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Field Study of Occupant Comfort and Office Thermal Environments in a Cold Climate

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ABSTRACT

This paper presents the findings of ASHRAE research project RP-821, a field study of occupant comfort and office thermal environments in 12 mechanically ventilated office buildings in southern Quebec. A total of 877 subjects were surveyed during hot and cold months. Each interview provided a set of responses to a questionnaire and a set of physical indoor climatic measurements. The incremental effect of chairs was included in the estimates of clo values. The observed temperature optima were somewhat consistent with the predictions of comfort models and standards based on mid-latitude climate chamber experimental data. The Montreal subjects' thermal sensation and acceptability ratings were much less accepting of non-neutral temperatures than either the PPD index or ANSI/ASHRAE Standard 55 predicted. There was a consistent request for higher air velocity, indicating that air movement guidelines may be too restrictive as set out by ANSI/ASHRAE Standard 55 and ISO 7730. Job satisfaction, general health status, and perceived levels of personal control were moderately correlated with overall generalized assessments of the workplace physical environment. Lighting levels and exposure to humidifiers outside the workplace had some relationship to specific environmental conditions occurring at the time of the interviews. There was little difference between the sexes in terms of thermal sensation, although there were significantly more frequent expressions of thermal dissatisfaction from the females in the sample, despite their thermal environment being no different from that of the males.

INTRODUCTION

ANSI/ASHRAE Standard 55-1992, Thermal Environmental Conditions for Human Occupancy (ASHRAE 1992), is used extensively in Canada. Each city and province has its own building, ventilation, and safety standards, yet ASHRAE Standard 55 is widely used as a reference for comfort levels. As more and more studies of Canadian buildings in the cold climate are emerging, it is apparent that the measured parameters satisfy the comfort limits as set out by ASHRAE, yet it is found that less than 80% of the occupants are satisfied (Donnini et al. 1994). ASHRAE Standard 55 is based almost entirely on data from climate chamber studies performed in temperate climates. This perhaps explains the discrepancies between occupant satisfaction in a cold climate and satisfaction of workers in a temperate climate. ASHRAE recognized a definite need to validate the comfort zones within different external climates.

The first project, RP-462, monitored the indoor environment and occupant responses in 10 office buildings in the San Francisco Bay area (Schiller et al. 1988). Protocols were developed for measuring the detailed physical environment of the occupants' workstations and for gathering the occupants' opinions and relevant personal data. Valuable information was obtained about the requirements for comfortable and acceptable office work environments in one climatic region (Mediterranean): typical environmental conditions in modern offices, the match of the ANSI/ASHRAE Standard 55-1981 comfort zone (ASHRAE 1981) and various comfort indices to occupant comfort perceptions, the effect of seasonal change on comfort requirements, and a range of other physical and psychological attributes affecting the occupants' acceptance of the work environment (Schiller 1990; Brager et al. 1994).

The second project, RP-702, monitored the indoor environment and occupant responses in 12 air-conditioned office buildings in Townsville, located in Australia's tropical north (de Dear and Fountain 1994). It duplicated the earlier ASHRAE investigation in San Francisco, with the primary aim being to examine the effects of a hot, humid climate on human thermal responses to the indoor climates of air-conditioned buildings. Its main points were that the incremental effect of chairs was included in the clo value estimates; the thermal environmental results were

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compared with ASHRAE Standard 55-1992 and ISO 7730 (ISO 1984) guidelines; thermal neutrality, preference, and acceptability results were compared with laboratory-based models and standards; the effects of gender, ethnicity, season, length of residence in the tropics, health, and acclimatization on thermal response to indoor climate were examined; psychological factors such as job satisfaction and perceived levels of environmental control were examined for their relationships with subjective assessments of both general and specific indoor climatic conditions; and the effect of air movement on comfort was studied in detail, especially since ASHRAE Standard 55-1992 contained new limits on air movement to reduce the risk of uncomfortable drafts.

This third project, RP-821, monitored the indoor environment and occupant responses in 12 air-conditioned office buildings in southern Quebec, Canada. It provides information on office thermal environments and occupant response in a climate with a severe dry, cold winter and a hot summer.

Research in Cold Climates

Davidge (1986) found that meeting current air quality and ventilation standards did not ensure a reasonable level of occupant satisfaction. A major Canadian government office building was studied in the winter of 1984-85. A questionnaire was administered to more than 600 employees. It was found that the ASHRAE ventilation, air quality, thermal comfort, and acoustic requirements were generally met. Thermal performance ratings showed that the occupants were moderately satisfied, leaning toward discomfort due to temperatures that were too warm. The air quality and ventilation ratings showed that the occupants found the ventilation, air freshness, and air movement to be poor. The apparent dissatisfaction of the occupants, compared with the apparently healthy and comfortable environment, questions (1) the validity of the performance measurement tools; (2) the compounded effect of satisfying only 80% for each individual criterion; (3) the criteria used to develop the standards, insinuating that a lack of perceived air motion may result in the perception of poor air quality; and (4) the unreasonable expectations of the building occupants.

A similar conclusion was arrived at by Haghighat et al. (1992). They examined the relationships between the indoor environment parameters on two floors of an 11-story Canadian building, as perceived by the occupants and as measured objectively. They showed that complaints reported by the occupants were associated with perceived rather than measured levels of indoor environmental parameters. The study was conducted over a four-week period and consisted of measuring environmental parameters and administering a questionnaire on comfort and health to 450 occupants. More than 32% of the occupants expressed that, in general, the thermal environment was unsatisfactory, even though almost all the measured thermal comfort parameters complied with the ASHRAE comfort standard. As was discovered in the questionnaire responses, more than 20% of the occupants were satisfied with neither the indoor air quality nor the thermal environment. However, the results of the measured parameters should satisfy at least 80% of the occupants.

In two earlier ASHRAE research projects, detailed sets of field data obtained from laboratory-grade instrumentation applied to existing buildings in the Mediterranean climate (RP-462) and in the tropics (RP-702) were compiled. Those measurements were made in full compliance with ASHRAE Standard 55-1992, ISO 7726, and ISO 7730 (ASHRAE 1992; ISO 1985, 1984). A third set of field data using similar or more stringent criteria is presented in this paper.

This project provides information on office thermal environments and occupant response in a climate with a severe dry, cold winter (hot summer). The study determines, for summer and winter, both the preferred thermal conditions for occupancy and the range of conditions found to be thermally acceptable by the occupants. The findings are compared to the conditions required by ASHRAE Standard 55 and ISO 7730. The effectiveness of existing predictive thermal indices (ET*, SET, DISC), as computed by J.B. Pierce's two-node model, and the ISO Standard 7730 algorithms were examined in light of the occupants' subjective responses. The influence of age, clothing, and gender and the potential acclimatization effects were investigated by correlating occupant responses with the prevailing outdoor conditions in the region and by comparing this database with the earlier two databases (RP-462 and RP-702). Air velocity preferences were also compared to ASHRAE Standard 55.

METHODS

Climatic Environment, Buildings, and Subjects

Canada is composed of six climatic regions: Arctic, Northern, Pacific, Cordillera, Prairie, and Southeastern. Each region is dependent on its geographic location and topography, as can be seen in Figure 1. The western regions provide the basic influence. The Cordilleras interfere with the general westerly flow of air from the Pacific Ocean and encourage intrusions of cold

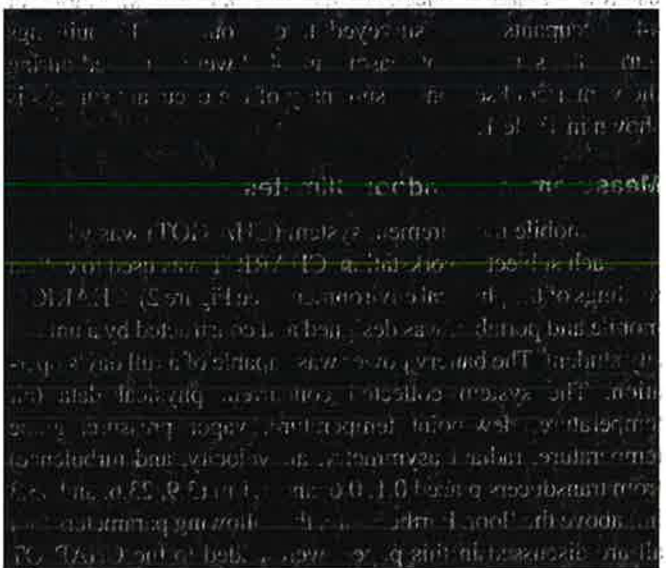


Figure 1. Climatic regions of Canada (Hutcheon et al. 1983)—dots of cities tested.

