Title

Locally controlled air movement preferred in warm isothermal environments

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LOCALLY CONTROLLED AIR MOVEMENT PREFERRED IN WARM ISOTHERMAL ENVIRONMENTS

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ABSTRACT

Air movement is one of the six main variables determining human thermal comfort; air temperature, relative humidity, mean radiant temperature, metabolic rate, and clothing insulation are the others. Recently, HVAC design innovations, energy conservation concerns, and new laboratory data on fan cooling and drafts have brought substantial attention to the issue of acceptable levels of air movement in office environments. Thermal comfort standards for indoor occupancy include air movement limits that are constructed from often conflicting evidence and are frequently difficult to apply. A primary reason is that, while air movement can provide desirable cooling in "warm" conditions, it can also increase the risk of unacceptably cool drafts. The transition zone from desirable cooling to uncomfortable draft is a complicated function of physics, physiology, and human expectation. This work focuses on air movement for cooling in the expected temperature range, 25.5°C to 28.5°C, of this transition zone.

Fifty-four human subjects were given control of the air supply velocity from a desk fan (FAN), a floor-mounted diffuser (FMD), and a desk-mounted diffuser (DMD) at a single ambient air temperature. The subjects were asked to adjust the air movement as they pleased to make themselves comfortable. These tests encompassed the full temperature range of the "transition zone," 25.5°C to 28.5°C. Physical measurements of the environment were made and subjective votes collected, including thermal sensation, thermal preference, work area preferences, personal control preferences, and health characteristics. A model that predicts the percentage of satisfied people (the PS model) as a function of air temperature and air movement in warm conditions is proposed.

INTRODUCTION

Thermoregulation and Sensation

Air movement is one of six main variables affecting human thermal comfort. The other five include three physical variables—air temperature, mean radiant temperature, and relative humidity—and two physiological variables—metabolic rate and clothing insulation. The concept of air movement encompasses not only air velocity but also the fluctuations in air velocity over time.

The human thermoregulatory system is responsible for regulating the heat balance of the body, maintaining a core setpoint of 37°C within the constraints of the six variables given above. The body's thermoregulation is very similar to a building's HVAC system, which controls different zones of a building with interior setpoints and the constraints of outside weather, internal loads, and shell insulation. Skin and core temperatures for the body are regulated to release metabolic heat through respiration and also via convective, radiative, and evaporative heat transfer through the skin. The convective heat transfer component varies with skin surface temperature, air temperature, and local air motion. Thus, the body's skin surface temperature is partly determined by the rate of convective heat transfer and, hence, local air movement.

Extensive laboratory studies have shown that the thermal sensation vote, an important method for measuring thermal comfort, is closely related to skin temperature in cool and comfortable conditions. Moisture on the skin has an increased effect on thermal sensation in warm and hot conditions, particularly after sweating mechanisms have been triggered. Local air movement is an important factor in thermal comfort and has been incorporated in comfort standards from their inception.

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HVAC is for People

HVAC engineers design systems to move energy and fresh air through buildings. Many, if not most, commercial buildings constructed since the middle of this century use air distribution systems to deliver heated and/or cooled air to occupied spaces. ASHRAE and other organizations have produced standards and guidelines for distributing this air, including such specifics as volume of air per unit time, percentage of outside air, type and location of duct outlets, etc. In general, design recommendations for achieving thermal comfort have favored specifying delivered cfm per square foot of occupied space rather than specifying air velocity. Yet the desired end product of HVAC systems is not cfm per square foot, a cooled building interior, or air movement per se; it is the comfort and satisfaction of building occupants. Beyond special cases such as laboratories, clean rooms, computer rooms, and manufacturing facilities, efforts in HVAC design are directed primarily at producing thermal comfort and air quality acceptable for breathing. The focus of the work reported here is the influence of the air movement created by an HVAC system on thermal comfort.

Comfort Standards Specify Indoor Thermal Environments

International thermal comfort standards for human occupancy, such as ASHRAE Standard 55-1992 (ASHRAE 1992) and ISO Standard 7730 (ISO 1984), specify the thermal conditions required for thermal comfort. The thermal comfort standards are used both as design and diagnostic tools for indoor environments, and many state building codes incorporate the ASHRAE standard by reference. The standards specify, for each of the physical variables that affect the indoor environment, ranges or limits that are required to maintain thermal comfort. In ASHRAE Standard 55-1992, lines drawn on a psychrometric chart are used to delineate the comfort zone boundaries. These limits have evolved during the course of this century primarily through laboratory investigations of human response. Detailed physical, physiological, and psychological data are required to establish the relationship between the physical environment, physiological state, and thermal sensation and satisfaction that the comfort standards present. Investigations are ongoing in laboratories around the world to increase knowledge about thermal comfort, thus refining and validating the standards with new information as it appears.

HVAC design innovations, energy conservation concerns, and new laboratory data on drafts have recently brought substantial attention to the issue of acceptable levels of air movement in the comfort standards and hence in office environments. Air movement can provide desirable cooling in "warm" conditions, but it can also increase the risk of unacceptable cool drafts. Noticeable air velocities can be perceived as providing freshness and pleasantness to the breathing air, but they may also be perceived as annoying. A specific air velocity has a variety of possible physiological and subjective consequences depending at the very least on the surrounding air temperature, mean radiant temperature, humidity, clothing, metabolic rate, and air movement preferences of the occupant. One of the goals of thermal comfort research has been to define thermally comfortable and acceptable levels of air movement for the widest possible group of individuals within an evolving architectural setting and to incorporate these results into an indoor environmental standard.

AIR MOVEMENT LIMITS IN THE 1992 ASHRAE COMFORT STANDARD

The Draft Curves and the Constant-Heat-Loss Curves

The current Standard 55-1992 (ASHRAE 1992) contains two figures for air velocity and comfort that are complementary but may be difficult to apply in engineering practice. Figure 3 in the standard (reproduced here as Figure 1) allows higher air velocities under occupant control to offset the effect of higher operative temperatures. It is applied by selecting the operative temperature rise of the environment and then choosing the air velocity needed for comfort along the appropriate "temperature difference" curve. Figure 4 in the standard (reproduced here as Figure 2) specifies a "still air" zone with the objective of eliminating drafts. It defines the effects of different levels of turbulence intensity in the airflow (*turbulence intensity* is defined as the standard deviation of fluctuating velocities divided by their mean for the measuring period). Together, the figures are designed to be applied within the combined temperature range of 20°C to 29°C. The curves represent percent "discomfort" curves, with 15% discomfort being used for Figure 2 and 20% for Figure 1.

The curves in Figure 1 are derived from a computer model for constant total heat loss (sensible and latent) at the skin surface under varying thermal conditions. Constant heat loss implies a locus of equal comfort, and the results are consistent with a number of laboratory studies (Rohles et al. 1983; Konz et al. 1983; Jones et al. 1986; Scheatzle et al. 1989; McIntyre 1978; Tanabe and Kimura 1987; Tanabe and Kimura 1989). However, as incorporated into ASHRAE Standard 55-1992, it can only be used if the local air movement is under the control of the occupant, with Figure 2 covering all other situations.

At the lower end of its temperature range, Figure 2 is solidly based on laboratory data (Fanger et al. 1988). However, in the higher temperature range, above 23°C, the draft risk curve is an extrapolation to conditions where data were not collected and where other experimental data are in disagreement (Rohles et al. 1974; Scheatzle et al. 1989, Mayer 1992). If this part of the curve is too restrictive, a number of possibly effective and potentially energy-efficient environmental conditioning strategies involving air movement may be excluded by the standard.

