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Authors

Arens, Edward A

Xu, T.

Miura, K.

et al.

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A study of occupant cooling by personally controlled air movement

Edward Arens^{*}, Tengfang Xu, Katsuhiko Miura, Zhang Hui, Marc Fountain, Fred Bauman

University of California, Berkeley, Dept. of Architecture, 390 Wurster Hall, Mail Code 1839, Berkeley, CA 94720-1839, USA

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Abstract

This study addresses the effectiveness of air movement cooling, an alternative to compressor-based cooling of the air itself. Subjects in an environmental chamber were exposed to a range of warm temperatures and allowed to adjust air movement to suit their individual preferences, while answering a series of questions about their comfort. Air movement was from the subject's side, in two modes of turbulent flow. The air speeds chosen by the subjects, and their subjective responses, are evaluated in the context of existing comfort standards and prediction techniques. Choosing air speeds up to 1.4 m/s, over 80% of subjects at 1.2 met were comfortable up to 29°C, and at 1.0 met up to 31°C. The cooling effectiveness was significantly affected by the nature of the turbulence. A zone is proposed within which personally controlled air movement provides a likely alternative to mechanical air conditioning. © 1998 Elsevier Science S.A.

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1. Introduction

When air movement cools the human body, it is possible to be comfortable at temperatures higher than the maximum comfortable temperature for still air. This underlies a number of energy-conserving measures applicable to the design and operation of buildings. Such measures were traditionally incorporated in the design of the building itself, where building form, room layout, windows and vents allowed the occupant to produce high rates of interior air movement when needed. Throughout the first half of this century, air movement was also promoted by mechanical devices such as whole-house fans, ceiling and room fans, and direct evaporative coolers, which typically produce substantial air movement as they cool.

The introduction of inexpensive air conditioning after WWII led to the displacement of such energy-efficient techniques. They can however still be very effective at reducing the need for compressor cooling, either for part of the cooling season or all of it. To encourage their reintroduction in common practice, some obstacles need to be overcome. One of the major ones is that it is impossible at this time to either design such measures, or assess the comfort they produce, to

the levels of certainty expected in heating, ventilating and air conditioning (HVAC) engineering today. This is due in part to insufficient knowledge of how elevated air speeds affect thermal comfort in warm conditions. Because drafts have traditionally been a major cause of HVAC complaints, most of the existing research on air movement has been done under cold-to-neutral conditions that may not be applicable to neutral-to-warm conditions. The relatively few studies of warm conditions in the literature have left questions in terms of their implementation in practice, or in thermal environmental standards. During the 1992 revision of ASHRAE Standard 55 [1] there was considerable disagreement about how to deal with the concept of cooling by air movement. ISO Standard 7730 [2] restricts allowable air movement to very low levels to ensure the avoidance of drafts.

A number of studies have examined air movement and comfort under warm conditions. Rohles et al. [3] exposed subjects to nine experimental combinations of air temperature and air speed within the ranges of 22.2° to 29.5°C and 0.2 to 0.8 m/s (all at 50% RH). They found strong relationships between air speed, air temperature, skin temperature and thermal sensation, but did not observe draft discomfort. The authors recommended an 'extended' summer comfort zone, extending to an upper air speed of 0.8 m/s, that became incorporated into ASHRAE Standard 55-81. A later study (Rohles et al. [4]) addressed the question of whether the 0.8

^{*} Corresponding author: Tel.: +1 510 6421158; fax: +1 510 6435571; e-mail: arens@ced.berkeley.edu

m/s limit was still applicable under the turbulent flow of a ceiling fan. The experimenters found that subjects considered air movement pleasant at levels beyond what had been previously considered reasonable (up to 1 m/s at 29.5°C). These results were closely matched in a study of comfort under both ceiling fans and whole-house fans by Spain [5]. He found that 0.25 m/s provided comfort to 27.8°C, while 1.0 m/s provided comfort to 29.4°C.

The Rohles ceiling fan study was repeated in Arizona by Schaezle et al. [6] who extended the test conditions to lower and higher relative humidities. They found the upper temperature limit of Rohles could be raised to 32°C at 39% RH, but must be lowered to 28°C at 73% RH. Wu [7] continued the Arizona study using oscillating room fans, and also found the acceptable zone to extend as high as 32°C at 40% RH.

Other experiments have given the subjects control over one of the environmental variables, allowing its preferred level to be detected for fixed levels of the other variables. Olesen et al. [8] allowed subjects at 0.6 clo to control the temperature to their preferred level while exposing them to a fixed horizontal air speed, finding a value of 27.5°C at 0.8 m/s. Burton et al. [9] exposed male subjects in shorts (0.3 to 0.4 clo) to temperatures ranging from 26.3 to 29.1°C, and a ceiling fan with a slowly increasing or decreasing fan speed. The subjects would throw a switch to reverse this change in the rotation rate of the fan whenever they preferred warmer or cooler conditions. In this way preferred air speeds could be approximated, as well as limits of acceptability (when the switch is thrown). They found the preferred fan speed at 29.1°C to be 1.2 m/s.

Acceptable air speed/temperature combinations may also be determined by fixing the temperatures and allowing the subjects to directly select the air speed that is most comfortable. Using this approach for a ceiling fan, McIntyre [10] found 28°C to be the highest comfortable temperature; at this temperature male subjects chose 1.4 m/s and females 1.0 m/s. Kubo et al. [11], tested female subjects (0.35 clo) in a wind coming horizontally toward the front of the subject. They found preferred velocities as follows: at 26°C, 0.6 m/s (for both 50% and 80% RH); at 28°C, 0.66 m/s (30% RH), 0.87 m/s (50%), and 1.02 m/s (80%); and at 30°C, between 1.06 and 1.27 m/s for 30 to 80% RH. At the preferred speed, the subjects' average thermal sensation was cooler than neutral, and their comfort sensation was positive, on the pleasant side of neutral. Subjects preferred a higher speed than predicted by the neutral condition for SET* (standard effective temperature) or PMV (the predicted mean vote).

Tanabe and Kimura [12] conducted similar preferred horizontal air speed tests at 50% RH, finding the preferred speed at 28°C to be 1.0 m/s, at 29.6°C, 1.2 m/s, and at 31.3°C, 1.6 m/s. They also examined various forms of fluctuating air movements across the range 27–31°C, finding that sine waves (with 10, 30, and 60 s cycles) produced significantly cooler thermal sensations at a given mean speed than did constant or step-change wind speeds.

2. Objectives

This study was planned to address the following issues.

The effectiveness of horizontal air movement at maintaining comfort in high air temperatures, up to 31°C. The source of such air movement might be a window or a fan.

The relative effect on comfort of 'naturally' fluctuating air speeds (such as may occur through a window) as opposed to more constant air speeds (as may be generated by an electric fan).

The effects of short bursts of activity, typical of a domestic or office setting, on comfort in warm environments where air-movement cooling is available to the occupant. This was to be compared to comfort under sedentary conditions, which has been the basis of all previous studies.

How to produce an average metabolic rate in the subjects that is the same as that assumed in the ASHRAE comfort standard (1.2 met). This had not been done before in chamber tests.

The risk that occupants will feel undesirable draft from the air movement in the 24 to 31°C temperature range.

If the air movement itself bothers the occupants under any of the conditions, to determine the nature of the complaints and their cause.

3. Methods

3.1. Overall approach

We decided to test clothing and activity levels as close as possible to those assumed in ASHRAE Standard 55. The Standard's activity level of 1.2 met was achieved by a combination of sitting and step-climbing activity. The subjects wore their own clothing, but were advised beforehand to wear ensembles approximating the 0.5 clo insulation specified for the ASHRAE summer comfort zone (equivalent to short-sleeved shirt and light slacks). The subjects sat on conventionally padded chairs, which were determined in manikin tests to increase the 0.5 clo clothing insulation to 0.73. The Standard does not discuss chair insulation, yet is surely intended to apply to people sitting in conventional chairs. So 0.73 clo is probably appropriate for testing the standard's summer comfort zone. Humidity was held as close as possible to 50% throughout. The tests were held in the summer, and the subjects started the tests close to thermal neutrality in order to simulate comfortable continuity, particularly in terms of their skin sweat content, and to counter the possibility of a comfort hysteresis effect in the experiment.

