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Acceptable Temperature Ranges in Naturally Ventilated and Air-Conditioned Offices

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ABSTRACT

The thermal environment in eight naturally ventilated and eight air-conditioned offices, located throughout England, was continuously monitored for one week in winter and one week in the following summer. The occupants assessed their thermal sensation (TS) every half-day on the ASHRAE seven-point scale. In total, 1,692 occupants made 11,450 votes in winter and 1,363 people made 9,505 votes in summer. Weighted regression analysis was used to compute the neutral temperature and acceptable temperature range relating to 3.5 ≤ TS ≤ 4.5.

The overall comfort range in naturally ventilated offices in winter and summer, 4.9°C and 3.9°C (8.8°F and 7.0°F), respectively, was wider than that found in air-conditioned offices, 2.6°C and 2.4°C (4.7°F and 4.3°F), respectively. The neutral temperature in naturally ventilated offices was 0.7°C (1.3°F) lower in winter and 2.1°C (3.8°F) lower in summer than in air-conditioned offices. However, there was only a marginal difference in clothing insulation and activity levels between the two types of offices. The lower neutral temperature in naturally ventilated offices in summer may partly be due to an overestimation of warmth due to conditions typically being warmer than the previous day. Discrepancies of up to 3.0°C (5.4°F) were found between the observed neutral temperatures and those predicted by ISO 7730 for naturally ventilated offices in summer. In contrast, for the air-conditioned offices in winter and summer and naturally ventilated offices in winter, the predicted neutral temperatures were much closer to those reported, with a maximum difference of only 0.6°C (1.1°F).

In winter, the percentage of occupants satisfied with the temperature in the naturally ventilated buildings (76%) was higher than in the air-conditioned offices (70%), whereas in summer, there was less satisfaction in the naturally ventilated offices (69%) than in the air-conditioned offices (73%). The occupants were less dissatisfied in the naturally ventilated buildings in winter than in summer, whereas there was only a marginal difference in dissatisfaction between seasons in the air-conditioned offices.

INTRODUCTION

Air-conditioned offices provide more tightly controlled environmental conditions, which, in theory, are more satisfactory than the range of conditions found in naturally ventilated offices. However, worldwide research indicates that occupants are tolerant of a wider range of thermal conditions in naturally ventilated offices than in air-conditioned offices and, therefore, find their conditions satisfactory. It may be possible to relax the control conditions in air-conditioned offices in the U.K. and save energy by allowing temperatures to drift slightly and increase the time that the heating/cooling system does not "kick in," i.e., the system deadband. Furthermore, as occupants tolerate wider temperature ranges than usually assumed, then air conditioning may only be required in climatic conditions more extreme than those found in the U.K.

One explanation for the wider acceptable temperature range in naturally ventilated offices is that the occupants adapt by such means as adjusting clothing, regulating their rate of activity, changing posture, and modifying the environment (Humphreys 1978; Baker and Standeven 1996). Anecdotal evidence indicates that air-conditioned buildings attract companies with a high corporate image and strict dress codes, etc. In contrast, there are less likely to be such constraints in naturally ventilated offices; thus, it is expected that the occupants should be more able to adapt to a larger range of thermal conditions. Humphreys observed that people come to accept the climatic conditions to which they are accustomed and that air-conditioned offices minimize the range of conditions;

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hence, they become accustomed to a much smaller range of internal conditions. Consequently, people may have higher expectations of environmental conditions in climate-controlled buildings.

Fishman and Pimbert (1982) collected hourly votes of 26 subjects for one year in one naturally ventilated and one air-conditioned office. They concluded that their "results indicate that the people in air-conditioned offices are less tolerant of temperatures above 24°C than those in naturally ventilated offices," but "since only seven of the subjects worked in an air-conditioned area, and temperatures above 24°C were not often encountered, these results should be treated with some caution." A study in Bangkok offices (Busch 1990) showed that the air temperature in naturally ventilated buildings was much higher (7.1°C) than those in air-conditioned ones. Furthermore, Busch found a neutral, or optimum, temperature (t_n) of 24.7°C in air-conditioned offices compared with 27.4°C in naturally ventilated ones. The range of temperatures at which the occupants were comfortable was also much greater in the naturally ventilated offices (up to 31°C) compared to the air-conditioned ones (22°C to 28°C).

A comparison of field studies conducted in two cities in Australia (de Dear and Auliciems 1985) showed that in Brisbane, the t_n was on average 1.7°C lower in air-conditioned buildings compared to naturally ventilated ones, whereas in Melbourne, the t_n was 1.3°C higher in the air-conditioned offices. At the time of the survey, the mean monthly outdoor temperature in Melbourne was approximately 4.7°C lower than in Brisbane. Furthermore, the indoor temperature in the naturally ventilated offices in Brisbane was 4°C higher than the air-conditioned ones, but there was only 0.7°C difference between the naturally ventilated and air-conditioned buildings in Melbourne. These measurements indicate that the occupants of the naturally ventilated Brisbane offices were appropriately adapting to the higher room temperatures, but the occupant interaction with the thermal conditions in Melbourne is not so clear.

Fanger's (1970) model of thermal comfort produces a "predicted mean vote" (PMV) on the ASHRAE seven-point thermal sensation scale, based on four physical and two personal parameters. The four physical parameters, i.e., air temperature (t_a), mean radiant temperature ($\bar{t}_r$), relative humidity (φ) and relative air velocity (v_r), are fairly straightforward to measure. In contrast, the two personal parameters, i.e., metabolic rate (M) and intrinsic clothing insulation (I_{cl}) are more difficult to establish, especially outside of controlled laboratory situations. The PMV can be used to calculate the predicted t_n. Unfortunately, there have been some discrepancies between the occupant requirements observed in real buildings and those predicted using the model or specified in standards based on the model, e.g., ISO 7730 (ISO 1994) and ASHRAE 55 (ASHRAE 1992).

For example, Brager (1992) studied offices in San Francisco and found that in winter, the PMV was generally lower (cooler) than the actual reported thermal sensation (TS), so that the predicted t_n of 24.8°C was 2.4°C higher than that observed. In a U.K. study, Brazier (1987) examined 492 occupants in one naturally ventilated and two air-conditioned offices. He found the PMV underpredicted the actual TS vote by 0.5 units, which is equivalent to overpredicting the comfort temperature by approximately 1.5°C. Similarly, a study of Melanesian office workers (Ballantyne et al. 1979) showed that the reported t_n was 1.4°C higher than that predicted by PMV. In Australia, de Dear and Auliciems (1985) found differences between the t_n, based on a reported and predicted thermal sensation, of 0.5°C to 3.2°C. In a later study, de Dear et al. (1993) surveyed 12 offices in Australia and found a 0.3 unit discrepancy between TS and PMV, which is equivalent to approximately 1°C. De Dear (1994) extended his analysis to include the work of Busch (1990) and Brager (1992). He reanalyzed the data sets, correcting for the lack of chair insulation, but still found discrepancies between the t_n based on a reported and predicted thermal sensation of 0.2°C to 3.3°C ($\bar{X}$ = 1.4°C).

