3829 (RP-702)

FIELD EXPERIMENTS ON OCCUPANT COMFORT AND OFFICE THERMAL ENVIRONMENTS IN A HOT-HUMID CLIMATE

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ABSTRACT

This paper presents the main findings of ASHRAE research project RP-702, a field investigation of indoor climates and occupant comfort in 12 air-conditioned office buildings in Townsville, located in Australia's tropical north. The project replicates an earlier ASHRAE investigation in San Francisco (RP-462). A total of 836 subjects provided 1,234 sets of questionnaire responses, each accompanied by a full set of physical indoor climatic measurements from laboratory-grade instrumentation. Clothing insulation estimates for seated subjects included the incremental effect of chairs. Thermal environmental results are compared with ASHRAE Standard 55-1992 prescriptions. Thermal neutrality, preference, and acceptability results are compared with laboratory-based models and standards. Gender and seasonal effects were minor, and many of the differences from the earlier San Francisco data were explicable in terms of clothing patterns. Most of the thermal dissatisfaction expressed within the Standard 55 comfort zone was associated with requests for higher air velocity.

INTRODUCTION

ANSI/ASHRAE 55-1992, Thermal Environmental Conditions for Human Occupancy, is based almost exclusively on data from climate chamber experiments performed in mid-latitude climatic regions (ASHRAE 1992). This poses potential problems when the standard is applied to working populations living in other types of climates. First, there is the ongoing doubt in the minds of practicing engineers about just how relevant the findings of laboratory research on college-age subjects are to "real" people actually at work in the office environment (e.g., Rohles 1978; McIntyre 1982; Prins 1992). This can be referred to as the "external validity" question. Second, different climatic regions, such as the tropics, may call for different levels of the comfort parameters mandated in the standard. Despite this concern, *ANSI/ASHRAE 55-1992* is used worldwide, and its International Organization for Standardization (ISO) counterpart, *ISO Standard 7730* (ISO 1984), is also based on the same type of climate chamber data. For convenience, this second methodological concern will be referred to as the "climatic adaptation" issue.

External Validity

In relation to the question of external validity, several thermal comfort studies have set out to validate laboratory research findings in actual buildings (e.g., Fishman and Pimbert 1979; Gagge and Nevins 1976; Howell and Kennedy 1979; de Dear and Auliciems 1985). Typically, such validation exercises have been based on samples of building occupants numbering several hundred. Each subject is given a thermal questionnaire on which he or she uses numeric scales of the type depicted in Table 1 to rate various aspects of the immediate workstation environment and also the thermal sensation experienced at the time of the interview. The questionnaire often takes inventories of the clothing garments being worn (from which clo values are estimated) and the types of activities performed just prior to the interview (metabolic rate estimates). At the same time the questionnaire is being filled in, the four basic comfort environmental parameters—air and radiant temperatures, air speed, and humidity—are also recorded, thus providing the essential data set for comparison with climate chamber studies and their associated comfort models (e.g., ISO 1984; Gagge et al. 1986).

The results of such validation exercises have often failed to support laboratory-based models and standards (e.g., Auliciems 1983; de Dear and Auliciems 1985). This has prompted criticism by various members of the comfort research community of the inferior instrumentation and procedures used in field studies compared to those of the climate chamber experimental method. The response of field researchers to this criticism has been a gradual improvement in their instrumentation and procedures, culminating in the ASHRAE-sponsored (RP-462) field experiment in San Francisco (Schiller et al. 1988; Schiller 1990) in which more than 2,300 visits were made to workers in 10 office buildings. In RP-462 a customized cart carrying laboratory-grade

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TABLE 1
Rating Scales of Thermal Sensation and Comfort with Associated Comfort Models Indicated in Parentheses

	TSENS scale (2-node)	Preference scale	DISC scale (2-node)	ASHRAE scale (PMV)	Bedford scale
+4	very hot		limited tolerance		
+3	hot		very uncomfortable	hot	much too warm
+2	warm	cooler	uncomfortable	warm	too warm
+1	slightly warm		slightly uncomfortable	slightly warm	comfortably warm
0	neutral	no change	comfortable + pleasant	neutral	comfortable
-1	slightly cool		slightly cool	slightly cool	comfortably cool
-2	cool	warmer	cool	cool	too cool
-3	cold		cold	cold	much too cool
-4	very cold				

indoor climatic instrumentation with measurement accuracies and response times in accordance with *ANSI/ASHRAE 55-1992* (ASHRAE 1992) and *ISO Standard 7726* (ISO 1985) at three heights above floor level was commissioned (Benton et al. 1990). To date, the San Francisco project remains the definitive field investigation of thermal comfort. The data collected in both summer and winter seasons included typical environmental conditions in modern offices, their match with the Standard 55 comfort zone (ASHRAE 1981), a variety of comparisons between comfort index predictions and occupant responses, the effect of season on comfort, plus a range of other physical and psychological attributes affecting the occupants' acceptance of the work environment (Schiller et al. 1988; Schiller 1990).

The Climatic Adaptation Issue

Because the San Francisco field validation study was carried out in only one climatic region (Mediterranean), it cannot sustain generalization to the comfort responses of building occupants acclimatized to more extreme climates than those found in the San Francisco Bay area. Review papers of thermal comfort field studies by Humphreys (1981), Auliciems (1983), and de Dear (1994) have all demonstrated a significant correlation between indoor comfort temperatures and levels of warmth prevailing in the outdoor climate. However, in most cases the field data upon which these correlations were based came from instrumentation and measurement protocols of a lower grade than those used in the San Francisco experiment, thus preventing unequivocal conclusions from being drawn.

Many countries in the tropical world (see Figure 1), particularly in hot and humid Southeast Asia, are undergoing rapid economic development at the present time. Despite a prolonged global recession in the early 1990s, the aggregate economy of Southeast Asia still managed to grow by 5.8% in 1992, including 8% GDP growth in Malaysia, 5.9% in Indonesia, 7.5% in Thailand, 8.3% in Vietnam, and 7% in Cambodia (ADB 1993).

Associated with this dynamic economic performance is a large amount of building construction and escalating demand for air-conditioning services. For example, the average annual growth rate in the value of commercial sector (largely air-conditioned) construction starts throughout the 1980s in Singapore was 98.6% (Singapore Ministry of Communication and Information 1990). Therefore, the tropics have a pressing need for their own empirical thermal comfort data base, but, to date, much less research has been conducted in this part of the world than in the temperate mid-latitude climates.

Comfort Research in Hot, Humid Climates Recently some field experiments on thermal comfort have been conducted in humid tropical locations including Singapore (de Dear et al. 1991a) and Bangkok (Busch 1990, 1992). Results from these studies indicated that thermal requirements for environments inside tropical buildings, particularly those that are naturally ventilated, could be significantly warmer and more acceptable to their occupants than predicted by comfort models and standards based on mid-latitude research. However, the physical measurements used in all of these studies were recorded at just one height above floor level by instrumentation; the anemometry, in particular, could not be referred to as laboratory-grade.

To date only a handful of climate chamber experiments on thermal comfort have been performed in hot, humid climates. de Dear et al. (1991b) replicated Fanger's Danish preferred temperature experiments (Fanger 1973) on location in the humid tropics (Singapore, latitude 1°N) using a sample of 32 college students. The sample's mean temperature preference of 25.4°C was not significantly different from that of Fanger's benchmark temperate-climate Danish subjects. Tanabe et al. (1987) replicated the classic studies (e.g., Nevins et al. 1966; McNall et al. 1968) using 172 college-age Japanese subjects during the hot, humid summer in Tokyo, but again the observed neutrality[1] was not significantly different from previous Danish and American

[1]The temperature found to be most frequently associated with votes of "0" on sensation scales of the type depicted in Table 1.

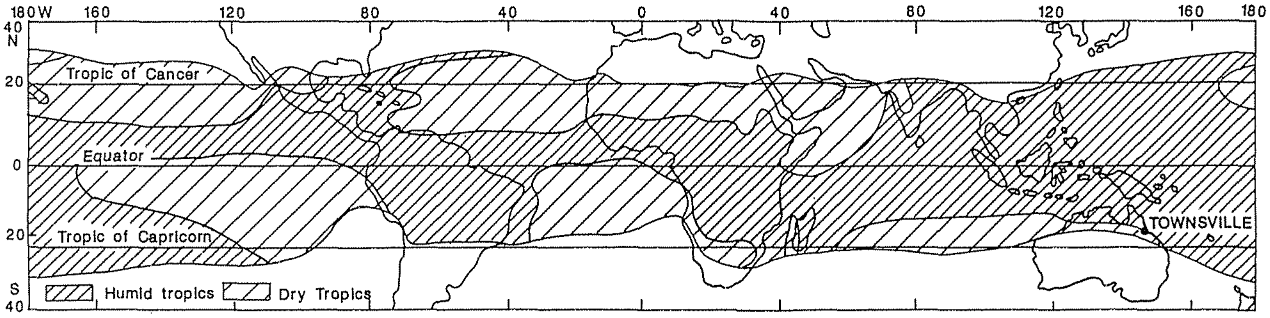

Figure 1 *Map of the tropical world indicating Townsville's location (after Nieuwolt [1977]).*

studies. Therefore, both the Singapore and Tokyo chamber experiments infer that, *ceteris paribus*, neither year-round nor seasonal hot, humid climatic exposures induce any change in subjective thermal neutralities or preferences.

This same null conclusion was extended to thermal acceptability by de Dear et al. (1991c) in another Singapore chamber experiment in which 100 college-age Singaporeans were used to establish the two temperatures coinciding with 20% warmth dissatisfaction at relative humidities (RH) of 70% and 35%, respectively. Since the 1,296 Danish and American subjects used by Fanger (1970) in the derivation of his predicted percentage dissatisfied (PPD) model had mid-latitude climatic backgrounds, this model was used by de Dear et al. (1991c) as a benchmark for comparison. The hot, humid sample's 80% thermally acceptable threshold was found to be no different from that of subjects with temperate climatic backgrounds.

