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THERMAL MANIKIN PREDICTION OF DISCOMFORT DUE TO DISPLACEMENT VENTILATION

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ABSTRACT

Thirty-six male and 36 female subjects wearing their normal preferred office clothing were randomly assigned to one of four conditions in a test room. Each subject worked sitting at a desk for 1 hour, estimating thermal comfort and local discomfort for each of 15 body sections on a 7-point scale at 30-minute intervals. Window temperatures and lighting were adjusted to simulate winter or summer conditions, with central room temperatures of 22.5° and 25.0°C, respectively. The room was cooled by displacement ventilation, with supply air at 19° and 17°C, respectively. Subjects sat at right angles to the supply air diffuser, which was 0.7 m high and situated on the floor by the wall opposite the windows. They sat at a distance of 1.1 m or 2.6 m from the diffuser under both conditions. The thermal manikin, VOLTMAN, was similarly exposed. Local thermal discomfort and equivalent homogeneous temperature values (EHT: the temperature of a climate chamber producing the same heat flow from the manikin section) were significantly correlated (r = 0.81). This relationship predicts that if a body section was below EHT = 22.1°C, more than 20% of subjects would feel it was "too cold." None of the four conditions was acceptable on this criterion, although all four conditions were within 1°C of the subjects' preferred whole-body condition EHT = 25.1°C, in which VOLTMAN's total dry heat loss was 47 W/m^2. In fact, 41 subjects (57%) reported local discomfort in at least one body section, mostly "too cold." At least 39% were thus dissatisfied with each of the four conditions. Near the floor, air temperature and velocity were negatively correlated (r = −0.73). Equations predicting EHT and % discomfort in terms of these parameters were therefore derived separately for conditions above and below chair height. Local discomfort predicted in this way exceeded 20% for all four conditions.

INTRODUCTION

In order to increase ventilation efficiency, a system known as "displacement ventilation" has been gaining popularity in Scandinavia. It appears to be acceptable in industrial halls and in hotel foyers, but problems have been encountered in adapting the system to offices where people sit still. Supply air at a temperature several degrees below room temperature is introduced via a diffusing vent low down on one wall. It spreads evenly over the floor and this clean air displaces polluted air, which is warmer, upward toward an exhaust vent in or near the ceiling. In rooms requiring continuous cooling, the system can achieve ventilation efficiencies as high as 130% of what is theoretically possible with complete mixing, where clean air merely dilutes polluted air (Sandberg and Blomqvist 1986). Complete mixing is seldom if ever achieved in offices because of the draft problems caused by the high air velocities that would be required.

Most modern offices require continuous cooling to remove the heat produced by people, lighting, and office machines, even when it is cold outside. The system therefore has very considerable advantages, but since it works by creating a vertical temperature difference, the risk of cold discomfort for the legs and feet, in conjunction with heat discomfort at head height, is a limiting factor. International standard ISO 7730 (ISO 1984) recognizes this by stipulating no more than a 3 K difference between air temperatures at 0.1 and 1.1 m above the floor, while ASHRAE Standard 55-1981 (ASHRAE 1981) stipulates no more than 3 K between 0.1 and 1.7 m, a considerably more stringent requirement. These recommendations are based on experience with conventional systems, which usually do not involve spreading cold supply air across the floor. Laboratory research results support these recommendations: Olesen et al. (1979) predict 5% dissatisfied with 2.8 K difference between 0.1 and 1.1 m and 10% dissatisfied with 3.7 K. Fishman and Semere (1977) and Fishman and Underwood (1977) specifically studied cold air currents along the floor of a 23°C room; 24°C was preferred for ideal foot comfort, but even 19°C corresponded to "comfortably cool" on average, with only about 20% dissatisfied. Air velocities below 0.25 m/s were found to have little influence on foot comfort in these experiments. Displacement ventilation as currently installed in Scandinavia is designed to comply with these comfort limits, but has been found to cause considerable discomfort in offices. An empirical study of simulated winter and summer operating conditions, using human subjects, was therefore considered necessary. The thermal manikin system VOLTMAN, developed at this institute for the assessment of non-

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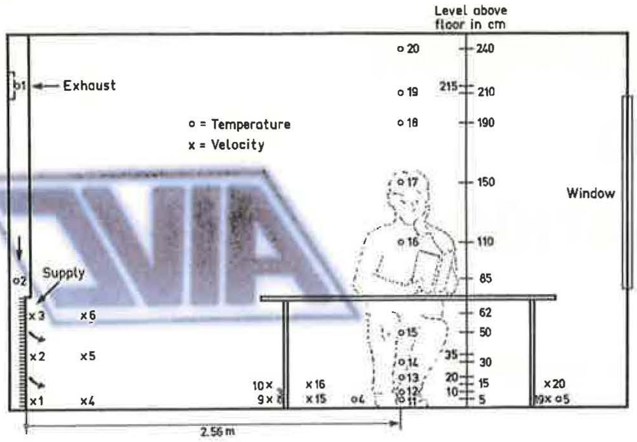

Figure 1 *Position of the sensors to which reference is made in Tables 1 and 2*

uniform thermal conditions, was exposed to the same conditions as the subjects to investigate the relationship between local heat flow and sensations of thermal discomfort.

