and, to the extent possible, those from different zones and floors of each building.

Measurements of the thermal environment were taken at each workstation following, or in some cases during, the completion of the questionnaire survey form, but usually within five minutes of one another. The "tool box" was placed on or very near the desk where the respondent was seated for at least one minute prior to starting a data sweep. A unique code number for each response was entered into the data logger and also written on the survey form, along with the starting time of the data sweep to ensure proper matching of data sets later. The hot-wire anemometer wand was held at the subject's torso level, as close to the respondent as decorum allowed (i.e., 0.5 meters at a minimum) on the side that intercepted the strongest discernible air flow impinging on the subject. A tell-tale made of thread was used to determine airflow direction. After four minutes of data collection, the "tool box" was shifted to the next workstation. Care was taken to allow the equipment to equilibrate when moving to zones with different temperatures.

Data Processing and Archival

Questionnaire data were numerically coded to facilitate statistical analysis. Individual clothing articles indicated in the survey responses were converted into their respective thermal insulation values (I_{comp}) in units of clo (1 clo = 0.155 m^2°C/W) as tabulated in McIntyre (1980). The overall clo value for each subject's entire clothing ensemble was then determined using the following empirical formulae, also from McIntyre (1980),

$$I_{clo,\,men} = 0.113 + 0.727\sum I_{comp}$$

$$I_{clo,\,women} = 0.05 + 0.77\sum I_{comp} \qquad (1)$$

Metabolic heat production was not directly measured, but since respondents were carefully prescreened to have been seated for at least 15 minutes, their metabolic rate was assumed to be 1.1 met (1 met = 58 W/m^2), which is the typical level given for light office activities (ASHRAE 1989). Later computation of various comfort indices required determining the body surface area (A_{Du}) of each subject in m^2 based on their reported weight (W) and height (H) (in kg and m, respectively) using the Dubois formula (McIntyre 1980),

$$A_{Du} = 0.202\,W^{0.425}H^{0.725} \qquad (2)$$

Mean radiant temperature (MRT) was calculated as prescribed in the 1984 *ASHRAE Systems Handbook* (ASHRAE 1984). A program adapted from the Doherty and Arens (1988) model was used for calculating environmental indices such as ET* and SET* and comfort indices such as PMV*, HSI, DISC, and TSENS. Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) were calculated using the method specified in the International Standards Organization Standard 7730 (ISO 1984).

Physical measurements were transferred from cassette tape to microcomputer files. Then non-linear analog sensor outputs were converted into physical units and all outputs processed into averages of three minutes' data for each workstation. These physical measurement data, along with the questionnaire data, were entered into microcomputer data bases for subsequent analysis and archival.

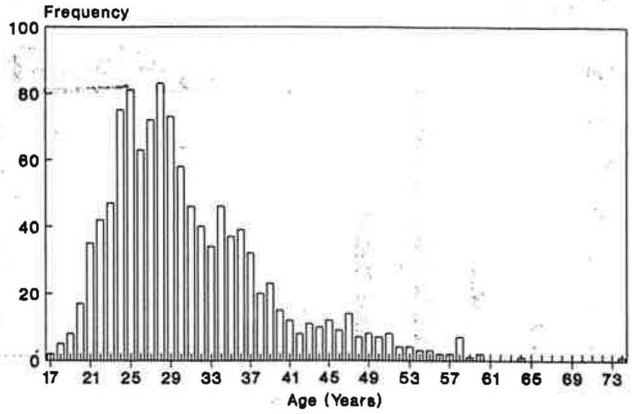

***Figure 3** Age frequency distribution*

RESULTS

Profile of the Sample

The total sample of responses numbered 1146 drawn from office workers in four buildings[1] during each of two seasons. Of these, 669 were women and 476 were men. Six hundred responses were obtained in the hot season and 546 in the wet season. In each season nobody was surveyed more than once, but some portion[2] of the respondents participated in both seasons. Two-thirds of the sample comes from the air-conditioned buildings (757), while the rest (389) were taken from naturally ventilated buildings. The distribution of ages in the sample is shown in Figure 3. The ages in the sample

1 One additional building served in a single-day pilot study in the hot season and the 25 responses from that building are included in the analysis.

2 For reasons of confidentiality, participant names were not tracked and therefore an exact figure of multiple-season respondents cannot be calculated.

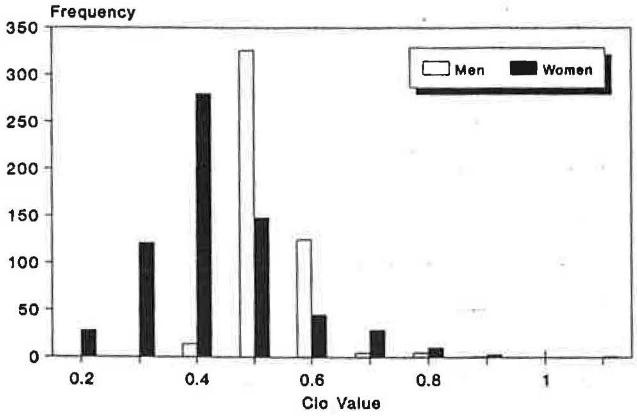

Figure 4 *Clo value frequency by gender*

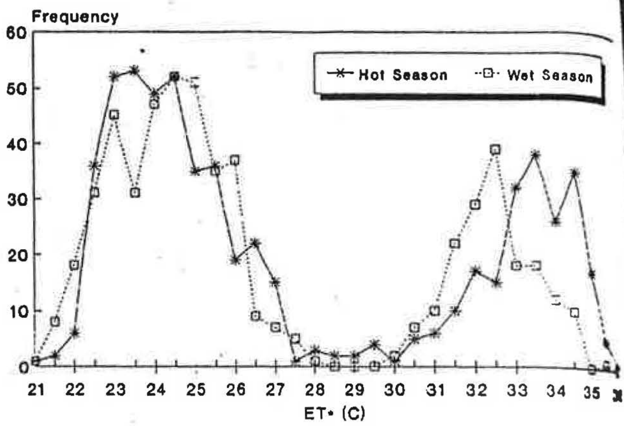

Figure 5 *ET* frequencies by season*

range from 18 to 75 years and have a mean of 32. The highest education attained was the Thai equivalent of high school for 431 of the respondents, a bachelor's degree for 586, and a post-graduate degree for 122. The overwhelming majority (1003) of respondents listed themselves in the lower category of job positions, with 127 in middle positions, and only 9 in upper positions. Because the sample included people from private-sector businesses and professional firms, government civil services, and universities, the survey question dealing with job rank was necessarily general and subject to interpretation in each situation. It is also possible that customary Thai modesty has skewed the choice of job rank lower.

The distribution of measured physical data is shown in Tables 1 and 2, broken down by building and season. Clo values ranged from 0.24 to 1.19, averaging 0.53 in both seasons. Figure 4 shows two histograms depicting the clo values for men (in the foreground) and women (in the background). Women had much more varied thermal insulation in their attire. The average Dubois body surface area (not shown in Table 1) for the entire Thai sample was 1.56 m² with a standard deviation of 0.17 and a range from 0.62 to 2.58 m². Air temperatures ranged from a low of 19.5°C in an air-conditioned building to a high of 34.2°C in a naturally ventilated building, averaging around 26°C for the sample with little difference between the hot and wet seasons. Vapor pressures reached a high of 28.4 Torr and went as low as 6.9 Torr, averaging 16.9 Torr, again with little seasonality. Air-conditioned buildings had an average air velocity of 0.13 m/s, while naturally ventilated buildings experienced higher air flows of 0.33 m/s on average. Because the latter buildings also utilized local fans, air velocities at the workstation went up as high as 2.25 m/s.