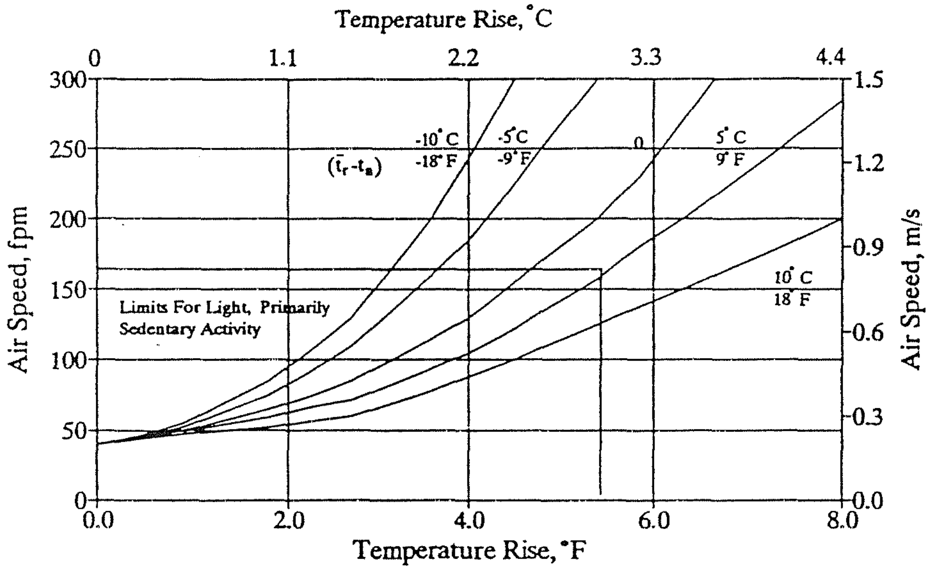

Figure 1 *Air speed required to offset increased temperature. The air speed increases in the amount necessary to maintain the same total heat transfer from the skin. This figure applies to increases in temperature above those allowed in the summer comfort zone with both* $\bar{t}_r$ *and* t_a *increasing equally. The starting point of the curves at 0.2 m/s (40 fpm) corresponds to the recommended air speed limit for the summer comfort zone at 26°C (79°F) and typical ventilation (i.e., turbulence intensity between 30% and 60%). Acceptance of the increased air speed requires occupant control of the local air speed.*

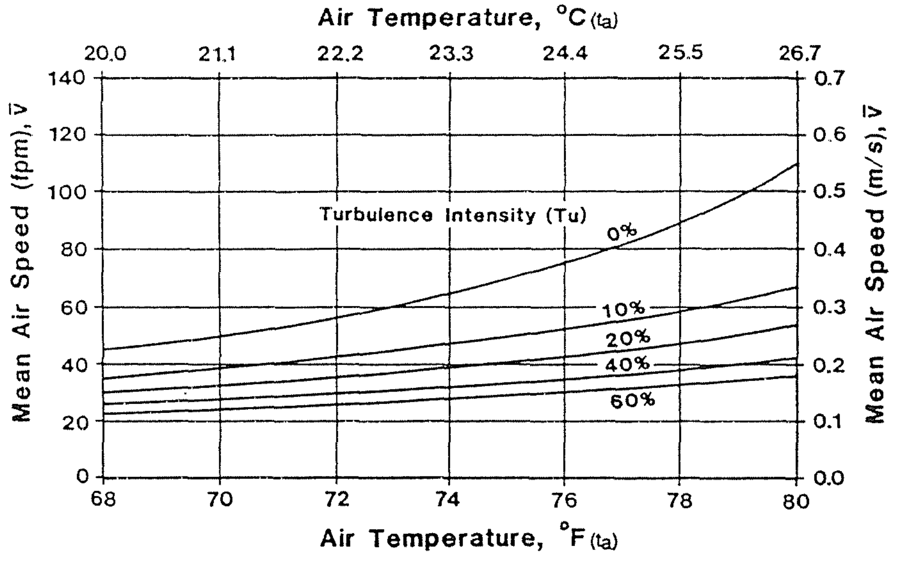

Figure 2 *Allowable mean air speed* ($\bar{v}$) *as a function of air temperature* (t_a) *and turbulence intensity (Tu). The turbulence intensity may vary between 30% and 60% in conventionally ventilated spaces. In rooms with displacement ventilation or without ventilation, the turbulence intensity may be lower (see Appendix B, Air Drafts). The diagram is based on a 15% acceptable level and the sensation at the head/feet level where people are most sensitive. Higher air speeds may be acceptable if the affected occupants have control of local air speed (see 5.1.6.4).*

Comparing the Draft and Constant-Heat-Loss Curves to Existing Experimental Data

As seen in Figure 3, the range in air velocity supported by various laboratory studies (see Fountain [1991] and Fountain and Arens [1993] for a more detailed discussion of the studies that contribute to this figure) is considerable. For example, draft risk data for a turbulence intensity of 40%, typical of indoor office environments, can be applied between 20°C and 26°C. Using the draft risk curve, air movement is restricted to 0.12 m/s at 20°C and 0.2 m/s at 26°C (only the portion of this curve above 22°C is shown in Figure 3). The $T_a = T_r$ curve from Figure 1 starts at the point 0.2 m/s, 26°C, and extends to 0.8 m/s, 29°C. Although Figure 1 was developed for 26°C and above, there is no reason why it cannot be applied in the range 23°C to 20°C to produce a zone of comfortable conditions. Figure 3 also shows data from three experiments (Rohles et al. 1983; Scheatzle et al. 1989; Tanabe and Kimura 1987), the zone generated by Figure 1, and the ASHRAE summer air movement standard for the previous decade (ASHRAE 1981). They are in broad agreement regarding the ability of the occupant-controlled air movement zone to provide comfort. On the other hand, the new draft risk limit represents a significant air movement restriction over the ASHRAE Standard 55-81 zone. The difference in the ranges of the acceptable conditions in Figures 1 and 2 is obvious and forms the main focus of the current investigation.

EXPERIMENTAL OBJECTIVES

The objective of these experiments was to examine human response to isothermal conditions through the following specific steps:

- Characterize human thermal comfort response to manually controlled airflow from small desk fans and local conditioning systems while subjects were exposed to various ambient air temperature setpoints to determine air movement preferences.
- Use physical measurements to evaluate the thermal environments produced by subjects under their chosen optimal comfort conditions.

METHOD

The human subjects tests followed the general procedure of a "preferred condition" test. That is, subjects were requested to adjust one variable of the thermal environment—the air velocity—as often as they pleased to make themselves comfortable. At the end of the exposure period, subjects were asked to move aside for five minutes while detailed physical measurements of the environments they produced were made. Each subject experienced only a single air temperature.