Advocates of the PMV model insist that any error in the predictions are mostly due to the incorrect estimation of M and I_{cl}, the two personal variables. However, the model is derived from heat balance theory and was evaluated under controlled steady-state laboratory conditions. As a consequence, the model does not adequately account for all types of adaptive behavior, particularly subtle and subconscious ones that are difficult to observe and quantify. Such minor behaviors may synergistically combine so that the preferred temperatures in real-world situations are different and more variable than those observed under laboratory conditions. However, the PMV model may be appropriate for predicting the optimum temperature in an air-conditioned office in which adaptive behavior and interaction with the environment are more constrained than in a naturally ventilated office.

The objective of the present study was to determine whether the occupants in naturally ventilated environments are comfortable at a wider range of temperatures than those in air-conditioned offices. The accuracy of the PMV model in predicting the optimum temperature in the two environments was also tested.

METHOD

Building Selection and Sample

The criteria for the building selection were fairly broad. The buildings needed to be (a) office buildings, (b) occupied for at least 12 months by the current occupants, (c) occupied by at least 150 occupants, and (d) either air conditioned or with simple natural ventilation rather than being mixed mode or naturally ventilated with passive cooling design features.

Table 1 shows that the final selection included eight air-conditioned and eight naturally ventilated office buildings that were between 3 and 97 years old at the time of the survey. The

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TABLE 1
Background Information of the Surveyed Buildings

ID	Location and Site	Age and Ventilation	Floor Area (m^2) and Layout	Occupancy and Stories	Energy, MJ/m^2 p.a.
1	SE city	1970s air-conditioned	44626 OP	2080 staff, 26 floors	2079
2	EM green	1992 air-conditioned	2955 OP	120 staff, 3 floors	1099
3	SE green	1960s naturally ventilated	2639 CO	120 staff, 4 floors	1085
4	NE city	1976 air-conditioned	16810 OP	1400 staff, 4 floors	1659
5	NE city	1897 naturally ventilated	9100 CO	490 staff, 7 floors	738
6	SE city	1960s naturally ventilated	56085 CO	2280 staff, 3×18 floors	1199
7	SE city	1990 air-conditioned	17486 OP	950 staff, 5 floors	1037
8	WM town	1980s naturally ventilated	3902 OP	400 staff, 5 floors	811
9	SE city	1992 air-conditioned	12913 OP	750 staff, 7 floors	2500
10	SE city	1960s naturally ventilated	10260 OP	450 staff, 11 floors	708
11	SE city	1988 air-conditioned	23800 OP	800 staff, 6 floors	1177
12	NE city	1980s naturally ventilated	2781 OP	350 staff, 7 floors	1235
13	NE city	1970s naturally ventilated	4109 OP	300 staff, 5 floors	702
14	NE city	1980s air-conditioned	4645 OP	450 staff, 4 floors	1500
15	SE city	1979 air-conditioned	N/A OP	300 staff, 5 floors	N/A
16	WM green	1985 naturally ventilated	3833 OP	180 staff, 4 floors	468

Notes: SE = southeast, NE = northeast, EM = East Midlands, WM = West Midlands, OP = open plan, CO = cellular office, N/A = not available, Energy = annual energy consumption of net floor space.

buildings have 3 to 26 storeys and are a mixture of open plan and cellular design with varying levels of occupant control over temperature. In general, the air-conditioned buildings tended to be more open plan and offer less occupant control than the naturally ventilated ones, but there was no clear difference in building age. The buildings studied were a mixture of central government offices, government agency offices, and local government administrative offices. The type of work carried out and corporate policy (e.g., dress code) was similar in all buildings.

Physical Measurements and Questionnaires

Previous studies of thermal comfort have tended to make "spot" measurements of the conditions within the office. However, variations in working conditions due to the heating and ventilating systems being switched off over night makes it necessary to take the measurements over a length of time. Unfortunately, practical restrictions, e.g., disruption of work and "survey fatigue," meant that monitoring could not be conducted indefinitely. As a compromise, the office's thermal environment and the occupants' perceptions were continuously monitored for one week in winter and one week in summer. Half of the buildings were surveyed in 1995 and the remainder in the following year.

Commercially available portable data-loggers were used to monitor air temperature (t_a), globe temperature (t_g), relative humidity (φ), and air velocity (v) at desk height (0.7 m). A mixture of hot-wire and bead transducers were used to measure v, capacitance transducers were used for φ, and bead thermistors with 40 mm black globes measured t_g. There were insufficient loggers to monitor the environmental conditions at each person's desk; however, sufficient temperature loggers were used to provide a minimum of approximately one set of data per every seven occupants. The loggers tended to be placed toward the middle of a room at the center of a cluster of desks but away from radiant sources such as equipment or windows. The measurements were, therefore, not as person specific as previous ASHRAE studies (e.g., de Dear et al. 1993), but the conditions were continuously monitored during the survey week. The data-logger sample period was set to five minutes, but the data were averaged for each hour in half-hour intervals throughout the working day, i.e., 7:30-8:30, 8:00-9:00, 8:30-9:30... 18:30-19:30. The occupants completed the half-day questionnaire just before lunch and just before going home. The time of completion noted on the questionnaire was then used to cross-reference the physical data and pick out the relevant mean measurements for the previous hour to completion.

The mean radiant temperature ($\bar{t}_r$) and operative temperature (t_o) were computed from t_a, t_g, and v using a rearranged version of de Dear's (1986) equation. The relative air velocity (v_r) was computed from v and the air velocity due to body movement, as explained in ISO 7730 (1994). The PMV was computed using the ISO 7730 algorithm and the values

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measured or estimated for t_a, t_r, φ, v_r, M, and I_{cl}. The minimum and maximum outdoor temperatures for each office were obtained from the British Meteorological Office and used to calculate the mean monthly outdoor temperature (t_{mo}), as instructed by Humphreys (1978).

Every half-day for one week the occupants completed a short one-page questionnaire. The questionnaire allowed the occupants to rate their thermal sensation (TS) on the commonly used ASHRAE seven-point scale and thermal preference (TP) on a seven-point scale labelled "much warmer" (1), "warmer" (2), "slightly warmer" (3), "no different" (4), "slightly cooler" (5), "cooler" (6), and "much cooler" (7), which corresponded to the TS scale. The scales used here are asymmetrically labeled from 1 to 7 with a midpoint of 4 rather than the often used symmetrical scale of –3 to +3 with a midpoint of 0. The PMV was also converted to an asymmetrical (1 to 7 point) scale.