TABLE 1
Distribution of Physical Data
Hot Season Study

Building*	D	M	P	S	T	All
Sample Size	99	97	25	195	196	600
Clothing (clo)						
average	.49	.50	.50	.55	.56	.53
std dev	.09	.09	.10	.12	.12	.12
min	.24	.28	.24	.25	.24	.24
max	.72	.68	.65	.89	.95	.95
Air Temperature (°C)						
average	30.0	32.6	30.2	23.2	24.0	26.3
std dev	1.5	0.8	1.5	1.1	1.4	4.0
min	25.9	31.4	24.0	19.5	19.7	19.5
max	32.1	34.1	31.3	25.8	26.5	34.1
Vapor Pressure (Torr)						
average	24.1	24.8	23.7	12.2	13.4	17.1
std dev	1.1	0.8	4.0	2.9	1.1	5.9
min	18.9	23.1	9.1	6.9	11.4	6.9
max	26.4	26.2	26.3	16.6	15.7	26.4
Air Velocity (m/sec)						
average	0.33	0.31	0.26	0.13	0.12	.20
std dev	0.26	0.18	0.21	0.03	0.02	.16
min	0.11	0.12	0.10	0.09	0.09	.09
max	1.68	1.20	0.83	0.31	0.19	1.68
ET* (°C)						
average	32.3	34.6	32.6	24.1	24.9	27.8
std dev	1.5	0.5	2.0	1.1	1.4	4.5
min	28.5	33.5	25.5	20.5	20.7	20.5
max	34.3	36.0	34.0	27.3	27.5	36.0

* Buildings D, M, and P are naturally ventilated while S and T are air-conditioned.

TABLE 2
Distribution of Physical Data
Wet Season Study

Building*	D	M	S	T	All
Sample Size	95	73	181	197	546
Clothing (clo)					
average	.50	.46	.55	.57	.53
std dev	.10	.11	.11	.11	.12
min	.27	.24	.27	.31	.24
max	.71	.65	.91	1.19	1.19
Air Temperature (°C)					
average	30.6	30.5	22.7	24.6	25.8
std dev	1.3	1.2	1.0	.95	3.4
min	28.3	28.1	20.5	22.7	20.5
max	34.2	32.4	25.3	26.9	34.2
Vapor Pressure (Torr)					
average	24.5	24.1	12.0	14.2	16.8
std dev	.9	.9	2.3	.7	5.4
min	22.5	22.1	7.0	12.7	7.0
max	27.9	28.4	16.7	18.0	28.4
Air Velocity (m/sec)					
average	.35	.32	.13	.12	.19
std dev	.38	.22	.02	.02	.21
min	.09	.11	.09	.09	.09
max	2.25	1.63	.25	.20	2.25
ET* (°C)					
average	32.9	32.6	23.5	25.4	27.0
std dev	1.0	1.1	1.0	1.0	4.0
min	30.7	30.1	21.2	23.5	21.2
max	35.5	34.6	26.0	28.2	35.5

* Buildings D and M are naturally ventilated while S and T are air-conditioned.

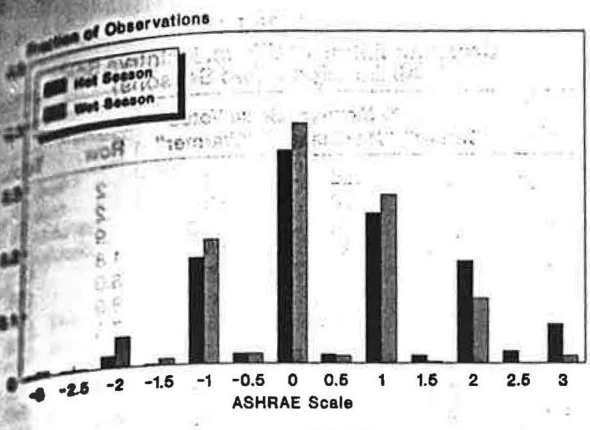

Figure 6 Relative frequency of ASHRAE votes by season

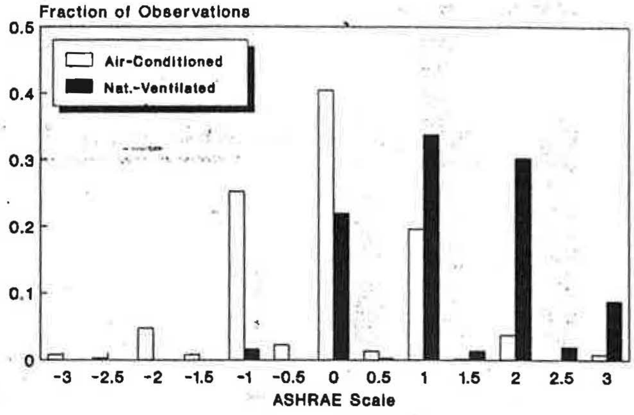

***Figure 7** Relative frequency of ASHRAE votes—AC vs. NV*

From these data we calculated the ASHRAE effective temperature (ET*), defined as that temperature at 50% relative humidity, mean radiant temperature equal to air temperature, and air velocity of 0.1 m/s that would produce the same thermal sensation as the actual environment. The resultant ET* averaged 27.5°C for the entire sample, extending up to 36°C and down to 20.5°C. Figure 5 is a frequency distribution of ET* with the hot and wet seasons depicted. The bimodal separation of the data between air-conditioned and naturally ventilated buildings in each season is clearly evident.

Distribution of ASHRAE and McIntyre Scale Responses

The survey participants cast their votes on the seven-point ASHRAE thermal sensation and three-point McIntyre scales in response to the immediate conditions at their desks. The distribution of votes for both scales

TABLE 3
Crosstabulation of ET* vs. ASHRAE Scale
All Buildings (Two Seasons)

	% ASHRAE Scale Thermal Sensation Votes[1,2]														
ET*	−3	−2.5	−2	−1.5	−1	−0.5	0	0.5	1	1.5	2	2.5	3	Row	Totals
20.5	0	0	0	0	0	0	50	0	50	0	0	0	0	.2	(2)
21	0	0	50	0	50	0	0	0	0	0	0	0	0	.2	(2)
21.5	0	10	10	10	40	0	30	0	0	0	0	0	0	.9	(10)
22	0	0	23.8	0	38.1	4.8	33.3	0	0	0	0	0	0	1.8	(21)
22.5	5.8	0	7.2	1.4	42.0	4.3	36.2	0	1.4	0	1.4	0	0	6.0	(69)
23	2.2	1.1	12	1.1	38.0	3.3	35.9	0	4.3	0	2.2	0	0	8.0	(92)
23.5	0	0	3.4	1.1	33.7	1.1	46.1	1.1	10.1	0	1.1	0	2.2	7.8	(89)
24	0	0	5.2	0	19.6	3.1	50.5	1.0	17.5	0	2.1	0	1.0	8.5	(97)
24.5	0	0	2.9	1	27.2	1.9	42.7	2.9	19.4	0	1.9	0	0	9.0	(103)
25	0	0	1.2	0	15.1	2.3	44.2	1.2	26.7	0	8.1	0	1.2	7.5	(86)
25.5	0	0	1.4	1.4	16.7	1.4	36.1	1.4	36.1	1.4	4.2	0	0	6.3	(72)
26	0	0	0	0	19.6	1.8	32.1	3.6	39.3	0	1.8	0	1.8	4.9	(56)
26.5	0	0	0	0	3.2	0	38.7	3.2	38.7	0	12.9	0	3.2	2.7	(31)
27	0	0	0	0	0	0	42.9	0	47.6	0	9.5	0	0	1.9	(22)
27.5	0	0	0	0	0	0	16.7	0	50	0	33.3	0	0	.5	(6)
28	0	0	0	0	0	0	0	0	0	0	100	0	0	.3	(3)
28.5	0	0	0	0	33.3	0	66.7	0	0	0	0	0	0	.3	(3)
29	0	0	0	0	0	0	100	0	0	0	0	0	0	.2	(2)
29.5	0	0	0	0	50	0	0	0	0	0	50	0	0	.3	(4)
30	0	0	0	0	0	0	66.7	0	33.3	0	0	0	0	.3	(3)
30.5	0	0	0	0	0	0	41.7	0	33.3	8.3	8.3	8.3	0	1.0	(12)
31	0	0	0	0	0	0	31.3	0	43.8	0	25	0	0	1.4	(16)
31.5	0	0	0	0	3.1	0	37.5	0	40.6	0	15.6	0	3.1	2.8	(32)
32	0	0	0	0	2.2	0	33.3	2.2	33.3	0	24.4	2.2	2.2	3.9	(45)
32.5	0	0	0	0	0	0	20.4	0	38.9	0	33.3	1.9	5.6	4.7	(54)
33	0	0	0	0	2.1	0	22.9	0	31.3	0	31.3	4.2	8.3	4.2	(48)
33.5	0	0	0	0	1.8	0	15.8	3.5	29.8	3.5	35.1	0	10.5	5	(57)
34	0	0	0	0	0	0	7.9	2.6	36.8	2.6	34.2	2.6	13.2	3.3	(38)
34.5	0	0	0	0	0	0	6.4	0	25.5	0	40.4	4.3	23.4	4.1	(47)
35	0	0	0	0	0	0	0	0	23.5	11.8	29.4	17.6	17.6	1.5	(17)
35.5	0	0	0	0	0	0	0	0	16.7	16.7	66.7	0	0	.5	(6)
36	0	0	0	0	0	0	0	0	0	0	0	0	100	.1	(1)
Column	.5	.2	3.1	.5	17.3	1.5	33.9	1.2	23.8	.7	12.7	1.0	3.6	100	
Totals	(6)	(2)	(36)	(6)	(198)	(17)	(389)	(14)	(273)	(8)	(145)	(11)	(41)		(1146)

