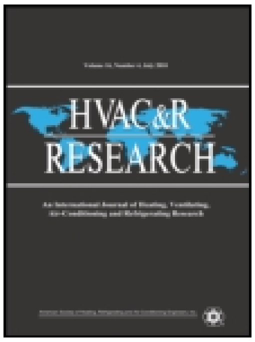

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The Acceptable Air Velocity Range for Local Air Movement in The Tropics

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The perception of locally applied airflow was studied with tropical subjects who had become passively acclimatized to hot conditions in the course of their day-to-day life. During the experiments, 24 subjects (male and female) performed normal office work in a room equipped with six workstations. They were exposed to local airflow from the front and toward the face at six air velocities (0.15, 0.3, 0.45, 0.6, 0.75, and 0.9 m/s) at ambient temperatures of 26°C and 23.5°C and local air temperatures of 26°C, 23.5°C, and 21°C. Each combination was maintained for 15 minutes, during which the subjects responded to computer-administered questionnaires on their thermal and draft sensations using visual-analogue scales.

The results showed that the subjects preferred air movement within a certain range, i.e., a higher percentage was dissatisfied at both low and high velocity values. Most dissatisfaction with air movement is caused by thermal sensation, with air movement perception accounting for a smaller proportion. The subjects preferred air movement to be between "just right" and "slightly breezy" and preferred their thermal sensation to be between "neutral" and "slightly cool."

The study also identified an acceptable air velocity range from 0.3 up to 0.9 m/s under the experimental conditions. This velocity range is relevant for the design of personalized ventilation in practice. This preferred velocity range is higher than the maximum velocity permissible under ASHRAE Standard 55 (ASHRAE 2004) in situations where subjects have no control over local air movement.

INTRODUCTION

Personalized ventilation supplies fresh air to each workplace and provides each occupant with the possibility of controlling the microenvironment according to his/her individual preference. Studies show that personalized ventilation in conjunction with background total volume ventilation is capable of creating a localized environment surrounding occupants, particularly the breathing zone, with better inhaled air quality and thermal comfort in a more energy-efficient way than total volume ventilation only (Melikov et al. 2003; Melikov 2004; Kaczmarczyk et al. 2004, 2006; Sekhar et al. 2003, 2005; Cermak et al. 2006). The personalized air, usually supplied cooler than the room air and close to the occupant, may cause draft and adversely affect

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people's comfort. *Draft* is defined as unwanted local cooling of human body due to air movement (ASHRAE 2004).

Human response to draft has been studied mainly under isothermal conditions, i.e., airflow temperature equal to room air temperature, both in whole body exposure to air movement (Fanger et al. 1988) and in exposure to locally controlled airflow (Fountain et al. 1994). There have been few quantitative studies of human response to locally applied non-isothermal flow (Ma and Qin 1991; Melikov et al. 1994; Zeng et al. 2002; Sekhar et al. 2005). In order to improve the perceived inhaled air quality and the cooling effect of the personalized flow, it is supplied several degrees cooler than the room air. In this connection it is important to improve our understanding of human perception of locally applied non-isothermal air movement. This is especially important for the practical development of personalized ventilation systems with high performance in terms of occupants' comfort and energy use.

This study explores human perception of local air movement under both isothermal and non-isothermal conditions and identifies the acceptable air velocity range needed for the design of personalized ventilation in the Tropics. A preference for local air movement is demonstrated, suggesting that personalized ventilation will find an application in the Tropics.