3.2. Test conditions

The controlled-environment chamber (CEC) used in these experiments is located at the University of California, Berkeley. It is described in detail by Bauman and Arens [13]. It measures 5.5 m × 5.5 m × 2.5 m, and is configured to appear

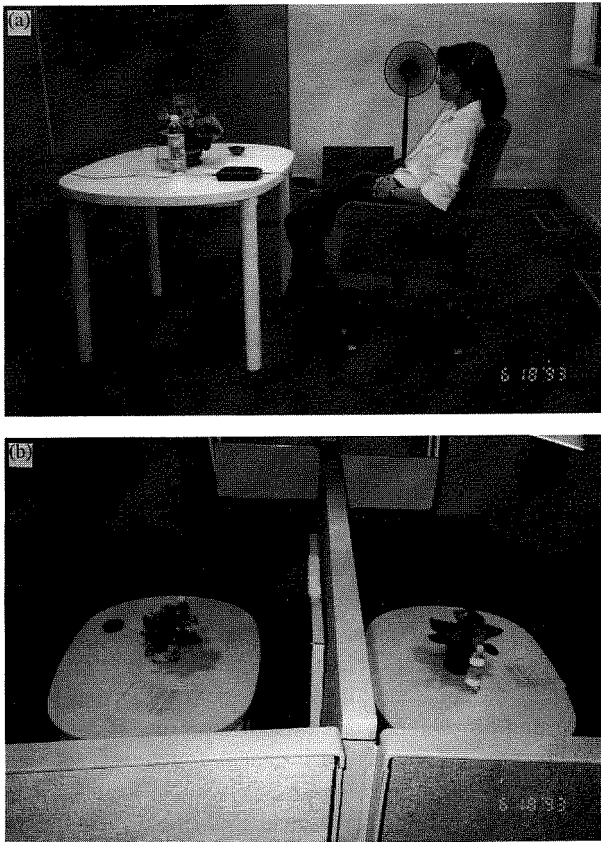


Fig. 1. (a) Experiment setup, with subject and fan. (b) Chamber configuration.

as a realistic residential or office space, to unconfound (at least partially) the psychological experience of being a human subject in a laboratory experiment. It has windows on two sides whose glass temperature can be controlled. In this experiment the glass temperature was held equal to indoor air temperature. A ceiling supply-and-return air distribution system was used to produce a uniform interior temperature with the lowest possible ambient air movement within the occupied zone.

Fig. 1 shows the experimental setup. A single partition divided the CEC in half with one subject occupying the south half and another subject occupying the north half of the chamber. Each part was furnished with a cafe-style table, flowers, a mineral water bottle and glass, a wall painting, and a selection of books and magazines, all of which were intended to create a home-like atmosphere. Both parts had views available to the outside. Each subject was seated at the table in a padded chair with armrests, representative of typical chairs used for sitting at a desk or table. The fan, a commercially available model, had built-in computer logic to produce a 'naturally fluctuating outdoor wind', as well as a more 'constant' fan mode. It directed air toward the subject's side from 2 m away, with its hub 90 cm above the floor. The observed velocity distribution of the fans was quite uniform within a range of 50 cm (knee height) and 130 cm (head height for a seated person).

Table 1
a. Fan speeds

Average fan speed (m/s)		
Fan level	Constant	Fluctuating
Off	0.05	0.05
1	0.33	0.45
2	0.63	0.55
3	1.04	0.74

b. Matrix of tests		
Air temperature	Constant mode	Fluctuating mode
≤ 25°C		12
26°C		12
27°C	8	12
28°C	12	13
29°C	10	14
≥ 30°C	12	14

Each subject had the choice of four fan speed settings in addition to 'off'. The settings were selected using a hand-held infrared remote controller, so the subjects did not need to leave their seats to make changes. The average velocity at the subject's seat is given in Table 1a. The experiment was conducted in two sections (Table 1b). A first group of subjects used only the 'naturally fluctuating' mode. A second group of subjects used only the fan's 'constant' mode, in which the inherent turbulence of the airstream was at higher frequencies than in the fluctuating mode.

Turbulence intensities between 50 and 130 cm height averaged 60% for both the fluctuating and constant fan speed modes. The average speeds produced by the constant speed mode were generally greater than those by the fluctuating speed mode (except at fan setting 1). Fig. 2 gives a spectral analysis of the air stream at the subject's position, measured at 90 cm above the floor. It represents the relative density of turbulent frequencies for the two modes. The constant speed mode has a higher proportion of turbulent eddies cycling in the 1 Hz (1 cycle/s) frequency band than is found in the fluctuating speed mode. Superimposed on the fan data are the frequency distributions for natural wind outdoors (ESDU, [14]). The closest fit to the constant-speed fan data is the curve for smooth rural terrain. The closest fit for the fluctuating mode is the curve for urban conditions; however the distribution is relatively filtered in the frequency range around 1 Hz. We hypothesize that the fan's fluctuating flow distribution would represent interior air flow near an open window better than would the constant mode, but have not systematically tested this.

3.3. Physical measurements

A mobile measurement cart was used for collecting physical environmental data during the tests. Although developed primarily for field work, the cart incorporates laboratory

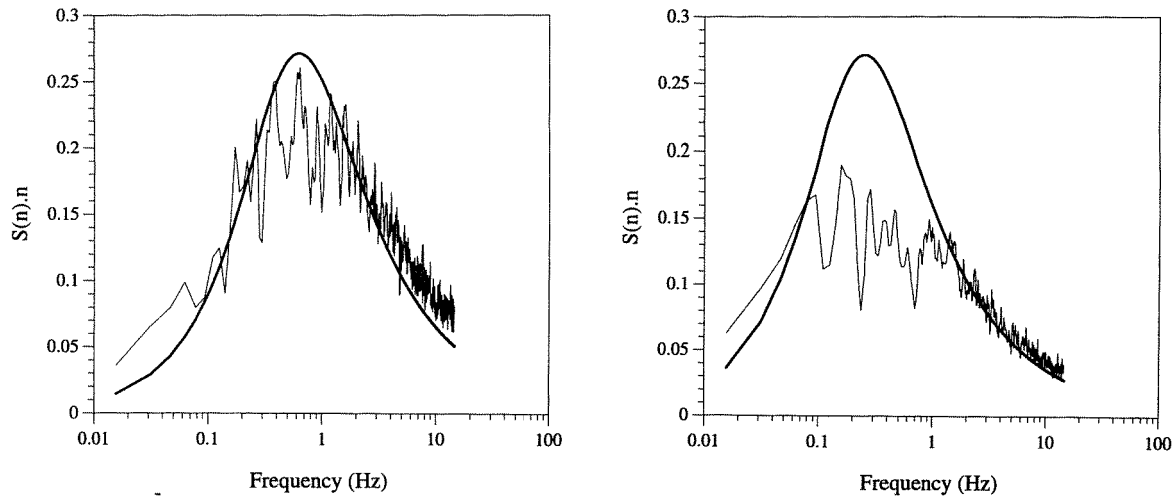


Fig. 2. Power spectrum: (a) constant setting, 200 cm from fan; (b) fluctuating setting, 200 cm from fan.

grade instrumentation and is useful for such experiments. See Benton et al. [15] for description of this instrument.

3.4. Survey instruments

Three approaches were used to elicit subjective responses. The first was a one-time background questionnaire asking demographic and general ‘preferred environment’ questions (Fig. 3a). The second was a ‘comfort’ questionnaire that was used repeatedly during the experiment to obtain current thermal sensation, thermal preference and other votes (Fig. 3b). Finally, general open-ended comments were solicited from the subjects just before they exited the chamber.

3.5. Experimental protocol

We recruited 119 subjects (57 female, 62 male) from the local community to participate in the experiment. Table 2 gives demographic and ethnographic statistics. The study was carried out in May–July during warm sunny weather. This was considered advantageous, in that the subjects would be acclimated to summer conditions like those being simulated in the controlled-environment chamber.

The protocol for both constant and fluctuating speed experiments was as follows. Upon arrival at the laboratory, the subject was assigned to one of the test stations in the chamber and given the background questionnaire to fill out. Since the laboratory chamber had been pre-heated to the test temperature, the subject was asked at the outset to adjust the air speed to continually maintain comfort while reading or doing paperwork. The subject was in the chamber for 80 min, adjusting the air speed for comfort as necessary, before the first set of physical measurements was made. During this period the subject performed a physical exercise every 10 min. The activity, walking up and down a step 12 times, maintained their metabolic rate at 1.2 met (or 70 W/m^2) when averaged over time (Fig. 4a).