Aims

The basic premise of the current field experiment was the collection of data from office buildings and their occupants in the tropics using a package of laboratory-grade instrumentation conforming with the specifications and methods detailed in *ANSI/ASHRAE 55-1992*, *ISO 7726*, and *ISO 7730*. As such, the current project is a replication of the earlier San Francisco field experiment (RP-462) in every detail, except that it was carried out in the hot, humid climatic setting of northeast Australia.

The specific aims of the research are as follows:

1. To develop a data base of the thermal environments and subjective responses of occupants in existing office buildings in a hot, humid climate.
2. To determine for each season (wet and dry) both the neutral and preferred thermal conditions for occupancy as well as the range of conditions found to be thermally acceptable by the occupants. These findings are to be compared to the conditions required by *ANSI/ASHRAE 55-1992* and *ISO 7730*.
3. To assess the effectiveness of existing predictive thermal indices (ET^*, SET, DISC) as computed by the Pierce two-node model used in the San Francisco field experiment and the predicted mean vote (PMV) and PPD indices.
4. To investigate the influence of clothing and gender and also investigate potential acclimation effects by (a) interseasonal comparisons and (b) comparing the hot, humid climate data base with that of the earlier mid-latitude San Francisco field experiment (Schiller et al. 1988; Schiller 1990).

METHOD

The Outdoor Climatic Context

The city of Townsville, at latitude 19°S on the northeast coast of Australia, lies near the climatological border between the humid and dry tropics, as depicted in Figure 1. The city's climate can best be classed as "wet and dry tropical" since rainfall and associated humidity have a marked seasonality (Nieuwolt 1977). The wet season spans the hot and humid summer months of October through March, during which the prevailing winds are onshore and laden with moisture after traversing the warm western Pacific, while the dry season spans the warm and dry months of April through September. Figure 2 indicates daily maximum and minimum temperatures and relative humidity recorded outdoors during the two survey periods of the experiment. Mean temperatures of the dry and wet seasons (i.e., average of mean daily minima and maxima) were 19.0°C and 27.0°C, respectively. Of particular importance is the wet season's mean daily minimum temperature exceeding 20°C while maximum (dawn) humidities were generally higher than 80% RH at the same time. The wet season's elevated daily minimum temperatures can be explained by a higher atmospheric water vapor content absorbing and reradiating nocturnal infrared radiative losses from the surface. From the human standpoint, the oppressive combination of heat and humidity persists throughout day and night during the wet season in Townsville and therefore provides a suitable climatic setting for the stated objectives of the present project.

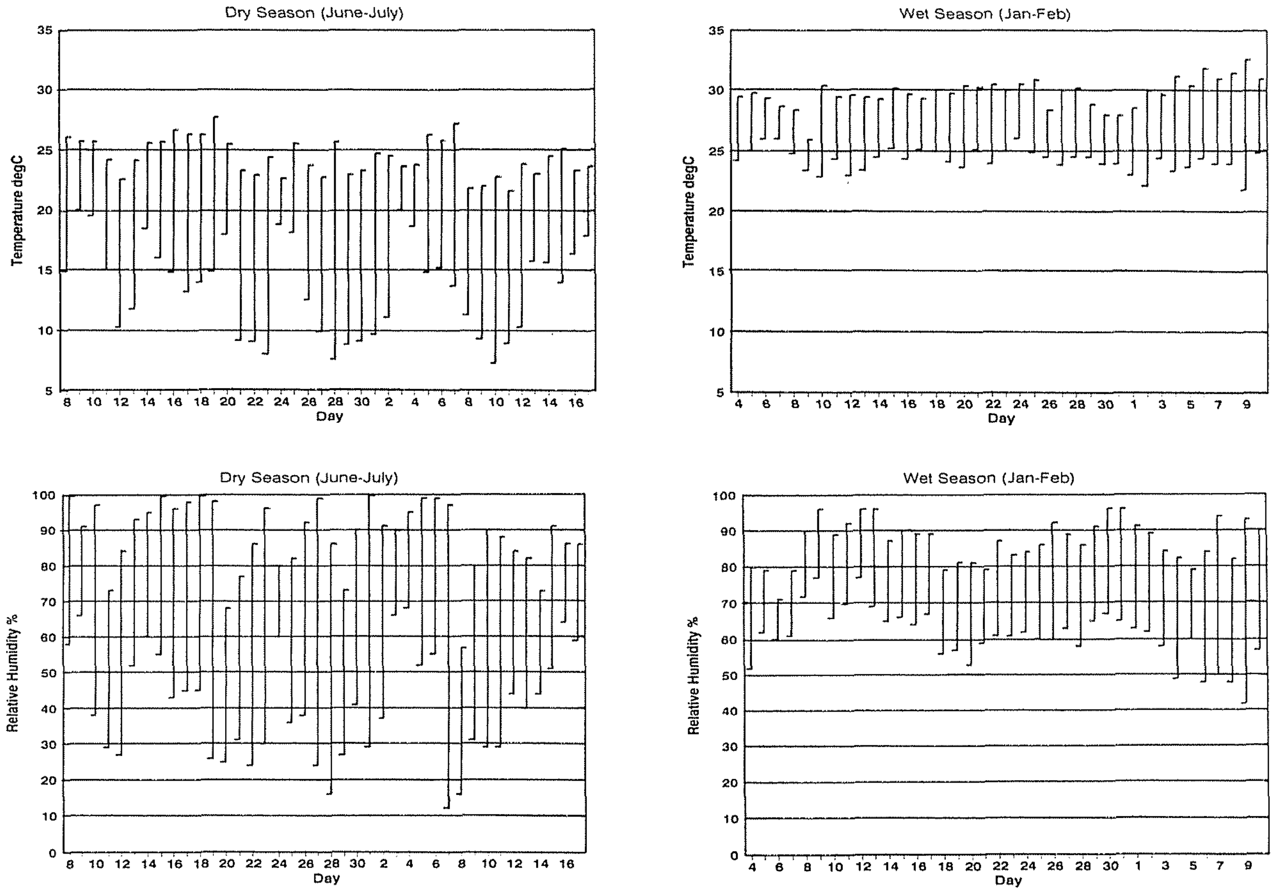

Figure 2 *Daily maximum and minimum outdoor temperatures and humidities during each of the two study periods (data supplied by ABM [1993]).*

Buildings Surveyed

The city of Townsville is the largest city in tropical Australia, having a population of 126,000 and performing primarily an administrative function for the far north region of the state of Queensland. Twelve office buildings were selected for the study, all with air conditioning, and their key characteristics are listed in Table 2.

Subjects

Sample sizes of 628 and 606 were achieved in the dry and wet season surveys, respectively. This total of 1,234 sets of data was given by 836 individuals, of whom 398 were interviewed in both seasons. A summary of the background characteristics of the subjects is provided in Table 3.

Instrumentation for Indoor Climate Measurement

A mobile measurement system, "Cart Mk II," was used on site in Townsville to collect measurements of indoor physical environments. Cart Mk II is an improved version of the mobile system used in the earlier San Francisco field experiment (Benton et al. 1990) and is depicted in Figure 3. The system's features and specifications include the following:

1. The system is capable of collecting concurrent physical data (air temperature, dew-point temperature, globe temperature, radiant asymmetry, air velocity, and illuminance) from three arrays of transducers placed 0.1 m, 0.6 m, and 1.1 m above floor level, representing the immediate environment of the seated subject's ankles, body, and neck, respectively. The "seat" of the instrument deliberately shielded the sensors in the same way that the occupant's chair shielded the subject.
2. The transducers and their automatic logging meet the *ANSI/ASHRAE 55-1992* and *ISO 7726* specifications for accuracy and response time. Air and globe temperature transducers were thermistors with accuracy within 0.2°C. The globes were fabricated from 38-mm-diameter table-tennis balls painted gray to approximate the emissivity of a clothed person. Air velocity was measured by three omnidirectional, fully temperature-compensated sensors having time constants better than 0.1 second, thus permitting an assessment of turbulence

TABLE 2
Summary of the 12 Office Buildings Surveyed

Building Code	Construction Date	Number of Floors	Area (Sq.m)	Type of Tenant	Number of Questionnaires	Air Conditioning Type	Floor Plan Layout
A	1985	3	2010	gov	100	VAV	mixed
B	1972	4	3944	gov	22	CAV	mixed
C	1986	12	17820	private	109	VAV	mixed
D	1974	4	4865	gov	45	CAV	mixed
E	1975	5	1860	gov	89	CAV	mixed
F	1975	8	4632	private	73	CAV	all open plan
G	1976	3	4851	gov	200	CAV	mixed
H	1986	5	7780	gov	203	CAV	mixed
I	1928	3	1727	gov	29	CAV	small offices
J	1975	3	2076	gov	124	VAV	mixed
K	1969	6	3942	private	33	VAV	mixed
L	1992	13	22910	gov	207	VAV	mixed

in the airflow (ASHRAE 1992; Melikov and Sawachi 1992). Dew-point temperature was registered by a chilled-mirror apparatus with a standard 100-ohm resistance temperature device. The radiant asymmetry probe was mounted in the vertical plane at 1.1 m above floor height and consisted of two hemispheric radiometers mounted back to back. Illuminance in the horizontal plane was measured at 1.1 m above floor level by a cosine-corrected silicon photometer.

3. The data-acquisition system provided a real-time display of measured values for error checking by research personnel. These data were displayed on a notebook computer out of the subject's view to avoid bias in the questionnaire responses.

Questionnaires

The initial contact with each subject involved completion of two separate questionnaires, which will be referred to as the ONLINE and BACKGROUND forms. The first form was a single sheet asking for rating-scale assessments of, among other things, air movement, thermal acceptability, temperature preferences, and thermal sensations exactly at that point in time and space. Side two of the ONLINE form consisted of clothing and activity checklists that were subsequently converted into ensemble clothing insulation and metabolic rate estimates using the data and methods specified in *ANSI/ASHRAE 55-1992*. The ONLINE questionnaire was typically completed in less than five minutes.