RESEARCH METHODS

Experimental Facilities

The experiment was conducted in a controlled indoor air quality (IAQ) chamber with dimensions of 6.64 m (length) × 3.74 m (width) × 2.6 m (height) in Singapore. The chamber adjoins a reference room, which is controlled at the same temperature as the chamber and serves as a "conditioning" room for the subjects. The chamber was served by two dedicated air-conditioning systems—a primary personalized ventilation system delivering fresh outdoor air to each workstation and a secondary total-volume mixing ventilation system providing supplementary ambient cooling. The same total-volume mixing ventilation system also serves the reference room (a detailed description of the experimental chamber and facilities can be found in Sekhar et al. [2005]). Interior partitions divided the chamber into six workstations, each equipped with a personalized air terminal device to supply conditioned outdoor air (Figure 1). The air terminal device used in this study was developed following that introduced by Bolashikov et al. (2003). It was shaped as a truncated cone with a circular inlet (∅70 mm) and a circular air outlet of perforated metal (diameter 180 mm). A thin layer of gauze was mounted closely inside the perforated cover of the outlet in order to make the air distribution more uniform. The air terminal device was located symmetrically in front of each subject.

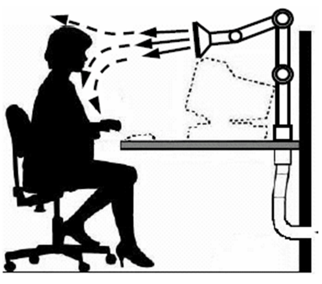

Figure 1. Diagram of local air movement.

Thermocouples were used to measure room ambient temperature with an accuracy of ±0.2°C. Relative humidity (RH) was measured using HOBO loggers with an accuracy of ±5%. Omnidirectional low-velocity anemometers were placed in the target positions of each workstation (defined below) to record air velocity, turbulence intensity, and air temperature in the facial region (velocity ±0.03 m/s and temperature ±1% of readings). Strictly speaking, a low-velocity anemometer with an omnidirectional sensor measures the magnitude of the velocity, i.e., the speed, which in this paper is referred to as *velocity*. All the equipment was calibrated before the experiments.

Experimental Conditions

The local air movement parameters were controlled and measured at target positions (15 cm from subjects' facial regions and in the center of the flow). Six air velocities (0.15, 0.3, 0.45, 0.6, 0.75, and 0.9 m/s) and local air temperatures of 26°C, 23.5°C, and 21°C were adopted as experimental interventions in this study at ambient temperatures of 26°C and 23.5°C (see Table 1).

The air terminal device was fixed in position on top of the computer monitor and the subjects were not allowed to move it. Before the experiments, the airflow from the air terminal device was studied by smoke visualization and a breathing thermal manikin. The airflow was directed to impact only the facial area of the manikin at the target position. During the experiment, the subjects were asked to adjust the height of their seats to a comfortable position such that the local air supply would be directed only toward their faces. The turbulence intensity at target positions was usually lower than 25% under all conditions.

Other than at workstations, the room air velocity was measured to be less than 0.1 m/s. Humidity in the chamber was not controlled but was monitored; it varied between 40% and 55% during the experiments. The ambient mean radiant temperature was approximately the same as the room air temperature, i.e., 26°C/23.5°C.

Subjects

Twenty-four subjects, 12 male and 12 female university students, participated in the experiments in four separate groups of six. The subjects had lived in Singapore for at least five years (and were therefore deemed to be passively acclimatized). They were volunteers and were paid S$5 per hour (USD 2.85). All subjects were healthy, without chronic disease or allergy, and were nonsmokers. The subjects were instructed to eat normally before arrival at the chamber and to avoid alcohol in the 24 hours prior to the experiment. They were also asked to wear normal attire with high-collar clothing to avoid possible draft to the neck, since the neck is one of the areas that is most sensitive to draft (Fanger et al. 1988). The anthropometric data of the 24 subjects are shown in Table 2.