The questionnaire also enquired about what activities the occupants had conducted in the office during the hour prior to completing the questionnaire and what they were wearing at the time of answering the questionnaire. The met values corresponding to the four main categories of activity, and the length of time that each activity was conducted were used to estimate the weighted mean hourly metabolic rate (M). The checklist of what the occupant was wearing was used to compute the intrinsic clothing insulation (I_{cl}). As the occupants were seated when completing the questionnaire, an extra 0.13 clo was added to the I_{cl} to account for the chair's insulation.

The questionnaire also asked the occupants if they found the thermal conditions acceptable in which to work. The responses to this question were used to calculate the percentage acceptability, a proxy for satisfaction.

Calculation of Neutral Temperatures

In order to determine the temperatures at which people are comfortable, it is necessary to obtain their reported ratings of thermal sensation (TS) for a wide range of temperatures and use regression analysis to interpolate the neutral temperature (t_n) when the thermal sensation is at the midpoint of the scale (i.e., TS = 4). An acceptable thermal sensation for 90% of the occupants is provided when votes between 3.5 and 4.5 are made on the TS scale.

In a laboratory situation, the subjects are exposed to a range of temperatures to which they provide an assessment of their thermal sensations. In the field, it is not always possible, or practical, to manipulate the environmental conditions. However, monitoring the conditions for one week allowed some variation in temperature to be obtained by chance. The data set consists of assessments made at different times of the day and on different days by the same occupants. This allowed for a range of conditions to be recorded per occupant. For clarity, in the following analysis and figures the room temperature was binned into 0.5°C (0.9°F) intervals, and the mean TS was calculated per 0.5°C. However, all regression analyses were weighted by the number of TS votes per temperature interval.

The PMV was actually computed to correspond to each individual vote made by each occupant based on the environmental conditions at the time of their vote. As with TS, the means of these votes were then computed for each binned temperature condition. It was these individual PMV scores that were used in most of the following analysis and compared with the TS vote. However, standards are used to predict the mean vote for a group of people by estimating the mean environmental conditions to which they are exposed, here termed the "PMV_g." The PMV_g was used to determine the predicted t_n by manipulating the temperature and keeping all other variables constant in the ASHRAE thermal comfort program (Fountain and Huizenga 1996). The percentage of people dissatisfied (PPD) was computed using the mean data for each building type and the algorithm in ISO 7730.

RESULTS

Sample

A total of 1,692 occupants participated in the study in winter and 1,363 the following summer, indicating a 20% dropout between seasons. The response rate, i.e., the ratio of returned completed questionnaires to those administered, was 69% in winter. The number of returned half-day questionnaires was 11,474 in winter and 9,523 in summer, i.e., approximately seven thermal sensation votes per respondent per season.

Mean Environmental Conditions

Figure 1 shows the mean daily outdoor temperature averaged across all locations for 1995 and 1996. The figure clearly illustrates that the outdoor temperature steadily increased throughout the summer survey period. In particular, the rise in outdoor temperature in the summer of 1995 was more rapid

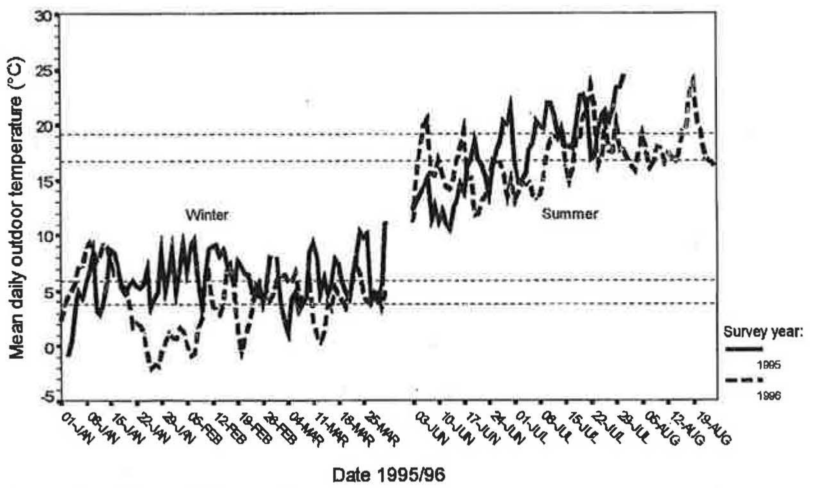

Figure 1 *Mean daily outdoor temperature of survey sites in 1995 and 1996.*

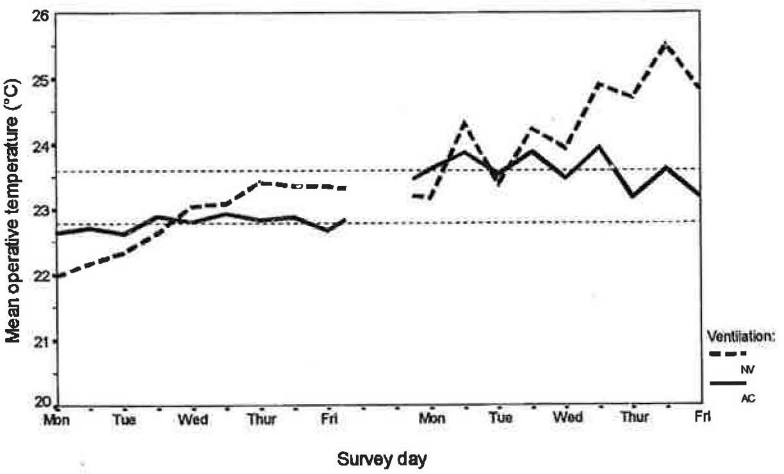

Figure 2 Mean indoor temperature during survey weeks.

than in 1996. The weather conditions did not differ significantly between buildings, but, as shown, the conditions did vary between the survey weeks. The occupants were, therefore, always subjected to a warmer outdoor climate than the week before the survey.

The outdoor temperature was fairly constant within each survey week. However, Figure 2 shows that the mean indoor temperature (t_o) in naturally ventilated offices gradually increased during the week, especially in summer. On average, the indoor temperature is 1.3°C (2.3°F) higher at the end of the week in winter and 1.6°C (2.9°F) higher in summer. Presumably, this effect is due to heat gains that only dissipate over the weekend period when the buildings are unoccupied. In contrast, for all air-conditioned offices, the mean t_o cycled around 22.8°C (73.0°F) by approximately ±0.1°C (0.2°F) in winter and around 23.6°C (74.5°F) by approximately ±0.4°C (0.7°F) in summer.