METHOD

Physical Conditions

A test room (Figure 1) was constructed in the institute's experimental hall in the form of a common type of office module (3.6 by 4.2 m, ceiling 2.5 m) with three narrow windows in the shorter wall (windows 0.85 by 0.30 m, sill height 0.80 m). This "external" wall was built against water-filled radiators that could be heated or cooled to simulate the effects of external weather conditions. The "windows" were uninsulated except for a thin canvas layer on which a "view out" was depicted for the sake of visual realism.

The radiator wall temperature was adjusted to maintain the canvas surfaces at 30°C for summer conditions, 17°C for winter. There were no sources of heat in the room other than the lighting, which was 195 W for summer conditions, 315 W for winter, in both cases including a table lamp. It may be assumed that the subject contributed about 100 W to the room.

The experimental hall was at a temperature of 21°C (±1°C), so the "internal walls" of the office did not transmit significant amounts of heat in either direction. The office was ventilated by means of a 70 cm high, semicircular diffuser attached to the rear wall, standing on the floor, through which 150 m^3/h were supplied in both conditions at 17°C for summer conditions and at 19°C for winter conditions. The air leaving the office through a slot above the door was 8.0° to 8.4° and 4.0°C warmer, respectively, than the supply air temperature in each case.

An office desk was placed on rails so that it was in a direct line from the diffuser to the window wall and could be moved along this line. A large number of sensors for air temperature and air velocity were attached to the desk, as shown in Figure 1. The experiments reported here were carried out using two desk positions: in one of them the subject's mid-point was only 1.1 m away from the diffuser, in the other it was 2.6 m away. In both cases the subject sat 90° to the diffuser-window line. The angle factor as defined by McIntyre (1980) for the windows and a seated subject was 0.031 at 1.1 m, 0.062 at 2.6 m from the diffuser. As is clear from the reported physical measurements, the cooler supply air falls rapidly to the floor and spreads out in a layer that is less than 0.1 m thick, rising as it warms. The conditions were chosen so that the average air temperature at 1.5 m above the floor in the center of the room was 25°C in summer, 22.5°C in winter, corresponding to the average preferred temperatures for this system for each season.

Subjects

Thirty-six men and 36 women, aged 18 to 68 and wearing their own preferred indoor clothing and footwear, were randomly assigned to the four conditions, with approximately equal numbers of each sex in each condition. The reason for allowing them to wear their own clothing was to increase realism: draft-sensitive people can be assumed to habitually use clothing to protect themselves from discomfort, and experiments in which standard clothing is used tend to find an increased, not a decreased, inter-individual difference in thermal preference.

Prior to admitting each subject, the conditions in the room were stabilized with an additional 100 W heater on the chair. This was switched off and removed as the subject entered the test room. Subjects read or wrote quietly at the desk without getting up. After 30 minutes and after 60 minutes they recorded their sensations of thermal comfort or discomfort by writing in a whole number between −3 and +3 on each marked section of a diagram of the human body. The sections correspond to those of the thermal manikin VOLTMAN. The numbers represent the seven categories of the Bedford scale: much too cold (−3), too cold (−2), cool but comfortable (−1), ideal (0), warm but comfortable (+1), too hot (+2), and much too hot (+3). The zone of acceptability is −1 to +1 and is clearly marked so that the subjects, not the experimenter, shall decide what is acceptable. Scales of warmth sensation taken from the field of psycho-physics are inappropriate in this context, as they leave open the question of what degree of warmth sensation can be considered acceptable. In simulation trials of new methods of heating and ventilation, the whole purpose of the experiment is thus lost. To confirm that they had not omitted a sign, subjects were asked to color sections that were "cold" blue, and sections that were "hot" red. They were also asked to record their total state of thermal comfort using the same scale.

Thermal Manikin VOLTMAN

The VOLTMAN system has been described by Wyon et al (1985, 1987). It was developed for a Swedish car manufacturer as a means of measuring the effects of the complex and asymmetrical thermal conditions in vehicles on human heat balance. It is a full-size model of a seated male person, with joints at shoulder, knee, and ankle. Electrical circuits built into the last few millimeters of the external surface allow a process computer to measure and control the average surface temperatures of 19 body sections (17 in the original version) to physiologically correct values for a sedentary person in a state of thermal comfort. The mean skin temperature used is 32.8°C: set values range from 31° on hands and feet to 34°C on the trunk. These surface temperatures are maintained within ±0.1°C by the process computer, which uses software PID regulators (Proportional/Integral/Differential), optimized for each body section.

TABLE 1
Air Temperatures and Conventional Thermal Gradients (between 0.1 and 1.1 m above the floor), Close to the Subject, in °C. Sensor Numbers Refer to Figure 1.

			Summer		Winter	
Condition:			**S2**	**S1**	**W2**	**W1**
Distance of subject from diffuser:			2.56 m	1.1 m	2.56 m	1.1 m
Height	**Sensor**					
1.5 m	(17)	Head	24.5	24.8	22.6	22.8
1.1 m	(16)	Body	24.0	24.1	22.4	22.5
0.5 m	(15)	Thigh	21.5	21.6	21.2	21.2
0.2 m	(13)	Calf	21.2	21.3	21.2	21.1
0.05 m	(11)	Foot	20.5	20.0	21.0	20.6
Gradient	(16-12)	°C/m	3.3	3.4	1.4	1.7