After 50 min in the chamber, the subjects were asked every 20 min to fill out the comfort questionnaire. After the first 80

min, he/she rolled the chair away from the desk to allow physical measurements to be taken. The measurement cart was positioned where the subject had been sitting, and collected data for 5 min (Fig. 4b). When the measurements were complete, the subject returned to the desk for an exact repeat of the first 80 min, but this time without the step-climbing activity. This second period is characterized by a sedentary metabolic rate of 1.0 met (or 58.2 W/m^2). We analyzed only the last questionnaire for each activity level, the one just before the physical measurements were taken at the end of that level. This was done to assure that the subject had come to thermal steady state at the time of sampling. 1.2 met was always tested first to assure that 1.0 met was fully reached at the end of the whole experiment. Before leaving, the subjects were asked to write comments, if any, on any aspect of the experiment.

3.6. Design of the exercise routine

The first half of each test was designed to equal the metabolic rate of 1.2 met assumed in ASHRAE Standard 55. This represents a typical activity level found in office work, and probably represents average domestic activity as well. Since there does not seem to be a standardized approach to creating this particular metabolic rate in people, the following periodic exercise protocol was devised.

The subject’s exercise protocol involved getting up from his/her seat once every 10 min, moving to a nearby 0.2 m step, and stepping up and down 12 times. The subject then returned to his/her seat. This is roughly equivalent to going up and down a residential flight of stairs every 10 min, with sedentary spells in between. The metabolic activity generated by this exercise is estimated as follows (assuming a muscular efficiency $\eta = 15\%$ for a person’s weight of 70 kg).

Extra-body work for each 12-step exercise = $70 \text{ kg} \times (0.2 \text{ m/step} \times 12 \text{ steps}) = 168 \text{ kg m}$.

The energy consumed for each exercise = $\text{work}/\eta = 168 \text{ kg m}/0.15 = 1120 \text{ kg m}$.

(a) Comfort Study ——— Background Survey

Please fill out both pages of survey completely. If you have any question about the form, please feel free to ask the researcher.

Background Characteristics

1. Name: _____
2. Date: _____
3. Phone number: _____
4. Home zip code: _____
5. How long have you lived in the Bay Area? _____
6. On the average, how many hours per day do you spend inside your home on working days? _____
7. On the average, how many hours per day do you spend inside your home on weekends or non working days? _____
8. What is your approximate height? _____ Feet _____ Inches
9. What is your approximate weight? _____ Pounds
10. What is your age? _____ Years
11. Your sex?
 1 Male
 2 Female
12. Your ethnic background?
 1 Asian American
 2 Black
 3 Caucasian
 4 Hispanic
 5 Other (please specify: _____)
13. Is English your primary language?
 1 Yes
 2 No
14. How many cigarettes do you smoke per day? _____ Cigarettes
15. How many cups of caffeinated beverages do you drink per day? _____ Cups per day
16. How many hours do you exercise per week? _____ Hours

(b) Comfort Study ——— Questionnaire

1. Please write down the time: _____
2. Please check () the box that best describes your present Thermal Preference:
 I want to be warmer
 I want no change
 I want to be cooler
3. Please check () the box that best describes your present Air Movement Preference:
 I want less air movement
 I want no change
 I want more air movement
4. Please tick (✓) the scale below in the place that best presents your Overall Thermal Sensation at this moment:

 -3 -2 -1 0 -1 -2 -3
 COLD COOL SLIGHTLY COOL NEUTRAL SLIGHTLY WARM WARM HOT
5. Please check () one box that best describes your Present Feeling in each of the five different parts of your body shown on the following figure:
 (A) Head comfortable
 warmer than comfortable
 cooler than comfortable
 (B) Left upper part comfortable
 warmer than comfortable
 cooler than comfortable
 (C) Right upper part comfortable
 warmer than comfortable
 cooler than comfortable
 (D) Left lower part comfortable
 warmer than comfortable
 cooler than comfortable
 (E) Right lower part comfortable
 warmer than comfortable
 cooler than comfortable
6. Does the present rate of air movement bother you in any way?
 1. Yes
 2. No
 If yes, how? (please don't include any influence of fan noise in your response) _____

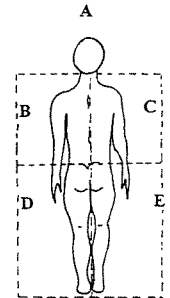


Fig. 3. (a) and (b).

Table 2

a. Subjects' demographic statistics

	Age (yr)	Height (m)	Weight (kg)	Years in bay area
Average	24.3	1.70	64.3	5.5
Maximum	52.0	1.93	95.5	52.0
Minimum	18.0	1.52	45.5	0.02
Stdev.	6.3	0.09	11.1	7.4

b. Subjects' ethnic composition

Ethnicity	Number	Percentage
Asian	33	28%
Black	4	3%
Caucasian	52	44%
Hispanic	10	8%
Other	20	17%

The thermal equivalent for each exercise = 1120 kg m × (0.002724 W h/kg m) = 3.05 W h.

The total energy for six exercises/h = 3.05 W h × 6/h = 18.3 W

At 1.8 m² average surface area, 1 met (58.2 W/m²) is equivalent to 104.8 W. Adding the energy associated with climbing, the average metabolic rate = ((104.8 + 18.3)/104.8) met ≈ 1.2 met.

Two additional points might be made. First, the ASHRAE Handbook of Fundamentals [16] suggests subtracting out the mechanical work done from the metabolic heat generated in rising treadmill types of tests. By *not* subtracting it out for the rising steps, we should be accounting for the heat that is subsequently liberated in the body by the down-steps (mechanical work done *on* the body). This is probably the most realistic way to treat the down-steps that are part of the round trip of climbing stairs. Second, the initial getting up from the chair (and sitting down again) should be equal to one or two steps' worth of exercise.

This turned out to be a very convenient type of exercise for the subjects in the chamber. In a subsequent project, we measured the oxygen consumption of subjects performing the step exercise, and found that the above estimate of metabolic rate was very close when averaged over the 10 min period. The instantaneous rate ranged between 1.75 to 1.0 met within the period (Bauman et al. [17]).

4. Results

4.1. Thermal sensation

Fig. 5a shows the percentage of subjects (at 1.2 met activity) voting in each thermal sensation category in the fluctu-

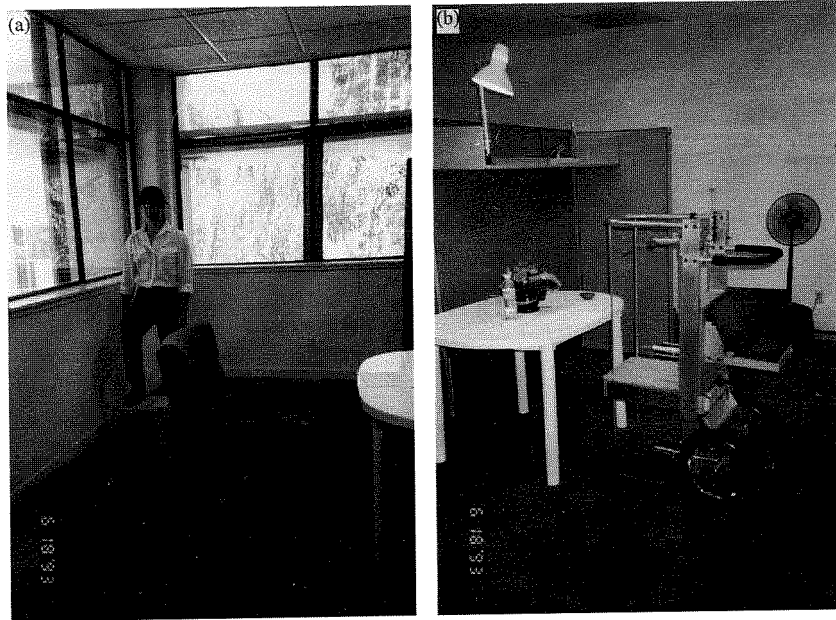


Fig. 4. (a) Subject performing step exercise. (b) Physical measurement at 80 and 160 min.