Arctic air and warm, moist air from the Gulf of Mexico. The interference between these three streams produces a succession of cyclones and anticyclones. The cyclones, characterized by low pressure and counterclockwise rotation, are the result of the northern projection of tongues of warm air. The anticyclones, with high pressure and clockwise rotation, result from the intrusion of air from the north. The cold, high-pressure areas dominate the interior of the continent in winter, while in summer the migrant low-pressure areas travel across on more northerly paths (Hutcheon and Hangegord 1983).

Montréal, Longueuil, Gramby, Cap-de-la-Madeleine, Shawinigan, Trois Rivières, Hull, and Maniwaki are the cities chosen for the study. They are all located along the border of the northern and southeastern limits. These cities have dry-bulb temperatures of 30°C (86°F) or more, which are exceeded for 2.5% of the hours in July, while in January they have dry-bulb temperatures of -25°C (-13°F) or less, which are exceeded for 2.5% of the hours in that month.

A building is usually required to provide an indoor environment that can be maintained within certain limits as required by the occupancy. In Canada, this means that most buildings must be heated in winter and cooled in summer. The current project involved two series of tests, one in each extreme season: summer/hot (June, July, and August) and winter/cold (January, February, and March).

The meteorological parameters recorded were hourly temperatures, wind speed and direction, relative humidity, daily precipitation, start and stop times of precipitation, and general conditions (EC 1994, 1995). The mean temperature and relative humidity (average of mean daily minima and maxima) for the summer season were 18°C (64.4°F) and 74%, respectively. For the winter season, the mean temperature and relative humidity were -7°C (19.4°F) and 72%, respectively. The 12 buildings studied varied greatly in surface area (from 3,000 m^2 to 68,200 m^2 [32,292 ft^2 to 734,096 ft^2]), occupant density, and building use (offices, jails, police stations, and courthouses). A total of 445 occupants were surveyed throughout the 12 buildings during the summer/hot season, and 432 were surveyed during the winter/cold season. A summary of the occupant surveys is shown in Table 1.

Measurement of Indoor Climates

A mobile measurement system (CHARIOT) was wheeled into each subject's workstation. CHARIOT was used to collect readings of the physical environment (see Figure 2). CHARIOT, mobile and portable, was designed and constructed by a university student. The battery power was capable of a full day's operation. The system collected concurrent physical data (air temperature, dew-point temperature, vapor pressure, globe temperature, radiant asymmetry, air velocity, and turbulence) from transducers placed 0.1, 0.6, and 1.1 m (3.9, 23.6, and 43.3 in.) above the floor. Furthermore, the following parameters (not all are discussed in this paper) were added to the CHARIOT measurements: temperature of air supply, air return, and room; illuminance; carbon monoxide, carbon dioxide, formaldehyde,

TABLE 1
Statistical Summary of Questionnaire Respondents

Sample Size		445 (summer/hot)	432 (winter/ cold)
Gender (%)	Male	50	49
	Female	50	51
Age (yr)	mean	41.2	41.9
	standard deviation	8.4	7.9
	minimum	16.0	22.0
	maximum	65.0	64.0
Height (cm)	mean	167.9	168.4
	standard deviation	9.5	9.9
	minimum	147.0	147.0
	maximum	193.0	194.0
Weight (kg)	mean	68.8	69.0
	standard deviation	15.2	15.7
	minimum	44.0	44.0
	maximum	120.0	130.0
Number of years in Canada (yr)	mean	34.8	40.8
	standard deviation	11.9	8.9
	minimum	1.0	7.0.
	maximum	65.0	64.0
Highest education level (%)	high school	20	23
	diploma/degree	65	63
	postgrad university	15	14
Primary language (%)	French	97	98
	other	3	3

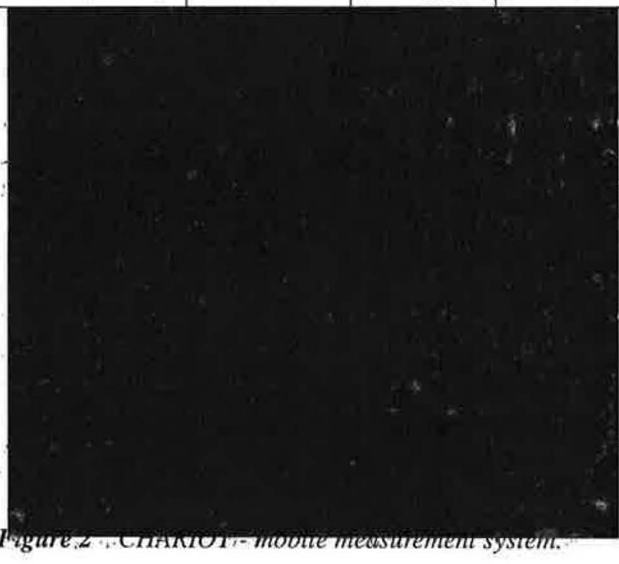


Figure 2 CHARIOT - mobile measurement system.

volatile organic compounds; and tracer gas decay. The transducers and measurement points were placed to represent the immediate environment of the seated subjects. The transducers meet the ASHRAE 55-1992 and ISO 7726 standards for accuracy and response time. The response time of the globe temperature sensor was relatively long (seven minutes) compared to the remaining sensors. However, it is still valid within this measurement protocol. As will be described in the following section, as the subject completed the "Online" portion of the survey, a research assistant approached the workstation with CHARIOT, allowed the sensors to stabilize (a minimum of five minutes), and, once the subject left the station, put CHARIOT in place (a maximum horizontal displacement of 40 cm [15.7 in.]); then the research assistant waited approximately two to three minutes before taking measurements. A three- to five-minute sample of the workstation's thermal environment was recorded (a minimum of five minutes). Therefore, a total minimum of 10 minutes to a maximum of 13 minutes expired before a reading was taken of the black globe. The research team felt this would not compromise the accuracy of the results.

The physical measurements were made at the exact physical position of the subject completing the subjective questionnaire as soon as the "Online" portion of the questionnaire was completed. The whole process of subjective evaluation and physical measurements was completed in nine minutes per workstation.

Questionnaires and Measurement Procedure

The subjective survey was divided into two parts—"Background" and "Online." The "Background" questions covered areas such as demographics and contextual and psychological factors. The on-line questions related to the subject's assessment of his or her immediate thermal environment at that point. The questions included in the "Online" section of the survey consisted of the traditional scales of thermal sensation and thermal preference, personal comfort, metabolic activity checklist, and two scales focusing on air movement. The "Online" section consisted of the first three pages of the form. Once those three pages were completed, the occupant was asked to move so as to place the CHARIOT at the workstation. The occupant was then asked to complete the "Background" section immediately. In total, 445 questionnaires were distributed and completed during the summer/hot season and 432 were completed during the winter/cold season (80% of those in the winter sample had participated in the summer sample).

As was done previously, metabolic rates were assessed by a checklist of office activities referring to four distinct time brackets in the hour preceding the testing: 0 to 10 minutes, 10 to 20 minutes, 20 to 30 minutes, and 30 to 60 minutes before. The quantification of the responses was based on the databases found in ASHRAE Standard 55-1992 and in ISO 7730.

The measurement procedure followed at each workstation consisted of the following steps: (1) The principal investigator approached the subject, asked if the time was convenient, and presented the questionnaire. (2) As the subject completed the "Online" portion of the survey, the principal investigator made a few notes and drew the workstation in a plan view; the research assistant approached the workstation with CHARIOT and allowed the sensors to stabilize. (3) Once the subject completed the "Online" portion of the survey, the principal investigator asked the subject to vacate the station and complete the "Background" portion of the survey at an adjacent vacant station. (4) Once the subject left the station, a research assistant put CHARIOT in place; the research assistant waited approximately two to three minutes before taking measurements. A three- to five-minute sample of the workstation's thermal environment was recorded; the principal investigator photographed any abnormality and then left to scout for the next subject. (5) Once measurements were completed, the research assistant reminded the subject to complete the survey, for it would be picked up within 15 minutes. (6) The principal investigator returned to guide the research assistant to the next station and then returned to pick up the completed survey.

Effect of Chair Insulation

The site visits in this Montreal study indicated a large variety of chairs being used by the occupants. The different chairs found in this study were categorized as to the amount of contact the person had with the chair. The recent work of McCullough et al. (1994) was used to determine the additional clo values of the chairs. These chair clo values were added to the garment clo values of the occupants. Table 2 summarizes their results for our purposes.