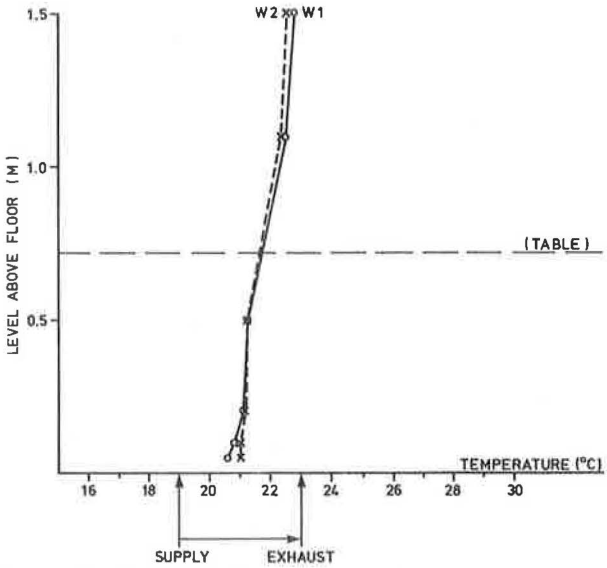

Figure 2 *Air temperatures measured in winter conditions W1 and W2 (1.1 m and 2.56 m from the diffuser)*

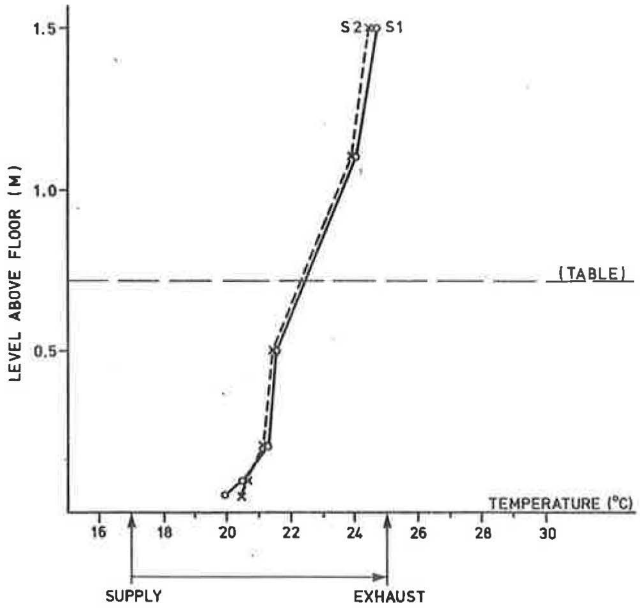

Figure 3 *Air temperatures measured in summer conditions S1 and S2 (1.1 m and 2.56 m from the diffuser)*

At equilibrium, the rate at which heat is supplied to each section is equal to the heat flow through the clothing to the environment. This measured heat flow in W/m² is related to the equivalent homogeneous temperature (EHT) by means of reference exposures: the manikin is placed in a draft-free, homogeneous environment in which all surface temperatures are equal to air temperature, wearing the same clothing, seated in the same posture, but in a string chair which does not insulate the back or thighs. EHT values in °C are usually found to be easier to evaluate than are heat flow values in W/m². "EHT = 15°C" means that a homogeneous environment would have to be as cold as 15°C to produce the same heat flow as was measured in the experiment. Drafts and cold surfaces close to the manikin increase the heat flow and lower the EHT, for example.

RESULTS

Physical Measurements

The air temperatures and air velocities measured during the experiments have been reported in full by Sandberg and Blomqvist (1989). The temperature measurements are summarized in Table 1 and Figures 2 and 3 of the present paper, from which it is clear that thermal gradients exceeded 3°C/m in the summer. Table 2 summarizes air velocities measured close to the calves and feet of the subjects, as used in the Application Note below. Relative humidity was close to 30% throughout. Operative temperatures experienced by the subjects were within 0.5 K of the air temperatures. The influence of the windows on radiation temperature was −0.34 K in winter, +0.31 K in summer, at 2.6 m from the diffuser, half these values at 1.1 m. The clothing worn by the subjects was their normal indoor clothing—usually trousers for both sexes, long-sleeved shirts or blouses, occasionally a thin sweater. Insulation values were estimated to be in the range 0.8 to 1.0 clo. Subjects were randomly assigned to winter or summer conditions.

VOLTMAN

Figures 4 and 5 show the results of the VOLTMAN measurements as "thermal profiles," i.e., sectional EHT values listed in order from head to feet, left preceding right, for the four conditions. Only those body sections for which a thermal vote was obtained from the human subjects are shown, together with the whole-body EHT values. The latter are influenced by the state of thermal balance of all body sections, including the scalp and sections insulated by the chair. It should be remembered that the reference exposures, to which EHT values relate, were made in a string chair, so even a normal typist's chair, as used in the experiments, will raise the total EHT.

TABLE 2
Air Velocity (Standard Deviation) in cm/s, Measured Close to the Calves and Feet of the Subjects. Sensor Numbers Refer to Figure 1.