Table 1. Experimental Conditions

Room Temperature T_a (°C)	26			23.5	
Target Temperature T_f (°C)	21	23.5	26	21	23.5
Target Velocity V_f (m/s)	0.15, 0.3, 0.45, 0.6, 0.75, 0.9				

Table 2. Anthropometric Data for the Subjects

Sex	**No. of Subjects**	**Age (years)**	**Height (m)**	**Weight (kg)**	**Skin Area (m^2)**
Female	12	20±1	1.60±0.05	50.0±7.0	1.49±0.11
Male	12	22±1	1.74±0.05	63.5±9.1	1.76±0.12
Female and Male	24	21±2	1.67±0.09	56.8±10.8	1.63±0.18

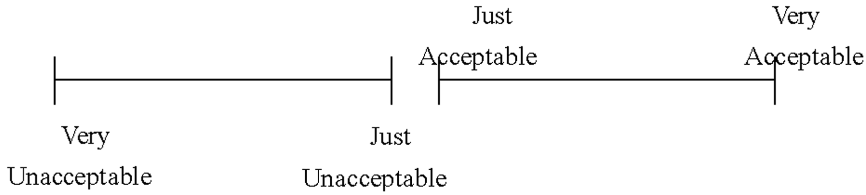

Figure 2. Linear visual analogue scales with intervals for assessment of air movement acceptability in the facial region.

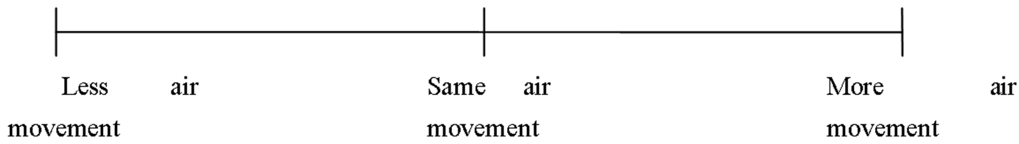

Figure 3. Linear visual analogue scales for assessment of air movement preference of whether the subjects want more, the same, or less air movement in the facial region.

Experimental Procedure

Unlike the experimental procedure in the draft study reported by Fanger et al. (1988), subjects in this study did not experience successively increasing air velocities. The sequences of air velocity exposure were designed in a randomized way for the 24 subjects among all the exposed levels of air velocity to provide an unbiased assessment. At the beginning the subjects remained for half an hour in the reference room. They were then exposed to the different velocity interventions, each for 15 minutes. In between any two exposures, the subjects returned to the reference room for 15 minutes to restore their thermal sensation and therefore eliminate cumulative effects from the preceding air movement exposure. In the reference room the subjects were encouraged to modify their clothing if they felt cool or warm. However, in the experimental room the subjects were not allowed to alter their clothing.

Questionnaires

English was the first language of the subjects and only English was used in the questionnaire. To evaluate thermal sensation for both body segments and whole body, the ASHRAE seven-point scale (ASHRAE 2004) was adopted in the computer-administered questionnaires: +3 = Hot, +2 = Warm, +1 = Slightly warm, 0 = Neutral, –1 = Slightly cool, –2 = Cool, –3 =Cold.

Subjects were also asked if they felt any air movement. If they felt air movement at any body segment, they were required to assess the air movement. To evaluate the perception of air movement at each body segment, the following scale categories were adopted: +3 = Much too breezy, +2 = Too breezy, +1 = Slightly breezy, 0 = Just right, –1 Slightly still, –2 Too still, –3 = Much too still.

Linear visual analogue scales with intervals were used. The subjects were asked to assess the acceptability of local air movement in the facial region (Figure 2) and indicate any preferred change in air movement at the face in the next question (Figure 3). These questions were asked three times, i.e., every five minutes in each 15-minute velocity exposure.

The end-points of the linear visual analogue scales were coded as –1 (very unacceptable) and 1 (very acceptable), with an interval in between at –0 (just unacceptable) and 0 (just acceptable) for the questions on assessment of air movement (Figure 2). Linear visual analogue scales without intervals between the two halves were used for the question about air movement preference (Figure 3). Subjects dissatisfied with the air movement were taken to be those who voted from –1 (very unacceptable) to –0 (just unacceptable) at least two times out of three. The percentage dissatisfied is expressed as a percentage of the sample size of 24 subjects.