The controlled-environment chamber (CEC) used in these experiments is described in detail by Bauman and Arens (1988). Measuring 18 feet by 18 feet by 8 feet, 4

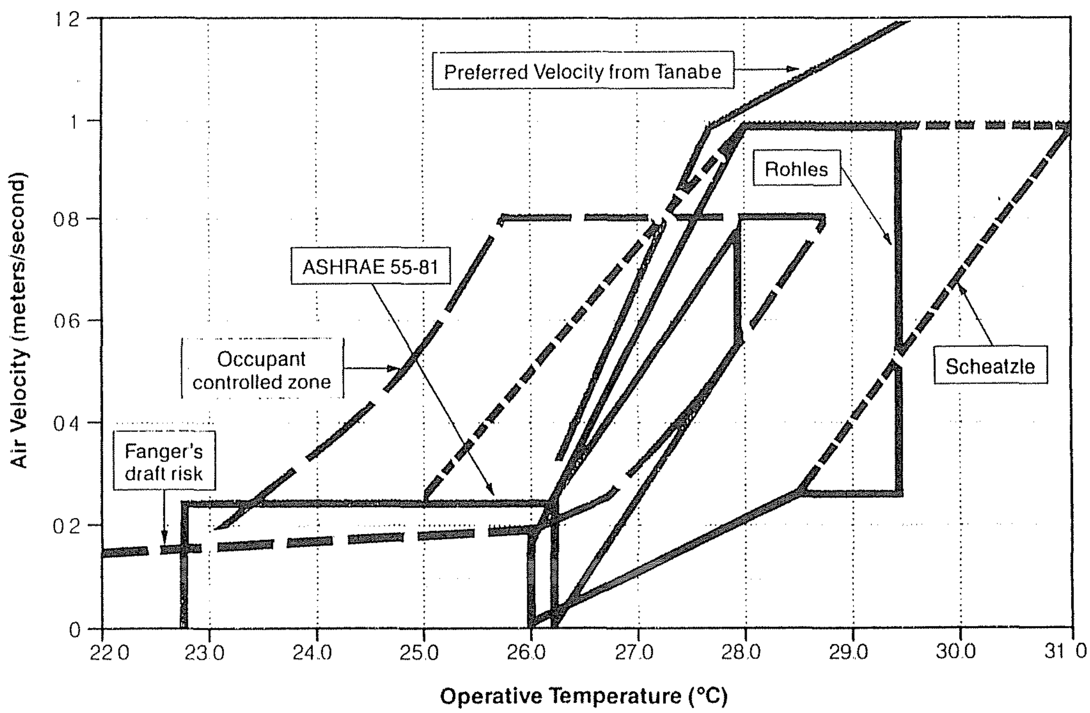

Figure 3 *Range of velocity requirements.*

inches, the CEC is configured to appear as a realistic open-plan office with partitions, floor coverings, windows, lighting, and furniture exactly as one would expect to find in any modern office building. It has a raised floor, enabling ducts to be placed anywhere with respect to the workstations. Air can be supplied and returned from the ceiling and floor simultaneously. A mobile measurement cart, similar to the cart presented in Benton et al. (1990), collected the measurements of the physical environment in the CEC. The anemometry was improved over the previous cart as well as the data collection and recording systems. Temperature measurements on the cart are accurate to better than ±0.1°C, and air velocities are accurate to better than ±0.01 m/s. Skin temperatures of the human subjects were measured at 14 sites on the body using thermistors calibrated in ice and warm water baths to an accuracy better than ±0.1°C. The subjects recorded their thermal sensation, thermal preference, air movement awareness, and air movement preference every 15 minutes during the experiment. In addition, the subjects completed a background survey investigating demographics, work area preferences, personal control preferences, and health.

Measurement Protocol

The subjects were instructed to arrive at the climate chamber wearing shoes, socks, underwear, jeans, and a T-shirt or other light short-sleeved shirt. This clothing ensemble (0.5-0.6 clo) was chosen to approximate the mean values of clothing insulation found in recent field studies of office environments during summer conditions (Schiller et. al. 1988; de Dear and Fountain 1994). A standard uniform, frequently used in previous laboratory comfort studies, was not used for the following reasons: 1) a uniform detracts from the realism of the experiment, 2) standard uniforms do not ensure uniform clothing insulation as this depends on how the clothing is worn, and 3) "Experiments in which standard clothing is used tend to find an increased, not a decreased, inter-individual difference in thermal preference" (Wyon and Sandberg 1990).

The experiment lasted approximately 3.5 hours and included three different air movement sources: a desk fan (FAN), a floor-mounted diffuser (FMD), and a desk-mounted diffuser (DMD). The thermal performance of the FMD has been described in detail by Bauman et al. (1991) and that of the DMD by Bauman et al. (1993). During the tests reported here, the CEC was maintained at a constant air temperature. The temperature control was generally better than ±0.5°C but in some cases varied as much as ±1.0°C while the subjects adjusted the air movement. Upon arrival at the laboratory, the subject's oral temperature was taken to confirm that he or she was not suffering from an illness that might bias thermal sensation. Accompanied by a same-sex research assistant, subjects were ushered in to the chamber and asked to undress to their underwear in order to apply skin temperature sensors. After re-dressing, they were randomly assigned to one of the four workstations in the chamber and given the background survey. Since the laboratory chamber had been pre-heated to the test temperature, the subject was asked immediately after being seated to adjust the source of air movement to continually maintain comfort while reading or doing paperwork. Figure 4 shows a subject adjusting the air movement from the DMD. The first hour served as a period of acclimation as the subject adjusted the level (but not the direction) of the air movement source for comfort before the first set of physical measurements were made. Every 15 minutes throughout the test, they were also asked to fill out the comfort survey (Appendix A). Every 45 minutes they were asked to move away from the desk for physical measurements. The mobile cart was placed exactly where the subject was and collected data for five minutes (Figure 5). When these measurements were complete, the subject returned to the desk and switched

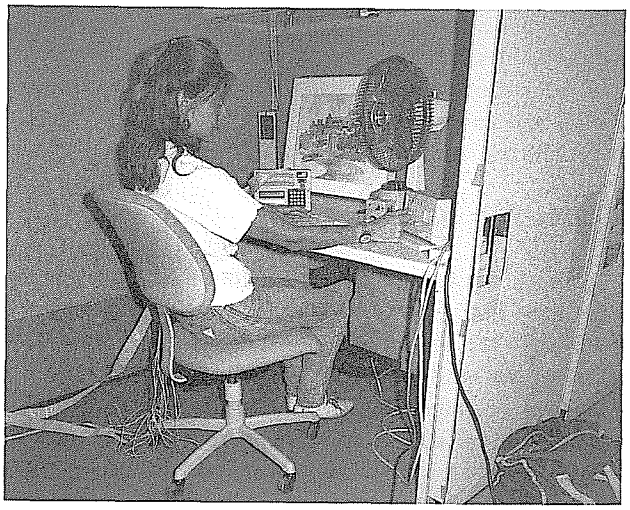

Figure 4 *Subject adjusting air movement from the DMD.*

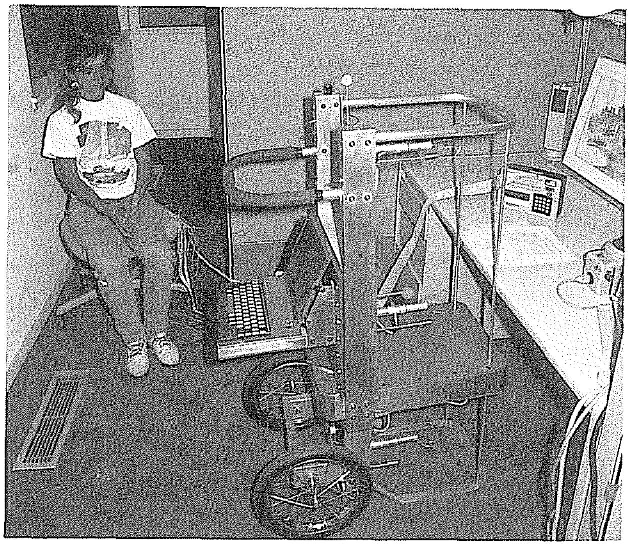

Figure 5 *Mobile cart collecting data in workstation.*

to a different air movement source for cooling. The order in which the subjects were told to adjust each diffuser was randomized. At the end of the experiment, the subject undressed to remove the skin temperature sensors, then dressed, was paid $20 for his or her time, and left the chamber.