The second form, the BACKGROUND questionnaire, required between 20 and 30 minutes to complete. It assessed various demographic characteristics of the subjects along with general information dealing with the length of time they had lived in the tropics, their exposure to air conditioning outside working hours, and their general level of satisfaction with other aspects of the work environment (e.g., lighting, noise, furniture, privacy, and decor). The subjects' degree of control over their personal thermal environment was also rated, as was their environmental sensitivity, general job satisfaction, and, finally, general health status at the time of the interview. The stated aims of the present paper confine the analysis mainly to the ONLINE questionnaire, drawing on the BACKGROUND data base mainly for demographic and anthropometric characteristics of the samples.

Procedure

The procedure for each workstation visit was as follows:

1. The researcher approached the subject at the workstation and sought the subject's cooperation in administering the ONLINE questionnaire.
2. The researcher time-stamped the ONLINE questionnaire for subsequent matching against Cart Mk II data, then the subject completed the ONLINE form.
3. The subject then left the desk and Cart Mk II was immediately wheeled into exactly the same place formerly occupied by the subject's chair.
4. A five-minute sample of the workstation's thermal environment was recorded and time-stamped by Cart Mk II.
5. During the survey, the researcher recorded additional observations (e.g., made an estimate of incremental clothing insulation afforded by the subject's chair, took photographs, checked Cart Mk II data).
6. After both subjective and physical environmental measurements were completed, the researcher presented the BACKGROUND questionnaire to the subject and scheduled a pickup later in the day (usually within half an hour).

Calculation of Comfort Indices

After matching data from the ONLINE questionnaires with their corresponding Cart Mk II data, environmental and comfort index calculations were performed with exactly the

TABLE 3
Summary of the Two Samples of Building Occupants

Season	Dry	Wet
Sample Size	628	606
Gender		
male	42%	41%
female	58%	59%
Age (year)		
mean	33.9	32.8
standard deviation	10.5	10.0
minimum	17.0	17.0
maximum	64.0	62.0
Height (cm)		
mean	170.2	169.9
standard deviation	9.8	9.9
minimum	148.7	130.0
maximum	198.0	198.0
Weight (kg)		
mean	69.5	69.2
standard deviation	14.8	14.7
minimum	37.0	40.0
maximum	126.0	145.0
Number of years in tropics mean	20.5	20.8
standard deviation	14.5	14.0
minimum	0.0	0.0
maximum	64.5	59.9
Highest education		
high school	54%	53%
diploma/degree	40%	41%
postgrad university	6%	6%
Ethnic Background		
Aborigine	4%	3%
Asian	1%	2%
Caucasian	93%	94%
Other	1%	1%
Primary language		
English	99%	99%
Other	1%	1%
Use of home air-conditioning during present season		
yes	2%	15%
no	63%	48%
not available	35%	37%

same programs as those used in the earlier San Francisco project, thus ensuring compatibility between the two data bases. Indices included operative temperature (t_o), mean radiant temperature ($\bar{t}_r$), the new effective temperature (ET^*), standard effective temperature (SET), predicted mean vote (PMV), predicted percentage dissatisfied (PPD), and DISC, along with the PD index (predicted percent dissatisfied due to draft) proposed by Fanger et al. (1988) and subsequently incorporated into *ANSI/ASHRAE 55-1992* (ASHRAE 1992).

For those indices having clothing insulation as an input parameter, calculations were performed twice, with and without the additional insulation effect of the subject's chair included. Recently, some discussions in thermal comfort research literature have focused on the effect of the chair on the value of clothing insulation for a seated person (e.g., de Dear 1994; Brager et al. 1994). The estimates used in this study were based on comparisons between clothing insulation measurements made on a thermal manikin seated in typical office chairs and those recorded for the manikin wearing the same ensemble but sitting in a string chair (Dr. S. Tanabe, personal communication, 1993).

The program used to calculate ET^*, SET, and DISC indices was the two-node Fortran code published by Gagge et al. (1986). For the PMV and PPD calculations, the *ISO 7730* (ISO 1984) Fortran code was used.

RESULTS

Indoor Climates

Table 4 provides statistical summaries of the indoor climatic measurements for the dry and wet season samples. These data represent the main thermal variables recorded at subjects' workstations by Cart Mk II. Mean air (t_a) and radiant ($\bar{t}_r$) temperatures (averaged across the three heights measured by Cart Mk II) generally fell within the 23°C to 24°C interval for both seasons. Thermal stratification was negligible, with vertical air temperature gradients on average about 0.11°C/m in the occupied zone. Average relative humidities fell within the 50% to 60% range for both seasons and air velocities (v) (averaged across three heights) were low, with a mean of 0.12 m/s and turbulence intensities (Tu) around 40%.

Figure 4 presents for each season a comparison of the indoor thermal environments found in Townsville to the *ANSI/ASHRAE 55-1992* comfort standard in psychrometric chart format. Since the standard's comfort zone has four edges, these can be projected to the margins of the psychrometric chart to delineate eight distinct regions around the central zone of the standard's 90% thermal acceptability prescription (the shaded region in Figure 4 between 23°C and 26°C ET^*).

The numbers depicted in Figure 4 represent percentages of each season's sample falling in each of the psychrometric chart's regions. Barely half of the indoor conditions sampled in Townsville buildings fell within the summer comfort zone of *ANSI/ASHRAE 55-1992*. While the bulk of the indoor environments sampled in the dry season had humidities within the standard's prescriptions, many (28.7%) were not within the temperature guidelines, falling beyond the cool margin most frequently (< 23°C ET^*). In the wet season, the overwhelming majority of indoor environments sampled fell within the standard's temperature prescriptions, but one in every four had a humidity exceeding the standard's upper limit (60% RH), reflecting (a) the much higher latent loads

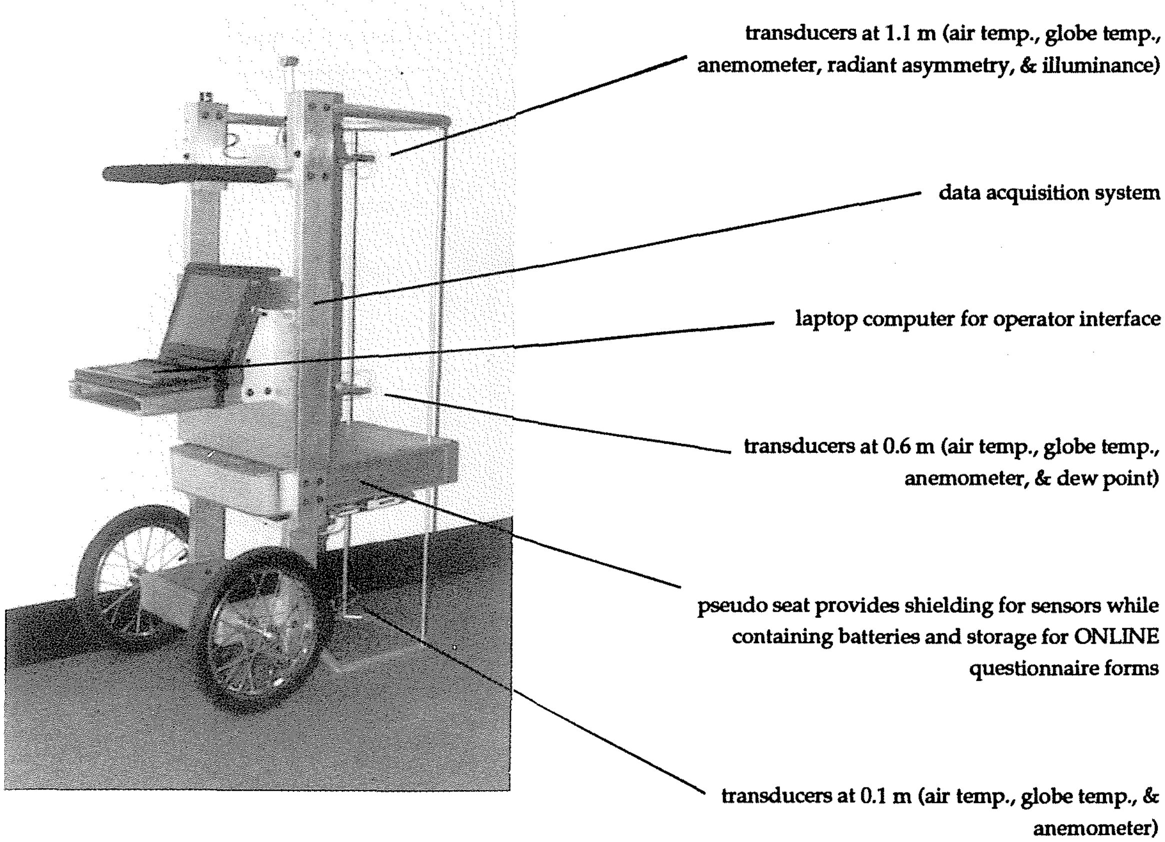

Figure 3 *Mobile measurement "Cart Mk II" used for indoor climatic data acquisition.*

on air conditioning during this season and (b) the lack of humidity control in many of the air-conditioning systems in the sample buildings.

Personal Comfort Variables

Table 5 presents summaries of the main personal thermal variables of clothing insulation and metabolic rates for each season. Intrinsic clothing ensemble insulation was estimated on the basis of garment values published in *ANSI/ASHRAE 55-1992* and was generally near the standard's assumed summer value of 0.5 clo, irrespective of sex. There was, however, some interseasonal variability, with the wet season's ensemble average being about 0.1 clo less than that of the dry season (t = 10.8, df = 1232, $p < 0.01$). Concomitant with this seasonal decrease was a decrease in the interindividual variability (standard deviation) from about 0.2 clo in the dry season toward 0.1 clo in the wet season, suggesting that the degrees of freedom for thermoregulation by clothing adjustments diminished as the amount of clothing approached the socially acceptable minimum.

Also listed in Table 5 is a second set of thermal insulation estimates that take into account the effect of the chairs on which subjects were sitting at the time they completed the ONLINE questionnaire. On average, the chair insulation increment amounted to 0.15 clo, lifting the insulation values used in subsequent thermal comfort index calculations to 0.7 and 0.6 clo in the dry and wet season surveys, respectively.

Based on a behavior/activity checklist referring to the hour just prior to sitting down to fill in the ONLINE questionnaire, metabolic rates of the subjects were estimated to be, on average, 78 W/m^2 or 1.3 met in both seasons and for both sexes.