Table 2 shows the mean environmental conditions in all the naturally ventilated and air-conditioned offices combined in winter and summer. As expected, in both naturally ventilated and air-conditioned offices, the summer measurements showed a higher temperature ($t = -44.9$, $df = 1{,}19776$, $p < 0.001$) and relative humidity ($t = -97.1$, $df = 1{,}20309$, $p < 0.001$) than in winter. Air velocity was of a similar magnitude across seasons. Table 2 also shows that the mean temperature and humidity were less similar between naturally ventilated and air-conditioned offices in summer compared to winter. Furthermore, in general, the standard deviations corresponding to t_o, φ, and v were larger in naturally ventilated offices, especially in summer, indicating more variation in the environmental conditions than in the more controlled air-conditioned environments.

The mean I_{cl} of 0.91 ($\sigma = 0.28$) clo in winter was significantly higher than the 0.63 ($\sigma = 0.16$) clo in summer ($t = 81.3$, $df = 1{,}19360$, $p < 0.001$). These clo values include a chair insulation of 0.13 so the I_{cl} from clothing alone was 0.78 and 0.50 clo, respectively. Table 2 also shows that the mean M of 1.25 ($\sigma = 0.15$) met in winter is fairly similar to the 1.27 ($\sigma = 0.16$) met observed in summer but slightly higher than the normally assumed level of office activity (1.2 met). This is because the occupants spent 10% of the day standing while conducting light activity (e.g., photocopying) and 9% of the time standing while conducting medium activity (e.g., carrying files). Table 2 shows that the mean M and I_{cl} were quite similar in naturally ventilated and air-conditioned offices, and the standard deviations of these variables were also similar. There was also little variation in the mean of these variables throughout the week.

TABLE 2
Mean Environmental Conditions

Parameter	Winter			Summer		
	Naturally Ventilated	Air-Conditioned	Both	Naturally Ventilated	Air-Conditioned	Both
t_a (°C)	22.6	22.3	22.4	24.2	23.2	23.7
t_r (°C)	22.9	23.3	23.1	24.3	23.9	24.1
t_o (°C)	22.8	22.8	22.8	24.3	23.6	24.0
φ (%)	31.0	30.4	30.7	43.3	39.8	41.5
v (m/s)	0.05	0.07	0.06	0.07	0.08	0.07
v_r (m/s)	0.13	0.15	0.14	0.15	0.15	0.15
M (met)	1.26	1.25	1.26	1.27	1.26	1.27
I_{cl} (clo)	0.92	0.90	0.91	0.63	0.63	0.63
TS (1-7)	4.1	3.9	4.0	4.8	4.2	4.5
PMV (1-7)	4.0	3.9	4.0	4.0	3.8	3.9
PMV_g	4.2	4.1	4.1	4.1	4.1	4.1

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TABLE 3
Neutral Temperatures Derived from Reported and Predicted Comfort Votes

Source	Winter				Summer			
	Naturally Ventilated		Air-Conditioned		Naturally Ventilated		Air-Conditioned	
	t_n	Range	t_n	Range	t_n	Range	t_n	Range
TS (mid-range)	22.3	19.8-24.7	23.0	21.7-24.3	21.1	19.2-23.1	22.9 (23.1)	21.3-24.6 (21.8-24.4)
TP	23.5	20.5-26.5	23.3	21.8-24.8	21.5	19.5-23.5	22.3	20.4-22.4
PMV	22.8	20.2-25.3	23.3	20.3-26.2	24.1	21.8-26.4	24.7	21.9-27.5
PMV_g	22.0	19.6-24.4	22.4	20.0-24.7	23.8	21.9-25.7	23.6	21.6-25.5

Notes: Temperature range is for 90% acceptability, i.e., 3.5 to 4.5 on thermal sensation scales; parentheses show recalculatio based on the mid-range subsample (see Figure 7).

Overall, the occupants rated their thermal sensation (TS) significantly warmer in summer than in winter ($t = -27.9$, $df = 1{,}20953$, $p < 0.001$), but this was not reflected by their predicted votes (PMV or PMV_g). In winter, the occupants rated themselves closer to neutral, but in summer, the occupants rated themselves as feeling marginally warmer than neutral in air-conditioned offices and voted "slightly warm" in naturally ventilated offices. PMV was significantly lower than TS in summer ($t = -40.6$, $df = 1{,}8038$, $p < 0.001$) but there was no practical difference in winter. Calculation revealed that the difference of 0.6 scale units between TS and PMV in summer is equivalent to 2.3°C (4.1°F). This summer, discrepancy is mainly attributed to the differences in naturally ventilated offices, i.e., 0.8 TS units and 3.1°C (5.6°F).

Neutral Temperatures and Comfort Range

Table 3 shows the t_n, computed from the regression analysis of the TS and TP scales, and PMV by the binned t_o. The analysis revealed that in winter, the acceptable (90% satisfied) range of temperatures in naturally ventilated offices is considerably wider (4.9°C, 8.8°F) than in air-conditioned offices (2.6°C, 4.7°F). The table also shows that in winter, naturally ventilated occupants accept temperatures 1.9°C (3.4°F) lower but with a t_n only 0.7°C (1.3°F) lower than in air-conditioned offices. However, in summer, the t_n in naturally ventilated offices is unexpectedly 1.8°C (3.2°F) lower than in air-conditioned offices, and the acceptability range was relatively similar, i.e., 3.9°C (7.0°F) compared to 3.3°C (5.9°F). Furthermore, the t_n in air-conditioned offices is similar in both seasons, i.e., 23.0°C (73.4°F) and 22.9°C (73.2°F), whereas in naturally ventilated offices, it was unexpectedly 1.2°C (2.2°F) lower in summer. The anomalies in TS may be considered to be related to thermal preferences. The preferred temperature (t_p), derived from TP and t_o, is quite similar to t_n in the air-conditioned offices in both winter and summer, i.e., a 0.3°C and 0.6°C discrepancy. In naturally ventilated offices, t_p is higher than the t_n in winter by 1.2°C (2.1°F) but only higher by 0.5°C (0.9°F) in summer. The t_n, based on TS, therefore appears lower than the preferred temperature except in air-conditioned offices in summer.

Table 3 also shows that the predicted t_n, derived from PMV_g, was similar for naturally ventilated and air-conditioned offices in winter and in summer because the mean environmental conditions were similar, whereas the t_n derived from the reported votes were quite different. The predicted t_n, derived from both PMV_g and PMV, were quite similar to those based on TS in both naturally ventilated and air-conditioned offices in winter, with up to a 0.6°C (1.1°F) difference. However, the discrepancy between the predicted t_n based on reported and predicted votes was much greater in summer, i.e., a 3.0°C (5.4°F) error for the naturally ventilated offices and 1.8°C (3.2°F) for air-conditioned environments.