Subjects

The age of the sample was evenly distributed between 20 and 40 years of age. There were slightly fewer participants below the age of 25 than in the older categories. This was due to encouraging the general public to participate rather than only college students. Roughly 60% of the sample were males and 40% females. Nearly 50% of the participants described themselves as "Caucasian." Most of the remainder responded in the "Asian American" and "other" categories. Many of the respondents in the "other" category were "Asian," not "Asian American." The majority spoke English as a first language; most of those who did not were in the "Asian" category. A high percentage of subjects (41%) were educated at or beyond the master's degree level. Most of the subjects were between 5 feet and 5 feet, 9 inches, tall and weighed between 125 and 175 pounds.

Physical Conditions Tested

Since 1) the human subjects controlled the air velocity, 2) all three devices were tested in each climate chamber session, and 3) four temperatures were tested between 25°C and 28°C, the base matrix for the human subject tests was a 4-by-3 or 12-cell design. Since a minimum of 12 cases in each cell of the design was the desired sample size for statistical purposes, experiments were performed at nominal room temperature setpoints of 25°C, 26°C, 27°C, and 28°C, yielding a target sample size of 144 (Table 1). Several additional experiments were planned in case of instrument malfunction or incorrect protocol to bring the sample size up to a total of 54 people. Each of the subjects used all three of the air movement devices.

The maximum air velocities at head height that could be created by the three devices ranged from a low of 0.8 m/s for the FMD to 2.0 m/s for the FAN. For whole-body cooling calculations, the high head-height air velocity must be averaged with the lower mid-body and foot-level air velocities. The maximum average (of three heights) air velocity for all three devices was approximately 0.8 m/s.

RESULTS

Physical Measurements

Statistics describing the physical environment in the workstations during the tests are presented in Table 2. Most important, the subjects who did not vote between −1 and +1 on the thermal sensation scale or "yes" on the air movement acceptability scale are not included in Table 2. These subjects, although they found a preferred air speed, will not be considered "comfortable" or "experiencing an acceptable air movement level," but will be considered "dissatisfied" for the analysis of preference. Of the 158 total experiments, just 14 (8.8%) were removed for this reason. Data from the remaining 144 experiments represent environments produced by "comfortable" people who adjusted the air movement source for 45 minutes and found the air movement acceptable for doing work at the desk.

TABLE 1
Isothermal Human Subjects Tests
(Each cell indicates the minimum number of subjects tested.)

Ta room	FAN	DMD	FMD
25 °C	12	12	12
26 °C	12	12	12
27 °C	12	12	12
28 °C	12	12	12

The maximum air velocity was nearly 2 m/s at the sitting head level, while the average of all cases was 0.37 m/s. Globe temperatures were slightly higher than air temperatures overall. Load variations in the climate chamber are more easily smoothed if the required response is heating, not cooling, a situation that results in this slight systematic bias. Furthermore, this climate chamber has a high thermal mass as a result of using real-world office furnishings. The trade-off for having a realistic environment is some sacrifice in the uniformity of climate control since surface temperatures are relatively slow to change. These transient effects were minimized by heating the chamber overnight and maintaining a steady-state temperature throughout each test. Operative temperature was calculated from measurements of globe temperature, air temperature, and air velocity—first by determining the radiative and convective heat transfer coefficients for a 38-mm globe, then the mean radiant temperature, and finally the operative temperature. Relative humidity in the CEC was well controlled at just below 50%. Our precaution of covering the windows with aluminum sheet and then paper yielded a very low radiant asymmetry of 0.2°C. Turbulence intensities were typical for office environments, with most ranging between 30% and 60% around an average near 50%. More than 40% of the preferred air velocity readings were above 0.3 m/s.

Comfort Model Predictions

Table 3 presents predictions based on several well-known computer models of thermal comfort. The models were run for each subject's exposure and only summary statistics are presented here. The models are 1) the two-node model reported in Gagge et al. (1986), 2) Fanger's PMV (ISO 1984), and 3) Fanger's draft risk model (ASHRAE

TABLE 2
Physical Environment Summary
(for "comfortable" people)

Statistics	Air Temperature 1.1 meters °C	Air Temperature 0.6 meters °C	Air Temperature 0.1 meters °C	Globe Temperature 1.1 meters °C	Globe Temperature 0.6 meters °C	Globe Temperature 0.1 meters °C
Average	26.5	26.6	26.3	26.6	26.7	26.3
Maximum	29.2	29.5	29.0	29.5	29.7	29.1
Minimum	24.5	24.5	24.4	24.5	24.5	24.4
Std Dev.	1.0	1.0	1.0	1.0	1.0	1.0

Statistics	Dewpoint Temperature 0.6 meters °C	Relative Humidity 0.6 meters percent	Plane Radiant Asymmetry °C	Air Velocity 1.1 meters m/s	Air Velocity 0.6 meters m/s	Air Velocity 0.1 meters m/s
Average	14.3	47.1	0.2	0.37	0.17	0.10
Maximum	18.5	57.7	1.6	1.95	0.57	0.20
Minimum	12.0	43.1	-1.2	0.07	0.05	0.05
Std Dev.	1.2	1.9	0.6	0.31	0.09	0.03

Values averaged across three heights

Statistics	Average Air Temperature °C	Average Globe Temperature °C	Average Operative Temperature °C	Average Air Velocity m/s	Average Turbulence Intensity percent
Average	26.5	26.5	26.5	0.21	0.47
Maximum	29.2	29.4	29.5	0.75	1.00
Minimum	24.5	24.5	24.5	0.06	0.17
Std Dev.	1.0	1.0	1.0	0.13	0.19

1992). Each model's input was derived from average values of the physical measurements for every visit. Since different comfort standards use different indices to define the comfort zone, the "comfortable" range for each index is defined according to the specific range in the comfort standard that incorporates that index. For example, since ISO Standard 7730 recommends –0.5 < PMV < + 0.5 (ISO 1984) and 0 < PPD < 10%, these values are considered the "comfort" zone for evaluating the comfort of the environments produced in this experiment when the PMV and PPD models are considered.

For ET* and SET*, the upper boundary of the comfort zone is 26.2°C, using the ASHRAE comfort zone. For DISC, the percent is the fraction above a scale value of 1. A person voting 1 feels that the environment is "uncomfortable but acceptable," 2 corresponds to "uncomfortable and unpleasant." For TSENS, the first percent is the fraction above a scale value of 1 and the second is the fraction above a scale value of 0.5. Splitting it at 1 follows the assumption that the central three categories of the thermal sensation scale are comfortable, which is the premise behind the ET* limits in the ASHRAE standard. Splitting it at 0.5 assumes that the thermal sensation scale is mapped point for point by the PMV scale and that the ISO 7730 (ISO 1984) limits on PMV (–0.5 < PMV < 0.5) apply.