Calculated Comfort Indices

Table 6 presents a statistical summary of the thermal environmental and comfort indices broken down by season. These indices include operative temperature t_o (average of t_a and $\bar{t}_r$); ET*; SET; DISC; and the PMV/PPD indices and the draft dissatisfaction index, PD. On average, t_o, ET*, and SET values fell within the 23°C to 24°C range, while the PMV calculations indicate marginally cooler than neutral conditions (–0.2 to –0.3). Contained at the bottom of these tables is a second set of index calculations taking into account the effects of chair insulation as discussed above. The average chair effect was reflected by an increase in mean SET of 1.4°C, an increase of 0.3 PMV units, and a reduction of PPD by about 3%.

TABLE 4
Statistical Summary of Indoor Climatic Data

		Dry	Wet
	Season	Dry	Wet
	Sample Size	627	604
Air Temperature (degC)	(average of 3 heights)		
	mean	23.3	23.6
	standard deviation	0.9	1.0
	minimum	20.1	21.3
	maximum	25.7	27.6
Mean Radiant Temperature (degC	(average of 3 heights)		
	mean	23.5	23.9
	standard deviation	0.9	1.0
	minimum	19.2	21.0
	maximum	25.8	27.8
Plane Radiant Asymmetry (degC)	(at 1.1 m)		
	mean	-0.2	-0.4
	standard deviation	0.8	1.0
	minimum	-7.4	-6.5
	maximum	1.6	5.0
Dew Point Temperature (degC)			
	mean	12.3	14.3
	standard deviation	2.6	2.0
	minimum	6.8	10.4
	maximum	17.6	19.1
Relative Humidity (%)			
	mean	50.8	56.3
	standard deviation	8.7	6.3
	minimum	34.0	44.0
	maximum	69.0	71.0
Vapor Pressure (hPa)			
	mean	14.5	16.4
	standard deviation	2.5	2.1
	minimum	9.8	12.6
	maximum	20.1	22.1
Air Velocity (m/s)	(average of 3 heights)		
	mean	0.12	0.13
	standard deviation	0.03	0.04
	minimum	0.10	0.10
	maximum	0.25	0.66
Turbulence Intensity (%)	(average of 3 heights)		
	mean	36.7	42.6
	standard deviation	24.4	32.4
	minimum	5.0	5.0
	maximum	195.0	325.0

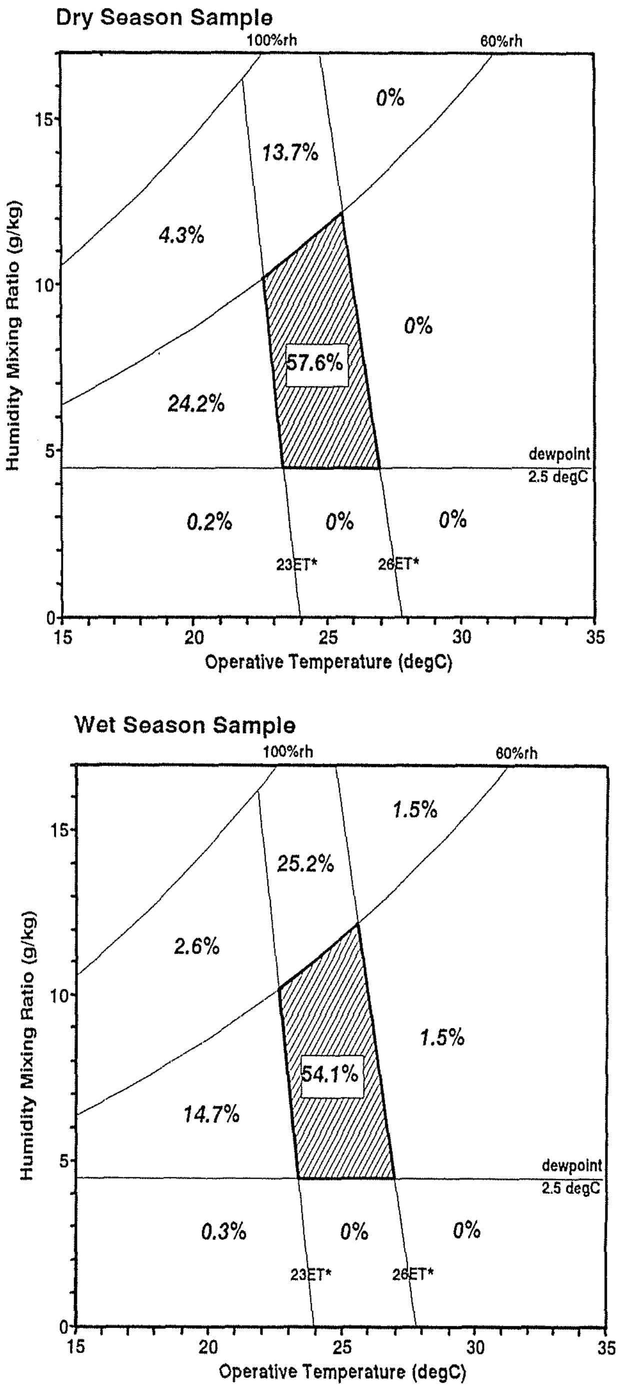

Figure 4 *Distribution of indoor climatic measurements on the ANSI/ASHRAE Standard 55-1992 summer comfort chart.*

Comfort Responses on the ONLINE Questionnaire

Table 7 statistically summarizes the ONLINE questionnaire comfort responses registered at subjects' workstations. As with previous tables, the data have been disaggregated by season.

Thermal Sensation Mean thermal sensations on the ASHRAE seven-point scale were marginally cooler than neutral (–0.3 to –0.4) for both seasons. For further analysis, the data were binned into 0.5°C intervals, and percentages of subjects voting warmer-than-neutral and cooler-than-neutral for each bin were calculated (with subjects voting neutral being split 50:50). Figure 5a shows each season's maximum likelihood probit model for these binned thermal sensation percentages against t_o. The same analysis was repeated using ET* as the independent variable in Figure 5b.

A useful application of probit analysis is in the determination of thermal neutralities, that is, temperatures most frequently coinciding with neutral thermal sensations (Ballantyne et al. 1977). These estimates are represented as temperatures corresponding to a 50% response rate in the probit model and are depicted in Figure 5 as vertical arrows descending from the fitted curves to intersect the temperature axes. The t_o neutralities were 24.2°C in the dry season (with 95% fiducial limits at 24.0°C and 24.6°C) and 24.6°C in the wet season (with 95% fiducial limits at 24.0°C and 25.8°C). The ET* neutralities were virtually identical in both seasons at about 24.3°C ET*.

The strength of association and the sensitivity of thermal sensation votes to temperature variations are most easily quantified using linear correlation/regression tech-

TABLE 5
Statistical Summary of Personal Thermal Parameters

Season	Dry			Wet		
Gender	Male	Female	Combined	Male	Female	Combined
Sample Size	266	362	628	248	357	606
Intrinsic Clothing Insulation (clo)						
mean	0.52	0.55	0.54	0.45	0.44	0.44
standard deviation	0.17	0.20	0.19	0.12	0.13	0.13
minimum	0.25	0.25	0.25	0.21	0.20	0.20
maximum	1.09	1.38	1.38	1.15	1.02	1.15
Clothing + Chair Insulation (clo)						
mean	0.68	0.70	0.69	0.61	0.59	0.59
standard deviation	0.18	0.20	0.19	0.13	0.14	0.13
minimum	0.32	0.40	0.32	0.30	0.29	0.29
maximum	1.24	1.53	1.53	1.30	1.17	1.30
Metabolism (W/sq.m)						
mean	78.2	77.5	77.8	77.8	77.5	77.6
standard deviation	12.3	13.0	12.7	13.4	13.7	13.6
minimum	58.2	58.2	58.2	58.2	58.2	58.2
maximum	116.4	116.4	116.4	116.4	151.3	151.3

niques. The analysis proceeded by taking mean votes within successive temperature bins as the dependent variable rather than individual votes. By weighting each data pair with the number of subjects falling in that particular bin, the effect of relatively large residuals at the less frequently encountered temperature extremes was de-emphasized.

The mean ASHRAE sensation votes for each half-degree t_o bin have been plotted in Figure 6. The regression line fitted to these bin means was highly significant (F = 636.2; Prob < 0.0001; r^2 = 0.97), and a standard error on the regression coefficient was 0.02 (Prob < 0.0001). The fitted equation was

$$\text{mean binned ASHRAE sensation vote} = 0.522 \cdot t_o - 12.67.$$

Superimposed on the same graph in Figure 6 are regression equations for mean binned PMV and DISC index values (both with the effects of chair insulation included). Clearly the regression gradients on these two models underestimate the observed sensitivity to operative temperature (approximately half a thermal sensation unit per °C). The net effect of this underestimation can be seen in Figure 6 as a rapid deterioration in both models' fit to the observed data away from the neutral region around 24.5°C.

Thermal Acceptability In the ONLINE questionnaire, the question immediately following thermal sensation was a direct thermal acceptability item. These data were binned by t_o and the resulting percentages of dissatisfaction are plotted as a function of temperature in Figure 7 (denoted as "Direct accept – obs" in the legend). The second-order polynomial weighted regression curves indicate minimum levels of thermal dissatisfaction at t_o = 23.5°C in both seasons, and it was only at this central temperature that the 90% acceptability goal of *ANSI/ASHRAE 55-1992* was actually met in the Townsville sample. Using the fitted "Direct regress – obs" curve in the combined season graph of Figure 7 as a guide, 80% acceptability appears to have been achieved between 22.5°C and 24.5°C, a somewhat narrower range than the three-degree band suggested in *ANSI/ASHRAE 55-1992* and *ISO 7730* for 90% acceptability.

A common assumption in thermal comfort research is that a vote outside the three central categories of the ASHRAE seven-point sensation scale (slightly cool, neutral, slightly warm) is an expression of dissatisfaction and is therefore unacceptable. The percentages of such votes within each of the t_o bins were calculated, and a second-order polynomial weighted regression model ("ASHRAE regress – obs") has been superimposed on the combined season graph of Figure 7. This indirect assessment of thermal acceptability coincides closely with the direct assessment reported in the preceding paragraph.