TABLE 2
Added Insulation of Chairs

Ensemble	Clothing area factor, F_{cl}	I_t, standing insulation(clo)	I_{cl}, standing insulation(clo)	Added insulation of chairs relative to no chair (clo)					
				stool	folding	computer	carrel	desk	executive
suit	1.32	1.60	1.11	0.13	0.10	0.22	0.32	0.26	0.33
trousers	1.15	1.14	0.57	0.11	0.10	0.18	0.19	0.17	0.22
straight skirt	1.29	1.10	0.60	—	—	—	—		0.17
pleated skirt	1.33	1.13	0.64	—	—	—	—		0.17

Comfort Indices

The data from the "Online" questions were matched with their corresponding CHARIOT data. Following the same programs as those used for the previous studies (RP-462 and RP-702), the environmental and comfort index calculations were performed for each workstation. The indices included operative temperature (t_o), mean radiant temperature (t_r) (ASHRAE 1993), effective temperature (ET*), standard effective temperature (SET), DISC (Gagge et al. [1986]; Doherty [1988] using Fountain and Huizenga [1995]), predicted mean vote (PMV), predicted percentage dissatisfied (PPD) (ISO 1984), and predicted percent dissatisfied due to draft (PD) (ASHRAE 1992).

RESULTS

Indoor Climates

Table 3 shows the statistical summaries of the indoor climatic measurements. Mean air and radiant temperatures (averaged across the three heights of 0.1, 0.6, and 1.1 m [3.9, 23.6, and 43.3 in.]) generally fell within 21°C (69.8°F) and 28°C (82.4°F) (summer/hot season) and 20°C (68°F) and 28°C (82.4°F) (winter/cold season). Vertical air temperature gradients were, on average, about 0.67°C/m (1.2°F/ft) in the occupied zone. Average relative humidities fell within 30% and 62% (summer/hot season) and within 10% and 39% (winter/cold season). Mean air velocities (average over the three heights) were quite low; they averaged 0.09 m/s (0.29 ft/s) and ranged from 0.04 to 0.24 m/s (0.13 to 0.78 ft/s) in the summer/hot season and averaged 0.08 m/s (0.26 ft/s) and ranged from 0.03 to 0.29 m/s (9.8 to 0.95 ft/s) in the winter/cold season, while turbulence intensities fell within 9% and 59% for the summer/hot season and 6% and 66% for the winter/cold season, averaging 32% to 33% for both seasons (ASHRAE 1993).

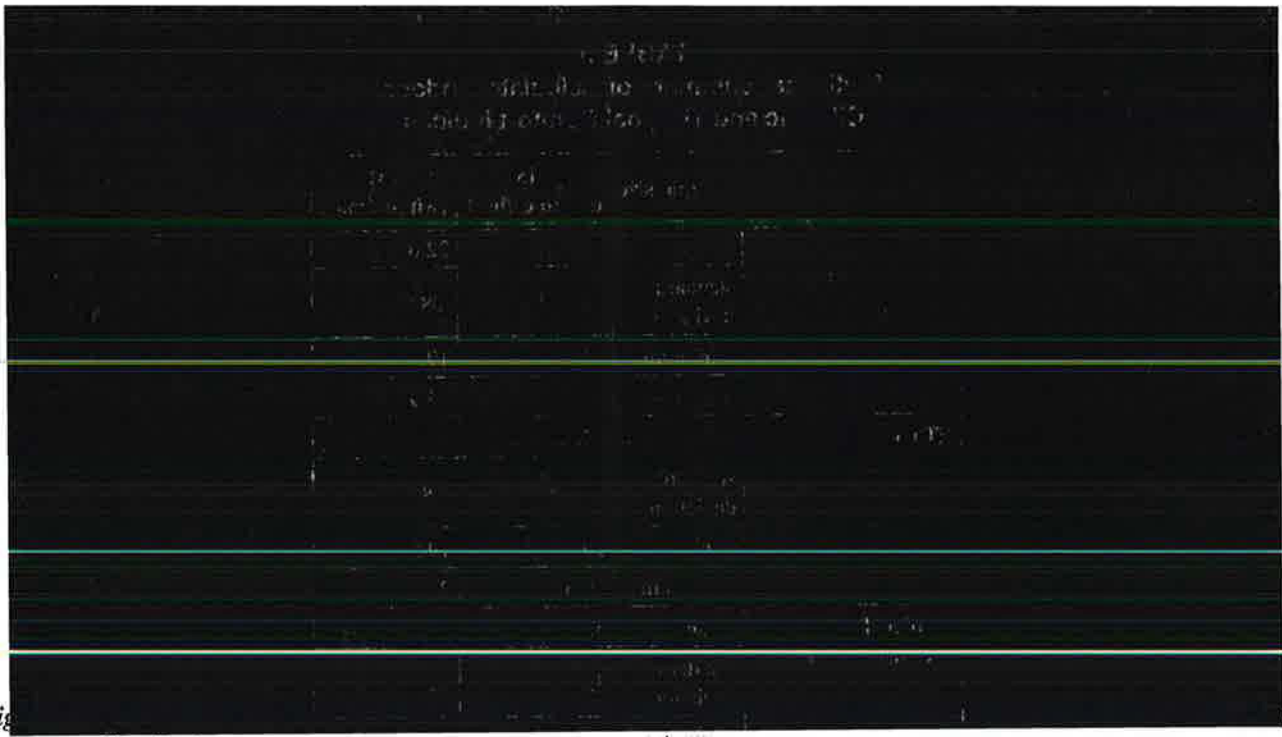
The data for each season are compared to the ASHRAE 55-1992 comfort standard in Figure 3. The indoor thermal environments were plotted on the psychrometric charts for both the summer/hot and winter/cold seasons. As the results were superimposed onto the chart for the summer/hot season, 63.4% of the measurements fell within the summer comfort zone of ASHRAE Standard 55-1992 (shaded area). The remaining 33.3% fell to the left of the comfort zone (within cooler temperatures). During the winter/cold season, 26.9% of the measurements fell within the winter comfort zone of ASHRAE Standard 55-1992 (shaded area). The remaining 73.1% fell below the 2.5°C (4.5°F) dew-point level (with 0.7% within cooler temperatures and 0.7% within warmer temperatures), indicating the difficulty of humidifying in our cold season.

Clothing, Metabolic Factors, and Calculated Comfort Indices

A summary of the main personal thermal variables of clothing insulation and metabolic rates is presented in Table 4. Intrinsic clothing insulation was estimated using the garment values published in ASHRAE Standard 55-1992. The intrinsic clothing value averaged 0.62 clo (males) and 0.53 clo (females) in the summer (about 16% higher than the 0.5 clo assumed in the standard) and averaged 0.93 clo (males) and 0.81 clo (females) in the

TABLE 3
Results of Indoor Climatic Data Collected by CHARIOT

	Sample size	445 (summer/hot)	431 (winter/cold)
Air temperature (°C) (average of 3 heights)	mean	23.9	23.0
	standard deviation	1.3	0.8
	minimum	21.2	20.3
	maximum	27.5	26.3
Mean radiant temperature (°C) (calculated) (average of 3 heights)	mean	23.3	22.2
	standard deviation	1.2	0.9
	minimum	20.7	19.5
	maximum	27.1	28.3
Plane radiant asymmetry (°C) (above 1.1 m)	mean	0.9	1.1
	standard deviation	1.0	1.1
	minimum	0.0	0.0
	maximum	10.3	10.0
Dew-point temperature (°C) (at 0.6 m)	mean	11.3	3.6
	standard deviation	2.3	2.5
	minimum	5.4	0.1
	maximum	15.4	9.1
Relative humidity (%) (calculated)	mean	45.0	21.4
	standard deviation	7.6	7.0
	minimum	29.5	9.7
	maximum	62.2	39.2
Vapor pressure (kPa) (at 0.6 m)	mean	1.4	0.6
	standard deviation	0.2	0.2
	minimum	0.9	0.3
	maximum	1.8	1.1
Air velocity (m/s) (average of 3 heights)	mean	0.09	0.08
	standard deviation	0.03	0.03
	minimum	0.04	0.03
	maximum	0.24	0.29
Turbulence intensity (%) (calculated) (average of 3 heights)	mean	32.6	31.6
	standard deviation	6.4	6.8
	minimum	9.0	6.0
	maximum	59.0	66.0



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Standard 55-1992 chart.