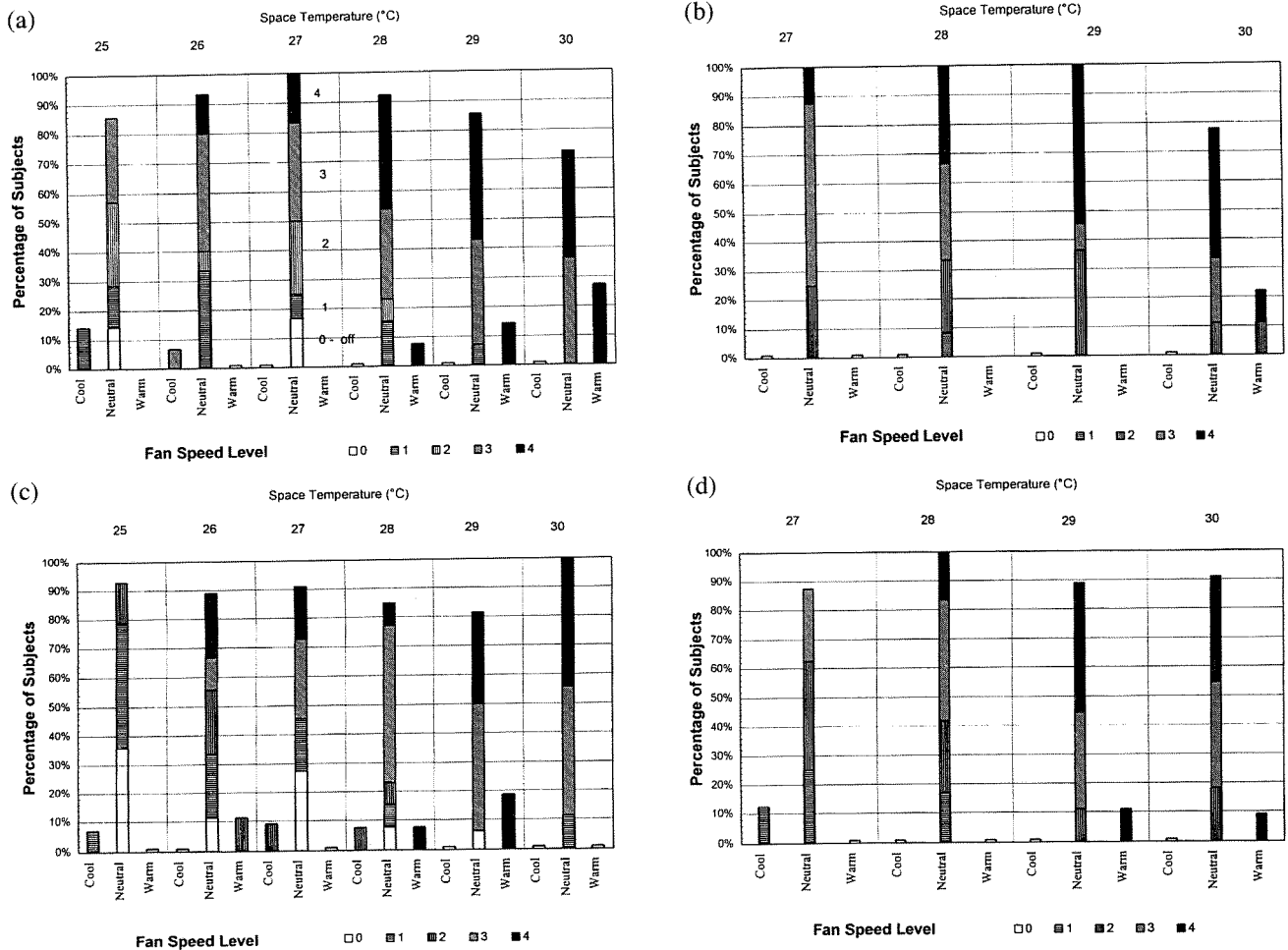


Fig. 5. Thermal sensation in each temperature range: (a) 1.2 met, fluctuating fan mode; (b) 1.2 met, constant fan mode; (c) 1.0 met, fluctuating fan mode; (d) 1.0 met, constant fan mode.

ating mode experiments. The category ‘neutral’ includes all thermal sensation votes from ‘slightly cool’ to ‘slightly warm’ (truncated within ± 1.5 on the continuous seven-point scale). This neutral sensation category has in the past been deemed equivalent to ‘thermally satisfied’ in producing both the PPD in the ISO comfort standard [2], and the comfort zone in ASHRAE Standard 55 [1]. Below the 27°C bin (26.49–27.5°C), two subjects registered votes below neutral, even though their fans were on. For 27°C all subjects were in the neutral category while selecting a full range of fan settings, half of which were at levels 3 and 4. By 28°C, 92% were in the neutral category, with 8% on the warm side. 85% of the fan settings were at levels 3 and 4. At 29° and 30°C virtually all subjects were using levels 3 and 4, and 14% and 28% respectively were voting ‘warm’ while at level 4, the top available speed.

Fig. 5b shows results for the constant mode at 1.2 met. Up through 29°C, all subjects rated the environment as neutral. At 30°C, however, slightly over 20% found the environment more than ‘slightly warm’. The constant speed mode was more successful at cooling than the fluctuating speed mode, mostly because the fan’s fluctuating mode has a lower top speed.

Fig. 5c and d present the same data for the sedentary 1.0 met activity. Under these conditions the proportion of neutral responses was somewhat less than at 1.2 met, largely because of votes in the ‘cool’ category. Since the cool votes came at substantial air movements selected by the subjects, one must conclude that the subjects considered them desirable. It is clear that under sedentary conditions, both fans provided more than 80% of the subjects with neutral thermal sensations for all temperatures.

Fig. 6 presents the final physical condition selected by each subject together with his or her simultaneous thermal sensation vote, arranged in the categories described above. The mean speeds associated with each of the four fan speed settings in the constant and fluctuating modes are seen to be different, allowing the various settings and modes to be observed separately. In fact, ‘c3’ and ‘f4’ happen to have the same mean value; we have exaggerated the spread between them to allow them to be identified.

4.2. Thermal preference

Fig. 7 presents the subjects’ thermal preferences (‘I want to be warmer, cooler, no change’) in the same format as Fig. 6. The thermal preference scale inherently produces more ‘non-neutral’ responses than the thermal sensation scale represented in Fig. 6. In offices, even at the neutral temperature, 40% of a typical population will be outside the ‘no change’ category, with half preferring conditions to be warmer and half cooler (Schiller et al. [18]). In comparison, at temperatures above 28°C in this experiment, 44% of all subjects at 1.2 met ‘wanted to be cooler’ while 6% wanted to be warmer; 22% of all subjects at 1.0 met wanted to be cooler while 4% wanted to be warmer.

4.3. Air movement preference

Fig. 8 presents the subjects’ air movement responses in the same format. The desire for *more* air movement is scattered rather broadly on both axes of the graph. It was expressed more often for the fluctuating mode than the constant mode. A preference for more air movement might suggest that the fan was incapable of providing more air. It might also suggest that the subject set the fan at a level that was the maximum acceptable for other reason (such as noise or distraction), and that this level was insufficient to provide the necessary cooling. These fans provided somewhat lower maximum speed than in Kubo’s and Tanabe’s experiments, where higher speeds were selected by the subjects. The desire for *less* air movement appears on the figure in two general locations: for the lower temperatures in the 1.2 met tests, and for subjects in the highest temperatures at either activity, who were choosing the highest speed settings.

4.4. Perception of air movement

The direct perception of air movement also affects comfort and the effectiveness of the air movement cooling. Roughly 35% of the subjects overall reported that they were ‘bothered by air movement’ at least in one of the repeated comfort questionnaires. The majority of these reports were found at the higher temperatures, where the fan speed setting was usually either 3 or 4. Interestingly, the ‘bothered’ comments have a strong tendency to come at the beginning of the experiment, when the metabolic activity is higher. The majority of comments *improved* as the experiment went on, dramatically so with the constant speed mode. This is significant because initial sensations like ‘dry eyes’ and ‘one side is cold’ got better with time rather than worse. The fluctuating mode did not improve as much over time. Comments on the fluctuating airflow cited ‘surges’, ‘inconsistency’, ‘gusts’, ‘distraction’, and ‘blowing papers’; a small number were favorable saying the wind felt ‘natural’ or ‘like out of doors’.

This picture is supported by the exit comments. In these, 18% of the fluctuating and 10% of the constant mode subjects made comments that could be construed as critical of the air movement. This is notable in that the constant experiments were done only at higher temperatures. The highest temperature where favorable comments about fluctuating air flow were recorded was 27.4°C and the lowest temperature where unfavorable comments about fluctuating air flow were recorded was also 27.4°C.

It is also interesting that more subjects in the constant mode experiments mentioned thermal asymmetry than in the fluctuating mode. The fluctuations might have the effect of reducing the subjects’ perception of the asymmetry. On the other hand, the result may be due to the lower mean speeds provided in the fluctuating mode. There was no significant difference in the air movement preferences between subjects who reported differences in thermal comfort votes for the different parts of their body and those who did not.