The third curve superimposed on the combined season graph of Figure 7 is a second-order weighted polynomial fit to the mean PPD index value within each of the t_o bins (denoted as "PPD regress – predict" in the legend).

An implication of the Townsville thermal acceptability data as depicted in Figure 7 is that there were large numbers of subjects who considered their workstation environments to be thermally unacceptable despite the fact that, on the objective criteria of t_o and humidity at least, they fulfilled the criteria specified in *ANSI/ASHRAE 55-1992* and *ISO 7730*. Since Figure 7 indicates little seasonal difference in acceptability, the following analysis refers to pooled results. A total of 255 subjects voted that their thermal environments were unacceptable. Of this subset of thermally dissatisfied subjects, more than half (132 subjects, or 52%) were in environments that fulfilled the *ANSI/ASHRAE 55-*

TABLE 6
Statistical Summary of the Calculated Indoor Climatic and Thermal Comfort Indices

	Season	Dry	Wet
	Sample Size	627	604
Operative Temp. (degC)	mean	23.4	23.8
	standard deviation	0.9	1.0
	minimum	19.8	21.2
	maximum	25.7	27.7
ET* (degC)	mean	23.4	23.9
	standard deviation	0.9	1.0
	minimum	19.8	21.2
	maximum	25.6	28.2
SET (degC)	mean	23.3	22.9
	standard deviation	1.8	1.5
	minimum	18.8	19.4
	maximum	30.7	28.7
DISC (from 2-node)	mean	0.1	0.1
	standard deviation	0.3	0.2
	minimum	-0.4	-0.2
	maximum	2.0	1.4
PMV	mean	-0.2	-0.3
	standard deviation	0.6	0.6
	minimum	-2.4	-2.1
	maximum	1.1	1.4
PPD (%)	mean	12.4	14.0
	standard deviation	11.8	13.6
	minimum	5.0	5.0
	maximum	91.8	82.5
Predicted Draft Dissatisfaction			
PD (%)	mean	9.7	11.4
	standard deviation	3.3	5.7
	minimum	5.3	5.0
	maximum	32.4	76.8
SET (degC)	(incl. chair insulation)		
	mean	24.7	24.3
	standard deviation	1.7	1.5
	minimum	20.1	20.8
	maximum	31.8	30.2
DISC	(incl. chair insulation)		
from 2-node model	mean	0.3	0.3
	standard deviation	0.4	0.3
	minimum	-0.2	-0.1
	maximum	2.5	1.9
PMV	(incl. chair insulation)		
	mean	0.1	0.0
	standard deviation	0.5	0.5
	minimum	-1.9	-1.6
	maximum	1.2	1.5
PPD (%)	(incl. chair insulation)		
	mean	9.9	10.4
	standard deviation	7.1	7.9
	minimum	5.0	5.0
	maximum	69.5	55.8

1992 comfort zone criteria. Conversely, 405 of the 955 subjects (i.e., 42%) who found their thermal environments acceptable were actually in conditions outside the comfort zone of *ANSI/ASHRAE 55-1992*.

Thermal Preference Subjects were also asked to indicate whether they would prefer to feel warmer or cooler. These thermal preferences have been binned into 0.5°C ET* intervals and the resulting percentages within each bin have been subjected to probit analyses. The resulting models are depicted in Figure 8. Assuming that the point of intersection between the "want to be cooler" and the "want to be warmer" probit models represents the optimum temperature, it can be seen in Figure 8 that this occurred at approximately 23.5°C ET*. However, even at this most preferred temperature, there was a sizable minority of subjects in each season (34% to 38%) indicating a desire for either warmer or cooler conditions.

Subjective Assessments of Air Movement The actual levels of air movement measured with Cart Mk II at the sampled workstations (Table 4) of 0.12 m/s with about 40% turbulence intensity were consistent throughout the 12 buildings and across both seasons, as indicated by the small standard deviations. The ONLINE questionnaire required subjects to assess the air movement at their workstations in terms of acceptability and preference. As indicated in Table 7, the mean air movement acceptability ratings were about midway between "slightly" and "moderately" acceptable. In total, 73% and 74% of all subjects in the dry and wet season samples, respectively, registered votes on the "acceptable" side of the scale. Despite this, a majority of subjects in both seasons still indicated a preference for air movement levels different from those prevailing at the time of the interview. As seen in Table 8, less than 10% of subjects in either season wanted less air movement than they were receiving at the time of the interview, whereas about half of all subjects expressed a desire for more air movement than they were getting.

DISCUSSION

Comparisons Between Indices, Models, and Observed Data

The average score on the basic PMV index in this study closely matched the average thermal sensation vote cast by the Townsville subjects on the ASHRAE scale (Tables 6 and 7, respectively). This agreement deteriorated slightly (about 0.3 PMV units) when the incremental insulation effect of chairs (0.15 clo) was introduced into the PMV calculations. As seen in Figure 6, the PMV regression model with chair insulation intersects "neutral" (zero) more than half a degree cooler than the actual thermal sensation votes' regression model did.

Either with or without the effect of chairs incorporated, however, the PMV index predicted neutralities of Townsville office workers reasonably well. It performed much less satisfactorily under non-neutral conditions, giving discrepancies on the order of half a sensation unit at the margins of the comfort zone (t_o of 23°C and 26°C). The shallow gradient of PMV on temperature depicted in Figure 6 suggests that subjects were adjusting other parameters in their heat balance, such as clothing, in a way that largely compensated for the departure of ambient temperatures from neutrality. In reality, though, the effects of these clothing adjustments appeared to have been overlooked when subjects were casting their thermal sensation votes, so

TABLE 7
Statistical Summary of the ONLINE Questionnaire Rating Scale Responses

	Season	Dry			Wet		
	Gender	Male	Female	Combined	Male	Female	Combined
	Sample Size	266	362	628	248	357	605
Thermal Sensation	(-3=cold; 0=neutral; +3=hot)						
(ASHRAE 7 point)	mean	-0.4	-0.4	-0.4	-0.2	-0.3	-0.3
	standard deviation	1.1	1.1	1.1	1.1	1.2	1.1
	minimum	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0
	maximum	3.0	2.7	3.0	2.8	3.0	3.0
Air Movement	(1=very unacceptable; 6=very acceptable)						
Acceptability	mean	4.4	4.2	4.3	4.4	4.3	4.4
	standard deviation	1.3	1.4	1.4	1.3	1.3	1.3
	minimum	1.0	1.0	1.0	1.0	1.0	1.0
	maximum	6.0	6.0	6.0	6.0	6.0	6.0
General Comfort	(1=very uncomfortable; 6=very comfortable)						
	mean	4.7	4.6	4.6	4.6	4.7	4.6
	standard deviation	1.1	1.1	1.1	1.1	1.1	1.1
	minimum	1.0	1.0	1.0	1.0	1.0	1.0
	maximum	6.0	6.0	6.0	6.0	6.0	6.0

observed mean votes' sensitivity to temperature was much more pronounced than theory (PMV) predicted. The regression model of DISC paralleled the PMV regression in Figure 6, but it was displaced even further away from the observed data.

Turning to observed and predicted levels of thermal dissatisfaction, as depicted in Figure 7, there was general agreement between the two common methods of empirical assessment. Both the direct approach—"Is the thermal environment acceptable to you?"—and the indirect approach—assuming ASHRAE sensation votes −3, −2, +2, and +3 to be unacceptable—yielded optimum temperatures in the 23.5°C to 24°C region. This same optimum temperature was also arrived at by the predicted dissatisfaction index in Figure 7 (PPD regress – predict). However, the levels of dissatisfaction predicted by PPD considerably underestimated the observations across the full range of temperatures encountered in this study except for 23.5°C. In effect, the subjects were much less accepting of temperatures away from 23.5°C than the PPD index predicted. For example, at the warm margin of the comfort zone (26°C), thermal dissatisfaction was observed to be as much as 20% to 30% above the level predicted by the index.

Comparisons Between Observed Comfort Data and the Standards

The range of temperature-humidity combinations considered acceptable by the Townsville office sample did not closely match those specified in the standards. Perhaps the most vexatious building occupant for the facilities manager is the one who complains about the air conditioning despite the fact that his or her workstation's physical environment matches the specifications laid down in the standards. Ever since Fanger's (1970) PPD index gave quantitative expression to the truism long recognized by facilities managers that "you can't please all of the people all of the time," complainants have been expected to represent at least 5% to 10% of building occupants. In Townsville, 690 of the 1,234 workstations visited had indoor climates within the *ANSI/ASHRAE 55-1992* comfort zone, but only 80% of the occupants of those workstations found them thermally acceptable, not the 90% suggested in the standard. To further confirm that this level of dissatisfaction was indeed anomalously high, the PPD index was calculated for all 690 sets of observations meeting the criteria of Standard 55, and the average came to just 12% PPD, underscoring the high degree of congruence between *ANSI/ASHRAE 55-1992* and *ISO 7730* but falling well under the 20% dissatisfaction actually observed.