Both versions of PMV (PMVG and PMVF) are split at a scale value of 0.5, also following the ISO limits. PPD or "predicted percent dissatisfied" is a mathematical function of PMV and thus follows the PMV limits directly corresponding to 10% dissatisfied. The number given in Table 3 is the percent of measurements falling outside the 10% PPD limits. Predicted percent dissatisfied due to draft (PD) is the fraction of measurements above 15%. Fifteen percent is the limit applied in ASHRAE 55-1992 for draft discomfort. The number given in Table 3 is the percent of measurements falling outside the 15% PD limits. The last entry in Table 3 combines the effect of operative temperature and air velocity as it is applied in ASHRAE 55-1992 (refer to Figures 1 and 2). The percentage in the table is the fraction of points falling above the air velocity limit, i.e., outside the comfort

TABLE 3
Comfort Model Results

Statistics	New Effective Temperature ET* °C	Standard Effective Temperature SET* °C	Predicted discomfort DISC scale units	Predicted thermal sensation TSENS scale units	Gagge's predicted mean vote PMVG scale units	Fanger's predicted mean vote PMVF scale units
Average	26.4	27.0	0.9	0.7	0.2	0.5
Maximum	29.1	30.0	1.8	1.2	0.8	1.0
Minimum	24.4	25.1	0.4	0.3	0.06	0.2
Std Dev.	1.0	0.9	0.3	0.2	0.1	0.2
percent of measurements outside the 'comfort' zone	56.9%	88.9%	31.9%	6.9% (87.5%)[2]	95.8%	66.7%

	Fanger's predicted percent dissatisfied PPD percent	Fanger's predicted percent dissatisfied due to draft PDF percent	Operative Temperature and mean air velocity combined Top and Vel
Average	15.4	17.0	NA
Maximum	48.3	81.5	NA
Minimum	5.3	2.1	NA
Std Dev.	8.0	14.4	NA
percent of measurements outside the 'comfort' zone	67.4%	63.2%	56%

zone. It is interesting to note that points fall above the limits given by both figures, not just the PD limit given in Figure 2. Overall, a majority of the environments preferred by the subjects in this experiment, considered comfortable and acceptable to them, would be classified by existing comfort standards as being "unacceptably warm."

Subjective Responses

The questionnaire (Appendix A) asked the subject to respond to a range of questions including

- favorite device (of the three choices),
- thermal sensation (on the seven-point ASHRAE scale),
- thermal preference (on a three-point scale),
- air movement awareness, and
- air movement preference.

The survey was administered every 15 minutes during the experiment. The results presented in this section are from the third and final survey in each exposure, representing the subject's responses after having adjusted the air movement source for at least 45 minutes.

We asked the subjects to tell us their favorite device of the three: FAN, FMD, or DMD. We found that the sample was evenly split among the three choices. The subjects generally had strong feelings about which one was their favorite, but no single device emerged as the overall favorite for the group. One might have expected that the favorite might change with operative temperature due to the various capabilities of each device, but this was not the case.

The subject's preferred mean air velocity varied according to the device being used at the time. At the lower air velocities, significantly more people were using the FMD, and at the higher air velocities, more were using the FAN. This difference is likely due to the larger flow field of the FMD in the workstation. On the other hand, more people preferred the DMD when they chose air velocities in the 0.1 to 0.3 m/s (average of three heights) range of air velocities.

The proportion of people voting in each category of the thermal preference scale is a function of operative temperature. While the overwhelming majority of responses are in the "want no change" category, as the operative temperature rises above 27°C, 15% to 20% of the subjects "want to be cooler." Conversely, below 27°C, 15% to 20% "want to be warmer."

The proportion of people wanting "more," "less," and "no change" in air movement (air movement preference) varies with the thermal preference category. Of those who voted "want to be warmer," only 10% wanted less air movement and fully half wanted more air movement. On the other side, of those who wanted to be cooler, many also wanted less air movement. That is, they were already using the air source to cool themselves but wanted to be even cooler despite wanting less air movement as well. The bulk of the "want cooler" responses occurred above 27°C.

Air movement preference does not show a trend with operative temperature. This result confirms that the experiment was a successful study of air movement preference for two reasons: 1) the air movement sources were able to provide enough air movement on the warm side, and 2) the ambient air velocities in the climate chamber were near "still." If 1) did not hold true, there would have been people at high operative temperatures voting "want more air movement." Conversely, if 2) did not hold true, there would be people at low operative temperature wanting "less air movement."

DISCUSSION

Preferred Velocities

In this section, a model of predicted percent of satisfied people, the PS model (Fountain 1993), is presented. The philosophy behind this approach is that building designers and HVAC system designers should attempt to assist building occupants as much as possible to achieve their ideal thermal environment. As suggested in a previous section of this paper, the PD limit incorporated into ASHRAE 55-1992 takes the opposite approach by attempting to prevent negative effects of air movement.

Figure 6 shows a scatter plot of the head-height velocities people chose for comfort at each operative temperature. Although the analysis that follows could easily be performed using an average air velocity from the three sensors, the head height was chosen since it was the height used for the Fanger et. al (1988) experiment. The sample size decreases at the extremes of the temperature range since the actual temperature in the workstation was not exactly equal to the target temperature in the experiment. For example, the experiments for the target temperature bin of 28°C are scattered from 27.5°C to nearly 29°C. The PD (from Figure 2) for a turbulence of 40% is also shown in Figure 6. Forty percent is slightly lower than the average turbulence (47%) measured for the isothermal experiment

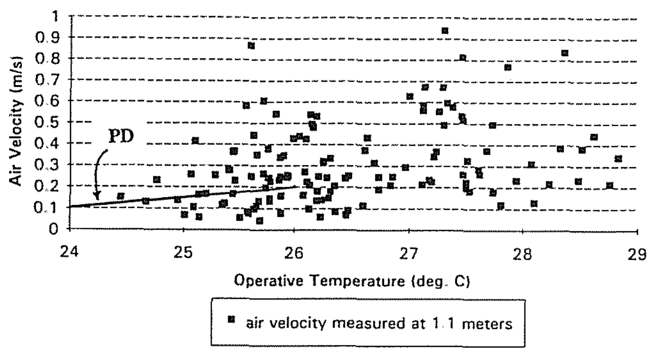

Figure 6 *Preferred air velocity (1.1 meter height).*

and is thus an overestimate of the air velocity suggested by the PD model (higher turbulences translate into lower velocity limits in the model). This velocity limit is at the level that resulted in 15% of the subjects expressing draft discomfort in the Fanger et. al (1988) experiment. Three things are clear in Figure 6: 1) there is a wide range of preferred air velocities, 2) the range of preferred air velocities increases with temperature, and 3) the PD is not a good predictor of the upper limit of air velocities that these people want.

In the temperature range where the PD model is intended to be applied, i.e., below 20°C, half of the subjects preferred a higher velocity than the PD limit and half preferred a lower velocity. In essence, half of the people would want more air velocity than the PD limits permit in ASHRAE 55-1992, i.e., 50% would prefer more air movement at the PD = 15% level. As the limit moves up (increased velocity at a particular temperature), more people may be dissatisfied due to draft, but fewer will be dissatisfied due to lack of air movement.

As the operative temperature increases, the range of preferred air velocities increases. There appears to be no lower limit on preferred velocity or no minimum air velocity required for cooling. This was unexpected. One would expect to find higher minimum velocities to cope with increased heat-loss requirements as the operative temperature increases.

Effect of Air Turbulence on Preferred Velocity

No turbulence effects are evident in the data. Figure 7 shows a plot of turbulence intensity vs. preferred air velocity. At least four possibilities could explain this result. First, the effect of turbulence on heat loss at the skin surface may be different (for this experiment) from that embodied in the draft risk model. Second, the effect of air turbulence on the subcutaneous thermoreceptors (particularly on the back of the neck) may produce an unpleasant sensation unrelated to heat loss. Third, turbulence may have no effect at all on

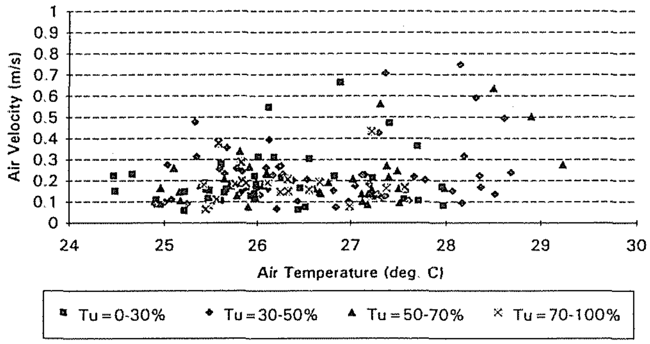

Figure 7 *Preferred air velocity for different turbulence intensities (1.1 meter height).*