[1]Percentages are calculated by row, e.g. within each ET* category.
[2]Numbers in parentheses are the total number of votes in the respective column or row.

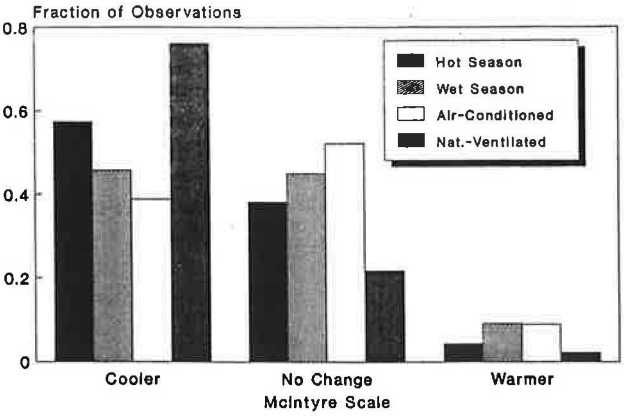

Figure 8 *Relative frequencies of McIntyre votes*

is shown in Figures 6 through 8. Almost 35% of the votes were cast in the ASHRAE scale zero category (e.g., "neutral") and three-quarters voted within the central three categories (between "slightly cool" and "slightly warm" or −1 and 1 on the scale). Few people chose to indicate their thermal sensation in the half-steps between whole-numbered categories. The ASHRAE Scale votes were not appreciably different between the hot or wet seasons, as shown in Figure 6, where they are juxtaposed. However, the distribution of votes is quite different for AC vs. NV buildings. They are compared in Figure 7. Almost 90% of the respondents in AC buildings selected between "slightly cool" and "slightly warm," whereas only about 57% of the NV building respondents did so. Responses to the McIntyre Scale (graphed in Figure 8) overall were 42% preferring "no change," 52% for "cooler," and 6% for "warmer." In the hot season, slightly more shifted their votes from the other two categories to "cooler" for a total of 58%. "Cooler" and "no change" had an equal percentage of the votes in the wet season at 45%, with slightly more preferring it warmer. Again, the biggest contrast exists between the samples in AC and NV buildings. Seventy-eight percent of the NV votes fell into the "cooler" category, whereas the fraction was 38% in the AC case. "No change" was the stated preference of 52% in the AC buildings, whereas only 20% chose similarly in the NV buildings. A surprising 2% voted to be warmer in the NV buildings, where temperatures never fell below 25.9°C. Misinterpretation of the question, however, cannot be ruled out.

The scale votes are, of course, taken in response to thermal conditions and therefore are most meaningfully displayed in juxtaposition with relevant environmental variables. In Tables 3 and 4 ET* is cross-tabulated with the ASHRAE and McIntyre scales, respectively. These tables show the percentage of votes at each scale category within 0.5°C ET* ranges (i.e., row-wise percentages). The bimodal character of the data is clear here, with the AC and NV samples overlapping only at ET* of 28°C. The pattern of voting on both the McIntyre and ASHRAE scales alludes to two populations whose thermal sensations (or tolerances or expectations) are distinct from one another.

Mean Responses The mean of all of the ASHRAE Scale votes is 0.37, or slightly warmer than neutral. On the McIntyre Scale, the mean response is 0.45. Humphreys (1976) regressed such mean responses vs. mean air or globe temperatures from 34 field studies worldwide encompassing some 200,000 observations and got the following relation:

TABLE 4
Crosstabulation of ET* vs. McIntrye Scale
All Buildings (Two Seasons)

	% McIntyre Scale Votes[1,2,3]				
ET*	"Cooler"	"No Change"	"Warmer"	Row	Totals
20.5	50	50	0	.2	(2)
21	0	50	50	.2	(2)
21.5	10.0	70.0	20.0	.9	(10)
22	4.8	81.0	14.3	1.8	(21)
22.5	17.4	62.3	20.3	6.0	(69)
23	19.6	62.0	18.5	8.0	(92)
23.5	30.3	62.9	6.7	7.8	(89)
24	38.1	52.6	9.3	8.5	(97)
24.5	35.0	57.3	7.8	9.0	(103)
25	52.3	45.3	2.3	7.5	(86)
25.5	59.7	34.7	5.6	6.3	(72)
26	53.6	42.9	3.6	4.9	(56)
26.5	77.4	22.6	0	2.7	(31)
27	59.1	40.9	0	1.9	(22)
27.5	100	0	0	.5	(6)
28	66.7	33.3	0	.3	(3)
28.5	0	100	0	.3	(3)
29	100	0	0	.2	(2)
29.5	50	50	0	.3	(4)
30	66.7	33.3	0	.3	(3)
30.5	50	50	0	1.0	(12)
31	75	25	0	1.4	(16)
31.5	62.5	34.4	3.1	2.8	(32)
32	75.6	22.2	2.2	3.9	(45)
32.5	70.4	25.9	3.7	4.7	(54)
33	83.3	14.6	2.1	4.2	(48)
33.5	86	14	0	5.0	(57)
34	84.2	7.9	7.9	3.3	(38)
34.5	85.1	14.9	0	4.1	(47)
35	94.1	5.9	0	1.5	(17)
35.5	83.3	16.7	0	.5	(6)
36	100	0	0	.1	(1)
Column	51.9	41.4	6.6	100	
Totals	(595)	(475)	(76)		(1146)

[1]McIntyre Scale indicates responses to the question, "I would like to be ."
[2] Percentages are calculated by row, e.g., within each ET* category.
[3] Numbers in parentheses are the total number of votes in the respective column or row.

$$\text{Standardized Mean Response} = -0.244 + 0.0166T_m \quad (3)$$

where the mean response is standardized by dividing the absolute mean response by the number of positive categories on the scale. For the Thai sample, the standardized mean ASHRAE scale response is 0.12 (the McIntyre Scale requires no standardization). The above equation predicts 0.19, which is quite close to the mean ASHRAE response but much less so for the mean McIntyre response.