			Summer		Winter	
Condition:			**S2**	**S1**	**W2**	**W1**
Distance of subject from diffuser:			2.56 m	1.1 m	2.56 m	1.1 m
Height	**Sensor**					
0.15 m	(20)	Left	5(2)	5(2)	5(2)	6(2)
	(16)	Right	13(3)	6(2)	9(3)	6(2)
0.05 m	(19)	Left	13(3)	8(2)	10(3)	5(2)
	(15)	Right	19(2)	14(2)	10(2)	11(2)

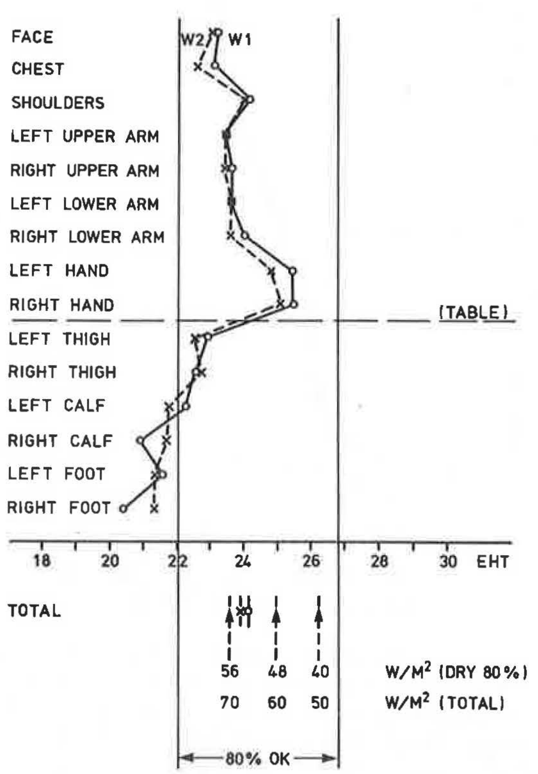

Figure 4 *EHT values measured using VOLTMAN in winter conditions W1 and W2 (1.1 m and 2.56 m from the diffuser). Total EHT values are shown below the X-axis, together with total EHT values corresponding to metabolic rates of 50, 60, and 70 W/m².*

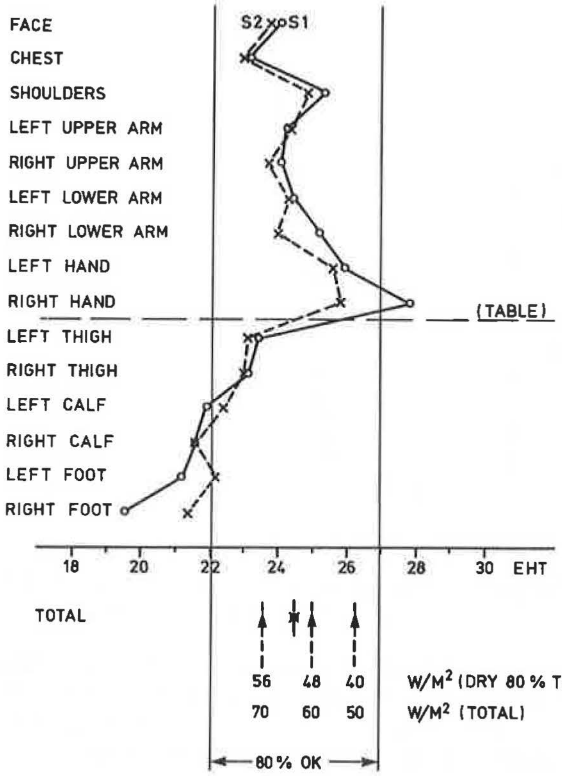

Figure 5 *EHT values measured using VOLTMAN in summer conditions S1 and S2 (1.1 m and 2.56 m from the diffuser). Total EHT values are shown below the X-axis, together with total EHT values corresponding to metabolic rates of 50, 60, and 70 W/m².*

Thermal Comfort Votes

The thermal votes obtained from the 72 human subjects for each of 15 body sections and for the body as a whole were combined arithmetically across subjects to give 16 mean thermal votes (MTV) describing the thermal comfort experienced in each of the four conditions.

Whole-Body MTV

The relationship between whole-body MTV values for male and female groups with the corresponding total EHT values was as follows:

$$MTV\,(WB) = -20.3 + 0.81 \times EHT\,(WB) \qquad \text{(Corr. coeff. } r = 0.61) \qquad (1)$$

This indicates an optimum EHT (WB) = 25.1°C for MTV (WB) = 0. The total dry heat loss from VOLTMAN at EHT = 25.1°C is 47.2 W/m². Assuming conventionally that this is 80% of body heat production, the metabolism of the subjects can be calculated as 59.1 W/m², which corresponds very well with the usual assumption of 1 met (58 W/m²) or 60 W/m² for sedentary work. The whole-body EHT values measured in the experiments were 24.0° and 24.5°C for winter and summer conditions, respectively, i.e., within about 1°C of the optimum 25.1°C indicated by the subjects.