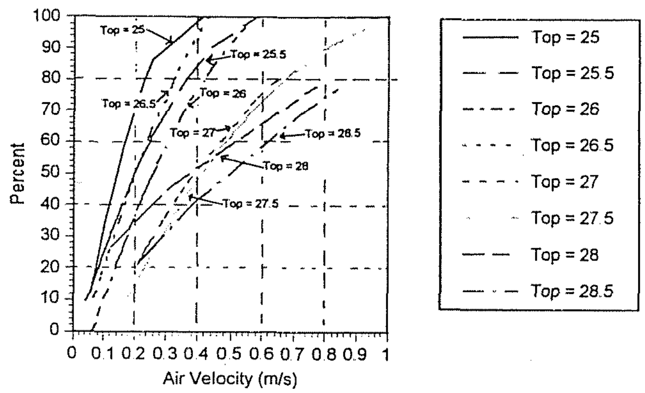

Figure 8 *Percent of the sample choosing a particular air velocity.*

heat loss or sensation. The distribution of turbulence with preferred velocities cannot be distinguished from chance variability in this experiment. Fourth, nonthermal factors in airspeed preferences may swamp any effect turbulence could have at these levels.

A Model of Predicted Percent Satisfied, the "PS" Model

Figure 8 shows the percent of the sample choosing a particular air velocity. Separate curves are shown for operative temperatures between 25°C and 28.5°C in half-degree increments. For example, at an operative temperature of 25°C, 85% to 90% of the subjects chose air velocities of 0.25 m/s or below. The other readily apparent feature of this plot is the slope change for the curves at 27°C and above. Above 27°C, the percentage of people choosing higher velocities increases faster than for temperatures below 27°C. For example, the percentage of subjects preferring 0.4 m/s or less at 28°C is roughly 50%, while the percentage of subjects preferring 0.4 m/s or less at 26°C is nearly 80%. This suggests that the effect of air velocity is "discontinuous" with temperature. That is, above a certain point, it takes proportionately greater air velocities to satisfy people.

The curves in Figure 8 provide the raw data for the PS model, a model of "predicted percent of satisfied people" as a function of locally controlled air movement available in the occupied zone. That is, the "percent satisfied" at a particular air velocity and operative temperature is defined as the fraction of the sample preferring a particular air velocity or lower. The "unsatisfied" fraction is those with higher preferred air velocities, as they would be unable to achieve their preferred air velocity if the air velocity were limited to the level in question, while those in the satisfied fraction could simply adjust the source to a lower level if they chose. To fit the PS model, the data in Figure 8 were recast as "percent of the sample" curves on a plot using air velocity and temperature as the axes instead of a map of temperature curves onto a plot with axes representing "percent of the sample" and air velocity.

Clearly, the model must be a function of operative temperature, preferred air velocity, and perhaps turbulence intensity. Two basic approaches were followed: 1) fitting a model of a functional form similar to the PD model to this data and 2) finding the best statistical model of Top, Vel, and Tu that describes these data. If the physical mechanisms utilized by the PD model are applicable to local cooling, then a model incorporating the same physical mechanisms should be the best model. On the other hand, perhaps a better model can be obtained by trying various transformations of the independent variables that may represent other (as yet undefined) physical or psycho-physical mechanisms. The transformations that were tried included squares, cubes, fourths, square roots, and logs. A stepwise multivariate regression was used to select the model from the many possible combinations of variables.

The "best" polynomial model turns out to have more predictive power than the PD-type model. Thus, it is presented as the PS model and used throughout the remainder of this discussion.

The best polynomial model is

$$PS = ATop^{0.5} + BTop + Cv^{0.5} + Dv,$$

where A = 1.13, B = -0.24, C = 2.7, and D = −0.99,

or

$$PS = 1.13Top^{0.5} - 0.24Top + 2.7v^{0.5} - 0.99v.$$

The goodness-of-fit statistics for this model are shown in Table 4.

The model is a good fit; the standard errors of the coefficients and the rms error of the model are low while the adjusted r-square is high. The probability that each of the parameters has non-zero coefficients in the model is significant at the 1% level (P<.0001). Figure 9 compares the measured PS to the predicted PS for all observations.

Figure 10 shows the PS model plotted in the traditional format of Figures 1 and 2, where operative temperature is the X-axis and air velocity is the Y-axis. The bottom curve

TABLE 4
Goodness-of-Fit Statistics for the Best Polynomial Model

	DF	Sum of Squares	Mean Square	F-value	Prob. >F
Model	4	41.28	10.32	1656.9	.0001
Error	112	0.69	.0062		
Total	116	41.97			

Variable	DF	Parameter Estimate	Standard Error	T for H:0 parameter = 0	Prob. > |T|
T	1	-0.24	0.015	-15.6	.0001
V	1	-.99	0.10	-9.6	.0001
Tsqrt	1	2.7	0.14	18.2	.0001
Vsqrt	1	1.12	0.08	14.1	.0001

Root mean square error	0.079
Sample mean of the dependent variable.	0.53
Coefficient of Variation	14.9
R-Square	0.98
Adj. R-Square	0.98

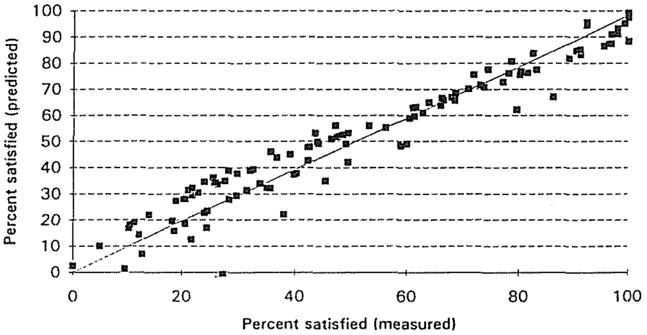

Figure 9 Comparison of measured percent satisfied vs. predicted percent satisfied (r = *0.98*).

is for a PS of 50%, i.e., only half of the people given a source of air movement adjustable up to this level will be satisfied. The top curve is for a PS of 90%, i.e., 90% of those given a source of air movement adjustable up to this level will be satisfied. Recall that a small percentage (9%) of the subjects in the experiment either voted outside the comfort zone in terms of thermal comfort (beyond +1) or found the air movement required for comfort to be unacceptable. These subjects cannot be considered "comfortable," so 9% must be subtracted from the percentage experiencing comfort at the upper limit of air velocity. However, the solution for these subjects lies not in reducing the air velocity limit but in reducing the space temperature or supplying cooler-than-ambient-temperature air. The experiments discussed here were repeated using supply temperatures that were cooler-than-ambient, and those results will be presented in a future paper.

Comparing PS and PD

Figure 11 compares PD with PS at the same level of dissatisfaction. The PD curve shown is for 15% dissatisfied (the level in ASHRAE 55-1992) at a turbulence intensity of 40%. The PS curve shown is for PS = 85%, or 15% dissatisfied. The difference between the curves may account for the discontent due to a lack of air movement found in some buildings (de Dear and Fountain 1994). The PD standard currently in use is designed to protect that portion of the population sensitized to drafts in the cool-to-neutral temperature zone on the psychrometric chart, i.e., less than 23°C. It is not designed to make the greatest number of people satisfied with the air movement. This would require individual control of a local air movement source.

