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Effect of airflow direction on human perception of draught

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Abstract

Forty subjects, 20 women and 20 men, were exposed to airflows from five different directions: horizontally towards the front, the back, and the left side and vertically upwards and downwards. The subjects were exposed to stepwise increased air velocities ranging from less than 0.10 m/s to 0.40 m/s at three temperature levels 20, 23 and 26°C. The results showed that airflow direction has an impact on perceived discomfort due to draught. At 20°C and 23°C, airflow from below was perceived as most uncomfortable followed by airflows towards the back and front. At 26°C airflow from above and towards the back caused most dissatisfaction due to draught, but generally only a few of the subjects perceived discomfort at this temperature. Discomfort due to draught was most often felt at the body regions directly exposed to the airflow. These were the legs, the feet, and the lower back at airflow from below; the neck, the shoulders and the hands at airflow from above; the neck, the back, the shoulders and the legs at airflow from behind; the knee and the arm facing the windbox when exposed to air movements directed towards the side; and the hands and the knees when exposed to air movements towards the front.

Introduction

Draught, defined as an unwanted, local convective cooling of the skin, has been the topic of numerous studies in laboratories and in the field throughout this century. Nevertheless, draught is still one of the most frequent causes of complaints of the thermal indoor environment. It has been documented that human perception of draught depends on the air velocity, air temperature and turbulence intensity (Fanger and Christensen 1986; Fanger et al. 1988; Mayer 1987, 1992). The turbulence intensity is defined as the ratio of the mean air velocity to the standard deviation of the air velocity. Based on experiments with human subjects, a model has been developed that predicts the percentage of persons dissatisfied due to draught as a function of mean air velocity, air temperature and turbulence intensity (Fanger et al. 1988). The model is valid for sedentary persons, dressed in normal indoor clothing, and has been included in European, American and international standards for the indoor environment (prENV 1752-1994; ASHRAE 55-1992; ISO 7730-1994). The model predicts the draught rating for persons exposed to air movements from behind.

In a previous study, Mayer and Schwab (1988) exposed 50 subjects to horizontal airflows towards the front and back and vertical upward- and downward flows at one temperature level and one (low) level of turbulence intensity. The study showed that the neck was more sensitive to air movements than the face. In addition, more subjects complained of draught on the face at upward than at downward flows.

The air movements in a space depend on the ventilation system and on the interior of the space. In mechanically ventilated spaces, the type of ventilation system is decisive for the airflow characteristics and the direction of the air movements in the space. With traditional mixing ventilation, the air is typically supplied through inlets located near the ceiling. Thus, the occupants in the space will be exposed vertically from above or horizontally from an arbitrary direction. With displacement ventilation, cool air is supplied near the floor, directly in the occupied zone, and exhausted through outlets located near the ceiling. The supply air is dispersed along the floor and rises upwards in the space. Underfloor ventilation is a rather new, and still not so common, method of ventilating spaces, where the air is supplied through the floor and exhausted near the ceiling. Several other types of ventilation system exist, which all cause different airflows from different directions. The selected type of ventilation system therefore determines the flow path of air from inlet to outlet, which will influence the comfort conditions for the occupants in a space. Furthermore, the interior of a space, i.e. the location of furniture in relation to the air supply devices, possibly impacts the airflow conditions in the space.

The purpose of this study was to investigate the effect of the airflow direction on human perception of draught, i.e. to investigate whether the relationship between perceived discomfort due to draught and air velocity, air temperature and turbulence intensity is the same for airflows from different directions.

Method

The present research addresses persons occupied with office work. In all experiments, the subjects therefore were seated at a desk, at which they could read or write. All subjects were exposed to stepwise increased mean air velocities from five different directions: horisontally towards the front, the back and the left side and vertically from above and below. In the single experiment, the airflow direction and the air temperature were kept constant. The aim was to attain a neutral overall thermal sensation, i.e. the subjects should feel neither too warm nor too cold. During the first 45 minutes of an experiment, the subjects therefore were encouraged to modify their clothing in order to feel thermally neutral. In this period, the subjects were exposed to a constant air velocity of 0.2 m/s. In the remaining 75 minutes of the experiment, the subjects were exposed to stepwise increased air velocities as shown in Figure 1. All experiments were carried out in a climate chamber in which the air and radiant temperatures were equal. The background air velocity in the chamber was about 0.06 m/s, directed from floor to ceiling.