Plots were made of the mean TS against the binned t_o for winter (Figure 3) and summer (Figure 4). Weighted regressions were computed to account for the number of assessments

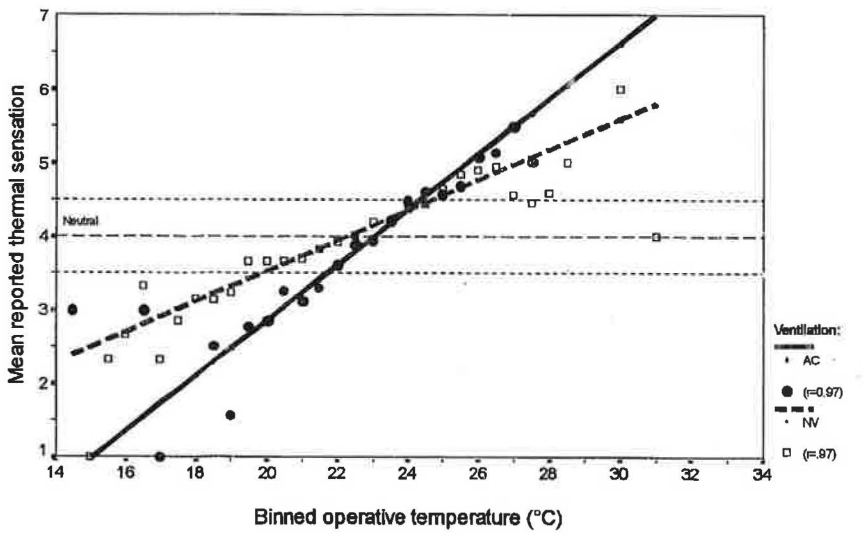

Figure 3 Reported thermal sensation in winter.

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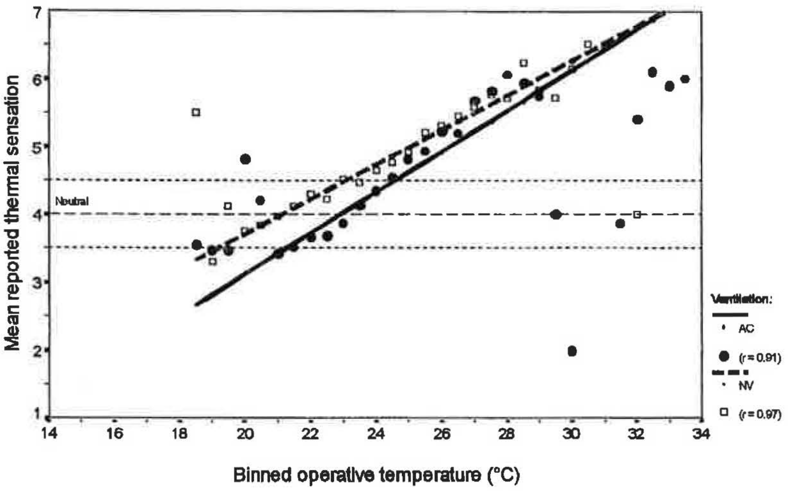

Figure 4 *Reported thermal sensation in summer.*

made at each temperature bin. Figures 3 and 4 confirm the results shown in Table 3. The neutral temperatures in air-conditioned offices are similar in both winter and summer, whereas t_n is lower in naturally ventilated offices compared to air-conditioned offices in both seasons. Unexpectedly, t_n is also lower in naturally ventilated offices in summer compared to winter. The acceptable temperature range is also much wider in naturally ventilated offices in winter and slightly wider in summer, although the lower limit of the range in the naturally ventilated offices is lower by 1°C to 2°C than in the air-conditioned offices.

Similarly, the mean of the predicted votes (PMV) was plotted against the binned t_o. Figures 5 and 6 show that the regression lines produce a similar t_n and acceptability range in the naturally ventilated and air-conditioned offices in winter ($\delta t_n = 0.5$°C) and also in summer ($\delta t_n = 0.6$°C). The gradients of the regression lines were also quite similar.

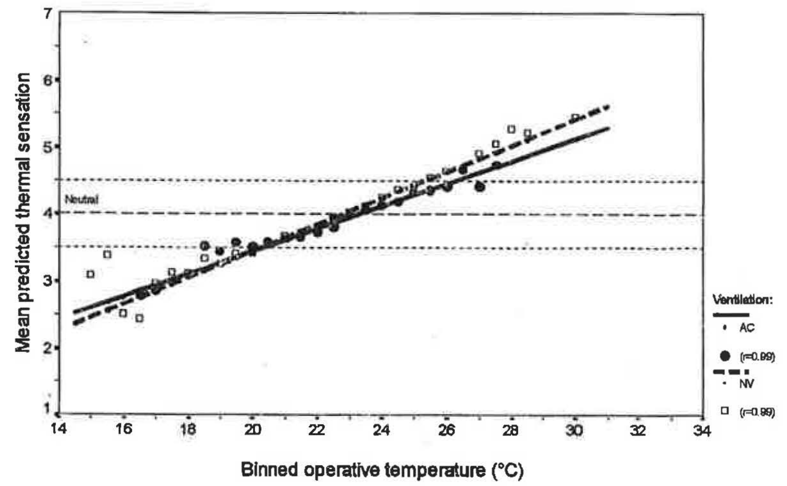

Figure 5 *Predicted thermal sensation in winter.*

Reexamination of Figure 4 reveals that in the air-conditioned offices in summer, there is a good relationship ($r = 0.99$) between TS and t_o in the mid-temperature range. In contrast, TS reaches a plateau when t_o is below 21.5°C (70.7°F) and above 28.5°C (83.3°F). Furthermore, only 3.2% of all the summer temperatures recorded in air-conditioned offices were below 21.5°C and only 1.2% were above 28.5°C, and these higher temperatures were all observed in Building 4, which was known to have a poor, possibly undersized, air-conditioning plant. However, excluding Building 4 from the data set did not significantly affect the observed t_n.

Figure 7 illustrates that the acceptable temperature range for the air-conditioned occupants exposed to the more typical indoor temperatures is 21.8°C to 24.4°C. Furthermore, the t_n is 23.1°C (73.6°F), compared to the 22.9°C computed for all occupants. This new t_n, shown in parentheses in Table 3, is closer to the 23.6°C (74.5°F) predicted from PMV_g. The main discrepancy in predicted and reported neutral temperatures is, therefore, for naturally ventilated offices in summer.