Figure 12 shows that the difference between PS and PD is a fundamental one. The PS (85%) curve from Figure 11 is added to the draft risk figure (Figure 4 in ASHRAE Standard 55-1992, reproduced here as Figure 2). The five curves from Figure 2 represent different turbulence intensities. The top two curves are for Tu = 0% and Tu = 10%. Tu = 0% describes laminar flow. The lowest turbulence intensity measured in the current experiment was 17% when the local air movement source was turned off by the subject. Seventeen percent is below what one researcher (Thorshauge 1982) concluded was a reasonable lower limit after extensive measurements of air movement in buildings. A new technology, displacement ventilation, may produce low-turbulence environments, but even at 10% turbulence intensity, the PS curve lies well above the PD curve.

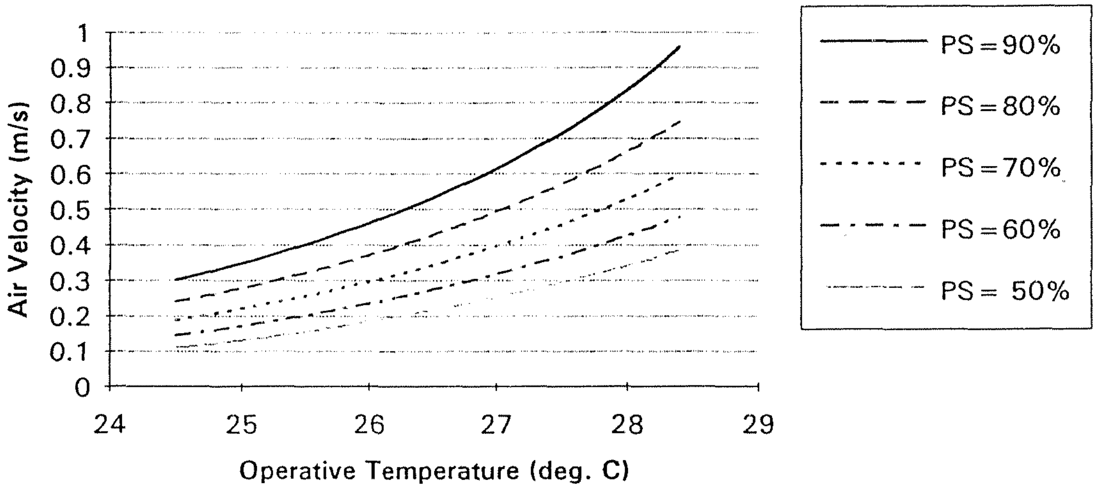

Figure 10 *Predicted percent satisfied (the PS model).*

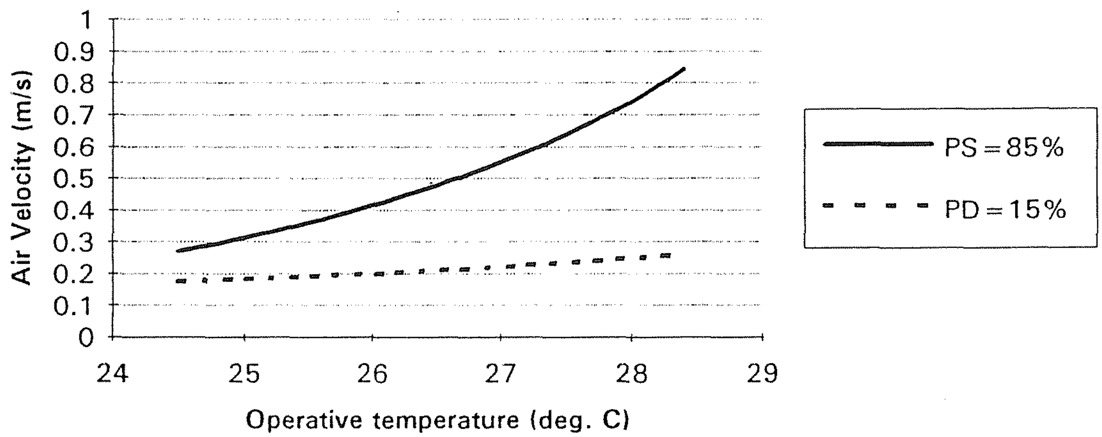

Figure 11 *Comparison of PS = 85% and PD = 15% (using 40% turbulence intensity for PD).*

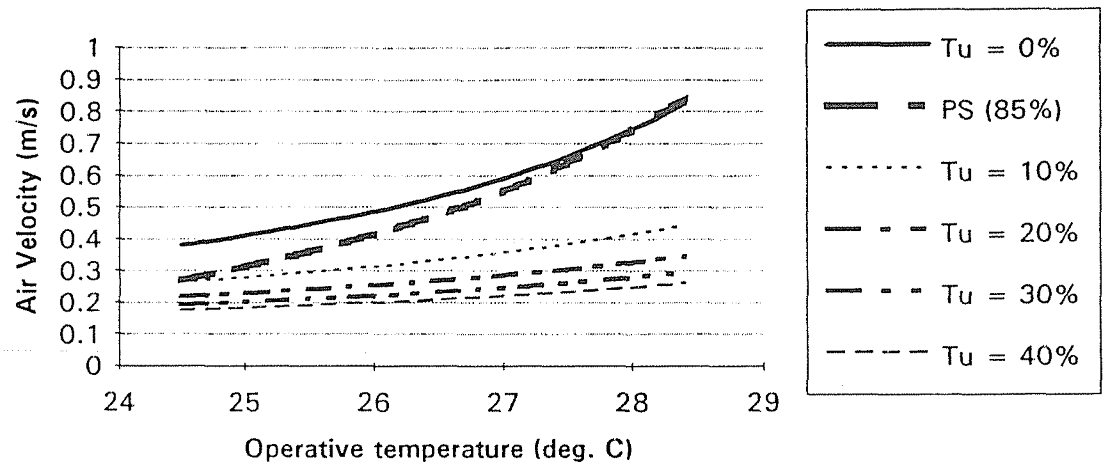

Figure 12 *Comparison of the PS = 85% curve with several PD = 15% curves.*

CONCLUSIONS

Fifty-four human subjects were given control of the air supply velocity from a desk fan (FAN), a floor-mounted diffuser (FMD), and a desk-mounted diffuser (DMD) at a single ambient air temperature. The subjects were asked to adjust the air movement as they pleased to make themselves comfortable. The tests encompassed the full temperature range of the "transition zone," 25.5°C to 28.5°C. Physical measurements of the environment were made and subjective votes collected, including thermal sensation, thermal preference, work area preferences, personal control preferences, and health characteristics. A model that predicts the percent of satisfied people (the PS model) as a function of air temperature and air movement in warm conditions is proposed.

A PS model was developed to predict the percent of satisfied people in an office environment when locally controlled air movement is available. The model could also be used to predict the percent of dissatisfied people due to not having enough air movement when locally controlled air movement is not available. Simply find the PS corresponding to the air velocity (measured or proposed) in an environment on the PS chart at the appropriate operative temperature and subtract the PS from 100%.

Finally, it is important to remember that while the PD, PPD, and PMV models represent environments as non-self-controlled, the PS model recognizes that people actively participate in shaping their environments. One might argue that the degree to which the designer, engineer, and builder can help office inhabitants achieve their ideal thermal environment is one good measure of the success of a building. The PS model should be used when designing an indoor space where the goal is to make the most people satisfied with the air movement in their environment. It embodies the perhaps unusual philosophy of attempting to achieve the positive rather than prevent the negative.

ACKNOWLEDGMENTS

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APPENDIX A

1) Please note down the time as indicated by the wall clock:____________

2) Please tick (✔) the box that best describes your present **THERMAL PREFERENCE**....