While it is expected that about 10% of thermal dissatisfaction within the comfort zone is due simply to interindividual variability, there remains approximately an additional 10% in the present study, that is, about half of the 132 cases of thermal dissatisfaction within the comfort zone, which warrants closer scrutiny. The approach adopted was to search for factors known to influence comfort but not included in the preceding analysis. Vertical temperature stratification is suggested in *ANSI/ASHRAE 55-1992* as a potential source of complaint. The standard specifies that the maximum allowable vertical gradient within the occupied zone is 1.9°C/m, but not one of the 132 cases of unexplained thermal dissatisfaction exceeded this guideline. Standard 55 suggests that radiant temperature asymmetries

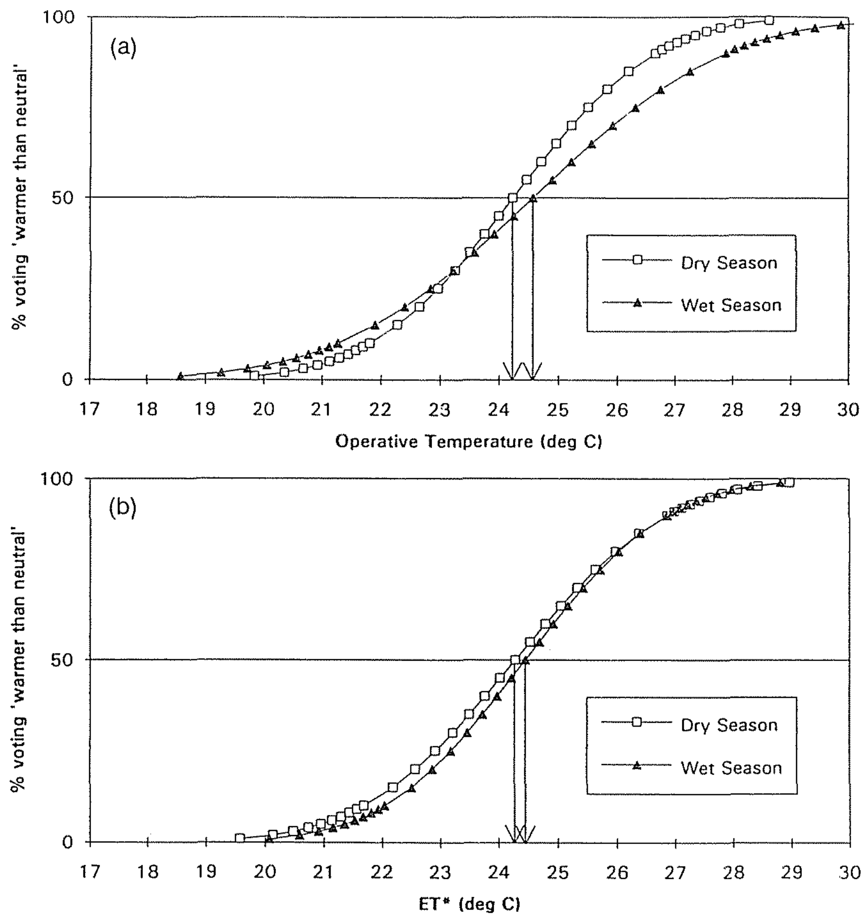

Figure 5 *Probit regression models fitted to thermal sensation percentages.*

in the vertical plane may be a source of complaint, but none of the 132 cases under investigation exceeded the standard's plane radiant asymmetry limit of 10°C (see Table 4).

Standard 55 also suggests that air movement characteristics can be a potential source of complaint in an otherwise acceptable thermal environment. Unwanted local cooling due to excessive velocity or turbulence is defined as draft. The standard recommends the application of the Fanger et al. (1988) PD model of draft risk to minimize complaints of this type and specifies that index values should not exceed 15% Of the 132 cases of unexplained thermal dissatisfaction, only 9 (7%) were experiencing PD index values greater than the suggested limit. In contrast, 72% of the thermally dissatisfied subjects within the comfort zone actually expressed a desire for higher, not lower, air speeds on the ONLINE questionnaire's air movement preference scale. Clearly draft is not as important a comfort issue in the hot, humid climatic zone as it is in cooler regions, and since desirable air movement and undesirable drafts are the subject of some contention in the comfort literature at present (Fountain and Arens 1993), the detailed data on these issues collected in Townsville should be subjected to a more thorough analysis in a future paper.

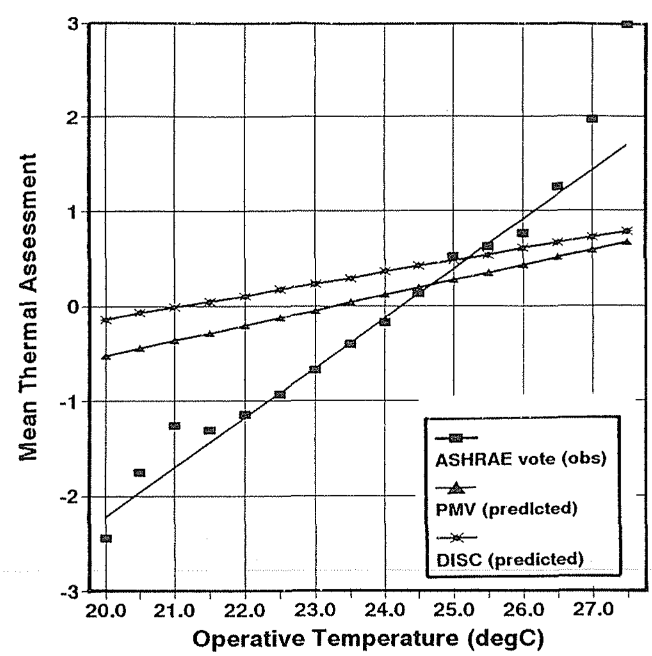

Figure 6 *Mean binned thermal sensation votes, PMV, and DISC calculations related to operative temperature.*

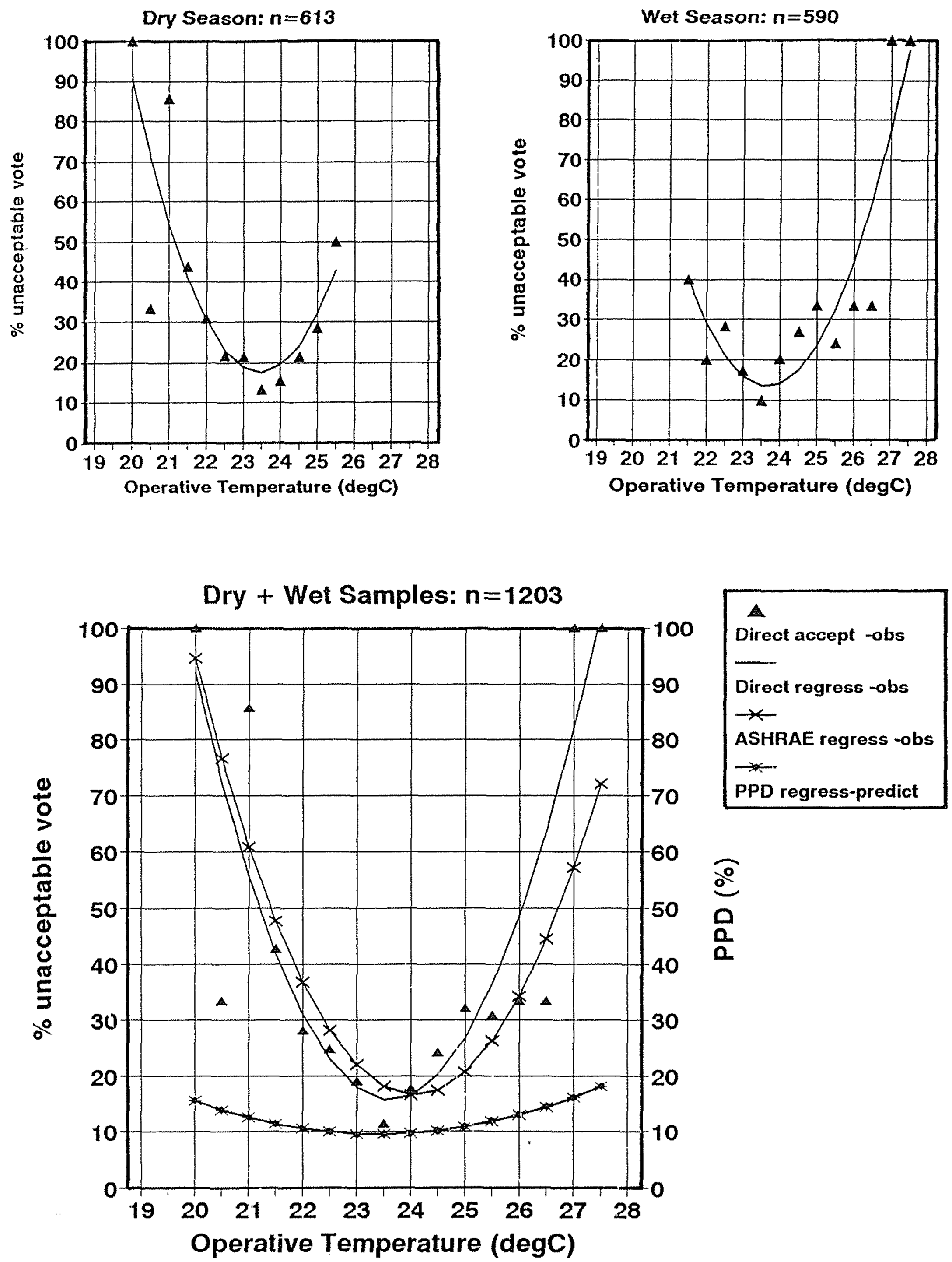

Figure 7 *Observed and predicted thermal acceptability related to operative temperature.*

Combining these potential thermal causes for complaint within the comfort zone, it appears that a small number of cases can be ascribed to drafts, but clearly the most likely explanation is that air speeds and/or turbulence intensities were not high enough, despite the fact that their mean values (Table 4) perfectly matched the prescriptions of Standard 55.