Regression Analysis

Simple linear regression was performed on the mean ASHRAE Scale responses (calculated at 0.5°C ET* intervals) vs. ET* to determine the strength of the relationship between them. All of the fits are weighted by the number of votes making up each mean response. Table 5 shows the slope, y-intercept, goodness of fit (R^2), and the number of points going into the fit for various aggregations

TABLE 5
Regression of *Mean* ASHRAE Scale Responses and ET*

	Slope	Intercept	R^2	Nr.Pts.	T_n(°C)
All	0.176	−4.406	.91	32	25.0
Hot Season	0.187	−4.586	.91	16	24.5
Wet Season	0.154	−3.959	.85	32	25.7
Air-Conditioned	0.324	−7.952	.88	26	24.5
Nat.-Ventilated	0.289	−8.247	.87	17	28.5
Men	.0175	−4.313	.84	28	24.6
Women	0.179	−4.553	.90	32	25.4
Hot Sea., Men	0.181	−4.391	.84	27	24.3
Hot Sea., Women	0.192	−4.743	.88	31	24.7
Wet Sea. Men	0.164	−4.111	.73	23	25.1
Wet Sea. Women	0.153	−4.032	.88	25	26.4
Hot Sea AC	0.235	−5.746	.80	21	24.5
Hot Sea., NV	0.237	−6.321	.69	19	26.7
Wet Sea. AC	0.329	−8.185	.88	15	24.9
Wet Sea. NV	0.157	−4.147	.63	12	26.4
Hot Men, AC	0.200	−4.847	.58	18	24.2
Hot Men, NV	0.224	−5.858	.61	15	26.2
Hot Women, AC	0.264	−6.475	.77	18	24.5
Hot Women, NV	0.246	−6.627	.58	18	26.9
Wet Men, AC	0.324	−8.004	.77	14	24.7
Wet Men, NV	0.157	−4.006	.17	10	25.5
Wet Women, AC	0.322	−8.061	.83	14	25.0
Wet Women, NV	0.170	−4.627	.71	11	27.2

of the data. The aggregations begin with the entire sample and move toward increased differentiation by season, gender, and space conditioning. For the whole sample, the resultant regression coefficient (slope) is 0.176/°C with an intercept of −4.406 and a high R^2 of 0.91. The regression coefficient is lower than the value of 0.23 found by Humphreys. Schiller's (1988) recent study of air-conditioned environments near San Francisco yielded regression coefficients of 0.328 and 0.308 over winter and summer seasons, respectively. Selecting the Thai data coming only from AC buildings results in a comparable 0.324/°C regression coefficient. Though not true in every case, there is a general tendency for the naturally ventilated samples to have a lower regression coefficient than their air-conditioned counterparts. This is particularly true during the wet season, reflecting perhaps some measure of adjustment or accommodation to prevailing outdoor conditions. The wet season directly follows the hot season in Thailand, giving the people in NV buildings longer exposure to hot and humid weather, and possibly more opportunity to acclimatize than workers in AC buildings. It is also true, however, that the correlations are less strong and based on fewer points in the NV disaggregations. There is a slight difference in the responses of men and women in relation to ET*, with women showing a higher tendency to change their vote due to changes in ET* (i.e., a higher regression slope).

TABLE 6
Regression of *Mean* ASHRAE Scale Responses and SET*

	Slope	Intercept	R^2	Nr.Pts.	T_n(°C)
Hot Season	0.194	−4.632	.92	33	23.9
Wet Season	0.157	−3.932	.84	33	25.0
Air-Conditioned	0.171	−4.178	.71	22	24.4
Nat. Ventilated	0.161	−3.787	.70	21	23.5

In Table 6 mean ASHRAE Scale responses are regressed against Standard Effective Temperature (SET*), which is defined similarly to ET* but with clothing and activity also standardized. For the Thai data set in particular, because respondents were pre-screened for "standard"-activity levels (seated for at least 15 minutes at a desk), SET* differs from ET* due to nonstandard clo levels only. Only a subset of the cases regressed on ET* are repeated with SET* and they differ from the ET* results mainly on the slope terms of AC and NV buildings; they are less by a factor of two with SET* the independent variable than with ET*. This suggests that voting distinctions between office workers in conditioned and nonconditioned buildings are explained at least in part by differences in clothing. This result confirms our qualitative observation of more informal dress in the NV buildings than in AC buildings and the roughly 0.5 clo calculated difference between them (see Tables 1 and 2).

TABLE 7
Regression of *All* ASHRAE Scale Responses and ET*

	Slope	Intercept	R^2	Nr.Pts.	T_n(°C)
Hot Season	0.187	−4.636	.48	599	24.8
Wet Season	0.154	−4.001	.32	545	26.0
Air-Conditioned	0.326	−8.090	.20	756	24.8
Nat.-Ventilated	0.289	−8.298	.19	363	28.7

It is customary in reporting on thermal comfort field studies to analyze the mean responses as a function of temperature, as has been done above, but regressions were also performed for four disaggregations of the data using all of the points, and these are shown in Table 7. With ET* the independent variable, the regression results are essentially identical to those obtained from mean responses except for lower R^2 values.

Neutral Temperatures

The expected temperature at which a given group would vote "neutral" can also be estimated from the regression of mean ASHRAE Scale response as a function of ET*. This neutral temperature (T_n) is the temperature at which the regression line crosses the x-axis. Computationally it is obtained by taking the ratio of the y-intercept and the regression coefficient. The neutral temperatures are shown in the last column of Tables 5 through 7. The full Thai sample produces a T_n of 25.0°C. This compares with other field studies in the tropics, notably those of Ellis (1952, 1953) in Singapore at 26.1°C and 26.7°C and Webb (1959) with 27.2°C and Rao (1952) with 26.0°C, although substantially lower than Nicol's (1974) work in Iran and India during their hot seasons, which had T_n of 32.5°C and 31.1°C. Since these are all taken in unconditioned environments, perhaps a better comparison with the above is the subgroup of NV buildings whose neutral temperature is 28.5°C, placing the Thai NV result well within the tropical study range. Auliciems (1986) found the neutral temperature of air-conditioned building occupants in northern Australia to be 24.2°C, very close to the Thai AC T_n of 24.5°C. Other studies done in air-conditioned buildings in temperate climates generally find lower thermal neutralities, such as Schiller's average of 22.3°C over two seasons.

Auliciems (1986) developed relations for predicting group neutrality based on either the mean indoor air temperature, mean outdoor temperature, or both, recorded

TABLE 8
Comparison of Neutral Temperatures (T_n)[1]

	T_i	T_o	Regression T_n	Auliciems $T_{n,i}$	Auliciems $T_{n,o}$	Auliciems $T_{n,i\&o}$	Humphreys $T_{n,i}$
All	26.1	29.9	25.0	24.5 (−.5)	26.9 (1.9)	25.9 (.9)	24.3 (−.7)
Hot Season	26.3	30.7	24.5	24.6 (.1)	27.1 (2.6)	26.1 (1.6)	24.5 (0)
Wet Season	25.8	29.1	25.7	24.2 (−1.5)	26.6 (.9)	25.7 (0)	24.0 (−1.7)
Air-Conditioned	23.6	30.5	24.5	22.6 (−1.9)	27.1 (2.6)	24.8 (.3)	22.2 (−2.3)
Nat.-Ventilated	30.9	28.7	28.5	28.0 (−.5)	26.5 (−2.0)	28.1 (−.4)	28.3 (−.2)
Men	25.4	30.1	24.6	24.0 (−.6)	26.9 (2.3)	25.6 (1.0)	23.7 (−.9)
Women	26.5	29.8	25.4	24.8 (−.6)	26.8 (1.4)	26.1 (.7)	24.6 (−.8)

[1] Numbers in parentheses are the differences between the neutral temperatures using regression and given equation.

over a field study. They are, respectively,

$$T_{n,i} = 5.41 + 0.73T_i$$
$$T_{n,o} = 17.6 + 0.31T_o$$
$$T_{n,i\&o} = 9.22 + 0.48T_i + 0.14T_o \qquad (4)$$

Results comparing group neutralities predicted by the above equations with those determined by regression are in Table 8. For the sample as a whole, $T_{n,i}$ is the best predictor of group neutrality, coming within 0.5°C. Over the sample of disaggregated results, though, $T_{n,i\&o}$ more reliably matches the regression results, averaging within 0.7°C of the latter. Not surprisingly, mean outdoor temperature alone does not anticipate the neutral temperature of AC building occupants. $T_{n,o}$ also poorly predicts group neutrality in the hot season but improves substantially for the wet season. Here again is perhaps some evidence of seasonal acclimatization. With the hot season coming on the heels of the cool season, followed immediately by the wet season (which is hot as well as humid), extended exposure to hot outdoor weather, even for occupants of AC office buildings, could possibly cause group neutrality to increasingly reflect outdoor conditions.