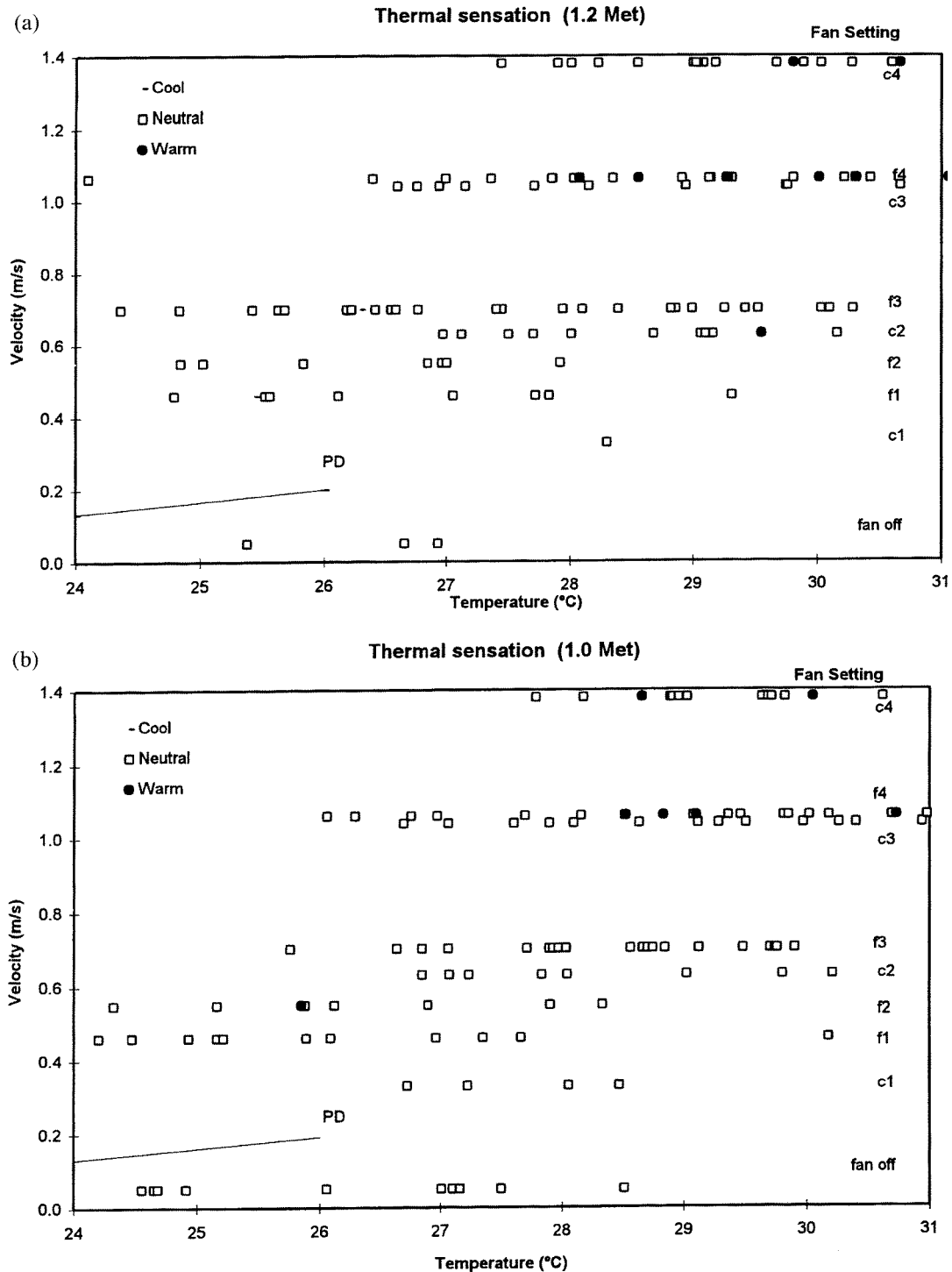


Fig. 6. Thermal sensation: (a) 1.2 met; (b) 1.0 met.

Some subjects commented on controllability of the fan in the constant fan speed mode. One reason given was that there was big difference in average speed between level 3 and level 4. Lack of controllability was also cited at the highest temperatures, when the fan provided insufficient cooling even at level 4.

4.5. Sensations on different body areas

The subjects considered their head area the coolest overall. This might be expected since the head is unclothed, is immersed in the strongest airstream, and has the highest skin thermal sensitivity. There was a difference in perceived tem-

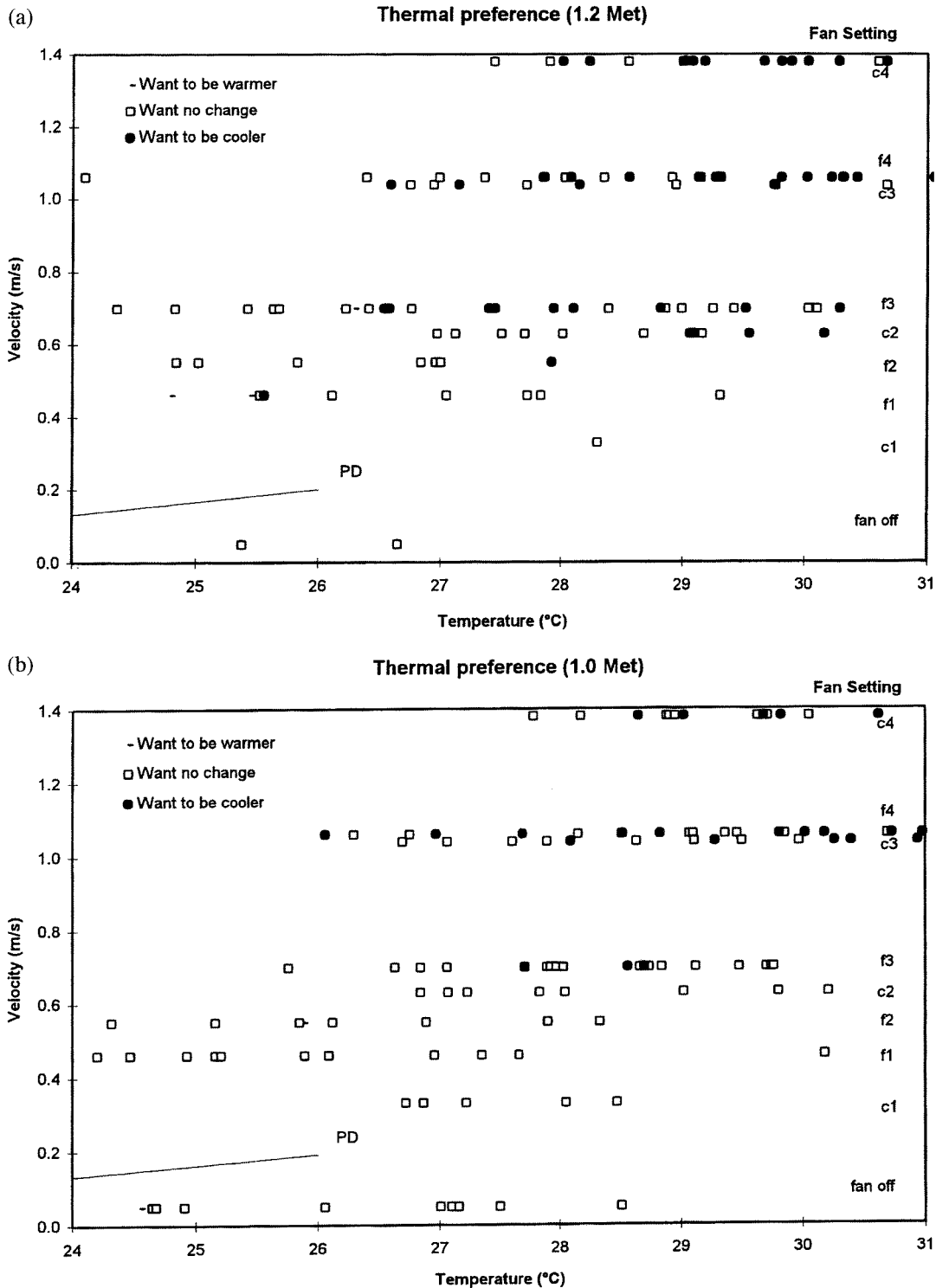


Fig. 7. Thermal preference: (a) 1.2 met; (b) 1.0 met.

perature between the lower body and upper body, with the lower body being perceived as the warmer. Since thermal environments that produce a cool head and warm feet are generally preferred and sometimes difficult to obtain with a conventional air conditioning, the test conditions might be considered a favorable ventilation arrangement.