Comparison Between the Seasons

The meteorological data in Figure 2 indicated a clear contrast between the hot, humid conditions of the wet season and the warm, arid conditions of the dry season. This raises the question of whether or not such a seasonal climatic forcing has any effect on the thermal comfort

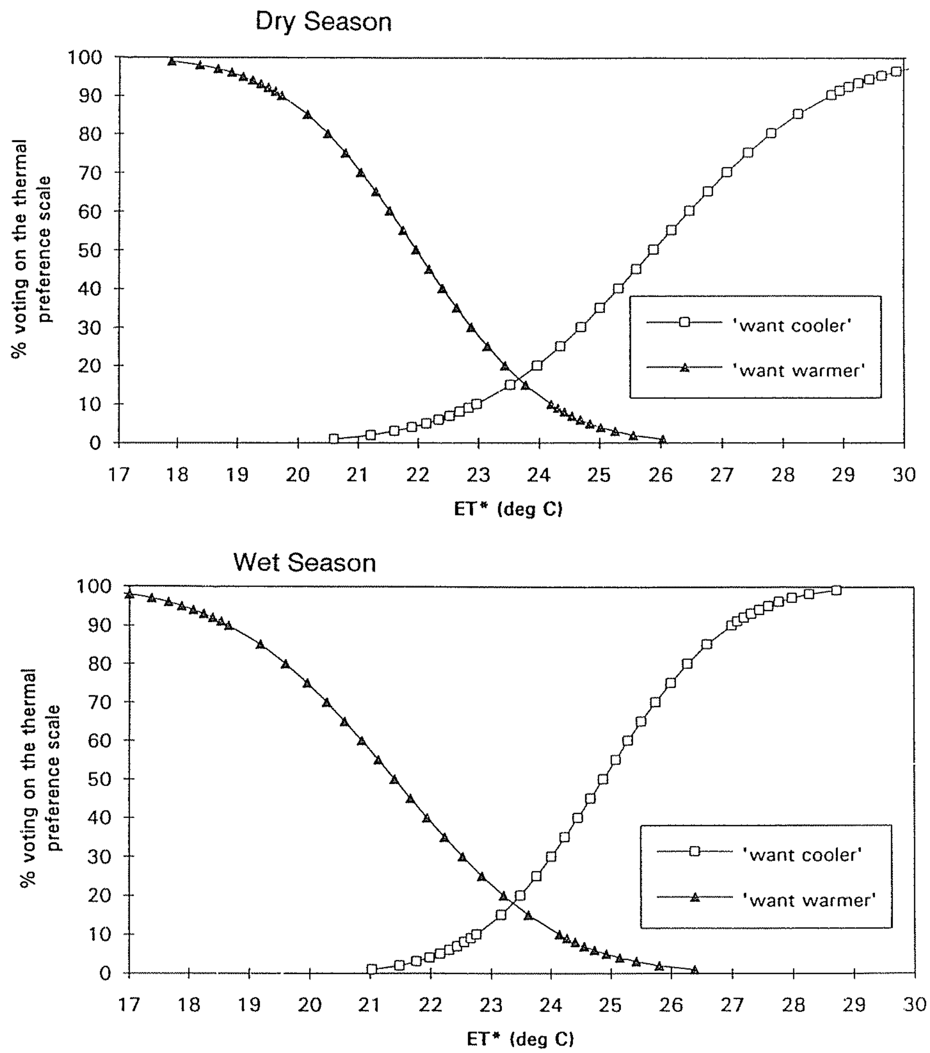

Figure 8 *Probit regression models fitted to thermal preference percentages.*

responses of office workers in air-conditioned buildings. In terms of clothing patterns in Townsville, there seemed to be some seasonal adaptation insofar as average intrinsic insulation levels were reduced by about 0.1 clo between the dry and wet seasons (Table 5). However, in terms of neutralities on the ASHRAE thermal sensation scale (Figures 5a and 5b), thermal acceptability (Figure 7), and thermal preferences (Figure 8), the interseasonal differences were, at most, within half a degree of each other and of no statistical or, indeed, engineering significance. Interestingly though, the half-degree offset closely corresponds to the $\partial clo/\partial T$ relationship for thermally neutral subjects published in *ANSI/ASHRAE 55-1992* and *ISO 7730.*

Comparisons Between Thermal Neutrality, Preference, and Acceptability

Several papers have raised doubts about the assumed equivalence between the concepts of thermal sensation, acceptability, and preference (e.g., Auliciems 1983; Brager et al. 1994). The Townsville data provide the possibility for comparisons between the physical environments associated with these psychological constructs. Neutrality, defined in terms of the 50% effective dose on the ASHRAE thermal sensation scale, fell at about 24.4°C. The optimum level

TABLE 8
Air Movement Preferences

Season	Dry	Wet
Sample Size	628	606
Prefer Less Air Movement	8.2%	3.8%
Prefer No Change in Air Movement	42.9%	41.8%
Prefer More Air Movement	48.9%	54.4%

according to thermal preference votes fell at about 23.5°C, which was the same temperature at which maximum thermal acceptability occurred. While it is difficult to establish the statistical significance of this one-degree offset, it is worth noting that it is precisely the same magnitude and direction as that observed in the de Dear et al. (1991b) preferred-temperature climate chamber experiment in Singapore. One possible explanation, proposed by McIntyre (1978), focused on a climatic bias in the semantics of sensation scales. McIntyre suggested that "neutral" may not be the preferred thermal state in all climate regions of the world—in particular, people in hot climates may, in fact, describe their preferred thermal state as "slightly cool," while people in cold climates may use the words "slightly warm" to denote their thermal preference. The current data are consistent with this hypothesis.

Effects of Gender

Earlier field studies of thermal comfort in office buildings have noted differences in thermal requirements of the sexes (e.g., Fishman and Pimbert 1979). Very often, however, such differences have been traced back to differences in clothing levels, with females having larger interseasonal and interindividual variances than males in the same environments. In Townsville, there were no differences between the sexes in this regard, and this was reflected in the coincidence of the sexes' neutralities, as derived from weighted linear regressions on t_o (males = 24.2°C; females = 24.3°C).

While the sexes could not be distinguished in terms of thermal neutralities, the same could not be said of thermal acceptability. In the total sample of 1,234 subjects comprising 58% females and 42% males, the former were overrepresented in the group expressing thermal dissatisfaction (68% female; 32% male; χ^2 = 12.9, df = 1, Prob < 0.005). This was despite the absence of any statistically significant differences in the physical character (t_o, PMV, ET*) of the environments occupied by each sex.

Comparisons with Other Thermal Comfort Field Experiments

The thermal neutralities observed in Townsville's air-conditioned office buildings at around 24.5°C were virtually identical to those obtained in an earlier office building study in Darwin, which is also located within Australia's wet-dry tropics (de Dear and Auliciems 1985). Furthermore, the same neutrality was found in air-conditioned offices in Singapore, which is located within the wet tropics (de Dear et al. 1991a). Busch (1990, 1992) independently arrived at the same result in air-conditioned buildings in Bangkok, also located within the wet tropics.

The corroboration of these earlier tropical findings suggests that the instrumentation and protocols used to generate them were accurate and reliable. Therefore, the anomalously high thermal neutralities and acceptability reported in naturally ventilated buildings in the tropics (Busch 1990; de Dear et al. 1991a, 1991b, 1991c) are indirectly supported by the present study also, since they were based on exactly the same instrumentation and protocols as the air-conditioned building experiments (de Dear 1994).

The San Francisco Bay area field experiment (RP-462) that the present study set out to replicate (Schiller et al. 1988; Schiller 1990) initially reported a tendency for the PMV, PPD, TSENS, and DISC indices all to underestimate thermal sensations actually observed in buildings. The discrepancy between observation and prediction was noted as being on the order of 0.5 to 1.0 thermal sensation units. However, in a reanalysis of those data, Brager et al. (1994) recently increased the clothing ensemble insulation estimates by applying revised *ANSI/ASHRAE 55-1992* garment data and also factoring in the effect of chairs. These adjustments, when combined with a new estimate of subjects' metabolic rates, managed to bring PMV predicted neutrality to within 0.2°C of the 22.4°C actually observed in San Francisco. The Townsville thermal insulation and metabolic estimation methods are perfectly consistent with the Brager revisions, and the result was also a reasonably good prediction of neutrality by the PMV index (within a single degree). Therefore, most of the 2°C difference between San Francisco and Townsville neutralities has been explained by the physical input parameters of the PMV index, in particular, clothing.

Compared to San Francisco subjects, the hot, humid subjects were considerably more sensitive to temperature variations. In San Francisco, Schiller et al. (1988) found a gradient of about one sensation unit per 3°C, which coincides with the gradients typically found in mid-latitude climate chamber experiments. However, in Townsville, the figure was closer to 2°C, and although Fanger's comfort model (1970) indicates that $\partial PMV/\partial T$ is an inverse function of clothing insulation, the magnitude of the observed thermal sensitivity increase was more than three times that predicted on the basis of clothing differences between the San Francisco and Townsville subjects. A more thorough comparison between the Townsville and San Francisco data bases will be the subject of a forthcoming *ASHRAE Transactions* paper.

In a thorough review of thermal comfort field studies, Auliciems (1983) regressed the neutralities observed in more than 50 such studies on the mean indoor and outdoor temperatures recorded during the studies. Since its input data came from all around the world, the Auliciems regression equation provides an easy method of comparison between the current Townsville data and those collected in a broad spectrum of climatic contexts:

$$t_\psi = 9.22 + 0.48(t_i) + 0.14(t_m)$$

where

t_ψ = neutrality on the ASHRAE or Bedford seven-point scale;

t_i = mean air, globe, or operative temperature; and
t_m = mean monthly temperature outdoors (average of mean daily minima and maxima).

The t_ψ predicted from the present dry season's data was 23.1°C, and the corresponding prediction for the wet season was 24.4°C, indicating the effect of eight degrees difference between seasons' t_m. Compared to the actual observations (Figure 5), the predicted t_ψ for the wet season was virtually a direct hit, whereas the predicted dry season t_ψ was more than a degree cooler than observed neutrality. Possibly the cause for the model's overestimation of interseasonal adaptation effects in Townsville can be traced to the fact that input data to the regression were derived from both air-conditioned and naturally ventilated buildings. Occupants of such buildings without heating, ventilating, and air-conditioning (HVAC) systems could be expected to demonstrate a greater sensitivity of clothing insulation, and therefore thermal neutralities, to outdoor climatic forcing than their counterparts in air-conditioned buildings. In Townsville, there was only a slight decrement of about 0.1 clo between seasons, despite an eight-degree difference in mean outdoor temperature, so the observed interseasonal difference in neutrality was less than half a degree.