This new representation of the air-conditioned summer data (Figure 7) is of a pattern similar to the winter data (Figure 3) except that the regression lines have shifted toward the upper-right corner of the plot. Consequently, the t_n in naturally ventilated offices in summer (2.1°C, 3.8°F) is even farther below that in air-conditioned offices, shown in Figure 4 (1.8°C, 3.2°F). As previously mentioned, the t_n in naturally ventilated offices in summer is also lower than in winter. This low t_n is not as predicted by adaptive theory, which proposes that the occupants of naturally ventilated offices adapt to higher room temperatures, and, therefore, their corresponding neutral temperatures should be higher in summer.

Each occupant made a thermal sensation vote every half-day; therefore, one possible explanation for the low t_n is that the occupants' previous use of the TS scale is affecting their subsequent votes because they use the scale relatively. For example, Figures 1 and 2 illustrate that summer outdoor temperatures gradually increased during the survey period and the indoor temperatures in the naturally ventilated offices gradually increased during the week, probably owing to internal casual and external incidental gains not being dissipated overnight. Furthermore, Figure 8 reveals that, on average, in the summer, the observed TS vote in naturally ventilated offices gradually increases during the week ($F = 30.3$, $df = 8{,}4601$, $p < 0.001$), whereas, the mean TS vote cycles around "neutral" in air-conditioned offices.

It, appears therefore, that the occupants of naturally ventilated offices are subjected to warmer room temperatures each day, and, as a

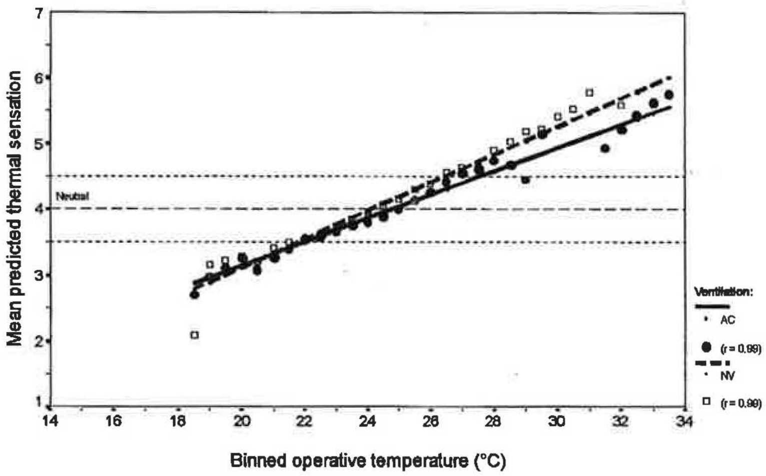

Figure 6   *Predicted thermal sensation in summer.*

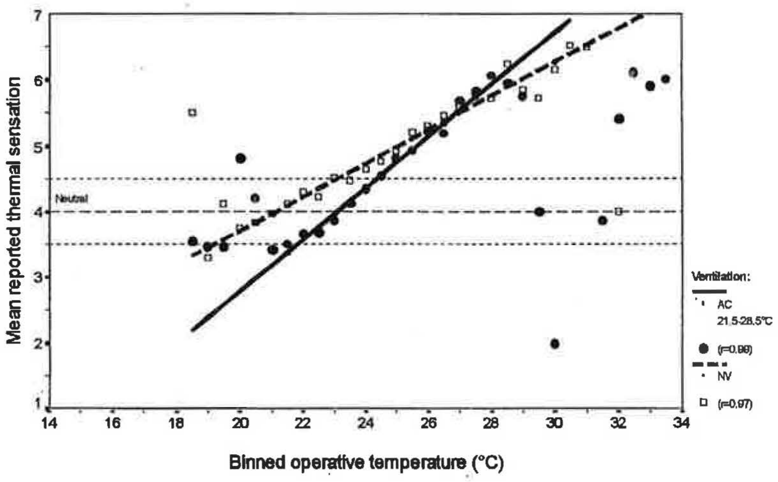

Figure 7   *Re-analysis of reported thermal sensation in air-conditioned offices in summer.*

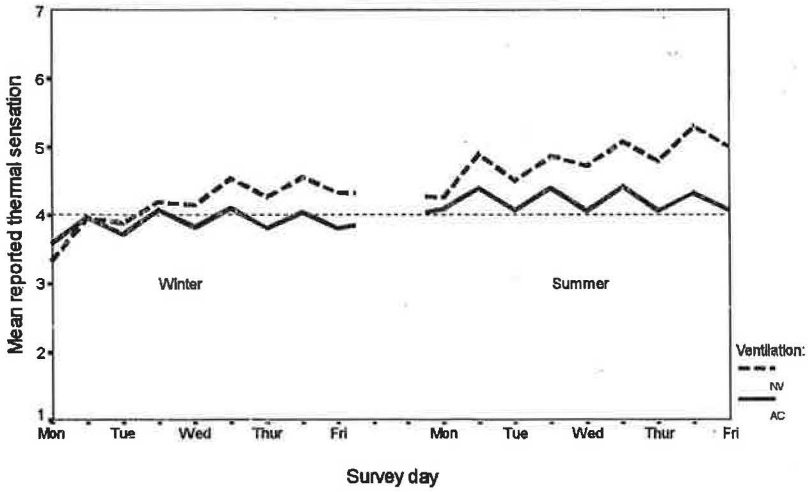

Figure 8   *Mean thermal sensation during survey week.*

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consequence, rate their TS higher than the day before. This is as expected, but a problem arises owing to the coarseness of the scale, only seven categorical points. This is because the occupants only have the option of rating the proceeding higher room temperature as one whole TS unit higher, even when they may feel only one-quarter or one-half a TS unit warmer. For summer conditions, one scale unit is equivalent to a 3.8°C (6.8°F) offset in optimum temperature. However, the mean TS only rises from the start to the end of the week by 1 unit in winter and 0.8 units in summer, rather than the hypothesized one unit per day. Nevertheless, as t_n is computed by regressing TS by t_o, and interpolating the temperature when TS = 4, any occupants forced to give a higher than required TS rating will have the undesired effect of artificially lowering t_n.

The above explanation of the lower summer t_n was tested by comparing the t_n computed from the occupants' first TS vote made Monday morning with their last vote made Friday morning. Indeed, for the occupants of naturally ventilated offices in summer, the t_n based on the first vote was 22.4°C (36.5°F) compared to 20.7°C (69.3°F) based on the last vote. Thus, the occupants' repetitive use of the scale had the effect of lowering the t_n by 1.7°C (3.1°F). In comparison, in the air-conditioned offices, the t_n based on the first vote was 23.4°C (74.1°F), whereas it was 23.1°C (73.6°F) when based on the last vote. The t_n based on first votes only was also lower in naturally ventilated offices in summer compared to air-conditioned ones. Unexpectedly, a similar effect was found in winter. The t_n based on the last vote in naturally ventilated offices was 3.2°C (5.8°F) lower than that based on the first vote, whereas the t_n in air-conditioned offices dropped by only 0.2°C (0.4°F) during the week. The unexpected lower t_n in naturally ventilated offices in summer must, therefore, be at least partly due to some other factor.