RESULTS

Due to the repeated exposures of the subjects to different local air movements, it was important to ensure that their thermal sensation had been restored by the 15-minute period in the control room. Subjects' whole-body thermal sensation data in the control room were classified according to the next value of local air velocity they were to be exposed to in the chamber room. The six groups of data obtained with target air velocities of 0.15, 0.3, 0.45, 0.6, 0.75, and 0.9 m/s in each ambient-local temperature condition were statistically analyzed separately. These tests were repeated for the five ambient-local temperature conditions of the study. It was found that there was no significant difference ($P > 0.7$) in thermal sensation at the end of this period and before their exposure to local air movement in the chamber room for all five ambient-local temperature conditions.

In this study, the subjects' mean whole-body thermal sensation during the 15-minute exposure in the chamber room remained within the range of slightly cool (–1) to slightly warm (1) of the ASHRAE seven-point scale, i.e., +3 = Hot, +2 = Warm, +1 = Slightly warm, 0 = Neutral, –1 = Slightly cool, –2 = Cool, –3 = Cold. The thermal sensation mean values at the six target velocities for the 24 subjects were, respectively, –0.76, –0.62, –0.37, –0.06, and 0.32 for the five ambient-local temperature conditions, i.e., 23.5°C–21°C, 23.5°C–23.5°C, 26°C–21°C, 26°C–23.5°C, and 26°C–26°C (ambient-local temperature [$T_a - T_f$] is adopted here and also for the figures that follow).

In the study, it was found that air movement could be too high or too low for the subjects. The relations between percentage dissatisfied and local air velocity/temperature are illustrated in Figures 4 and 5, respectively, for preference of less/more air movement using logarithmic regression.

The subjects were dissatisfied at both low and high air velocities. Usually when they were dissatisfied at low velocities they preferred more air movement, and when they were dissatisfied at high velocities they preferred less air movement. This "bi-polar" perception of local air movement is similar to human perception of air temperature, as in the PMV model in Fanger (1970).

The effect of temperature on percentage dissatisfied was as expected. At higher temperatures the percentage of dissatisfied subjects who preferred less air movement was lower, while the percentage of those dissatisfied who preferred more air movement was higher.

The most acceptable velocity range for each $T_a - T_f$ combination was derived. The range is determined by applying the criteria that at least 85% of all subjects should be satisfied. This is in accordance with the allowed maximum of 15% dissatisfied due to draft as specified in ASHRAE Standard 55 (ASHRAE 2004). The range is derived by starting from a velocity with the most satisfied votes. If the velocity with its adjoining velocity can satisfy at least 85% of all subjects, the range is extended to include the two velocities. If the subjects' voting of the two velocities does not meet 85% satisfaction of all subjects, responses at other adjoining velocities are examined in the same manner. The most acceptable velocity ranges were determined and are summarized in Table 3. The percentage satisfied within the designated range is also shown in the table. As expected, it is observed that the range values increase as ambient air temperature increases.

The optimum air velocity in each condition was also derived. Figure 6 shows the quadratic regression between overall percentage dissatisfied and local air velocities. The curves show that the overall percentage dissatisfied usually decreases first and then increases when air velocity

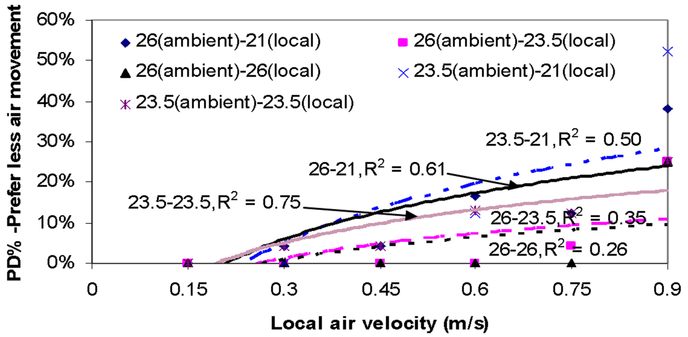

Figure 4. Percentage dissatisfied because the subjects would prefer less air movement.