TABLE 4
Clothing Insulation and Metabolic Rates of Respondents

SEASON		HOT			COLD		
GENDER (sample size)		Male (221)	Female (224)	Combined (445)	Male (212)	Female (220)	Combined (432)
Intrinsic clothing insulation (clo)	mean	0.62	0.53	0.58	0.93	0.81	0.87
	standard deviation	0.24	0.19	0.22	0.30	024	0.28
	minimum	030	0.30	0.30	0.40	0.30	0.30
	maximum	1.60	1.30	1.60	1.80	1.80	1.80
Clothing + chair insulation (clo)	mean	0.84	0.62	0.73	1.19	0.95	1.06
	standard deviation	0.28	0.23	0.28	0.34	0.28	0.33
	minimum	0.30	0.30	0.30	0.40	0.40	0.40
	maximum	1.92	1.52	1.92	2.13	2.02	2.13
Metabolism (met)	mean	1.21	1.22	1.22	1.18	1.23	1.20
	standard deviation	0.19	0.16	0.18	0.18	0.18	0.18
	minimum	1.00	1.00	1.00	1.00	1.00	1.00
	maximum	1.60	1:60	1.60	1.60	1.60	1.60

winter (about 3% lower than the 0.9 clo assumed in the standard). As the chair insulation value was added to the clothing values, average levels increased by 0.22 clo (males) and 0.09 clo (females) in the summer and 0.26 clo (males) and 0.14 clo (females) in the winter, thus lifting the insulation values to 0.84 clo (males) and 0.62 clo (females) in the summer and 1.19 clo (males) and 0.95 clo (females) in the winter. The clothing insulation values were much higher (about 0.11 clo) for the males than for the females in both seasons. This difference was even greater when the effect of chairs was included (about 0.23 clo). Metabolic rates of the subjects were estimated using the typical tasks also published in ASHRAE Standard 55-1992. The occupants were asked to identify their activity up to one hour prior to completing the questionnaire. The metabolic rate, on average, was 1.2 met in both seasons and for both sexes (equivalent to light, primarily sedentary activity as assumed in the standard).

A statistical summary of the thermal environmental and comfort indices is shown in Table 5. On average, operative temper-

TABLE 5
Statistical Summary of Calculated Indoor Climatic and Thermal Comfort Indices

	Sample size	445 (summer/hot)	431 (winter/cold)
Operative temperature (°C)	mean	23.6	22.6
	standard deviation	1.2	.08
	minimum	21.0	19.9
	maximum	26.9	25.9
ET (°C)	mean	23.5	22.1
	standard deviation	1.2	0.8
	minimum	20.9	19.5
	maximum	26.6	24.8
Predicted draft dissatisfaction (%)	mean	5.7	5.2
	standard deviation	3.5	3.8
	minimum	0.0	0.0
	maximum	35.3	23.5
SET (°C) (including chair insulation)	mean	24.7	25.7
	standard deviation	2.2	2.3
	minimum	19.8	20.3
	maximum	32.2	32.1
DISC (from 2-node) (including chair insulation)	mean	0.1	0.2
	standard deviation	0.4	0.5
	minimum	-0.5	-0.4
	maximum	2.0	2.1
PMV (including chair insulation)	mean	0.0	0.0
	standard deviation	05	0.5
	minimum	-2.1	-2.0
	maximum	1.2	1.1
PPD (including chair insulation)	mean	11.1	11.2
	standard deviation	9.5	9.1
	minimum	5.0	5.0
	maximum	79.0	79.0

ature and ET* values fell within the 22°C to 24°C (71.6°F to 75.2°F) range. The last four items of the table show the effect of adding the chair insulation values. This resulted in a 1.2°C (2.1°F) to 1.3°C (2.3°F) increase in SET and a 0.2 to 0.3 increase in PMV units. The corresponding PPD decreased by 2.0% to 2.4%.

Subjective Assessment of Workstation Thermal Environments

The statistical summaries of the thermal sensation and general comfort responses are shown in Table 6. Mean thermal sensations on the ASHRAE seven-point scale were marginally cooler than neutral, at -0.3, for both seasons. The data were binned into 0.5°C (0.9°F) intervals. Percentages of subjects voting "warmer than neutral" and

TABLE 6
Statistical Summary of On-Line Workstation Responses

	Sample Size	445 Summer	431 Winter
Thermal sensation (ASHRAE 7-point)	mean	-0.3	-0.3
	standard deviation	1.3	1.2
	minimum	-3.0	-3.0
	maximum	3.0	2.0
Air movement acceptability (1= very unacceptable, 6 = very acceptable	mean	4.0	3.8
	standard deviation	1.6	1.4
	minimum	1.0	1.0
	maximum	6.0	6.0
General Comfort (1= very uncomfortable, 6 = very comfortable	mean	4.4	4.2
	standard deviation	1.3	1.3
	minimum	1.0	1.0
	maximum	6.0	6.0

"cooler than neutral" for each bin were calculated. The numbers of subjects voting "neutral" were split in half. Each season's maximum likelihood probit model for these binned thermal sensation percentages against operative temperature is shown in Figure 4. Figure 5 shows the same analysis using ET* as the independent variable.

The probit analysis was used to determine the thermal neutralities. These are 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. The operative temperature neutralities were 24.0°C (75.2°F) in the hot season (with 95% fiducial limits at 23.8°C [74.8°F] and 24.3°C [75.7°F]) and 23.1°C (73.5°F) in the cold season (with 95% fiducial limits at 22.9°C [73.2°F] and 23.5°C [74.3°F]). The ET neutralities were 24.1°C (75.3°F) in the hot season (with 95% fiducial limits at 23.9°C [75°F] and 24.4°C [75.9°F]) and 22.6°C (72.6°F) in the

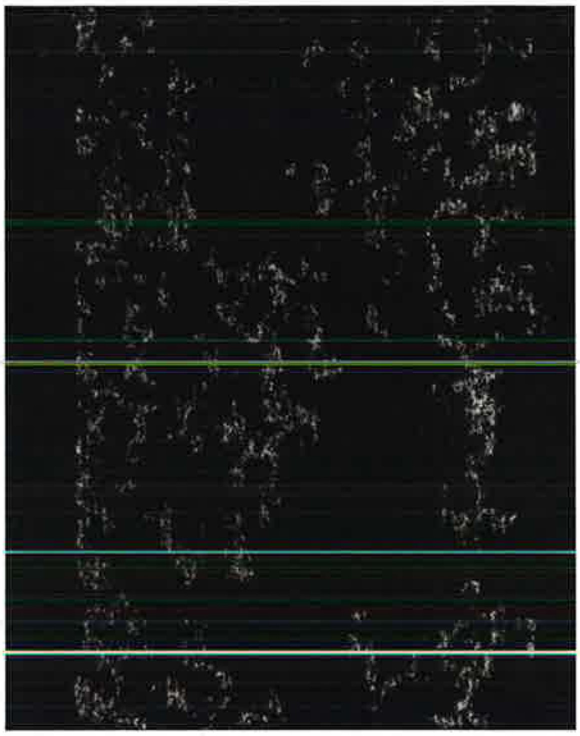

Figure 4 *Probit regression model (thermal sensation and operative temperature).*

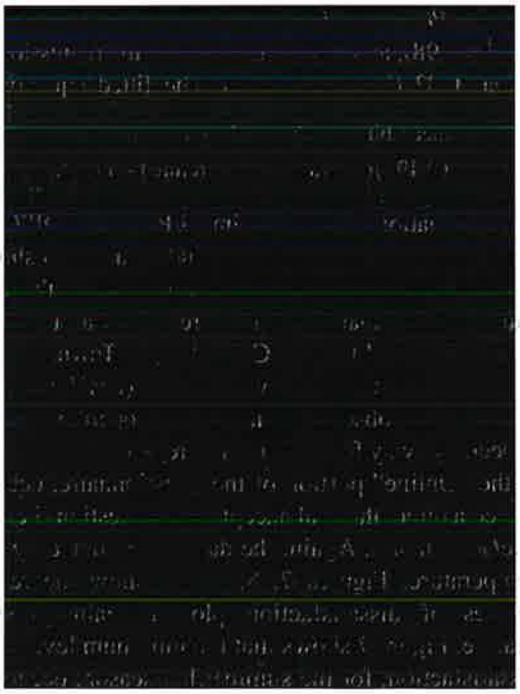

Figure 5 *Probit regression model (thermal sensation and ET).*

cold season (with 95% fiducial limits at 22.3°C [72.1°F] and 23.1°C [73.5°F]).