Humphreys (1976) had his own empirical equation for predicting neutral temperature based on mean indoor temperature, namely,

$$T_{n,i} = 2.6 + 0.831T_i \qquad (5)$$

Table 8 shows this equation to bear similar results to Auliciems' $T_{n,i}$, though with slightly lower values.

Thermal Acceptability

The concept of thermal acceptability has been widely debated in the literature but in practice is difficult to determine experimentally. The convention arrived at assumes that votes within the central three categories of the seven-point scales (i.e., from −1 to 1) connote satisfaction with the thermal environment. ASHRAE (1981) uses this criterion, along with the objective of satisfying 80% of building occupants (thermally speaking) to establish their comfort standard. The McInytre Scale represents an alternative method of determining thermal acceptability by assuming that any desire for change is tantamount to dissatisfaction. One can look at the interplay of the two scales by examining the cross-tabulations shown in Tables 9 and 10 for AC and NV buildings, respectively. While 52% of the respondents in AC buildings indicated "no change," a much higher 89% voted within the central three categories on the ASHRAE Scale. Similarly, only 22% wanted "no change" on the McIntyre Scale in NV buildings, but by the ASHRAE Scale thermal acceptability criteria, 58% were satisfied. Figure 9 is a

TABLE 9
Crosstabulation of ASHRAE Scale vs. McIntrye Scale Air-Conditioned Buildings (All Seasons)

ASHRAE Scale	% McIntyre Scale Votes[1,2,3] "Cooler"	"No Change"	"Warmer"	Row	Totals
−3	0	0	100	.8	(6)
−2.5	0	0	100	.3	(2)
−2	5.6	38.9	55.6	4.8	(36)
−1.5	0	50	50	.8	(6)
−1	7.9	74.9	17.3	25.2	(191)
−0.5	29.4	64.7	5.9	2.2	(17)
0	29.1	70.3	.7	40.4	(306)
0.5	90	10	0	1.3	(10)
1	94.6	4.7	.7	19.6	(148)
1.5	100	0	0	.1	(1)
2	96.4	3.6	0	3.7	(28)
2.5	0	0	0	0	(0)
3	100	0	0	.8	(6)
Column Totals	38.8 (294)	52.2 (395)	9 (68)	100	(757)

[1] McIntyre Scale indicates responses to the question, "I would like to be..."
[2] Percentages are calculated by row, e.g., within each ASHRAE Scale category.
[3] Numbers in parentheses are the total number of votes in the respective column or row.

TABLE 10
Crosstabulation of ASHRAE Scale vs. McIntrye Scale Naturally Ventilated Buildings (All Seasons)

ASHRAE Scale	% McIntyre Scale Votes[1,2,3] "Cooler"	"No Change"	"Warmer"	Row	Totals
−3	0	0	0	0	(0)
−2.5	0	0	0	0	(0)
−2	0	0	0	0	(0)
−1.5	0	0	0	0	(0)
−1	0	66.7	33.3	1.6	(6)
−0.5	0	0	0	0	(0)
0	40	60	0	22	(80)
0.5	100	0	0	.3	(1)
1	78.9	18.7	2.4	33.8	(123)
1.5	80	0	20	1.4	(5)
2	94.5	3.6	1.8	30.2	(110)
2.5	100	0	0	1.9	(7)
3	100	0	0	8.8	(32)
Column Totals	76.1 (277)	21.7 (79)	2.2 (8)	100	(364)

[1] McIntyre Scale indicates responses to the question, "I would like to be..."
[2] Percentages are calculated by row, e.g., within each ASHRAE Scale category.
[3] Numbers in parentheses are the total number of votes in the respective column or row.

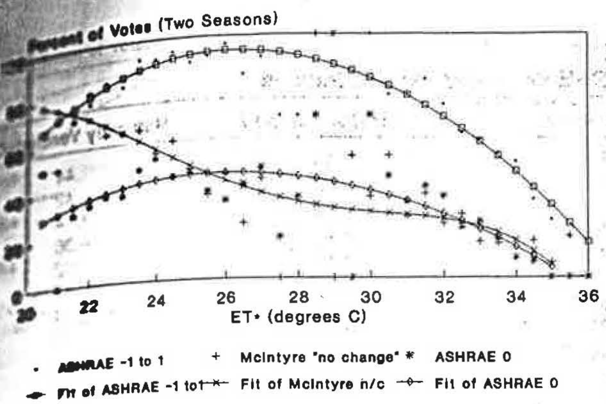

Figure 9 Thermal acceptability

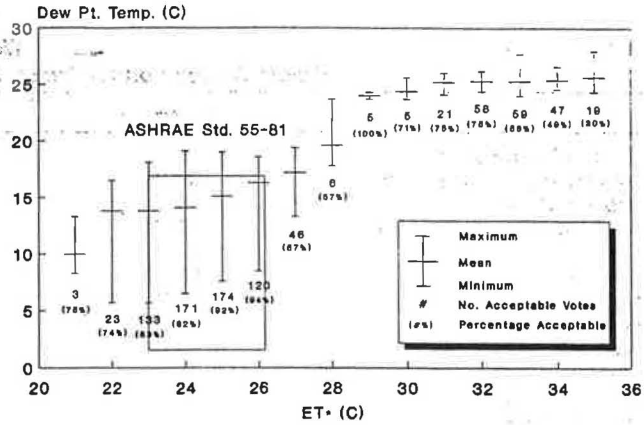

Figure 10 "Acceptable" votes vs. ASHRAE Standard

relative frequency plot of the percentage of votes at "neutral" (ASHRAE = 0), at "thermal acceptability" (ASHRAE between −1 and 1), and at "no change" (McIntyre = 0), at each 0.5°C ET* bin over the range of temperatures. The smooth curves are fits of these data weighted by the number of votes in each ET* bin. The "thermal acceptability" curve (by ASHRAE criteria) crosses the 80% line at roughly 22°C and 30.5°C, the latter going 4°C beyond the warm boundary of the ASHRAE summer comfort zone. The percentage of ASHRAE Scale votes strictly within the "neutral" category is much lower, at 45% or less over a broad range of ET*. Where Schiller's study showed the ASHRAE "neutral" category to be a stricter standard than the McIntyre "no change," here this is true only at ET* less than 25°C, and there is virtual consonance between them, especially at temperatures above 30°C.

ASHRAE Standard 55-81 (ASHRAE 1981) depicts a summer thermal comfort "zone" bounded by loci of ET* 22.8°C to 26.1°C and dew point temperatures of 1.7°C to 16.7°C. This thermal comfort zone is shown in Figure 10 along with bars indicating the range and mean of dew point temperatures experienced by Thai respondents who voted within the central three ASHRAE Scale categories. Below each bar is printed the number of "acceptable" votes, and the percentage of votes these make up within each 1.0°C temperature bin. Roughly three-fourths are satisfied over a wide range of conditions, much wider, in fact, than the standard allows. If the "acceptable" criteria were constructed of 75% of a population voting within the central three categories (instead of 80%), the Thai thermal comfort zone would stretch from 21°C to 32°C ET*. Mean dew point temperatures for those voting acceptable are either just under or well above the ASHRAE Standard 55-81 upper dew point threshold. Other considerations besides comfort play a part in ASHRAE's choice of upper dew point temperature boundary, health especially. Yet in view of the tremendous savings potential in relaxed comfort standards, it would be fruitful to reassess the upper dew point boundary, along with the 80% satisfied criterion.

Correlations between Variables

We looked at a number of Pearson product-moment correlations among the four rating scales and among the ASHRAE Scale responses and other potential explanatory variables.

Comfort Scales Tables 11 and 12 show correlations among the ASHRAE, McIntyre,[3] airflow, and humidity scales for each season and for each of the AC and NV buildings. As might be expected, there is a rather high correlation between the ASHRAE and McIntyre scales, except for the NV buildings, where it drops off. Ratings on the air velocity are somewhat correlated to those on the ASHRAE and McIntyre scales in the wet season and in air-conditioned buildings. This is interesting since the air velocities are higher and more varied in NV buildings. Responses from NV buildings on the ASHRAE and McIntyre scales are mildly correlated with perceptions of humidity levels. Other correlations are extremely weak or statistically insignificant.