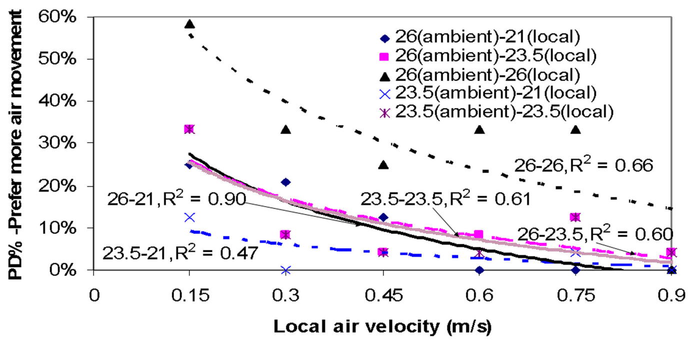

Figure 5. Percentage dissatisfied because the subjects would prefer more air movement.

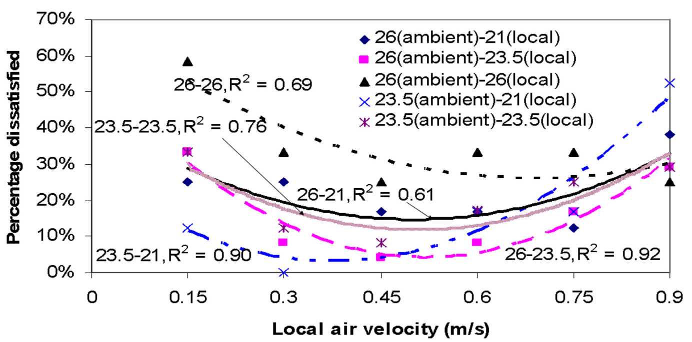

Figure 6. Percentage dissatisfied as a function of local air velocity.

increases. The optimum velocity is defined as the velocity value associated with the lowest proportion dissatisfied. These values are also given in Table 3. It may be seen that optimum velocities derived in this way generally increase as air temperature increases, as would be expected.

The optimum velocity and range derived in this study may be compared with the optimum velocity derived by a Danish study of personalized ventilation (Kaczmarczyk 2003) with a similar air terminal device (a round movable panel). In his study, local air was supplied at 20°C, and the optimum mean velocity (determined from subjects' most often selected flow rate) was

Table 3. Summary of Optimum Velocity and Range

Experimental Condition (°C)	23.5–21	23.5–23.5	26–21	26–23.5	26–26
Optimum Velocity (m/s)	0.38	0.51	0.50	0.52	0.69
Most Acceptable Velocity Range (m/s)	0.3–0.45	0.3–0.45	0.3–0.6	0.3–0.6	0.75–0.9
Percentage Satisfied in Most Acceptable Range	100%	92%	96%	96%	96%

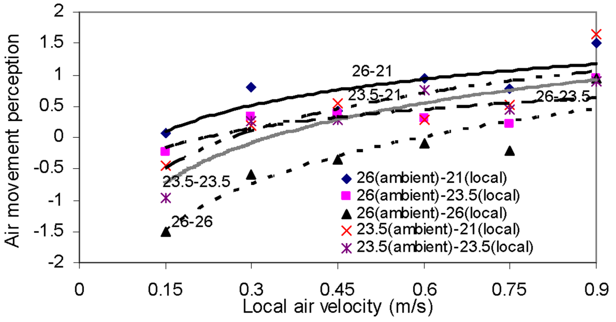

Figure 7. Logarithmic regression of air movement perception (y-axis: –3 = Much too still, –2 = Too still, –1 = Slightly still, 0 = Just right, 1 = Slightly breezy, 2 = Too breezy, 3 = Much too breezy).