Humphreys (1981) also regressed field study neutralities on prevailing warmth outdoors but did so separately for what he called "climate controlled" and "free running" building studies. The former were those with centralized HVAC systems in operation at the time of the survey, while the latter were naturally ventilated:

$$t_\psi = 23.9 + 0.295(t_m - 22)$$
$$\exp(-((t_m - 22)/(24 \cdot 2^{0.5}))^2) .$$

The neutralities predicted (t_ψ) with this model, using t_m = 19°C and 27°C for the dry and wet seasons, were 23.0°C and 25.3°C, respectively. In effect, Humphreys' model underestimated the dry season result by more than a degree and overestimated the wet season observation by a similar magnitude, despite the fact that it was based exclusively on climate-controlled buildings such as those used in the present Townsville experiment. Possibly the explanation for the poorer performance of Humphreys' model compared to Auliciems' is that the latter had the benefit of a larger set of input data, especially from warmer climates.

CONCLUSIONS

- A replication of the ASHRAE-sponsored San Francisco field experiment (RP-462) was performed in 12 air-conditioned office buildings located in the tropical city of Townsville, Australia. A total of 836 subjects provided 1,234 sets of data spread across both the wet and dry seasons. The experiment used the San Francisco questionnaires with some minor adaptations to local language and climatic conditions. Indoor climatic data were collected by a mobile cart carrying laboratory-grade instrumentation complying with *ANSI/ASHRAE 55-1992* and *ISO 7726* recommendations for accuracy and response times.
- Clothing insulation levels approximated the Standard 55 assumed summer value of 0.5 clo, with slightly more (0.1 clo) being worn in the dry season than in the wet. Chairs were estimated to add 0.15 clo to the clothing insulation of the office workers. On average, their metabolic rates were estimated to be 78 W/m^2 or 1.3 met.
- Thermal neutrality according to the ASHRAE seven-point scale occurred at about 24.4°C in both seasons. Preferred temperature, defined as a minimum of subjects requesting temperature change, was one degree cooler than neutrality, at 23.5°C. Thermal acceptability peaked at 90% also at 23.5°C but fell off to 80% at 22.5°C and 24.5°C.
- The PMV index with the effects of chair insulation taken into account adequately predicted the optimum temperatures of the Townsville subjects, whether defined in terms of thermal neutrality, thermal acceptability, or thermal preference.
- Little more than 50% of the indoor climatic observations fell within the Standard 55 summer comfort zone. Neither *ANSI/ASHRAE 55-1992* nor the *ISO 7730* PPD index matched observed levels of thermal acceptability with useful accuracy. Townsville office workers were generally much less accepting of non-neutral temperatures than either the PPD index or Standard 55 predicted.
- In Townsville's air-conditioned offices, draft or unwanted local cooling due to excessive air movement was much less of a problem than insufficient levels of air movement. Most of the thermal dissatisfaction expressed by subjects whose thermal environments fell within the Standard 55 summer comfort zone appeared related to air that was too still. These findings suggest that draft guidelines in Standard 55 and *ISO 7730* may be inappropriate for hot, humid climatic zones. This issue is the subject of a forthcoming paper by the authors.
- Group mean thermal sensations showed a heightened sensitivity to temperature, changing approximately one unit on the ASHRAE seven-point scale per 2°C change in operative temperature.
- There was little difference between the sexes in terms of thermal sensations, although there were significantly more frequent expressions of thermal dissatisfaction from the females in the sample, despite their thermal environments being no different from the males'.
- The effects of Townsville's hot-humid/warm-dry seasonality on thermal comfort responses of office workers was minor, amounting to less than a 0.5°C shift in neutrality, and within the range expected on the basis of the difference in clothing insulation levels of approximately 0.1 clo between seasons.

- Compared to the earlier ASHRAE field experiment in San Francisco (RP-462), neutralities in Townsville were approximately 2°C warmer. However, the relatively good prediction of both experiments' neutralities by the PMV model suggests that most of this offset can be explained by differences in physical parameters, notably clothing. Where the San Francisco and Townsville office populations were significantly different, however, was in the dependence of thermal sensation on temperature, with Townsville's office workers being more sensitive.
- The discovery of significant differences in thermal sensitivity, acceptability, and air movement preferences of office populations who have been naturally acclimatized to a hot, humid climate highlights the importance of extending this series of ASHRAE-sponsored field validation experiments to other climatic extremes as well, notably cold climates and hot, dry climates. *ANSI/ASHRAE 55-1992* requires these extensive validations before it can be classed as an international standard.

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DISCUSSION

Veronica I. Soebarto, Research Fellow/Ph.D. Student, College of Architecture, Texas A&M University, College Station: What is the background of the people in your study? Are they used to living in air-conditioned spaces? I think if people are used to living in non-air-conditioned spaces, the results might have been different.

Richard J. de Dear: This is an interesting issue and we thank you for raising it. The questionnaires we used in this project asked about the extent to which air conditioning (AC) was being used in the subjects' homes and cars during the months of the two surveys. During the survey in the hot-humid wet season, for example, 32.6% of the sample were using AC in their bedrooms, 12.5% were using AC in their living rooms, while about half were using their car's AC at that time of the year. From these numbers, it seems clear that a significant section of our sample had very little exposure to the hot-humid climate of Townsville, so in order to assess this, a simple index of "air-conditioning exposure" was calculated for each subject on the basis of their answers to the questions above. In a very simple comparison (t-test) between the office thermal sensations of those with the least and most AC exposure, we were unable to discern any significant differences ($P > 0.05$). However, your question about the effects of subjects' backgrounds on their responses to office environments warrants a more sophisticated statistical analysis of the ASHRAE RP-702 data base than has been conducted to date.

Gail S. Brager, Associate Professor, Department of Architecture, University of California, Berkeley: Your findings regarding people's preference for more air movement were similar to what we found in the earlier San Francisco study—many people who were feeling neutral or cool thermal sensations still complained of low air movement.

You showed a figure where people in the field showed a *greater* sensitivity to temperatures that deviated from neutral, as compared to that found in laboratory-based predictive methods. This was also similar to the trends found in the field study in the more temperate climate of San Francisco.

P.O. Fanger, Professor, Laboratory of Heating and Air Conditioning, Technical University of Denmark, Lyngby: The authors should be complimented for having performed an excellent study of human responses to the thermal environment in offices in the tropics. It is without doubt the most comprehensive, careful, and detailed field study ever performed in the tropics.

It is quite remarkable that the operative temperatures felt neutral by people in the tropics agree so well with the PMV model, which was based on subjects from temperate climates. Living in the tropics has obviously not adapted people to prefer a warmer climate, at least not in air-conditioned offices. One might also expect that people in the tropics would be more tolerant to warmth. But, on the contrary, they evaluated warmer-than-neutral environments as more severe than did subjects from temperate climates. This certainly does not indicate any adaptation to warmth.

Another interesting observation is that few of the occupants said they would prefer less air movement, while quite many preferred more air movement. Based on this information, I would be reluctant to conclude that people in the tropics should be more tolerant to air movement in air-conditioned spaces. First, the air velocities measured in the offices were *low*, so it is not surprising that there were few bothered by too much air movement. In HVAC engineering, the basis for design has traditionally been to provide low air velocities in the occupied zone. This protects the draft-sensitive occupants. For people who prefer more air movement, it is very simple to provide a small disk fan with individual control.

If high velocities were generally allowed in the occupied zone it would be difficult to protect the draft sensitive. We should remember that draft is one of the most common complaints in many air-conditioned or mechanically ventilated spaces with higher air velocities than in the present study. It has taken decades of R&D to establish methods for proper design of air distribution in spaces to reduce the risk of draft in the occupied zone. This development has been essential for improving the image of air conditioning and we should therefore have very good reasons to change the philosophy of protecting draft-sensitive persons.

de Dear: We think it is logical to answer the questions from Professors Brager and Fanger together, since the important issues of comfort theory and research that they raise seem to be interconnected.

First, in relation to Professor Fanger's PMV model, we agree that it *did remarkably well* at predicting the sample's neutrality—the model stands out as possibly the single most useful achievement of thermal comfort research to date.

On the issue of *adaptation*, far from negating its existence, we think these tropical field data merely serve to reinforce its importance. The mean operative temperatures to which these subjects were exposed in their air-conditioned offices were between 23.5°C and 24°C. This is what they have come to *expect* in their workplaces, so it is not surprising at all that this corresponds closely with the *neutrality* we observed in their questionnaire responses. Townsville building occupants have become so closely adapted to tightly controlled temperatures in their offices that they were *more sensitive* to temperature excursions away from neutrality than PMV comfort theory predicted. As Professor Brager pointed out, the same thermal *hyper*-sensitivity was also observed in the responses of San Francisco air-conditioned office workers during ASHRAE RP-462.

Still in connection with this issue of adaptation, it is worth noting that the so-called "adaptive" model of comfort originally proposed by Michael Humphreys and Andris Auliciems also performed adequately when predicting neutralities for the current hot-humid field investigation. You will recall that the simple regression equations forming the bases of Humphreys' and Auliciems' early models had mean *indoor temperature as the most significant independent variable.*

Finally, in relation to the question about air movement preferences, the air speeds measured in Townsville offices were indeed low on average, probably because that's what ASHRAE Standard 55-1992 prescribes. Section 5.1.6.4 of the standard stipulates that the *maximum allowable* air speed at a typical turbulence intensity of 40% is 0.15 m/s at 23°C and 0.2 m/s at 26°C. We've cited these two temperatures because they define the lower and upper limits of the summer comfort zone. The mean air speeds actually measured in Townsville at these same comfort zone margins were 0.12 m/s and 0.15 m/s, respectively, in full compliance with the standard. However, a clear *majority of subjects* in each half-degree (°C) temperature bin across virtually the entire width of the ANSI/ASHRAE Standard 55-1992 summer comfort zone *requested higher air speeds* than they were getting at the time of measurement. Perhaps one of the clearest messages that Professor Fanger has given the HVAC profession is that "you can't please all of the people all of the time but you must strive to please as many as possible." This is as it should be, so to limit the permissible air speeds to those in ANSI/ASHRAE Standard 55-1992 to protect draft-sensitive occupants seems to be a case of "the tail wagging the dog" when one considers that the number of such persons (i.e., those wanting less air speed) interviewed within the summer comfort zone in this tropical investigation represented a mere 4%. We do, however, agree with Professor Fanger's suggestion that probably the only 100% satisfactory solution to this persistent problem of interindividual differences in thermal requirements will be the devolution of environmental control to the level of individual workstations.