Figure 6 shows the mean ASHRAE sensation votes for each half-degree operative temperature bin. The regression line fitted to the bin means was highly significant (F = 510.9; Prob <

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

0.0001; $r^2 = 0.98$), and a standard error on the regression coefficient was 0.02 (Prob < 0.0001). The fitted equation was:

$$\text{mean binned ASHRAE sensation vote} = (0.493)(\text{operative temperature}) - 11.69.$$

Regression equations for mean binned PMV and DISC index values, with the chair insulation included, are also shown in Figure 6. The graph duplicates what was found in the Townsville study, except that the neutral region is around 23.5°C (74.3°F) (as opposed to 24.5°C [76.1°F] in Townsville). The regression gradients on the two models (PMV and DISC) underestimate the observed sensitivity to operative temperature, especially away from the neutral region.

In the "Online" portion of the questionnaire, occupants were asked a direct thermal acceptability question (i.e., unacceptable/acceptable). Again, the data were binned by operative temperature. Figures 7, 8, and 9 show the resulting percentages of dissatisfaction plotted against operative temperature. Figure 7 shows that the minimum level of thermal dissatisfaction, for the summer/hot season, occurs at an operative temperature of 23°C (73.4°F), which is lower than the 24.5°C (76.1°F) optimum (ASHRAE Standard 55-1992, Table 3). Acceptability at 90% was achieved between 22.0°C (71.6°F) and 23.5°C (74.3°F), which is narrower and lower than the three-degree band suggested in ASHRAE Standard 55-1992 (23°C to 26°C [73.4°F to 78.8°F]).

Figure 8 shows that the minimum level of thermal dissatisfaction for the winter/cold season occurs at an operative temperature of 23.5°C (74.3°F), which is higher than the 22°C (71.6°F) opti-

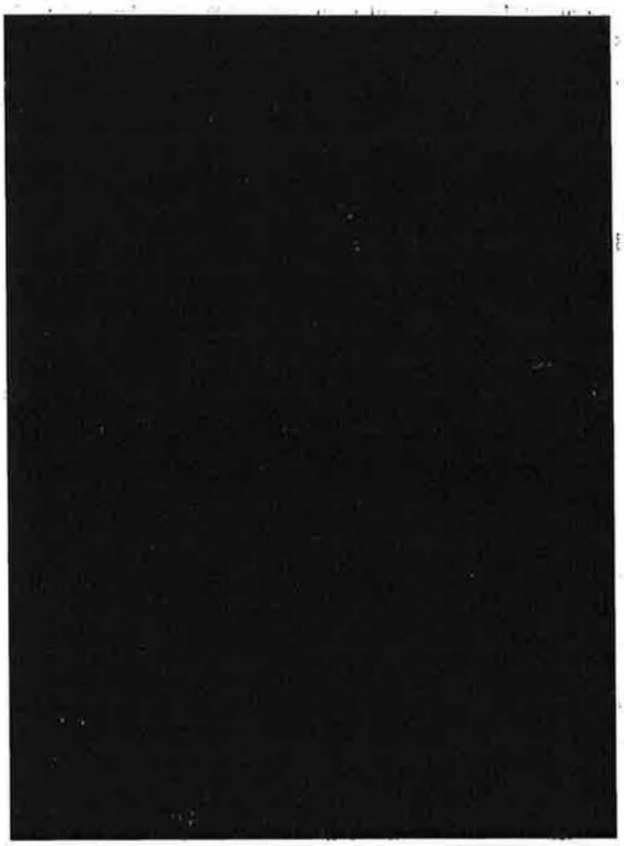

Figure 7 *Observed thermal acceptability related to operative temperature (summer/hot season).*

Figure 8 *Observed thermal acceptability related to operative temperature (winter/cold season).*

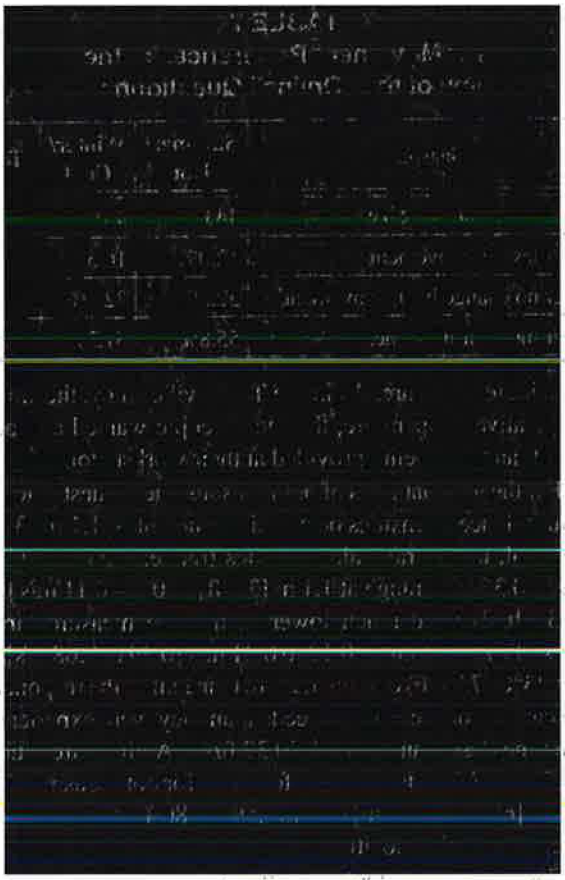

Figure 9 *Observed and predicted thermal acceptability related to operative temperature.*

mum (ASHRAE Standard 55-1992, Table 3). Acceptability at 80% seems to be achieved between 21.5°C (70.7°F) and 25.5°C (77.9°F), which is slightly wider and higher than the 3.5-degree band suggested in ASHRAE Standard 55-1992 (20°C to 23.5°C [68°F to 74.3°F]). Figure 9 shows the combination of both seasons with the "direct accept (obs)" notation. Acceptability at 90% seems to occur at an operative temperature of 23°C (73.4°F). Acceptability at 80% occurs between 21.5°C (70.7°F) and 24.5°C (76.1°F).

The percentages of ASHRAE seven-point sensation scale votes outside the four central categories (i.e., "cold," "cool," "warm," and "hot") were binned to operative temperature. This second-order polynomial weighted regression model ("ASHRAE (obs) corresponding line) was superimposed onto Figure 9. This indirect assessment of thermal acceptability coincides closely with the direct assessment reported but only for operative temperatures above 24°C (75.2°F).

The mean PPD index values binned to operative temperature (including the effect of chair insulation) are also plotted in Figure 9. This last curve closely resembles the one plotted in the Townsville study. A total of 129 subjects (out of 872) voted directly that their thermal environments were unacceptable (67 in the summer/hot season and 62 in the winter/cold season). Of this group of dissatisfied subjects, more than 80% (70% in the summer/hot season and 94% in the winter/cold season) were in environments that fulfilled the ASHRAE Standard 55-1992 whole-body comfort zone criteria with respect to operative temperature. Of the 743 subjects who voted directly that their thermal environments were acceptable (374 in the summer/hot season and 369 in the winter/cold season), 22% were actually in conditions outside of the ASHRAE Standard 55-1992 comfort zone (41% in the summer/hot season and 3% in the winter/cold season). From this, it seems that the votes coincided with the comfort zone the best during the winter season and then only for those voting on acceptable thermal environments. In summary, 69% of those surveyed agreed with the ASHRAE Standard 55-1992 comfort zone (54% in the summer/hot season and 84% in the winter/cold season).

Another question in the survey asked the occupants their thermal preference—whether they would prefer to feel warmer or cooler. Their responses were binned into 0.5°C (0.9°F) ET* intervals. A probit analysis was performed on the resulting percentages (shown in Figures 10 and 11). As in the Townsville study, it was assumed that the point of intersection between the "want cooler" and "want warmer" probit models represents the preferred temperature. In the summer/hot season, the preferred temperature was 23°C (73.4°F) ET*, and it was 22°C (71.6°F) ET* in the winter/cold season. At this optimum temperature, in the summer/hot season, 32% of the occupants indicated a desire for either warmer or cooler conditions. In the winter/cold season, 40% of the occupants indicated a desire for either warmer or cooler conditions.