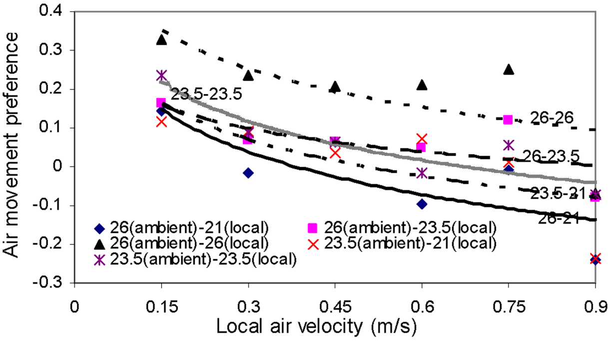

Figure 8. Logarithmic regression of air movement preference (y-axis: –1 = Less air movement, 0 = No change, +1 = More air movement).

0.39 m/s at a room air temperature of 23°C and 0.42 m/s at 26°C. These values are very close to those found in the present study, which would have predicted around 0.36 m/s and 0.46 m/s in these two cases.

The relations between air movement perception/preference and local air velocity are depicted in Figures 7 and 8, respectively. Preference of air movement up to around 0.45 m/s may be observed in Figure 8.

DISCUSSION

Among all subjective responses, 22.1% were dissatisfied with local air movement; the reasons expressed for dissatisfaction are shown in Figure 9.

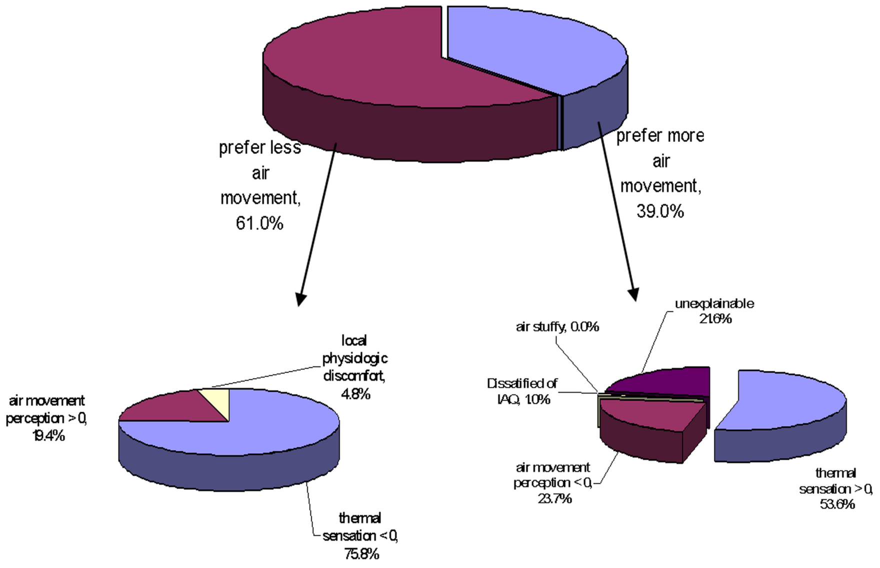

Figure 9. Reasons for dissatisfaction with air movement.

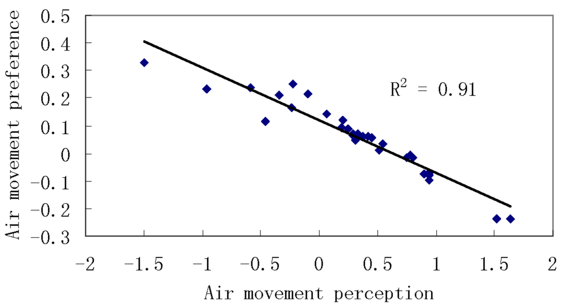

Figure 10. Linear regression of air movement perception and preference (x-axis: –3 = Much too still, –2 = Too still, –1 = Slightly still, 0 = Just right, 1 = Slightly breezy, 2 = Too breezy, 3 = Much too breezy; y-axis: –1 = Less air movement, 0 = No change, +1 = More air movement).