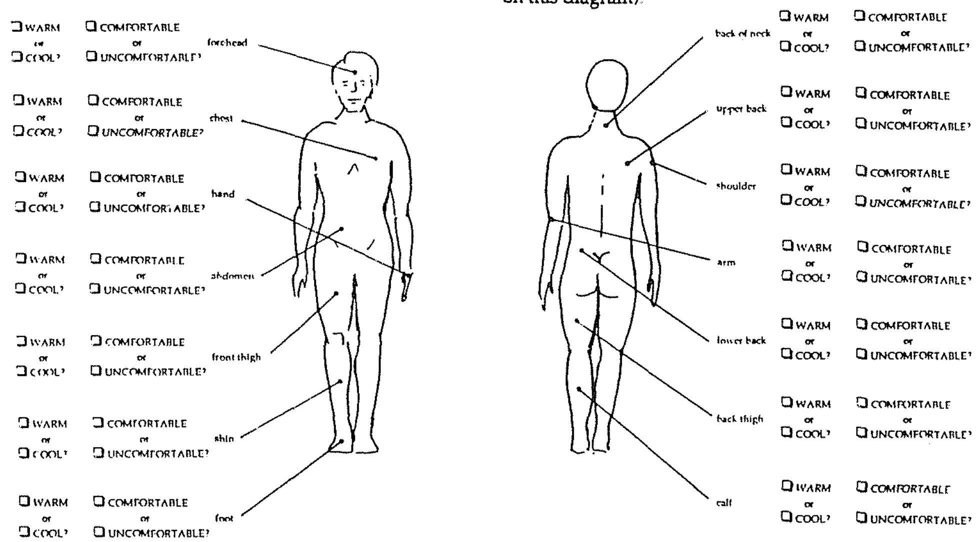
- ❑ I want to be WARMER
- ❑ I want NO CHANGE
- ❑ I want to be COOLER

3) Please tick (✔) the scale below in the place that best represents your **OVERALL THERMAL SENSATION** at present....

-3	-2	-1	0	+1	+2	+3
COLD	COOL	SLIGHTLY COOL	NEUTRAL	SLIGHTLY WARM	WARM	HOT

4) Do you feel **COOL** or **WARM** on any part of your body at the moment?

- ❑ NO (go directly to Q.5)
- ❑ YES (If YES, please indicate where with ✔s on this diagram).



5) Please tick (✔) the box that best describes your present **AIR MOVEMENT PREFERENCE**....

- ❑ I want LESS AIR MOVEMENT → Why?______________
- ❑ I want NO CHANGE
- ❑ I want MORE AIR MOVEMENT → Why?______________

6) Is the present rate of air movement **ACCEPTABLE** for carrying out paperwork at your desk?

- ❑ YES
- ❑ NO

DISCUSSION

R.F. Goldman, Senior Consultant, Arthur D. Little, Cambridge, MA: You did a nice job, considering the large human variability, in teasing out of the data a reasonable fit to the PS/PD model. While this lends support to the growing feeling of the importance of individual control of one's own local climate, would you comment on the statistical significance of the data and/or its regression fit?

Marc Fountain: The statistical significance of the fit of the model to the data is very good. However, the statistical significance of the experiment itself is limited by the sample size and must be verified by independent repetitions.

Arsen Melikov, Research Associate, Laboratory of Heating and Air Conditioning, Technical University of Denmark, Lyngby: The authors should be congratulated for their study, which will contribute to the understanding of the human response to air movement at air temperatures higher than the range of comfortable temperatures, i.e., between 25°C and 30°C. This study is one of the first to compare different types of personally controlled air supply devices. I have some comments on the results presented in the paper.

Individual differences make it difficult to find *one* thermal environment that suits everybody. Individual control of the local environment therefore has the obvious advantage—that (in principle) it should be possible to satisfy all persons in a space. By selecting air velocity as the individually controlled variable, the advantage of a higher operative temperature can be maintained, i.e., the potential for energy savings.

The practical application of your PS equation is that it may predict the air velocity required to keep even the warmest person thermally neutral. For individually controlled environments, there is no reason to strive for anything less than 100% satisfied. Therefore, the maximum required velocity provided by the air supply device is useful rather than the PS model. The air velocity required to keep people thermally neutral may also be evaluated by the PMV model. At 1 met, 0.5 clo, and 28°C, a mean velocity of 1.7 m/s over the entire human body would be required to maintain thermal neutrality. This is not far from the 1.2 m/s required for PS = 100%.

Results of the present study and a draft study by Fanger et al. (1988) are compared in the paper. However, I believe this is not justified because the two studies are completely different. The present study is on human response to personally controlled air movement in a warm environment, where the occupant is not in thermal neutrality. In this case, the preferred velocity selected is defined by a compromise (different for each subject) between decreased warm discomfort and increased discomfort due to draft or annoyance from the pressure of the jet. The study by Fanger et al. applies when the occupant feels thermally neutral but may experience a local discomfort due to draft. In this paper, the subjects were asked whether the air movement was "acceptable for carrying out paperwork at the desk," but not whether the air movement was acceptable from a comfort point of view. The classification of all subjects who answered yes to this question as "satisfied" may be somewhat problematic.

Furthermore, the comparison of the present results and the previous results by Fanger et al. (1988) is made by extrapolation of Fanger's results up to 28.5°C, which is above the range of comfortable temperatures for which they are defined, namely between 20°C and 26°C (for example, Figures 11 and 12). In the subsection "The Draft Curves and the Constant-Heat-Loss Curves," the incorrect statement is made that ". . . in the higher temperature range, above 23°C, the draft risk curve is an extrapolation to conditions where data were not collected. . . ." If the authors go through the referenced paper more carefully, they will find that the draft risk curves are based on human subject experiments in the temperature range of 20°C to 26°C.

Fountain: We appreciate the comments by Melikov. It must be said that the bulk of his comments were not presented verbally, but have been conceived after the fact. We will address them in sequence.

(1) Melikov suggests there should be *one* environment that satisfies everybody. We disagree and would like to point out that the current experiment was designed to seek out a range of environments that are considered comfortable.

(2) Melikov says that "the maximum required air velocity provided by the air movement source is useful rather than the PS model." The PS model can be used as a design tool to determine what that maximum velocity should be for a particular situation.

(3) We agree that the PMV model predicts similar, and in many cases higher, air velocities than the PS model.

(4) Melikov is incorrect in stating that the subjects in this experiment were not in a state of thermal neutrality. This is described in the section entitled "Measurement Protocol."

(5) Melikov suggests that the air movement selection in this experiment is a compromise between "decreased warm discomfort" and "increased discomfort due to draft." This is an incorrect interpretation. The subjects were thermally neutral and few reported feelings of discomfort due to draft. Melikov says "the study by Fanger et al. applies when the occupant feels thermally neutral but may experience local discomfort due to draft." The same statement applies to the current study. In addition, both studies apply when the occupant feels thermally neutral but may experience discomfort due to not having enough air movement.

(6) The question asked of the subjects with regard to the air movement being "acceptable for carrying out paperwork at the desk" was designed to encompass both thermal and nonthermal aspects of acceptability. All subjects

who responded to the question with a "yes" may be classified as "finding the air movement acceptable for carrying out paperwork at a desk."

(7) Melikov suggests that our statement "in the higher temperature range, above 23°C, the draft curve is an extrapolation to conditions where data were not collected" is incorrect. In the abstract of Fanger et al. (1988), which is the reference cited for the draft curves, the authors state that "the air temperature was kept constant at 23 degrees Celsius." The extrapolation beyond that temperature is based on other previously conducted experiments where the turbulence intensity (a major defining factor in the draft curves) was not considered. Clearly, this extrapolation must be verified by human subject data. (See: Fanger, P.O., A. Melikov, H. Hanzawa, and J. Ring. 1988. Air turbulence and sensation of draught. *Energy and Buildings* 12: 21-39.)