By calculating the percentage of people in each temperature bin who perceived a side-to-side thermal comfort difference, we find thermal asymmetry at low temperatures and low air speeds (a perception of draft), and at the high temperatures and air speeds. Asymmetry was noted predominantly for the upper body segments. Table 3 combines the

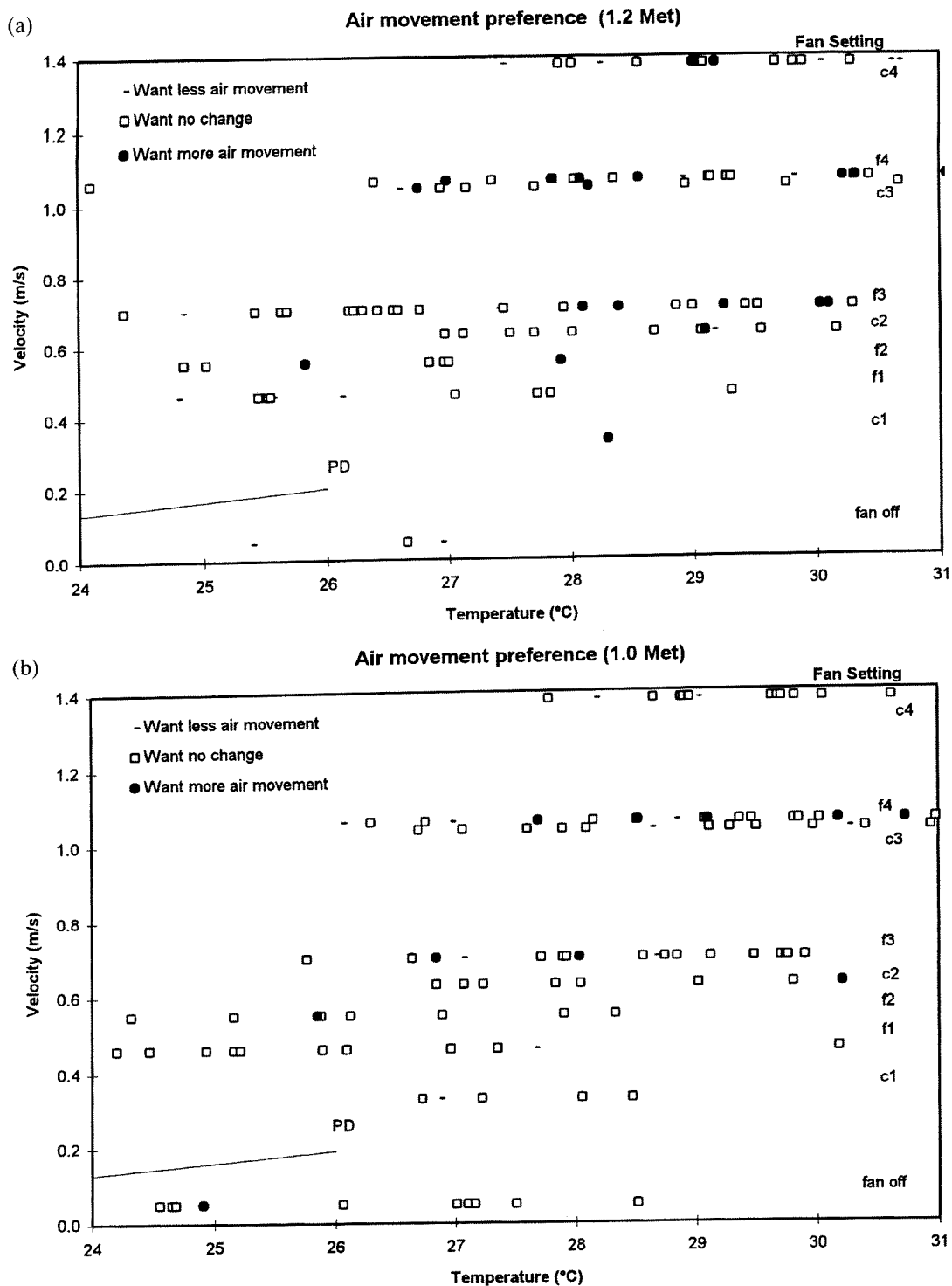


Fig. 8. Air movement preference: (a) 1.2 met; (b) 1.0 met.

subjects' votes on air movement preference (want less, no change, more), and whether the air movement bothers them in any way, for those who observed a side-to-side asymmetry in comfort versus those who did not. Among those people who did not want to change air movement, 76% found their

comfort symmetrical, and the portion of these who were 'not bothered' was much higher than of those who found it asymmetrical. Of those who wanted *less* air movement, most were 'bothered', whether or not they felt symmetrical. Of those calling for *more* air movement, one-half felt 'bothered' but

Table 3
Effects of comfort asymmetry on air movement perception and preference

Air movement preference	Asymmetric		Symmetric		Subtotal	Total
	Bothered	Not bothered	Bothered	Not bothered		
<i>Upper part of body</i>						
Want less air movement	44%	3%	44%	9%	100%	36
No change	7%	16%	12%	64%	100%	164
Want more air movement	12%	18%	38%	32%	100%	34
<i>Lower part of body</i>						
Want less air movement	17%	0%	72%	11%	100%	36
No change	2%	7%	18%	73%	100%	164
Want more air movement	6%	12%	44%	38%	100%	34

among this half a majority felt symmetrical. Asymmetry was thus not the dominant factor for ‘bother’ at high air speeds. A similar pattern was found for the lower half of the body.

5. Analysis

5.1. Comparison with computer comfort model results

The indices TSENS (Gagge et al. [19]) and PMV (ISO [2]) have scale values equal to the thermal sensation scale used on the comfort questionnaires. The indices were computed for each subject’s exposure and compared to the votes measured by the questionnaires. 9.2% of the votes (in both the fluctuating and constant tests) were outside the neutral band of ± 1.5 thermal sensation. In comparison, the TSENS model predicted only 0.4% to be outside of ± 1.5 , while the PMV model was very close with 9.7%.

The experimental results may also be compared to the comfort zone extension shown in Fig. 3 of ASHRAE Standard 55-92. Since the boundaries of the comfort zone are also ± 1.5 thermal sensation boundaries, one can compare the percentage of test conditions falling outside the boundaries of the comfort zone with the percentage of people who voted outside ± 1.5 thermal sensation. The curves in ASHRAE’s Fig. 3 are started from 26°C ET* to make the warm boundary of the summer comfort zone, and from 23°C ET* to make the cold boundary. In both the 1.2 met and 1.0 met tests, 4% of this experiment’s total subjects were to the outside of the cold boundary of the comfort zone, and of the rest 38% and 47% respectively were outside the warm boundary. If one includes on top of this the limit of 0.8 m/s recommended by the Standard 55 as the maximum air speed or sedentary activity, the percent of subjects outside the comfort zone climbs to 68% at 1.2 met, and 75% at 1.0 met. If one assumes from the definition of the comfort zone that at least 20% of any subjects outside the comfort zone *must* be dissatisfied, a minimum of 14% of the total subjects at 1.2 met should be dissatisfied, and 15% at 1.0 met. Since the experiment found 9.2% dissatisfied, the Standard 55 comfort zone (and its extension) overestimates the discomfort reported by the sub-

jects. If one removes the 0.8 m/s limit, the comfort zone might approximate the results of this study.

5.2. Comparison with the draft limit

Figs. 6–8 show the speeds chosen by the subjects under various temperatures, including those covered by the draft limit (Fanger et al. [20]) that has been incorporated into ASHRAE 55-92. This limit, labeled ‘PD’ is shown for comparison on the figures (speeds above the line are to produce more than 15% of subjects uncomfortable due to draft). Clearly, the speeds chosen by the subjects exceed the allowable limits in the great majority of cases, including cases where they register being cool. The draft limit is however designed only to protect the most draft-sensitive 15% of the population, and in this experiment the number of subjects choosing speeds below the limit does approximate 15%.

5.3. Analysis of thermal sensation, thermal preference, and air movement acceptability

Fig. 9 plots thermal sensation as a function of air temperature, with a slope (for 1.2 met) of one scale value of thermal sensation to 3.7°C of air temperature. At 1.0 met, one thermal scale value spanned 6.5°C. 3°C per scale value is a typical value for this slope found in most field and laboratory studies of thermal comfort near the center of the comfort zone (without the subject having control of air movement). The flatter slopes observed in this study show that people can widen their comfort zone with air movement that is under their control. The neutral temperature of the regression was 25.5°C for 1.2 met activity, and 27.3°C for 1.0 met.

In Fig. 10, the regressions of chosen air speeds against air temperature are shown for subjects pooled by acceptable thermal sensation (± 1.5), thermal preference (want no change), and air movement preference (want no change). The three lines are very close, indicating the similarity of the dependence of preferred air speed on air temperature for subjects that were comfortable. On average, these subjects tended to increase the air movement approximately 0.1 m/s per 1°C temperature rise.