Thermal sensation was the most common reason for expressing a preference for less (75.8%) or more (53.6%) air movement, while air movement perception was an alternative and less frequent reason for expressing a preference for less (19.4%) or more (23.7%) air movement. Local physiological discomfort, i.e., dry nose, eyes, and mouth, only accounted for a small portion (4.8%) of the preference for less air movement. Air-quality–related reasons are only a very small portion (1%) accounting for the preference for more air movement. However, it may be observed that a relatively high percentage (21.6%) of those expressing preference for more air movement did so for no apparent reason.

As expected, subjects preferred more air movement when they felt the air to be still and less air movement when they felt it was breezy. However, as can be seen in Figure 10, subjects still

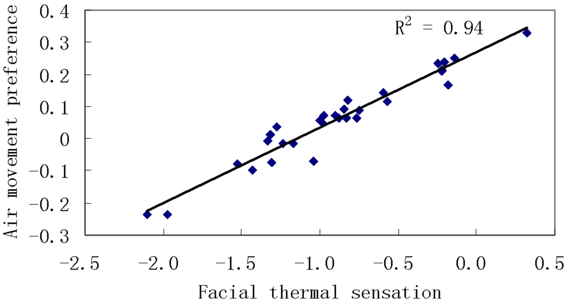

Figure 11. Linear regression between facial thermal sensation and air movement preference (x-axis: –3 = Cold, –2 = Cool, –1 = Slightly cool, 0 = Neutral, 1 = Slightly warm, 2 = Warm, 3 = Hot; y-axis: –1 = Less air movement, 0 = No change, +1 = More air movement).

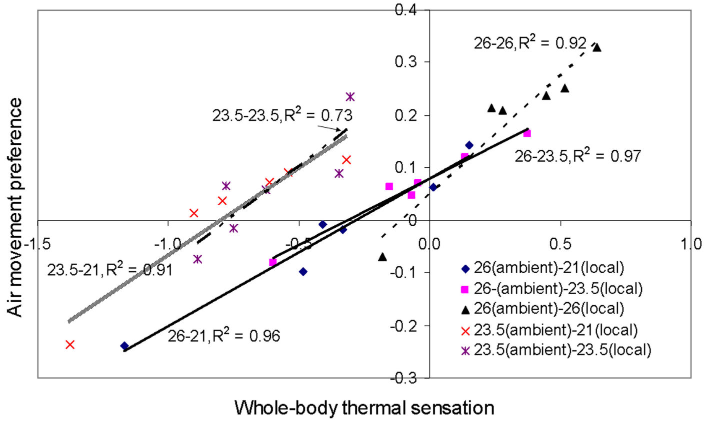

Figure 12. Linear regression between whole-body thermal sensation and air movement preference (x-axis: –3 = Cold, –2 = Cool, –1 = Slightly cool, 0 = Neutral, 1 = Slightly warm, 2 = Warm, 3 = Hot; y-axis: –1 = Less air movement, 0 = No change, +1 = More air movement).

preferred some air movement when they reported that the air movement was "just right" (coded as "0" for air movement perception in the questionnaire).

It has already been discussed that thermal sensation was the most common reason for expressing air movement preference. Subjects preferred more air movement even when their thermal sensation was on the cool side, as can be seen in Figure 11 with facial thermal sensation and Figure 12 with whole-body thermal sensation. The highest acceptability was also reported as a slightly cool (–1) thermal sensation (Figure 13).

The preference of a cooler-than-neutral thermal sensation was observed in other tropical studies. In a natural ventilation study (Feriadi and Wong 2004), a strong preference (nearly 80% of those surveyed) was observed of people who voted for "just right/no change" on the thermal preference scale (the McIntyre scale, i.e., –1 = a preference of warmer, 0 = no change, and +1 = a preference of cooler), even though they voted for "cool" on the ASHRAE seven-point scale (–2). In a series of call center studies performed in an air-conditioned environment in Singapore (Tham and Willem 2005), the preference of a slightly cool thermal sensation was alluded to as