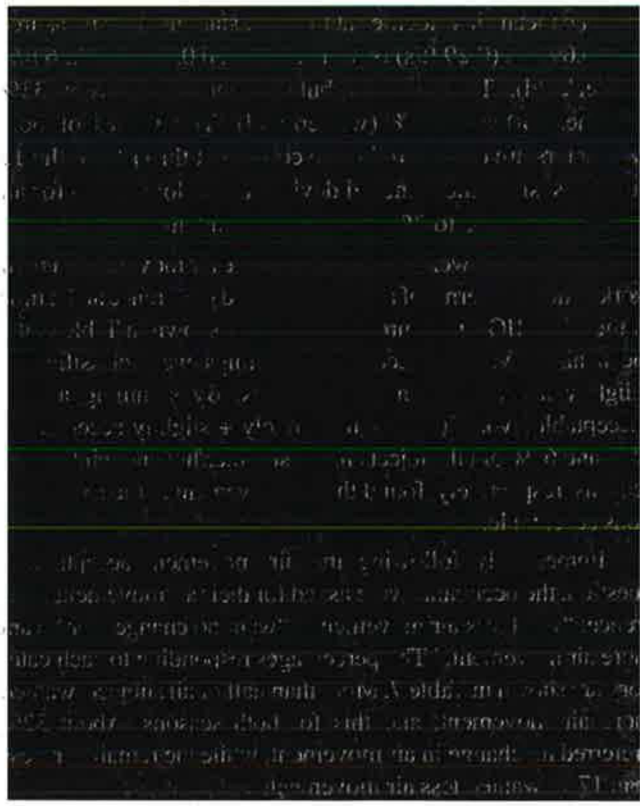

Figure 10 *Probit regression models fitted to thermal preference percentages (summer/hot season).*

Figure 11 Probit regression models fitted to thermal preference percentages (winter/cold season).

The mean air velocities at the workstations were measured to be 0.09 m/s (0.29 ft/s) (summer/hot) and 0.08 m/s (0.26 ft/s) (winter/cold). The mean turbulence intensities were 33% (summer/hot) and 32% (winter/cold). The values of both parameters are considered to be consistent throughout the 12 buildings, since the standard deviation was low—0.03 for air velocities and 6% to 7% for turbulence intensities.

The subjects were asked to assess the air movement at their workstations, in terms of acceptability and preference at the time of the CHARIOT measurements. As was shown in Table 6, the mean air movement acceptability ratings were classified as "slightly acceptable" in both seasons. By summing all the "acceptable" votes (very + moderately + slightly acceptable), 65% and 64% of all subjects in the summer/hot and winter/cold seasons, respectively, found the air movement at their workstations acceptable.

Immediately following the air movement acceptability question, the occupants were asked for their air movement preference: "want less air movement," "want no change," or "want more air movement." The percentages responding to each category are shown in Table 7. More than half of all subjects wanted more air movement, and this for both seasons. About 32% preferred no change in air movement, while the remainder (less than 17%) wanted less air movement.

The air movement preferences were binned with operative temperature measured at the same time. The linear regression fit to the data suggested a linear dependence of air velocity preference with temperature. As in the Townsville study, the warmer the operative temperature, the more people wanted air speeds higher than those being provided at their workstations.

TABLE 7
Air Movement Preferences at the Time of the "Online" Questionnaire

Season	Summer/ Hot	Winter/ Cold	Total
Sample Size	443	431	874
Prefer less air movement	12.0%	16.5%	14.2%
Prefer no change in air movement	32.3%	32.3%	32.3%
Prefer more air movement	55.8%	51.3%	53.5%

For the total data sets of both seasons, the highest velocities and turbulence intensities occurred at a height of 1.1 m (3.6 ft). In general, the average air velocities (range: 0.06 to 0.11 m/s [0.19 to 0.36 ft/s]; range at 1.1 m [3.6 ft]: 0.05 to 0.11 m/s [0.16 to 0.36 ft/s]) were much lower than those measured in the Townsville study (range: 0.12 to 0.21 m/s [0.39 to 0.68 ft/s]). At about 23°C (73.4°F) or higher, more than half of the respondents were calling for greater air speeds than they were experiencing at the time (less than 0.10 m/s [0.32 ft/s]). At the extremities of the ASHRAE Standard 55 comfort zone for both seasons (20°C to 26°C [68°F to 78.8°F]), from 25% to 80% of the occupants wanted higher air velocities.

For the summer/hot season, the average air velocities (range: 0.06 to 0.20 m/s [0.19 to 0.65 ft/s]; range at 1.1 m [3.6 ft]: 0.08 to 0.26 m/s [0.26 to 0.85 ft/s]) were again much lower than those in the Townsville study. At about 23°C (73.4°F) or higher, more than half of the respondents were calling for greater air speeds (experiencing less than 0.11 m/s [0.36 ft/s]). At the extremities of the ASHRAE Standard 55 comfort zone for the summer season (23°C to 26°C [73.4°F to 78.8°F]), from 50% to 85% of the occupants wanted higher air velocities.

For the winter/cold season, the average air velocities (range: 0.06 to 0.13 m/s [0.19 to 0.42 ft/s]; range at 1.1 m [3.6 ft]: 0.05 to 0.20 m/s [0.16 to 0.65 ft/s]) were again much lower than those in the Townsville study. At about 22°C (71.6°F) or higher, more than half of the respondents were calling for greater air speeds (experiencing less than 0.10 m/s [0.32 ft/s]). At the extremities of the ASHRAE Standard 55 comfort zone for the winter season (20°C to 23.5°C [68°F to 74.3°F]), from 35% to 55% of the occupants wanted higher air velocities.

For the total data set of both seasons, the highest turbulence intensities occurred at a height of 1.1 m (3.6 ft). In general, the average turbulence intensities ranged from 0.28 to 0.39, and at 1.1 m (3.6 ft), they ranged from 0.27 to 0.47. At about 23°C (73.4°F) or less, more than 15% of the respondents were calling for lower air speeds than they were experiencing at the time (turbulence intensities between 0.31 and 0.35).

For the summer/hot season, the average turbulence intensities ranged from 0.30 to 0.35, while at a height of 1.1 m (3.6 ft), they ranged from 0.33 to 0.39. At about 23°C (73.4°F) or less, more than 15% of the respondents were calling for lower air speeds than they were experiencing at the time (turbulence intensities between 0.32 and 0.37).

For the winter/cold season, the average turbulence intensities ranged from 0.28 to 0.39, while at a height of 1.1 m (3.6 ft), they ranged from 0.22 to 0.47. At about 23°C (73.4°F) or lower, more than 15% of the respondents were calling for lower air speeds than they were experiencing at the time (turbulence intensities between 0.31 and 0.34).

The air movement preference scale and the temperature preference scale were cross-tabulated. Similar to the Townsville study, a clear majority of subjects (86%) requested cooler temperatures and more air movement. However, a large minority (30%) also requested more air movement but with warmer temperatures. So there does seem to be an inverse relationship between the air movement preference scale and the temperature preference scale, as suggested by heat balance theories of thermal comfort.

DISCUSSION OF RESULTS

Comparisons Between Indexes, Models, and Observed Data

The average prediction on the basic PMV index in this study was almost identical to the average thermal sensation vote cast by the subjects on the ASHRAE scale, and this for both seasons. When the incremental insulation effect of chairs was added into the PMV calculations, the results differed by 0.3 PMV units. The PMV (including chair insulation) regression model on operative temperatures intersected the neutral mean thermal assessment at a point 0.5°C (1.8°F) cooler than did the actual thermal sensation votes' regression model.

The PMV index predicted neutralities well, with and without the effect of chair insulation. However, large discrepancies were found as the temperatures progressed away from neutral. At the lower margin of the winter comfort zone (20°C to 23.5°C [68°F to 74.3°F]), the PMV index differed by about 1.5 sensation units. Similarly, at the higher margin of the summer comfort zone (23°C to 26°C [73.4°F to 78.8°F]), the PMV index differed by about 1 sensation unit. This indicated that the observed mean votes' sensitivity to temperature was more pronounced than theory (PMV) predicted. The regression model of DISC on operative temperature followed the PMV regression closely; however, it differed from the observed data by about a 0.5 sensation unit more than the PMV did.