TABLE 11
Simple Correlations between Comfort Scales

Wet Season → ↓ Hot Season	ASHRAE Scale	McIntyre Scale	Air Flow Scale	Humidity Scale
ASHRAE Scale		−.67***	−.25**	.02
McIntyre Scale	−.67***		.23***	.05
Air Flow Scale	−.10*	.12**		.10*
Humidity Scale	−.13***	.09*	.21***	

* Significant beyond .05
** Significant beyond .01
*** Significant beyond .001

TABLE 12
Simple Correlations between Comfort Scales

Naturally-Ventilated → ↓ Air-Conditioned	ASHRAE Scale	McIntyre Scale	Air Flow Scale	Humidity Scale
ASHRAE Scale		−.47***	−.12*	−.21***
McIntyre Scale	−.69***		.14**	.21***
Air Flow Scale	−.25***	.23***		.13*
Humidity Scale	−.09*	.07*	.19***	

* Significant beyond .05
** Significant beyond .01
*** Significant beyond .001

[3] For the purpose of interpreting the signs in the McIntyre Scale, a response of "cooler" is coded as −1, "warmer" as 1, and "no change" as 0.

TABLE 13
Simple Correlations between ASHRAE Scale and Various Indices

	Hot Season	Wet Season	Air-Conditioned	Naturally Ventilated
Outdoor Temperature	.70***	.58***	.44***	.44***
Mean Radiant Temperature	.69***	.57***	.42***	.42***
Vapor Pressure	.65***	.51***	.26***	.14***
Air Velocity	.33***	.19***	−.13***	−.06
Clo	−.27***	−.20***	−.16***	.02
ET*	.69***	.56***	.45***	.43***
SET*	.66***	.53***	.29***	.34***
Gender	.08*	−.03	−.09*	−.05
Age	.13*	.16***	.03	.09
Use of Home AC	−.06	−.02	.06	.07
Temperature Sensitivity	.03	−.03	−.01	.08
Humidity Sensitivity	.02	0	−.02	−.05
Air Flow Sensitivity	.01	−.03	.02	−.04

* Significant beyond .05
** Significant beyond .01
*** Significant beyond .001

ASHRAE Scale and Other Indicators In Table 13 the correlations between responses on the ASHRAE Scale of selected subgroups to various physical and demographic factors are depicted. Indoor dry-bulb and mean radiant temperature, ET* and SET*, and vapor pressure correlate fairly well with votes on the ASHRAE Scale for both seasons. The correlations are generally lower, however, when disaggregated by space-conditioning type for these same factors. Air velocity has a mixed correlation with ASHRAE for the sample subgroupings; that is, there is a weak yet significant relation between increased air velocity and *higher* ASHRAE Scale votes (counter to intuition) in the two seasons but *lower* ASHRAE Scale votes (as one would expect) in air-conditioned buildings. Air velocity is apparently unrelated to thermal sensation (as measured by the ASHRAE Scale) for NV buildings. In fact, one would expect that the conditions in NV buildings (e.g., higher and more variable air flow) would produce a stronger linkage with thermal sensation. One possible explanation for this is that among the occupants of the NV buildings studied, there were some who were accustomed to the high air flows from fans at their desks from habitual use and perhaps these respondents just incorporated high air flows into their normal thermal expectations. The negative correlation between air velocity and ASHRAE Scale vote in the AC buildings is undoubtedly influenced by the higher air flows coinciding with cool air emerging from supply air diffusers. Conversely, air movement in NV buildings is usually associated with warm or hot air and may not provide much cooling sensation. Clo values are mildly negatively correlated with ASHRAE Scale votes. Other factors, such as gender, age, and expressed sensitivity to several environmental parameters, have insignificant relationships to ASHRAE Scale responses.

Respondents were asked to indicate the level of use of home air conditioning, whether they never used it (coded 0), seldom (1), usually (2), or always (3). This question was intended as a rough proxy for indicating the thermal context of the respondents' time away from the office. Their answers produced no simple direct correlation with their responses on the ASHRAE Scale, as shown in Table 13. But because responses to the ASHRAE Scale should reflect a combination of the state of the *immediate* thermal environment as well as that to which the respondent is normally accustomed, the differences of the office thermal environment were factored out by binning responses by ET*. Table 14 shows the correlation between home air conditioning and ASHRAE votes binned by 1°C ET*. The correlations are generally insignificant with the exception of a few ET* bins, and for those the correlations are not particularly strong. Obviously it would be more informative to have a more quantitative description of the domestic thermal environment than our rather imperfect indicator.

TABLE 14
Correlation between ASHRAE Scale and Use of Home AC (binned by ET*)

ET*	Correlation	Significance	Nr. Points
21	.26	.742	4
22	.40	.024	31
23	.02	.755	161
24	−.04	.595	186
25	.20	.005	189
26	.06	.491	128
27	−.01	.953	53
28	.24	.540	9
29	.41	.495	5
30	−.50	.257	7
31	−.12	.553	28
32	.20	.076	77
33	.19	.062	102
34	−.14	.172	95
35	.11	.402	64
36	.36	.426	7

Probit Analysis

Probit analysis (Finney 1971) is a technique whereby data are sorted into two categories: those that possess some quality and those that do not, often at different levels (or bins) of some explanatory variable. These binary sets are transformed into percentages within each explanatory variable bin. The resulting percentages can also be thought of as relative frequencies within each bin. These relative frequencies done over the range of bins are, in effect, a cumulative relative frequency distribution. The

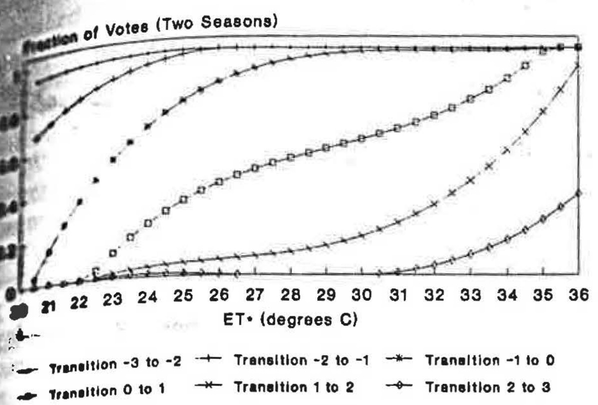

Figure 11 Probit analysis of ASHRAE scale votes

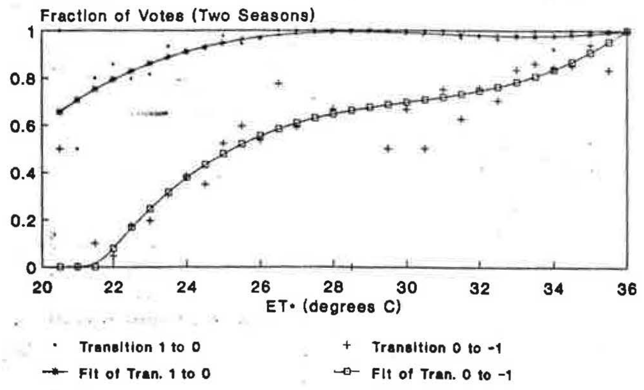

Figure 12 Probit analysis of McIntyre scale votes

technique was originally developed for use in analyzing the effectiveness of pesticides. In that particular case, the binary sets were a percentage of insect kills vs. non-kills at different insecticide dose levels. Probit analysis has been used to evaluate thermal comfort responses on rating scales as a function of temperature (Ballantyne 1977; Humphreys 1976). The binary sets are percentages of votes greater than or equal to—versus less than—a given vote category. A family of curves results when done over the range of comfort scale categories. For example, using the ASHRAE Scale, one binary grouping would be the percentage of votes equal to or greater than "neutral" and those less than "neutral," done at 0.5°C ET* intervals. The result is a set of curves, each depicting the transition to higher voting categories. This technique tells one the temperatures at which the majority of the sample population would change their votes from one category to the next (i.e., the transition temperatures) as well as the category widths of the scales in question. The chief feature of probit analysis is that it circumvents the assumption of equal scale category widths embedded in regression analysis.