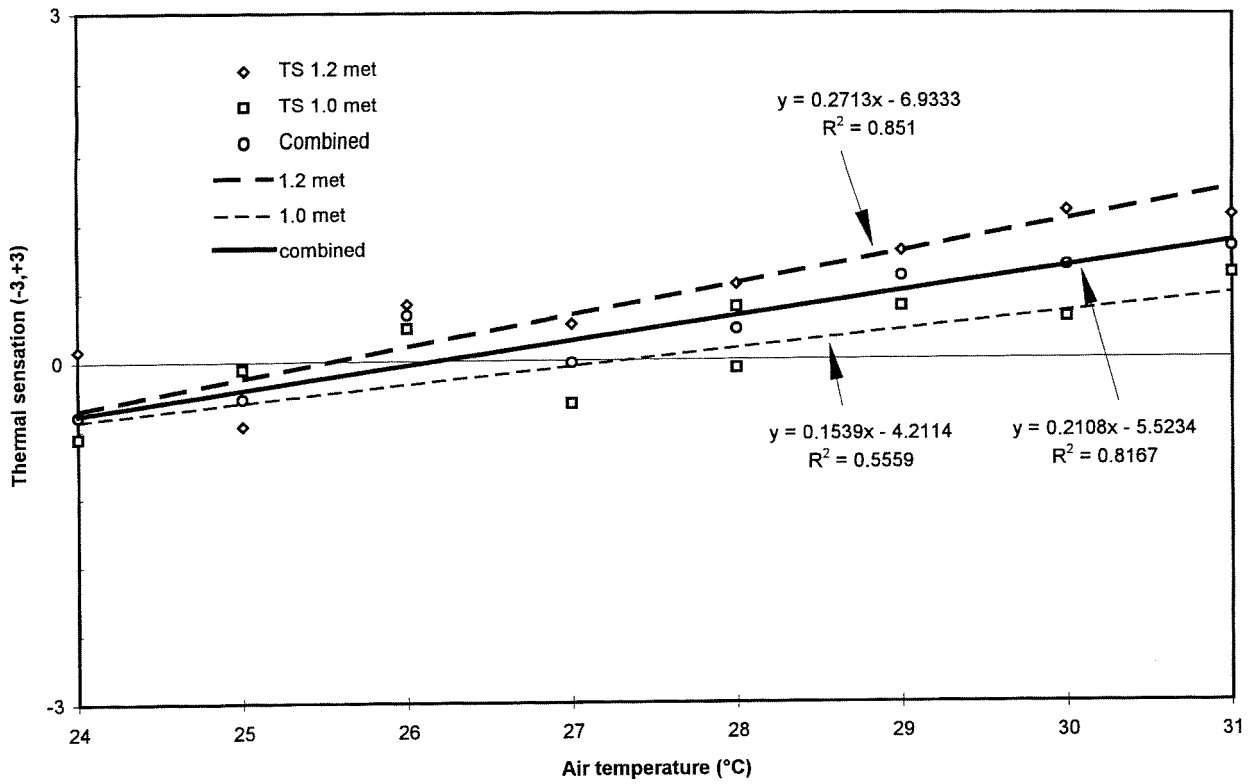


Fig. 9. Thermal sensation.

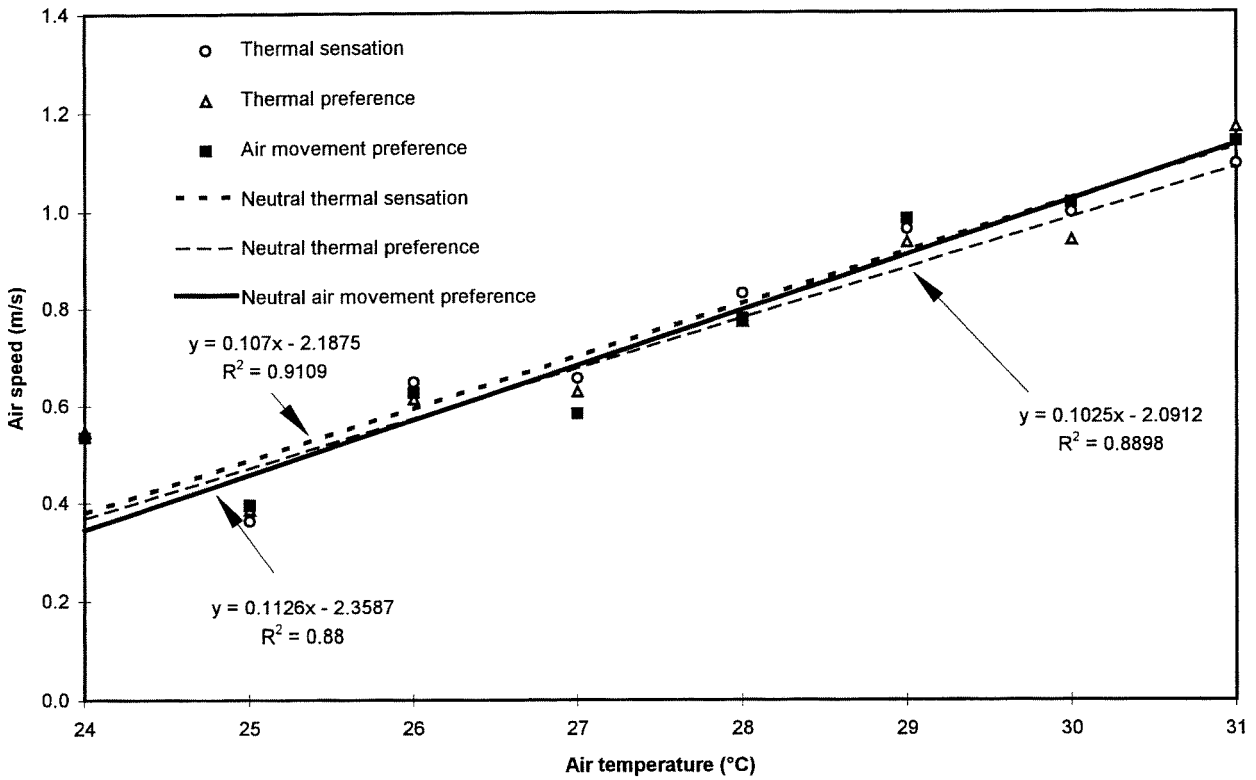


Fig. 10. Preferred air speeds.

Table 4
Significant differences between groups

Group	Subjective votes	Comparison	Test of significance	<i>P</i> -value of significance
Gender	Air movement preference	Males (want more air movement)	Mann–Whitney	< 5%
met	Thermal sensation	1.2 met (feel warmer)	T-test	< 1%
met	Present feeling	1.2 met (feel warmer than comf.)	Mann–Whitney	< 2%
met	Thermal preference	1.2 met (want to be cooler)	Mann–Whitney	< 1%
met	Measured air speed	1.2 met (air speed higher)	T-test	~ 10%
met	Air movement accept.	1.2 met (fewer vote acceptable)	Mann–Whitney	< 5%
Mode	Measured air speed	Constant (air speed higher)	T-test	< 5%
Mode	Air movement preference	Fluctuating (want more air movement)	Mann–Whitney	< 5%

5.4. Significant differences between groups

Tests were done to determine whether significant differences existed between groups and categories in the experiments. *T*-tests were used for continuous variables such as thermal sensation votes and measured air movement, and Mann–Whitney's test was used for the category variables such as thermal and air movement preference, fan setting, present feeling, and air movement acceptability. The groups that yielded significant differences were gender, metabolic activity level, and whether a constant speed or fluctuating fan was used. Table 4 shows the groups, the parameter that separated the groups, which group yielded the higher parameter value, the test used, and the significance level.

HVAC engineers commonly note that females feel drafts and complain about them more often than males. The data from Table 4 suggest that females also prefer less air movement to be comfortably cooled at elevated temperatures. In general, higher metabolic activity produced for both genders the desire for lower temperature and increased air movement.

While we do not see significant difference in the measured air speed for the two metabolic rates (*P*-value of 10%), we see that the air movement acceptability was significantly higher at 1.0 met than 1.2 met (*P*-value < 5%). This may indicate that although the variation of subject-preferred speed was wide within each activity level (see also Figs. 6–8), there was a tendency for subjects at 1.0 met to select lower fan settings. Given the freedom to adjust air movement, fewer subjects felt bothered by the air movement at 1.0 met.