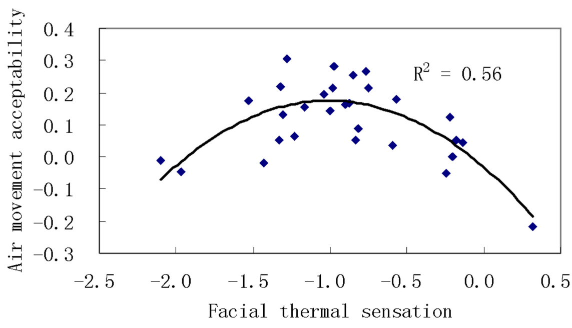

Figure 13. Quadratic regression of facial thermal sensation and air movement acceptability (x-axis: –3 = Cold, –2 = Cool, –1 = Slightly cool, 0 = Neutral, 1 = Slightly warm, 2 = Warm, 3 = Hot; y-axis: 1 = Very unacceptable, 0 = Just unacceptable/acceptable, +1 = Very acceptable).

"thermal relief" among call center operators when discussing their improvement in productivity arising from interventions in temperature from slightly warm to slightly cool.

This study shows that subjects usually prefer some perceptible air velocity, which is consistent with previous findings. Higher air speed with individual control has been recommended to decrease dissatisfaction when the air temperature is above 26°C (ASHRAE 2004), while there is no such recommendation when the air temperature is below 26°C. The present findings suggest that some air movement is preferred by the subjects even when the room air temperature is below 26°C.

The findings also suggest that the subjects preferred conditions between "just right" and "slightly breezy" and between "neutral" and "slightly cool." The reasons for the preferences need further exploration.

In four ASHRAE field studies (Schiller et al. 1988; de Dear and Fountain 1994; Donini et al. 1997; Cena and de Dear 1999) conducted in different climatic regions, there is evidence that subjects prefer some air movement. Toftum (2004) examined air movement preferences for those subjects who returned votes of "slightly cool" through "slightly warm" (thermal sensations –1 through +1) in the de Dear (1998) database of the ASHRAE field studies. Only metabolic rates in the range of 1.1 to 1.4 met and temperatures in the range of 22.5°C to 23.5°C were included in that analysis. The air velocities measured at 1.1 m above the floor were usually less than 0.25 m/s. Very few occupants complained of draft and preferred less air movement, while most subjects preferred no change/more air movement in the temperature range of 22.5°C to 23.5°C and an air velocity range of 0 to 0.2 m/s. It was even the case that many occupants with a thermal sensation of "slightly cool" preferred more air movement despite the fact that more air movement would make them feel even cooler. The present findings support the conclusions of Toftum (2004), even though a wider air velocity range (0.15–0.9 m/s) was studied in this experiment.

The results of this study do not conflict with those of Fanger et al. (1988), since the subjective exposure to air movement in the two studies was different and this may have led to higher preferred air velocities in the present study.

In the present study the facial region of each subject was exposed to local air movement, while in the study by Fanger et al. (1988) the airflow was from behind the subjects and the whole bodies of subjects were exposed to air movement. It has often been reported that people seem to be most sensitive to airflow from behind (Ostergaard et al. 1974; Mayer and Schwab

1988; Toftum et al. 1997), and it is clear that heat loss will be greater when the whole body is exposed to air movement rather than just the facial region.

CONCLUSIONS

- Subjects prefer air movement within a certain range, the values of which are dependent on the particular combination of ambient and local temperatures. At an ambient temperature of 23°C, people in the Tropics prefer local air velocities ranging from 0.3 to 0.45 m/s, while at an ambient temperature of 26°C, they prefer local air velocities from 0.3 to 0.9 m/s. This preferred velocity range is higher than the maximum velocity permissible under ASHRAE Standard 55 in situations where subjects have no control over local air movement.
- Most dissatisfaction with air movement is due to thermal sensation and, to a lesser extent, to air movement perception.
- Subjects preferred air movement to be between "just right" and "slightly breezy" and thermal sensation to be between "neutral" and "slightly cool."
- This research suggests that there is a need for more research on preference for air movement in the hotter and more humid parts of the world.

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