Figures 11 and 12 show probit analysis of ASHRAE and McIntyre Scale votes, respectively, for the Thai data binned by ET*. The number of curves is always the number of categories minus one, so in Figure 11 there are six curves and in Figure 12 just two. For reasons of visual clarity, only the curves (and not the actual data points) have been plotted in Figure 11. The transition temperature is a value often quoted in the literature and is defined as that temperature at which the majority (i.e., 50% or more) of the respondents would change their votes to the next higher category. In the ideal case, a sufficient temperature range would allow the plotting of each curve from 0% to 100% of the votes. However, in this study only three of the six curves of the ASHRAE Scale probit analysis pass across the 50% line, allowing determination of transition temperatures. The transition from "slightly cool" (−1) to "neutral" (0) takes place at approximately 22.5°C; from "neutral" to "slightly warm" (1) at 27.5°C; and from "slightly warm" to "warm" (2) at 33.5°C. These transition temperatures imply category widths of 5°C and 6°C, respectively, for the "neutral" and "slightly warm" categories. The ASHRAE Scale categories from the Thai sample are considerably wider as compared to those of McIntyre (1980), who used a large data set collected at a state university and found corresponding transition temperatures of 3.8°C and 3.1°C, respectively. Ballantyne (1977) presented results of a study of Melanesians in Papua, New Guinea, and found the transition temperature from "cool" to "neutral" at 24.4°C and from "neutral" to "warm" at 30.0°C, implying an even wider 5.6°C central category width.[4]

On the McIntyre Scale, only the transition temperature from "no change" to "cooler" is defined, and it is about 25.5°C. It is not possible to determine any category width for the McIntyre Scale with these data.

It is interesting to note that the point at which 20% of the Thai respondents changed their votes from one or below to higher than one (i.e., 80% retained their choice) is 30.5°C, identical to the earlier finding of the upper bound of thermal acceptability. In fact, Figure 11 is useful for determining the Thai comfort zone under different criteria of "thermal acceptability." For instance, suppose the transition temperatures were used as the criteria (i.e., 50% shifting their votes). The rightmost boundary of the comfort zone would slide over to 33.5°C ET*!

Other Comfort Indices

In the results reported so far we have used effective temperature (ET*) for combining the thermal effects of the four environmental variables—temperature, radiant temperature, humidity, and air velocity—into a single index. Other comfort indices exist, however, and in this section distinctions between some of the more widely used indices and their relative merits in the Thai context are explored.

Rational Indices The Standard Effective Temperature (SET*) is an extension of ET* in that it also normalizes for the two personal variables, clothing insulation and metabolic rate. Standard clothing insulation values are based on metabolic rate. Thus, SET* is defined as the value of an isothermal enclosure with radiant temperature equal to the air temperature, at 50% relative humidity, and air velocity of 0.1 m/s, in which a person with standard clothing for the actual activity level would have the same heat loss at the same mean skin temperature and the same skin wettedness as he or she does in the

[4] Note that Ballantyne employed a five-point scale instead of the usual seven-point scale. Other studies have shown that scales using fewer points have wider categories. This makes the Thai results surprisingly close to those using subjects in a similar climate yet with a "broader" scale.

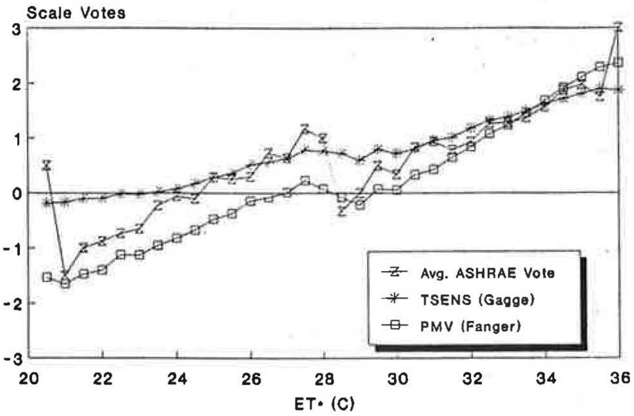

Figure 13 *ASHRAE vote, TSENS, PMV vs. ET**

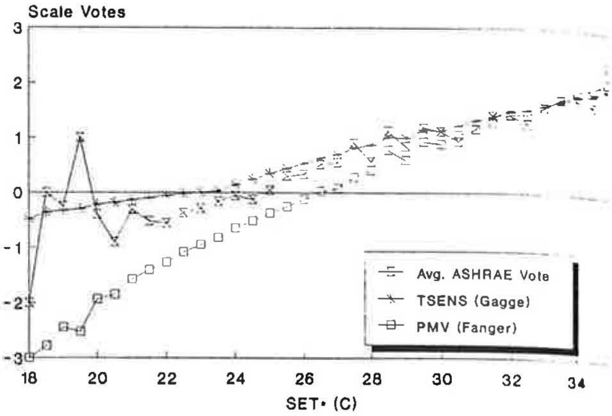

Figure 14 *ASHRAE vote, TSENS, PMV vs. SET**

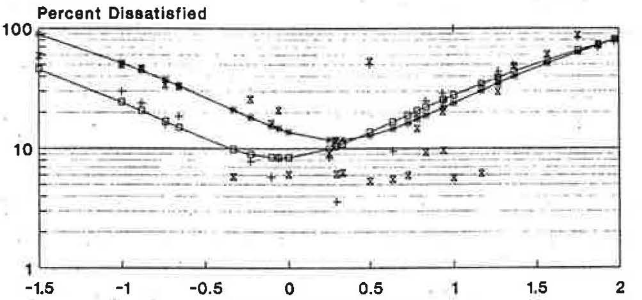

Figure 15 *Percent dissatisfied vs. ASHRAE vote*

actual environment with the actual clothing insulation after one hour of exposure. Like ET*, SET* is an index based on analysis of the thermoregulatory response of the body to thermal stress, which is represented in a two-node heat transfer model (Gagge et al. 1972). The key physiological determinants of human comfort used in the model are skin temperature in cooler than neutral exposures and skin wettedness in warmer than neutral exposures. Skin wettedness is the fraction of the skin surface covered with sweat and is related to the ability of the body to lose heat through evaporation in the given environment. Numerous experiments in warm, humid environments have confirmed a strong relationship between skin wettedness and thermal discomfort. TSENS is a comfort index calculated with the J.B. Pierce model analogous to, and used for, predicting votes on the ASHRAE seven-point scale. TSENS is based on the mean body temperature, which, in turn, is related to skin wettedness when body temperature is regulated by sweating (Doherty and Arens 1988).

Fanger (1970), the pioneer in developing rational methods for predicting thermal comfort responses, produced two linked indices with his comfort equation: predicted mean vote (PMV) and predicted percentage dissatisfied (PPD). Fanger's central premise is that thermal sensation relates to the state of the body rather than the environment. The original comfort equation he devised performed a heat balance between the body and the environment, coupled with two key empirical observations: that both the skin temperature and evaporative heat loss *at comfort* are linearly proportional to metabolic rate. PMV is an expression of the difference between the actual metabolic rate and that required to maintain "comfort" as determined by the heat balance calculation. PMV is essentially a rational prediction of the population mean vote on the ASHRAE seven-point scale (same as used in this study). PPD is derived from the the distribution of votes from thermal comfort laboratory experiments as a function of temperature that were related to PMV and the ASHRAE acceptability criteria (that votes outside the central three categories are votes of dissatisfaction).

A criticism of Fanger's method is that the results become increasingly inaccurate at conditions away from comfort, e.g., at high temperatures, humidities, or metabolic rates, and further, that the data upon which it is based come from a fairly homogeneous group of white, college-aged subjects whose responses may not be representative in all possible contexts.