Sectional MTV and % Discomfort

As subjects themselves stated whether or not they

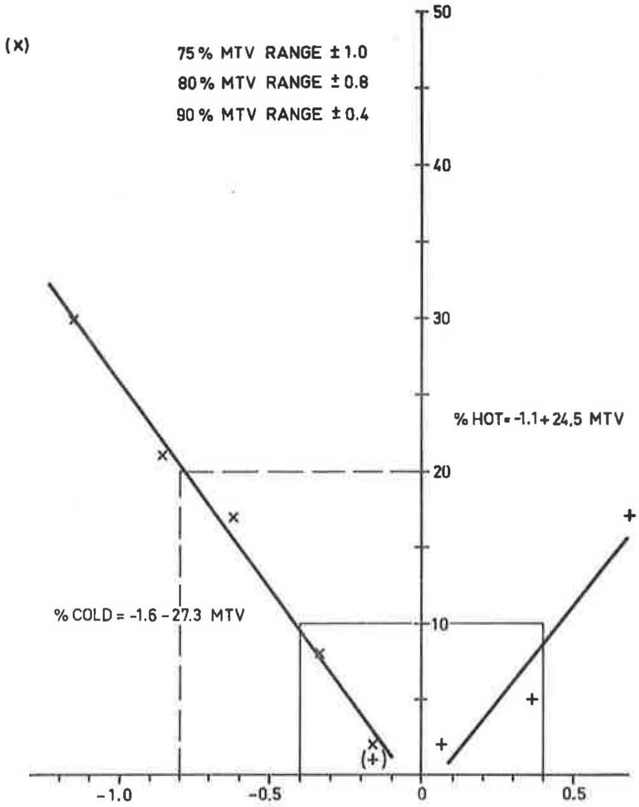

Figure 6 *% too cold and % too hot as a function of MTV (mean thermal vote) for the 2304 votes obtained from all 72 subjects, who made 16 estimates twice. The empirical regression equations for the lines are given.*

were comfortable by choosing clearly marked categories of response, it is possible to examine the relationship between % (discomfort) and MTV. The following equations describe the empirical regressions, shown in Figure 6:

$$\% \text{ too cold} = -1.56 - 27.3 \times MTV \qquad (\text{Corr. coeff. } r = 0.996) \qquad (2)$$

(for $-1.25 < MTV < 0$, and for $2 < \%$ too cold < 30)

$$\% \text{ too hot} = -1.14 + 24.5 \times MTV \qquad (\text{Corr. coeff. } r = 0.956) \qquad (3)$$

(for $0 < MTV$, and for $2 < \%$ too hot < 20)

These equations were derived from all 2304 thermal votes obtained from the 72 subjects, who each made 16 estimates twice. The equations indicate 100% satisfied for $-0.05 < \text{MTV} < 0.05$, 90% satisfied for $-0.4 < \text{MTV} < 0.4$, 80% satisfied for $-0.8 < \text{MTV} < 0.8$, and 75% satisfied for $-1 < \text{MTV} < 1$. The conventional zone of acceptability for real situations is usually taken as 80%.

Sectional MTV

Forty-one of the 72 subjects (57%) reported thermal discomfort in one or more body sections, usually "too cold." At least 39% of the subjects exposed to any of the four conditions reported thermal discomfort in one or more body sections. The exposures were for only one hour, and there were more complaints after one hour than after 30 minutes, as was to be expected as those body sections exposed to draft became steadily colder. Figures 7 through 10 show the sectional MTV values obtained for men and women under each of the four conditions, with the "80% satisfied" zone derived above clearly marked.

Sectional MTV and EHT

MTV values obtained for head, feet, and hands were poorly correlated with EHT. This is probably due to variations in footwear, thermal history, and expectation, and more subjects would be required to obtain a systematic relationship. There was no tendency for any section to appear more sensitive than any other to changes in EHT. The following relationship was derived for the eight clothed sections of the arms and legs of the 72 subjects:

$$MTV = -8.20 + 0.335 \times EHT \qquad (\text{Corr. coeff. } r = 0.81) \qquad (4)$$

This relationship indicates an optimum sectional EHT = 24.5°C for MTV = 0, and an 80% acceptability range ($-0.8 < \text{MTV} < 0.8$) of $22.1 < \text{EHT} < 26.9$°C. As indicated in Figures 7 through 10, all four conditions fail to meet this criterion.

Sectional MTV and Air T

Taking the air temperatures measured closest to each body section, the corresponding relationship was:

$$MTV = -5.52 + 0.226 \times T \qquad (\text{Corr. coeff. } r = 0.72) \qquad (5)$$

This indicates an optimum Air T = 24.4°C for MTV = 0, and an 80% acceptability range of $20.9 < \text{T} < 28.0$°C, but as air temperatures and velocities tend to be negatively correlated in displacement ventilation, the more specific, two-zone analysis set out in the Application Note is preferred.

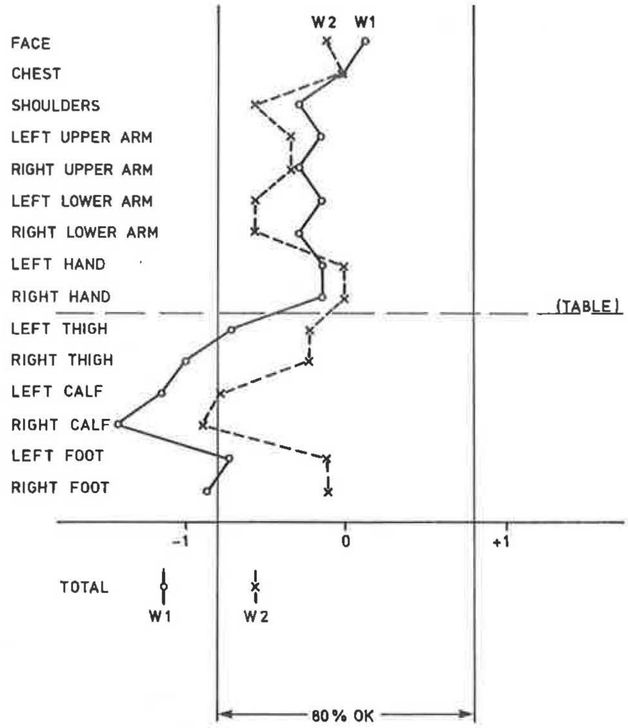

Figure 7 *Mean thermal votes obtained from male subjects in winter conditions W1 and W2 (1.1 m and 2.56 m from the diffuser)*