5.5. Constant vs. fluctuating mode

The comparison of the constant and fluctuating speed modes is not straightforward. The subjects with the fluctuating mode chose lower speeds than those with the constant mode (*P*-value < 5%), which may simply result from the fluctuating fan's lower mean speed at high settings. This interpretation is supported by the observation that people who were using fluctuating fans stated a preference for more air movement more often than those who were using constant speed fans (*P*-value < 5%), and also tended to feel warmer.

On the other hand, this effect might have occurred because the speed fluctuations were irritating to subjects, causing them to limit for non-thermal reasons the air movement that they

need to remain comfortable. This is supported by the number of subjects who criticized, in both the comfort survey and the exit survey, the large abrupt speed increases that occur in the fan's fluctuating mode.

Finally, comparison of the constant mode and fluctuating mode at the same mean wind speed (c3 versus f4) shows that the constant mode cools better. This could be explained by the relation between the peak turbulent frequencies of the two modes and the peak sensitivities of warm and cold receptors in the skin. The constant speed mode of the fans produced a power spectrum peaking between 0.7 and 1 Hz, while the fluctuating speed fans produced peaking frequencies around 0.2 to 0.4 Hz (Fig. 2). The higher frequencies produce greater cooling sensation because cold receptors in the skin are closer to the surface than warm receptors (0.2 versus 0.5 mm), and therefore respond to transients more readily. Ring et al. [21] modeled sinusoidal stimuli applied at skin surface under different frequencies (ranging from 0.001 to 100 Hz), predicting peak sensitivities for the cold receptors around 1 or 2 Hz, and around 0.2 Hz for the deeper warm receptor.

5.6. The zone of likely use

A 'zone of likely use' (ZLU) is proposed in Fig. 11 for locally controlled air movement in a residential setting, where activity levels might vary between 1.0 and 1.2 met. The concept is intended to define the conditions within which fans or naturally-produced air movement will cause a substantial fraction of occupants to be sufficiently comfortable that, given the choice, they might be expected to rely on air-movement cooling rather than resort to air conditioning. It approximates 80% acceptability based on the ± 1.5 thermal sensation criterion, depending on the mix of activity levels. It also approximates the same percentage of neutral thermal preference responses that we find in office building field studies, depending again on the mix of activities expected. Although males tended to prefer more air speed than females, the zone applies to both genders. It should be valid for time spans of at least 3 h, the duration of these tests.

Fig. 11 includes for comparison two air movement recommendations drawn from existing literature on thermal comfort, Schaetzle et al. [6], and Fountain et al. [22]. The zone from Schaetzle is very close to the ZLU at the warm side, but the ZLU extends one degree to the left on the cold

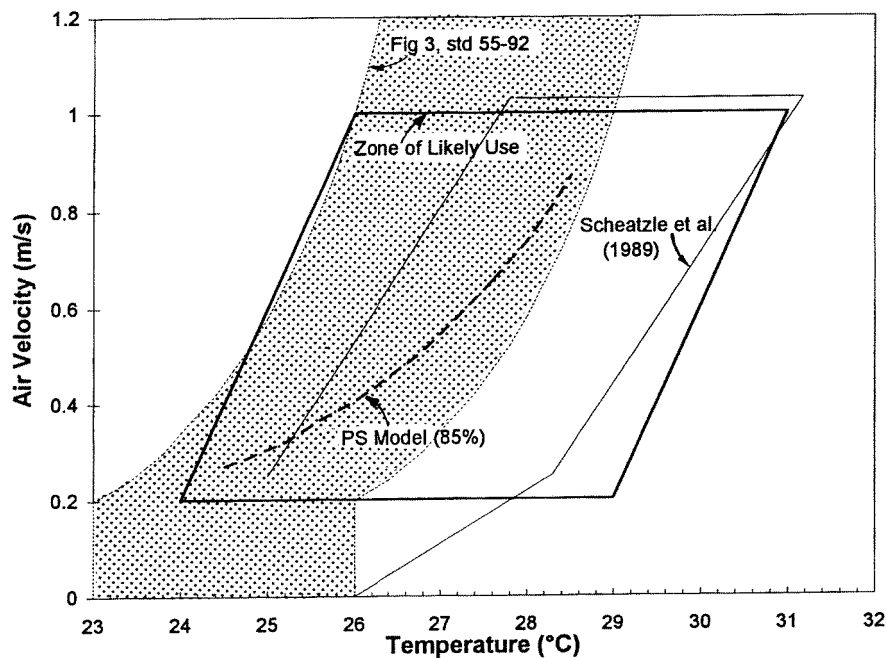


Fig. 11. 'Zone of likely use' compared to other comfort zones.

side, since we observed subjects using fans throughout that region. The Schaeztle zone is quite similar to the others by Rohles and Wu (not shown). The PS ('percent satisfied' index) from Fountain, representing 85% satisfied below the curve, cuts across the left third of the ZLU. The speeds referred to by the PS index are for air jets that are more local on the body than the air movement produced by the fans in this experiment or by the ceiling fans in Schaeztle's. They may therefore be expected to have lower acceptable maximums than those in this experiment, where the moving air covered larger parts of the body. Taken together, these studies are in reasonable accordance with the zone's boundaries.

A similar zone might apply to the design of task-ambient air conditioning in offices, although for workers at a steady activity of 1.2 met the maximum would likely be less by 1 or 2°C. This would depend on the turbulence and directional characteristics of the airflow produced by the specific task-ambient system. For the particular airflow configuration in this study, in both turbulence modes, the highest acceptable temperature at a fixed 1.2 met would be 29°C.

6. Conclusions

In conclusion, it is possible to maintain comfortable conditions up to 31°C (1.0 met) and 29°C (1.2 met) if air speed of 1 m/s or greater is available over the upper body. The zone within which substantial numbers of subjects at both activity levels were comfortable was put into a 'zone of likely use' for fans, in which residential occupants with a choice of air conditioning could be reasonably expected to use economical air movement cooling instead of air conditioning. This zone matches the findings of previous laboratory studies of ceiling

fans and oscillating fans. However, in an office setting where continuous activity levels of 1.2 met may be prescribed by the work, these data do not support the zone extending beyond 29°C. It may be possible to raise this limit by providing more effective air movement to the occupant than the configuration tested in this study.

Because these fans provided a lower maximum air speed over a more confined body area than the fans used by Kubo et al. and Tanabe et al., there is a higher percentage of subjects voting warm and preferring more air movement than reported from their studies. In this respect these tests are conservative. They are also conservative for simulating residential occupants because they forced the subjects to be in a fixed orientation relative to the air flow throughout the test. The freedom to move one's position could have alleviated some of the discomfort symptoms reported (assuming the air movement to be available throughout the space). This may not be a conservative assumption for offices, however, since people often cannot change their position.

The fluctuating fan produced significantly more 'bothered' responses, both in the surveys and in the exit comments. Distraction, disturbed hair, and eye irritation were noted, the latter presumably due to shortened eye-film breakup time. Given that the 'constant' speed mode in fact fluctuated to a similar extent as the fluctuating mode but with less abrupt swings from extreme to extreme, it appears that the nature of the fluctuation is important. This supports findings by Tanabe and Kimura [12] that fluctuating fan controllers should provide smooth sinusoidal transitions.

The effects of metabolic rate are noticeable in the results, with higher cooling rates demanded of the fans at 1.2 met versus 1.0 met. An exercise method was devised to simulate the 1.2 met rate of Standard 55. This procedure, based on an

assumption of 15% muscular efficiency, was supported by respired oxygen measurements. It simulates the realistic effect of climbing a flight of stairs, or of getting up and moving about, and is practical to administer in the laboratory.

Thermal sensation increased one scale value for each 3.7°C temperature rise at 1.2 met, and 6.5°C at 1.0 met. The typical slope for near-neutral environmental conditions observed in field studies is 3°C per scale value. There is therefore a wider comfort zone when air movement is under occupant control. Subjects experiencing comfort in this study increased the air movement 0.1 m/s per 1°C temperature rise. The three comfort rating indices performed very similarly.

The neutral temperatures in this study were found to be 25.5°C for 1.2 met activity, and 27.3°C for 1.0. Both values are approximately 2°C higher than their corresponding still-air values for equivalent clothing, as found in field and laboratory studies.

The study supports the finding of Tanabe et al. and Kubo et al. that calculated SET* values for temperature-speed combinations that subjects select and rate as thermally neutral are higher than 26°. Tanabe suggested the predicted values might be lowered the correct amount by adjusting the minimum skin wettedness parameter from 0.06 to 0.03 to represent the drying effect of air movement. We have not yet examined this suggestion using these data.

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