Percentage Acceptable

The occupants were asked if they considered the thermal environment acceptable (Question 3). The percentage of respondents who voted "slightly warm" to "slightly cool" (i.e., comfortable) and the percentage who said they wanted no different or slightly different environmental conditions (i.e., preferred) were also computed.

Table 4 shows statistically significant differences in the acceptability of naturally ventilated and air-conditioned offices. In winter, slightly more (6%) occupants in the naturally ventilated offices find the conditions acceptable than in the air-conditioned offices, whereas in summer, fewer (4%) people found the naturally ventilated offices acceptable. Slightly more (3%) occupants of air-conditioned offices found the temperature acceptable in summer compared to winter, whereas 7% less occupants considered naturally ventilated offices acceptable in summer than in winter.

Similar numbers of those who preferred no change or only a slight difference in temperature were present in air-conditioned offices in winter and summer, whereas more (10.2%) occupants in naturally ventilated offices required a change in summer. There was only a marginal difference between the percentage comfortable in the two types of offices in winter, whereas 7.3% fewer people found the naturally ventilated offices comfortable in summer. The naturally ventilated offices are, therefore, more acceptable than air-conditioned offices in winter, but air-conditioned offices are preferred in summer.

TABLE 4
Percentage Satisfied with Thermal Environment

Scale Used in Calculation	Winter		Summer	
	Naturally Ventilated	Air-Conditioned	Naturally Ventilated	Air-Conditioned
Acceptable	76.0***	70.0***	69.0***	73.0***
Comfortable	73.8*	71.7*	64.2***	72.5***
Preferred	82.3**	80.0***	72.1***	79.8***
Predicted	95.0	94.0	94.0	93.0

Notes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 4 also shows that the observed percentage satisfaction was quite different to that predicted (100 - PPD), which was 93% to 95%. The converted seven-point rating scales, "preferred" and "comfortable," produced similar trends to the two-point acceptability rating. However, the percentage of occupants who rated themselves on the midpoint only, "neutral" (31.5% to 38.0%) or "no different" in conditions (38.9% to 45.3%), was much lower. This indicates that the central three categories on the TS and TP scales are associated with acceptability rather than the central category only.

DISCUSSION

The I_{cl} values in winter were 0.1 clo lower than assumed typical of offices (ISO 1994), whereas the values in summer were 0.13 clo higher than usually assumed. The addition of 0.13 clo insulation from chairs would explain the higher I_{cl} in summer but not the lower value for winter. Thus, in winter, the buildings were warmer than necessary or perhaps clothing has changed over a period of years to the extent that temperatures have been raised to compensate. The difference is probably due to the fact that many of the office workers did not wear jackets (0.25 clo). Similarly, metabolic rate is traditionally considered to be 1.2 met in offices. However, the mean value of the offices surveyed was 1.25 to 1.27 met because the occupants spent some of their time moving around the office (e.g., filing, meeting colleagues). As previously demonstrated, these small differences in I_{cl} and M can have a large effect on the t_n. For example, under typical winter conditions, a change of 0.1 met is offset by 0.8°C (1.4°F), and a change of 0.1 clo is offset by 0.7°C (1.3°F). This adjustment to the optimum temperature (and set point) has potential implications for energy savings.

The air temperature and humidity were slightly higher on average and more varied in naturally ventilated offices in

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summer compared with air-conditioned offices. Consequently, the occupants of naturally ventilated offices in summer rated themselves as "slightly warm" (4.8) on average, whereas in winter and in air-conditioned offices in both seasons, the occupants voted closer to "neutral" (4.2). The difference of 0.6 scale units on the TS scale may seem small, but it was found to be equivalent to an offset in a neutral temperature of 2.3°C (4.1°C).

ISO 7730 and ASHRAE 55 are aimed at achieving thermal conditions that are acceptable to 90% of the occupants, which is equivalent to an observed or predicted rating on the TS scale of 3.5 to 4.5 (or –0.5 to +0.5 on the symmetrical scale). Any temperature that produces a TS vote within this range should in theory provide an optimum thermal environment. It is, therefore, feasible in air-conditioned offices to allow the room temperature to drift within this acceptable range without adversely affecting comfort. Relaxing the temperature control strategy in this way may create a wider system deadband, as the air-conditioned system does not need to "kick in" so frequently in order to maintain the wider temperature range. The relaxed control strategy will lead to savings in energy consumption and in some systems may reduce maintenance costs due to unnecessary system cycling. Furthermore, the observed wider acceptable temperature range in naturally ventilated offices shows that air conditioning may not be required as often as usually assumed and may only be necessary in climatic conditions more extreme than those found in the U.K.

In winter, the acceptable temperature range was 4.9°C (8.8°F) wide in naturally ventilated offices compared to only 2.6°C (4.7°F) in air-conditioned ones, despite more occupants in naturally ventilated offices finding the conditions acceptable. On first appearance, the acceptable temperature range was found to be similar in naturally ventilated and air-conditioned offices in summer, i.e., 3.9°C (7.0°F) to 3.3°C (5.9°F). However, only a few (4.9%) of the occupants in air-conditioned offices in summer were exposed to temperatures below 21.5°C (70.7°F) and above 28.5°C (83.3°F), and most of these were in one building that had a poor air-handling system. Excluding these occupants produced a relationship between TS and t_o similar to that found in winter and an acceptable temperature range of 2.4°C (4.3°F). These results confirm those found in previous studies, which compared comfort conditions in naturally ventilated vs. air-conditioned offices (see "Introduction").

The naturally ventilated occupants' acceptance of a wide range of temperatures indicates that control strategies in air-conditioned offices could be relaxed from the typical set-point temperature ±1°C (0.2°F) to up to ±2.5°C (4.5°F). However, this strategy will need to be verified in air-conditioned offices, as the naturally ventilated occupants' temperature tolerance may be due to behavioral and psychological factors, such as being more able to adapt to the temperature range or having a lower expectation of the building's climate control capability.