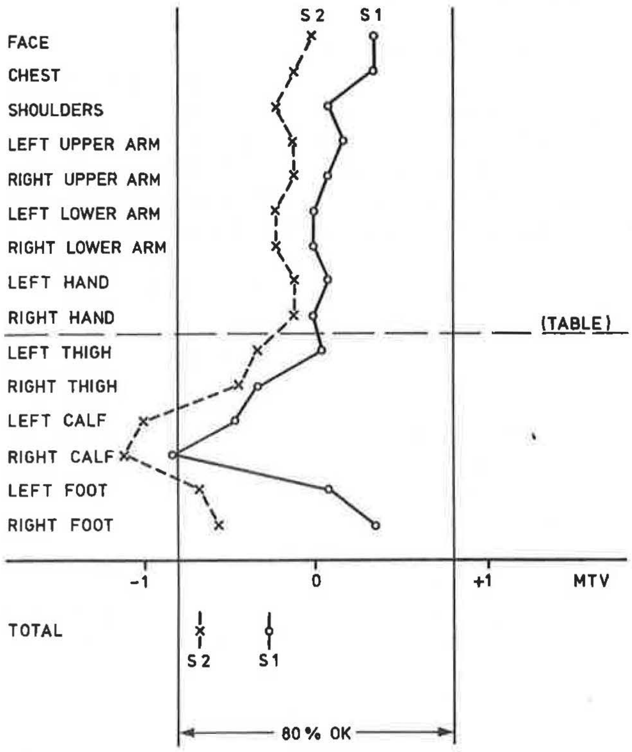

Figure 8 *Mean thermal votes obtained from male subjects in summer conditions S1 and S2 (1.1 and 2.56 m from the diffuser)*

Left/Right Asymmetry

As may be seen in Figures 4 and 5, for virtually all body sections below the desk, EHT values are lower on the right-hand (upstream) body section. However, no statistically significant differences between thermal votes for corresponding left and right sections could be shown.

Male/Female Differences

The only systematic difference between the sexes was for the right foot. Under winter conditions, it was judged significantly colder by female subjects ($P < 0.02$).

Local Thermal Discomfort

Of the 49 subjects who used colors, 63% used them to indicate exactly which part of particular body sections felt too cold or too hot, although this was not envisaged in the instructions, which were to color whole sections. Male and female responses, and 30- and 60-minute responses, were similar in this respect.

DISCUSSION AND CONCLUSIONS

The air temperatures and velocities in Tables 1 and 2 are not outside currently recommended limits for moderate thermal environments, e.g., ISO (1984), with the exception of thermal gradients in summer conditions, which exceed the recommended limit of 3 K/m by fractions of a degree K. It is not difficult to see why displacement ventilation appeared to be suitable for office environments. Although the ASHRAE standard for vertical temperature differences was exceeded in the summer conditions by about 50% (i.e., by 1.5 K), it was not even approached in the winter conditions, which were equally disliked. The inlet temperatures

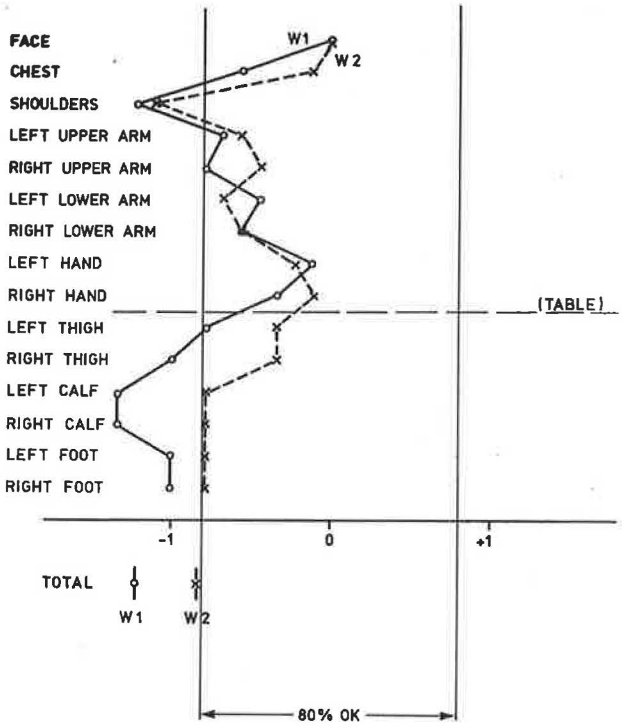

Figure 9 *Mean thermal votes obtained from female subjects in winter conditions W1 and W2 (1.1 m and 2.56 m from the diffuser)*