The mean PMV and mean TSENS are plotted with the mean ASHRAE Scale vote from the sample of Thai office workers as a function of ET* in Figure 13 and SET* in Figure 14. TSENS overpredicts the average Thai ASHRAE vote below 24°C ET* but is generally within 0.5 Scale units in warmer conditions. Surprisingly, PMV is within 0.5 Scale units of average Thai ASHRAE votes over most of the range and *underpredicts* it below 33°C ET*. When plotted vs. SET* (Figure 14), all of the curves smooth out. TSENS and the average ASHRAE vote show remarkable agreement over the range, much more so than with ET*. PMV, on the other hand, diverges from the average ASHRAE vote below 25°C SET* by more than one Scale unit. PMV, TSENS, and the Thai votes agree quite well above 28°C SET*. This suggests that either the Gagge or Fanger models can be used to predict the average Thai office worker response in NV buildings. Thus, while Fanger's method is theoretically lacking in relatively extreme situations away from comfort, in the Thai context it is apparently vindicated. For Thai AC environments, however, the Gagge model is preferred.

Figure 15 compares the percent dissatisfied (those voting *outside* the central three ASHRAE scale categories) of the Thai sample and the PPD calculated using the Fanger model. These are plotted as a function of the average ASHRAE scale vote. Each PPD point represents the average of all the PPDs calculated for each individual *within a given 0.5°C ET* bin.* Similarly, the percent dissatisfied from the Thai data are taken from ET* bins. For each series we show a second-order polynomial fit to the data weighted by the number of data points behind each plotted point. The y-axis scale is logarithmic to facilitate comparison with Fanger's (1970) classic PPD vs. PMV plot also using this format. The PPD fit grossly overpredicts Thai dissatisfaction below thermal neutrality by as much as 25% but is quite accurate in the region above about 0.3 on the ASHRAE scale. Figure 15 is consistent with Figure 13, and this is to be expected since PPD and PMV are linked. One final point worth noting is that the minimum point in the percent dissatisfied curve occurs slightly below the zero scale point. It has been suggested that people accustomed to a hot climate might find a slightly cool environment preferable to a neutral one. To the extent that minimal dissatisfaction connotes "preference," the small offset of the curve may demonstrate this effect on the part of the Thai sample.

Empirical Indices Field studies performed in the tropics have yielded numerous empirical indices for predicting the response to thermal conditions. Most of these empirical indices are simple to compute using commonly measured variables. A disadvantage of this class of comfort index is that the applicability of the index is limited to the conditions found in the data set from which the index is derived. For field studies, where the researcher exercises little or no control over the environmental conditions (the usual case), the range of applicability can be rather narrow. Comparisons of empirical indices applied to the Thai data set are beyond the scope of this paper.

CONCLUSIONS

A sample of thermal comfort responses and environmental data was collected for 1146 Thai office workers. Preliminary findings from analyzing two seasons of data gathered in four Bangkok buildings are as follows:

1. There is little apparent gender or seasonal bias in the responses, although different clothing insulation between men and women could be masking real differences, and the weather differences between the hot and wet seasons in Bangkok in 1988 were more subtle than usual.

2. Two distinct populations emerged from our analysis: those who worked in air-conditioned offices and those who worked in naturally ventilated offices. The latter group expressed satisfaction with temperatures and humidities well above those deemed acceptable in the HVAC industry.

3. Regression of the mean ASHRAE Scale responses produced a rather shallow slope term, indicating less sensitivity on the part of the Thais to thermal environment change relative to other populations studied in the literature. This finding is also supported by an analysis showing the ASHRAE Scale category widths to be substantially wider than other studies have found using the seven-point scale.

4. The Thai neutral temperature of 25°C is in agreement with other field studies done in the tropics but above most from temperate climates.

5. This sample registered thermal acceptability (as defined by ASHRAE [1981]) over a broader effective temperature range than previous works, from 22°C to 30.5°C. This extends the hot and humid boundary of the summer comfort zone 4°C outward. The implications of this finding, if put into practice, could have a profound impact on energy use in commercial buildings located in the tropics. Relaxing the criteria for defining the comfort zone boundaries (on the humidity or temperature "edges") even slightly from the present choice could push the savings significantly further.

6. Gagge's TSENS model predicts the average Thai thermal sensation well over the range of temperatures experienced in this study. Fanger's PMV does less well at lower temperatures but at temperatures above 28°C is quite accurate.

ACKNOWLEDGMENTS

Many people assisted on various aspects of the project and without them it never would have gotten off the ground. Among those gratefully acknowledged are Ed Arens for his overall guidance on the project; Rick Diamond and Richard deDear for their advice on the survey instrument; Tawachai Prathuangsit and Vimolsiddhi Horayangkura for translating the survey into Thai; Marc Fountain for significant help in setting up the instrumentation; Boonpong Kijawatanachai for help in selecting, gaining access to, and later surveying the buildings; Surapong Chirarattananon for enthusiasm and logistical support in the data collection phase; Jinda Kaewkeaw and Patana Rugkwamsook, who facilitated student participation and helped with measurements; Thai graduate students Kuskana Kubaha, Nuansri and Chutima Kitsuwannawong, Pichai Paromadilok, Surapong Wangsupakitakosol, Paritas Aramwanich, Jomjai Siriporn, Pucharee Chantabuppa, and Chaiyoot Sripadet, who helped carry out the surveys. And last, but certainly not least, the Thailand-U.S. Educational Foundation is gratefully acknowledged for its financial support during the year in Bangkok.

REFERENCES

ASHRAE. 1981. ASHRAE Standard 55-1981, "Thermal environmental conditions for human occupancy." Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

ASHRAE. 1984. *ASHRAE handbook—1984 systems.* Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

ASHRAE. 1989. *ASHRAE handbook—1989 fundamentals.* Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Auliciems, A., and deDear, R. 1986. "Air conditioning in a tropical climate: impacts upon European residents in Darwin, Australia." *International Journal of Biometeorology*, Vol. 30, No. 3, pp. 259–282.

Ballantyne, E.R.; Hill, R.K.; and Spencer, J.W. 1977. "Probit analysis of thermal sensation assessments." *International Journal of Biometeorology*, Vol. 21, No. 1, pp. 29–43.

Doherty, T.J., and Arens, E. 1988. "Evaluation of the physiological bases of thermal comfort models." *ASHRAE Transactions*, Vol. 94, Part 1, pp. 1371–1385.

Ellis, F.P. 1952. "Thermal comfort in warm, humid atmospheres—observations in a warship in the tropics." *Journal of Hygiene*, Cambridge, Vol. 50, pp. 415–432.

Ellis, F.P. 1953. "Thermal comfort in warm, humid atmospheres—observations on groups and individuals in Singapore." *Journal of Hygiene*, Cambridge, Vol. 51, pp. 386–404.

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

Gagge, A.P.; Nishi, Y.; and Gonzalez, R.R. 1972. "Standard effective temperature—a single temperature index of temperature sensation and thermal discomfort." *Thermal Comfort and Heat Stress*, Proceedings of the CIB Commision W45 (Human Requirements) Symposium held at the Building Research Station, 13–15 September, His Majesty's Stationary Office.

Humphreys, M.A. 1976. "Field studies of thermal comfort compared and applied." *Building Services Engineer*, Vol. 44, pp. 5–27.

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 Standards Organization.

McIntyre, D.A. 1980. *Indoor climate*. London: Applied Science Publishers Ltd.

Nicol, J.F. 1974. "An analysis of some observations of thermal comfort in Roorkee, India and Baghdad, Iraq." *Annals of Human Biology*, Vol. 1, No. 4, pp. 411–426.

Rao, M.N. 1952. "Comfort range in tropical Calcutta—a preliminary experiment." *Indian Journal of Medical Research*, Vol 40, No. 1, pp. 45–52.

Schiller, G.E.; Arens, E.A.; Bauman, F.S.; Benton, C.; Fountain, M and Doherty, T. 1988. "Thermal environments and comfort in office buildings." *ASHRAE Transactions*, Vol. 94, Part 2.

Webb, C.G. 1959. "An analysis of some observations of thermal comfort in an equatorial climate." *British Journal of Industrial Medicine*, Vol. 16, pp. 297–310.