In winter, the observed neutral temperature in the naturally ventilated offices of 22.3°C (72.1°F) was 0.7°C (1.3°F) lower than that found in the air-conditioned offices. This is consistent with adaptive theory since it is argued that the occupants will adapt to cooler air temperatures (indoor and outdoor), and, therefore, t_n will be lower than found in tightly controlled environments with fixed set-point temperatures. Unexpectedly, in summer, the t_n in naturally ventilated offices of 21.1°C (70.0°F) was 1.8°C (3.2°F) lower than found in air-conditioned ones. This difference was exaggerated (2.1°C, 3.8°F) when excluding a poorly operating air-conditioned office and recomputing the regression analysis. In practice, any temperature between approximately 22.0°C (71.6°F) and 24.5°C (36.9°F) appears to provide acceptable conditions in air-conditioned offices in summer. The t_n for naturally ventilated offices in summer is also lower than that found in naturally ventilated offices in winter. This suggests that it is the responses in the naturally ventilated offices that are causing the unexpected results rather than the responses made in the air-conditioned offices.

One possible explanation for this result is that the offices were surveyed during a week when the outdoor temperatures were much hotter than in previous weeks, such that the occupants felt relatively much warmer. Furthermore, in summer, the indoor temperatures gradually increased during the week in naturally ventilated offices, whereas they were comparatively constant in air-conditioned offices. Thus, every day the naturally ventilated occupants were exposed to higher room temperatures and, therefore, rated themselves warmer than the day before. However, owing to the coarseness of the seven-point categorical thermal sensation scale, the occupants were able to indicate a slight increase in warmth only by rating one whole scale unit higher. Unfortunately, one unit was equivalent to 3.8°C (6.8°F); thus, the occupants overestimated their thermal sensation and, consequently, the computed neutral temperature was lower. Further evidence for this effect was produced by comparing the neutral temperatures computed from the occupant's first vote of the week with those based on their final vote. The neutral temperatures at the end of the week were 1.7°C (3.1°F) lower than at the beginning of the week. However, the mean thermal sensation vote only increased by 0.7 units from the beginning to the end of the week rather than the hypothesized one unit per day. Furthermore, the effect was also noticed in the naturally ventilated offices in winter. Nevertheless, this problem may be avoided by using continuous line scales in future studies.

An alternative explanation is that the occupants of naturally ventilated offices simply rated themselves differently to how they actually felt. This might be the case if the occupants were disgruntled with their thermal environment and thought that rating it worse than it really was, i.e., cooler in winter and warmer in summer, would result in some course of action to rectify the situation. The occupants did not realize that neutral temperatures would be calculated and that overestimating their thermal sensation would result in distorting the final

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value. Unfortunately, this hypothesis can not be fully tested with the data set as the level of complaints was not recorded. However, in summer, the percentage of occupants who rated the building acceptable was only marginally lower (4%) in naturally ventilated offices than in air-conditioned ones. Thus, there is a lack of evidence to support this hypothesis. This is fortunate because lack of validity in subjective responses would have serious repercussions for all conclusions based on occupant surveys. This anomaly requires further investigation, particularly if it is a statistical error or form of range effect caused by a repeated measures style survey.

The predicted thermal sensation was computed using Fanger's (1970) PMV model. The predicted mean vote was predicted for each type of office in each season by entering into the algorithm the overall mean of the six key thermal parameters into the algorithm, as suggested in ISO 7730. In addition, the predicted vote was computed for each individual by entering the conditions to which they were exposed at the time they completed the questionnaire. Both these predicted mean votes were then used to compute their corresponding neutral temperatures. The first observation is that the neutral temperatures predicted by these two methods differed by up to 2.8°C (5.0°F). The former method is that recommended by ISO 7730, but the latter method is more similar to the way that researchers derive the neutral temperature from the observed thermal sensation votes. There is, therefore, some inconsistency in the two approaches, but agreement between researchers and practitioners is required on the most appropriate one.

The predicted neutral temperature based on the mean environmental conditions was better at predicting the observed neutral temperature in naturally ventilated offices in winter and air-conditioned offices in summer, with errors of 0.3°C (0.5°F) and 0.4°C (0.7°F), respectively. The predicted neutral temperature based on the environmental conditions corresponding to each individual vote was better at predicting the observed neutral temperature in air-conditioned offices in winter, producing a 0.3°C discrepancy compared to 0.6°C (1.1°F) produced by the former method. Both methods produced large errors when attempting to predict the neutral temperature in naturally ventilated offices in summer, i.e., 3.0°C (5.4°F) and 3.7°C (6.7°F). This range of discrepancies in reported and predicted votes is quite similar to that reported by de Dear (1994). However, in the current study, it is not clear if the PMV model was simply not appropriate for naturally ventilated offices in summer, as suggested by de Dear, or whether the discrepancy was due to the anomaly in the weather and the resulting offset in the observed neutral temperature. However, in a preliminary analysis of the data set (Oseland 1997), the author found that Humphreys' (1978) adaptive model was more accurate in predicting the neutral temperature in naturally ventilated offices in summer. Humphreys' model is empirically derived from an analysis of worldwide field studies and predicts the neutral temperature from mean monthly outdoor temperatures.

CONCLUSIONS

The acceptable range of temperatures in naturally ventilated offices in winter and summer was wider than that found in air-conditioned offices by up to 2.5°C (4.5°F). It may, therefore, be possible to relax the temperature control strategy in air-conditioned buildings in order to conserve energy without causing discomfort. Furthermore, as occupants in naturally ventilated offices find acceptable a wider temperature range than previously assumed, then air conditioning may not be required as often as suggested and only be necessary in extreme climatic conditions. However, the effect of factors such as expectations and adaptive opportunities also need to be considered.

The neutral temperature in naturally ventilated offices was 0.7°C (1.3°F) lower in winter and 2.1°C (3.8°F) lower in summer than in air-conditioned offices. However, there was only a marginal difference in clothing insulation and activity levels between the two types of offices. The lower neutral temperature in naturally ventilated offices in summer may partly be an overestimation of warmth due to repeatedly assessing a steady increasing daily temperature. This statistical anomaly or range effect requires further investigation.

For the air-conditioned offices and naturally ventilated offices in winter, there was little difference in the observed neutral temperatures and those predicted by ISO 7730, with a maximum discrepancy of 0.6°C (1.1°F). Discrepancies of up to 3.0°C (5.4°F) were found between reported and predicted neutral temperatures in naturally ventilated offices in summer; however, it is unclear whether this discrepancy is partly due to an anomaly in the data collection.

In winter, the percentage of occupants satisfied with the temperature in the naturally ventilated buildings (76%) was higher than in the air-conditioned offices (70%), whereas, in summer, there was less satisfaction in the naturally ventilated offices (69%) than in the air-conditioned offices (73%). The occupants were less dissatisfied in the naturally ventilated buildings in winter than in summer, whereas there was only a marginal difference in dissatisfaction between seasons in the air-conditioned offices. In terms of thermal comfort, this study indicates a preference for buildings with natural ventilation combined with summer cooling.

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