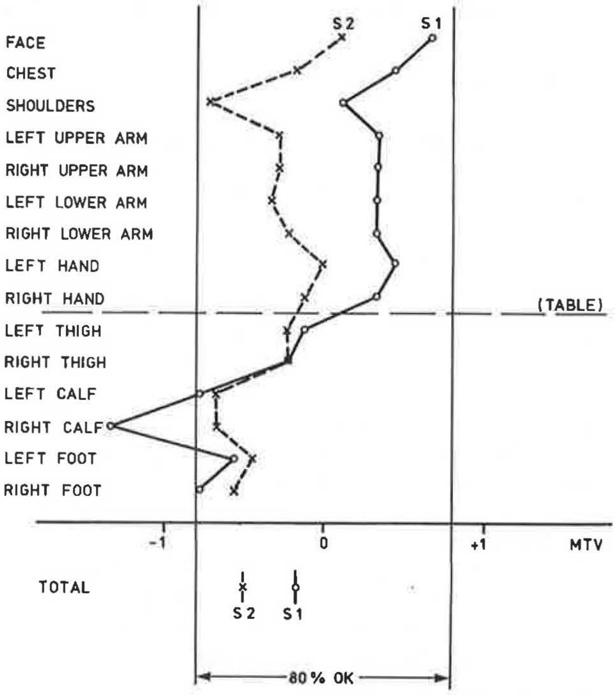

Figure 10 *Mean thermal votes obtained from female subjects in summer conditions S1 and S2 (1.1 m and 2.56 m from the diffuser)*

and average room temperatures in this study were selected on the basis of manufacturers' recommendations for limiting summer and winter use. It is worth noting that the total heat loss from VOLTMAN, wearing the same trousers and long-sleeved shirt for both summer and winter exposures, was only greater in the winter condition by an amount corresponding to 0.5°C, although central room temperatures differed by 2.5°C. The excellence of the guidelines based on "good practice" is further illustrated by the fact that the human subjects would have chosen as their ideal equivalent temperature a value within about 1°C of what it actually was, under all four conditions. They may thus be assumed to have been in a state of thermal comfort, i.e., not vaso-constricted. Their selection of an ideal equivalent temperature resulting in an empirically measured total dry heat loss of 47.1 W/m^2 from VOLTMAN supports the assumption of 80% dry heat loss and metabolic heat production of 1 met (or 60 W/m^2) for sedentary subjects.

Mean thermal votes have been used until now mainly to investigate whole-body thermal comfort. Subjects are commonly believed to be unable to estimate local thermal discomfort. Their color-coding responses suggest that estimates could be obtained for more than 15 body sections. Wyon (1968) did obtain three MTV values for upper, middle, and lower body sections from surgeons and operating theater staff, but thermal indices derived from physical measurements made at three different heights correlated only slightly better than air temperature with them ($r = 0.5$). The technique of relating % discomfort to MTV for the whole data base, then MTV to EHT values derived from sectional heat losses, is more successful in predicting local thermal discomfort caused by displacement ventilation. For clothed body sections, it accounts for two-thirds (66%) of the variance. In the Application Note, equations predicting EHT from measurements of air temperature and velocity have been derived for the specific case of displacement ventilation, for use when no thermal manikin is available.

Thermal conditions above table height were found largely acceptable. Most of the discomfort was due to cold legs, ankles, and feet. The subjects in this experiment were less tolerant of cold air below table height than would be predicted by the work of Olesen et al. (1979) or Fishman and Semere (1977) and Fishman and Underwood (1977). They were dressed for conventional indoor conditions in Sweden, where operative temperatures are in the region of 20° to 22°C. One way to avoid cold floor drafts with displacement ventilation would be to dress more lightly and raise the inlet temperatures, thus approaching the conditions studied in the experiment reported by Olesen et al., in which clo values were 0.6 and operative temperatures close to 24°C. However, as shown by Andersson et al. (1975), air temperatures above 22°C lead in practice to significantly increased complaints of dryness in Swedish winter conditions, where indoor relative humidities are often as low as 20% for long periods.

This report is not intended merely as documentary proof that there are problems associated with displacement ventilation, but also as a step toward their solution. The next step will be to use the feedback obtainable from thermal manikin measurements to develop acceptable modes of operation. Inlet temperatures; flow rates; the design and placement of the diffusers, including ways of permitting room occupants to move them about so as to "furnish the room with fresh air"; the air circulation in the room; the detailed design of the desk and the protection it affords the sedentary office worker from draft; perhaps even perforated floors to avoid the kind of floor draft hitherto associated only with open fires in combination with untight windows and doors, can all be manipulated and combined until the sectional heat flows measured on the manikin are within the acceptable limits found in this experiment. Displacement ventilation is a promising method of increasing ventilation efficiency, and there is no need to consign it to the scrap heap of heating and ventilation history simply because it causes complaints of draft when installed in its present form.

APPLICATION NOTE

Thermal manikins are not available to all those concerned with the optimization of displacement ventilation. Equations predicting the percentage of subjects experiencing local discomfort have therefore been derived in terms of air temperature and velocity for two zones: above chair height (0.5 m) and below it. Air velocities close to the subject are assumed to have been less than 0.1 m/s above chair height, as they were measured to be at 0.15 m (Table 1), and an empirical equation was obtained for body sections 1 through 11 (head to thighs):

$$EHT\,(1\text{-}11) = 14.10 + 0.428 \times T \qquad \text{(Corr. coeff. } r = 0.46) \qquad (6)$$

The equations for body sections 12 through 15 (calves and feet) were:

$$EHT\,(12\text{-}15) = 22.63 - 13.003 \times V \qquad \text{(Corr. coeff. } r = -0.74) \qquad (7)$$

$$T = 21.56 - 7.713 \times V \qquad \text{(Corr. coeff. } r = -0.73) \qquad (8)$$

From these relations, the following equation was derived:

$$EHT\,(12\text{-}15) = T - 5.29 \times V + 1.07 \qquad \text{(Corr. coeff. } r = 0.67) \qquad (9)$$

These equations predicting thermal manikin EHT for body sections above and below chair height in terms of air temperature and air velocity may be combined with the previously derived equations relating MTV to EHT, and % (discomfort) to MTV, exactly as was done for EHT measured on the manikin. This yields the following equations, whose results are shown in Figures 11 and 12:

Above chair height (> 0.5 m above floor, air velocity < 0.1 m/s)

$$\begin{aligned} \%\ \text{too cold} &= 93.35 - 3.914 \times T \\ \%\ \text{too hot} &= -86.31 + 3.513 \times T \end{aligned} \qquad (10)$$

Below chair height (< 0.5 m above floor)

$$\begin{aligned} \%\ \text{too cold} &= 212.51 - 9.15 \times T + 48.38 \times V \\ \%\ \text{too hot} &= -193.26 + 8.21 \times T - 43.42 \times V \end{aligned} \qquad (11)$$

The predicted % too cold below chair height on the present, two-zone analysis was 20% to 26% for both calves and both feet in all four conditions, which thereby fails to meet the 20% criterion. The equations predict that if air velocities are 0.2 m/s, fewer than 20% will complain of local

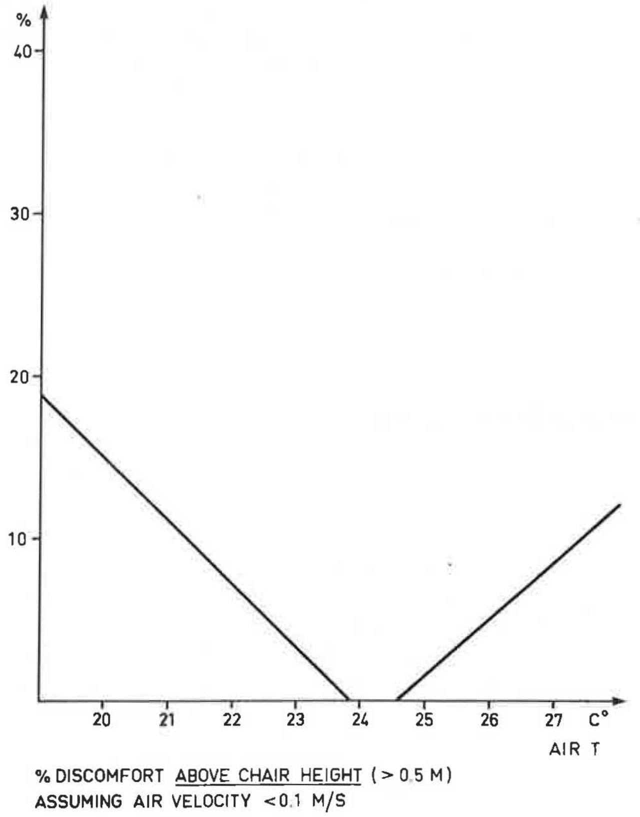

Figure 11 *Predicted % discomfort as a function of air temperature for body sections above chair height (> 0.5 m) assuming 0.1 m/s air velocity. Note that the prediction refers to local discomfort, assuming the subject is in thermal balance (see Application Note).*

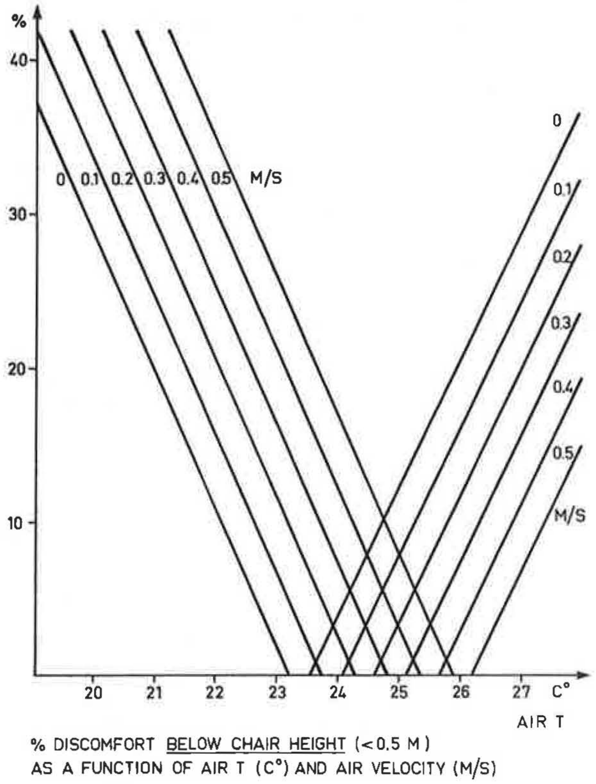

Figure 12 *Predicted % discomfort as a function of air temperature and velocity for body sections below chair height (< 0.5 m). The prediction is of local discomfort, assuming the subject is in thermal balance (see Application Note).*

discomfort below chair height in the air temperature range of 22.1° to 27.0°C. For 0.1 m/s, the 20% range is 21.6° to 26.5°C. The 30% ranges are 21.0° to 28.3°C for 0.2 m/s and 20.5° to 27.7°C for 0.1 m/s. Predicted % too cold at the feet exceeded 30% in the summer. Above chair height, assuming 0.1 m/s, fewer than 10% are expected to complain of *local* discomfort in the air temperature range of 21.3° to 27.4°C; clothing, posture, work rate, and chair insulation will determine whether they are in thermal balance. These equations should not be used to predict local discomfort arising from high-velocity ventilation systems whose purpose is to achieve complete mixing, but may apply to downdrafts from windows and cold surfaces as well as to displacement ventilation.

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