There was general agreement between the two common methods of empirical assessment for observed and predicted levels of thermal dissatisfaction. The direct approach ("Is the thermal environment acceptable to you?") and the indirect approach of assuming ASHRAE sensation votes -3, -2, +2, and +3 to be unacceptable both yielded optimum temperatures in the 23°C to 23.5°C (73.4°F to 74.3°F) region. The PPD index also resulted in the same optimum temperature. The levels of dissatisfaction predicted by PPD (including the effect of chair insulation) estimated remarkably well the direct acceptability within the 22°C to 24°C (71.6°F to 75.2°F) range. Below 22°C (71.6°F), the PPD underestimated the direct acceptability by up to 24%; above 24°C (75.2°F), the PPD underestimated the direct acceptability by up to 50%. The PPD underestimated the unacceptable ASHRAE sensation votes by 6% (toward the 23.5°C [74.3°F] mark) to 52% (away from 23.5°C [74.3°F], in both directions). At the extremities of the summer comfort zone (23°C to 26°C [73.4°F to 78.8°F]), thermal dissatisfaction was observed to be as much as 7% (at 23°C [73.4°F]) to 29% (at 26°C [78.8°F]) above the predicted index. At the extremities of the winter comfort zone (20°C to 23.5°C [68°F to 74.3°F]), thermal dissatisfaction was observed to be as much as 5% (at 23.5°C [74.3°F]) to 24% to 52% (at 20°C [68°F]) above the predicted index.

Comparisons Between Observed Comfort Data and the Standards

In Montreal, 398 of the 877 workstations visited had indoor climates within the comfort zone (temperature and humidity) of ASHRAE Standard 55-1992: 282 of 445 in the summer/hot season and 116 of 432 in the winter/cold season. About 85% of the occupants of those workstations found them thermally acceptable (82% in the summer/hot season and 86% in the winter/cold season), which is lower than the 90% suggested in the standard for whole-body comfort. The predicted percentage dissatisfied (PPD), including the effect of chair insulation, was calculated for all 398 sets of observations meeting Standard 55's criteria. For the total, summer, and winter seasons, the PPDs were 11%, 10%, and 11%, respectively, which underestimate the actual 15%, 18%, and 14%, respectively.

It is expected that 10% of thermal dissatisfaction within the comfort zone is due to interindividual variability. However, there seems to be an additional 4% to 8% in this study. ASHRAE Standard 55 specifies that the maximum allowable vertical gradient within the occupied zone is 1.9°C/m (3.4°F/ft). Upon closer scrutiny of the dissatisfied, it was found that 1% (summer/hot season) to 3% (winter/cold season) had vertical gradients surpassing the maximum allowable. Standard 55 suggests that radiant temperature asymmetries in the horizontal plane may be a source of complaint, but only 0.4% of the summer/hot season exceeded the limit of 10°C (1.8°F). Unwanted local cooling due to excessive velocity or turbulence is defined as draft. Standard 55 recommends the use of the PD model (Fanger et al. 1988) of draft risk, which specifies that index values should not exceed 15%. Of the 60 cases of unexplained thermal dissatisfaction, none experienced PD index values greater than the suggested limit. In contrast, 71% of the thermally dissatisfied subjects within the comfort zone actually expressed a desire for higher, not lower, air speeds (89% in summer and 55% in winter). The Townsville study implied that draft is not as important a comfort issue in hot, humid zones as it can be in cooler regions. This is difficult to show in this study, since none of the workstations tested had PD index values surpassing the comfort limit.

Therefore, by considering the 1% to 3% nonconforming vertical gradients and the 0.4% nonconforming radiant temperature asymmetries, some of the causes for complaint within the comfort zone could be attributed to local discomfort causes. However, it seems that the most likely explanation is that air speeds and/or turbulence intensities were not high enough (even though the mean values complied with Standard 55, Table 3).

Comparison Between the Seasons

There is a definite difference between the hot and humid conditions of the summer/hot season and the cold conditions of the winter/cold season. In terms of clothing patterns in Montreal, average intrinsic insulation levels were increased by about 0.3 clo between the summer and winter seasons. In terms of neutralities on the ASHRAE thermal sensation scale, thermal acceptability, and thermal preferences, the interseasonal differences varied from 0.5°C to 1.5°C (0.9°F to 2.7°F). This offset corresponds well with the clothing insulation/operative temperature relationship in ASHRAE Standard 55-1992 (Figure 1) and ISO 7730.

Comparisons Between Thermal Neutrality, Preference, and Acceptability

Neutrality, defined in terms of the 50% effective dose on the ASHRAE thermal sensation scale, fell at 24.0°C (75.2°F) (summer/hot) and 23.1°C (73.5°F) (winter/cold) operative temperatures and 24.1°C (75.3°F) (summer/hot) and 22.6°C (72.6°F) (winter/cold) ET*. The optimum temperature (according to thermal preference votes) and the maximum thermal acceptability occurred at 23°C (73.4°F) (summer/hot) and 22°C (71.6°F) (winter/cold) ET*. This one-degree offset was manifested in both seasons, with thermal neutrality being higher than both thermal preference and acceptability. A similar phenomenon was noted in the Townsville study, where de Dear and Fountain (1994) mentioned a possible explanation proposed by McIntyre (1978a, 1978b, 1978c). It was suggested that people in hot climates may describe their preferred thermal state as "slightly cool," while people in cold climates may use the words "slightly warm" to denote their thermal preference instead of "neutral." Although the Townsville data were consistent with this hypothesis, the Montreal data were not. However, they do suggest that the acceptability/preference data should be used in setting up comfort zones rather than thermal sensation.

Effects of Gender and Personal, Contextual, and Psychological Factors

The thermal neutralities, as derived from weighted linear regressions on operative temperature, were 23.5°C (74.3°F) for the males and 23.8°C (74.8°F) for the females. Therefore, there does not seem to be a difference in the thermal requirements of the sexes. The same could not be said of thermal acceptability. In the total sample of 877 subjects, of which 50% were males and 50% were females, the females were overrepresented in the group expressing thermal dissatisfaction (63% female, 37% male; $Chi^2 = 8.9$, df = 1, Prob < 0.003). However, the only difference found between the physical character of the environments occupied by each sex, between operative temperature, PMV index, and ET*, was for the PMV index (including the effect of chair insulation); females voted 0.9 units below the males. Ethnic differences in thermal response could not be examined in this study due to the extremely small numbers of non-Caucasian subjects (3%) and office workers in the sample and population, respectively.

The "Background" questionnaire's job satisfaction question was compared with general, overall assessments. Job satisfaction appears to be related only to overall office work area acceptability. It is weakly related to generalized assessments of the overall quality of the physical environment and not related to specific thermal environmental conditions occurring at the time of the interview.

The "Background" questionnaire's health symptom frequency question was investigated for correlations with several factors. The correlations between the health index and the "Online" section of the questionnaire yielded only moderately negative relationships with ratings of air movement acceptability and with ratings of general comfort. Work area satisfaction with temperature, air quality, ventilation and air circulation, and overall comfort all yielded moderately negative dependencies. Perceived overall comfort, air movement acceptability, and perceived humidity all yielded moderately negative dependencies. The satisfaction with level of control also yielded a moderately negative dependency. Finally, environmental sensitivity to cold, too little air movement, and poor air quality yielded moderately positive dependencies. To assess if the number of years spent in Canada had any influence on the response to workplace thermal environments, correlations were performed on several parameters. No statistically significant association was found.

It was expected that extensive exposure to air conditioning might diminish physiological and psychological acclimatization to heat and humidity. There were 325 subjects who said they did not use or did not have such equipment, while 120 subjects did use it. Exposure to air conditioning outside working hours had no effect on reactions to indoor office climates. A similar exercise was performed for the winter/cold season, except that "air conditioner" was replaced with "humidifier." There were 311 subjects who said they did not use or did not have such equipment, while 121 subjects did use it. There may have been an extremely weak effect on the reaction to indoor office climates (by those having humidifiers).

The degree of control that subjects perceived they had over their workstation's thermal environment was positively correlated with several factors: overall satisfaction ratings of work area temperature, air quality, ventilation, and air circulation, perceived overall comfort, and acceptability. However, all correlations were moderate.

The possibility that the visual environment inside buildings may interact with perceptions of the indoor climates was examined. Thermal sensation votes were correlated with the simultaneously measured lux value to yield a weak positive dependence.

Comparisons with Previous Thermal Comfort Field Studies

The Townsville study (24.5°C [76.1°F]) showed a 2°C (3.6°F) difference between its findings and those in San Francisco (de Dear and Fountain 1994). In this study, the operative temperature thermal neutralities were found to be 24.0°C (75.2°F) (in summer/hot) and 23.1°C (73.5°F) (in winter/cold). The ET* neutralities occurred at 24.1°C (75.3°F) (in summer/hot) and 22.6°C (72.6°F) (in winter/cold). The summer/hot neutralities are similar to those of the Townsville study. However, the winter/cold neutralities are similar to those of the San Francisco study. This can be explained by the fact that Montrealers wear more clothing in the winter season and therefore need lower temperatures to feel "neutral" thermal sensations.

The San Francisco subjects were less sensitive to temperature variations than the Townsville and Montreal subjects. A gradient of one sensation unit per 3°C (5.4°F) was found in the San Francisco study, while a gradient of one sensation unit per 2°C (3.6°F) was found in both the Townsville and Montreal studies.

Both the San Francisco and Townsville samples experienced lower levels of thermal acceptability than could be accounted for in terms of either general thermal discomfort (i.e., PPD index) or local factors such as draft, radiant asymmetry, and vertical temperature stratification. In the San Francisco study, the PPD index predicted that for the observations near neutrality (22.4°C [72.3°F]), 5% of subjects should have expressed thermal dissatisfaction, whereas in the actual sample there was 12% dissatisfaction (based on votes outside the central four categories of the ASHRAE sensation scale). In the Townsville study, minimum dissatisfaction was predicted to be about 10%, but the actual level of dissatisfaction was observed on both the ASHRAE sensation scale and a direct acceptability question to be up to 10% higher than PPD predictions. A majority of the unexplained thermal dissatisfaction was attributed to levels of air movement falling below the building occupants' preference. In the Montreal study, minimum dissatisfaction was predicted to be about 10%. The actual level of dissatisfaction was indeed observed to be 10% on a direct acceptability question. However, on the ASHRAE sensation scale, the actual level of dissatisfaction was observed to be 6% higher than PPD predictions. Again, a majority of the unexplained thermal dissatisfaction was attributed to levels of air movement falling below the building occupants' preference.

In all three studies, thermal dissatisfaction increased much more rapidly than was predicted by the PPD index as temperatures departed from neutrality. All three studies observed a significantly greater sensitivity of thermal dissatisfaction to temperature than expected by PPD index calculations. Both the San Francisco and Townsville studies found that this underestimation could amount to as much as 20% of the sample when temperatures fell near the margins of the ASHRAE Standard 55 comfort zone. In the Montreal study, this underestimation was much higher; at the extreme higher margin of the summer zone and at the extreme lower margin of the winter zone, it could amount to as much as 28% to 52%, respectively, of the sample. The 90% or even the 80% acceptability limits defining the current margins of the comfort zones of both ASHRAE Standard 55 and ISO 7730 may be optimistic; a more realistic comfort zone should cover a narrower temperature range.

CONCLUSIONS AND RECOMMENDATIONS

A replication of the ASHRAE-sponsored San Francisco (RP-462) and Townsville (RP-702) field experiments was performed in 12 air-conditioned office buildings located in and around the city of Montreal, Canada. A total of 877 subjects provided data for the two extreme seasons in this climate: summer/hot and winter/cold. The questionnaire used in the present study was essentially the same as the one used in the previous two studies, with some minor adaptations. Indoor climatic data were collected by a mobile cart carrying laboratory-grade instrumentation complying with ASHRAE Standard 55 and ISO 7726 recommendations for accuracy and response time.

Clothing insulation levels (0.7 clo in summer and 1.1 clo in winter) were slightly higher than those assumed in ASHRAE Standard 55 of 0.5 clo in summer and 0.9 clo in winter. This was due to the fact that the clothing insulation effect of chairs added up to 0.15 clo in the summer and 0.19 clo in the winter. Metabolic rates were estimated to be 1.21 met.

Thermal neutrality, according to responses on the ASHRAE seven-point sensation scale, occurred at about 24.1°C (75.3°F) in the summer and at about 22.8°C (73°F) in the winter. Preferred temperature, defined as a minimum of subjects requesting temperature change, was approximately one degree cooler than neutrality in both seasons at 23°C (73.4°F) in the summer and 22°C (71.6°F) in the winter. Direct assessments of thermal acceptability peaked at 90% at 23°C (73.4°F) but fell off to 80% at 21.4°C (70.5°F) and 24.7°C (76.4°F). After the effects of chair insulation were accounted for, the PMV index adequately predicted optimum temperatures for the Montreal subjects in terms of thermal neutrality, acceptability, and preference.

Only 63% of the indoor climatic observations fell within the ASHRAE Standard 55 summer comfort zone; 27% of the observations fell within the winter comfort zone. Neither the ASHRAE Standard 55 nor the ISO 7730 PPD index matched observed levels of thermal acceptability with useful accuracy. The only exception is for the operative temperature range of 22°C to 24°C (71.6°F to 75.2°F), where the PPD index matched the direct acceptability vote by the subjects. Montreal office workers were generally much less accepting of non-neutral temperatures than either the PPD index or Standard 55 predicted.

The observed air velocities and turbulence intensities respected the guidelines as set out in the standards. As was found in the Townsville study, draft or unwanted cooling due to excessive air movement was much less of a problem than were insufficient levels of air movement. The thermal dissatisfaction expressed by subjects whose thermal environments fell within the ASHRAE Standard 55 summer and winter comfort zones appeared to be related to not enough air movement. This suggests that air movement and draft guidelines in Standard 55 and ISO 7730 may be inappropriate for both hot, humid and cold climatic zones.

Group mean thermal sensations showed a heightened sensitivity to temperature, changing approximately one unit on the ASHRAE seven-point scale per 2°C (3.6°F) change in operative temperature. The same was found in the Townsville study. In San Francisco, the ratio was slightly different—one unit per 3°C (5.4°F).

There was little difference between the sexes in terms of thermal sensation, although there were significantly more frequent expressions of thermal dissatisfaction from the females in the sample despite their thermal environments being no different from those of the males.

Apart from gender, other personal, contextual, and psychological factors investigated for relationships with thermal responses of building occupants included job satisfaction, general health status, physical fitness, length of residence in Canada, exposure to air conditioning and humidification outside the workplace, perceived levels of control over workplace thermal environments, and total amount of lighting. While job satisfaction was moderately and positively correlated with overall generalized assessments of the workplace physical environment, it is not possible to infer cause and effect from these data. Furthermore, job satisfaction had no relationship with assessments of specific environmental conditions occurring at the time of the interviews. General health status showed moderately negative dependencies with overall generalized assessments of the workplace physical environment. However, the only relationships found with assessments of specific environmental conditions occurring at the time of the interviews were air movement acceptability and general comfort (moderately negative). Perceived levels of personal control seemed to have a small influence on office occupant evaluations of indoor climate. Physical fitness and length of residence in Canada registered no statistically significant association with any environmental rating. Exposure to air conditioning outside the workplace did not register any relationship with both generalized and specific assessments of workplace thermal environments. However, exposure to humidification outside the workplace and lighting levels did indicate effects on thermal sensation. Ethnic differences in thermal response could not be examined in this study due to a small number of non-Caucasian subjects.

The effects of Montreal's hot/cold seasonality on thermal comfort responses of office workers was minor, amounting to less than a 1.5°C (2.7°F) shift in neutrality, well within the range expected on the basis of the clothing insulation differences of approximately 0.3 clo between seasons.

Compared to the earlier ASHRAE field experiments in San Francisco (RP-462) and in Townsville (RP-702), summer neutralities in Montreal approximated those from the Townsville study, while winter neutralities were closer to those in the San Francisco study. However, the relatively good prediction of all three neutralities by the PMV model suggested that most of this offset could be explained by differences in clothing.

As was found in the Townsville study, metabolic estimates need further attention in the field research methodology since they appear to be a major source of confusion when one compares different field studies. For example, San Francisco initially estimated 1.1 met for office workers, Townsville estimated 1.3 met, and Montreal 1.2 met. It was thought that the three samples of office workers were essentially doing the same type of work.

Only recently has the importance of considering the incremental effect of chairs on the clothing insulation of office workers been acknowledged. The Montreal study also incorporated the effect of different types of ensembles sitting on different chairs. This relationship also should be included in future revisions of the standard. Furthermore, more detail is needed to explain the differences in clothing perceptions from one climate to another. For example, a "heavy" Montreal garment may not necessarily be the same as a "heavy" Townsville garment.

Further work on air movement preferences is required. Montreal office workers were not accepting of the air movement levels at their workstations, even though those levels satisfied the standards. The concept of draft risk does not appear to be relevant in Montreal's climate.

This northern project replicated work conducted in a Mediterranean climatic zone (RP-462) and in a tropical climatic zone (RP-702). Further replication is desirable in a hot, dry climate. This would complete the climatic variations to be considered in ASHRAE Standard 55 revisions. This study in an extremely cold climate has shown that occupants' responses to indoor climates differ from those in mid-latitude and tropical climatic zones.

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