Air movements

The subjects were exposed to controlled air movements from five directions at two identical workstations. A workstation consisted of a windbox containing two cross-flow fans, a dummybox with no fans, a desk, and a chair made of a mesh to prevent blocking of the air movements. To mask the applied airflow direction for the subjects, the windbox and the dummybox appeared identical on the outside. At exposure towards the front, the back and the side, the windbox was set on end while the subject was sitting on the dummybox as shown in Figure 2. At exposure from below, the windbox was placed horizontally on the floor of the climate chamber with the dummybox set on end. The mean air velocity at the position of the subject was controlled from outside the climate chamber by adjusting the rotational speed of the fans. Airflow from above was generated by recirculating part of the air exhausted from the

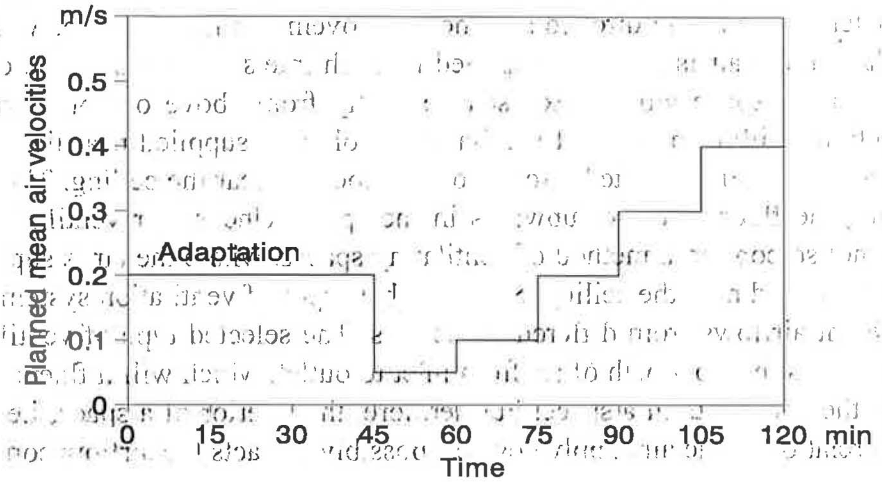

Figure 1: Planned mean air velocities in the experiments.

chamber. The recirculated air was led through a duct system containing a fan in front of the inlet through the ceiling in the climate chamber. The temperature increment of the air when passing the fan and the duct system was negligible.

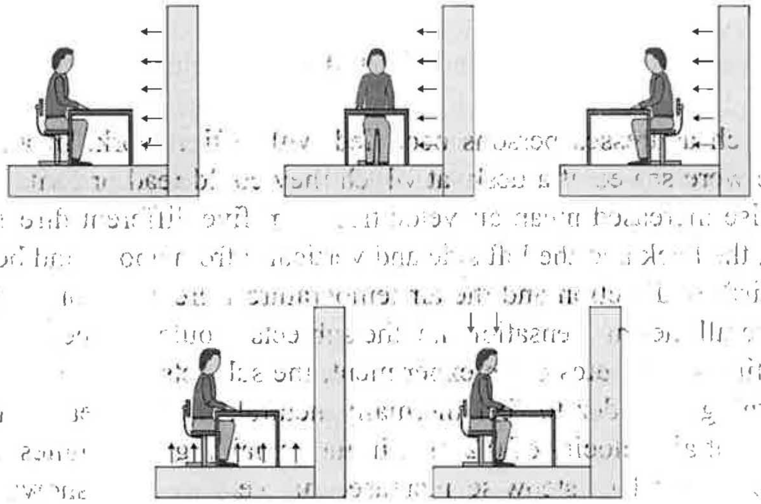

Figure 2: The subject's position on the windbox and on the dummy box, respectively, according to the airflow direction.

Measurements and data collection

Air velocity, turbulence intensity and air temperature were measured at heights of 0.1 m, 0.6 m, and 1.1 m between the windbox and the subject at a distance of approximately 0.2 m from the subject. The same parameters were measured at a height of 1.7 m at a position above the subjects' head. The airflow characteristics were measured with a Dantec Multichannel Flow Analyzer type 54N10 with omnidirectional, temperature-compensated probes with a time constant of 0.1 s. Air velocity and air temperature were registered twice per second throughout successive periods of 220 s. From the recorded values, mean air velocity and turbulence intensity were calculated for the periods of 220 s and monitored with the air temperature on a computer located outside the climate chamber. The mean air velocity at the position of the subject was controlled and adjusted by the experimenter. It was attempted to expose the subject to an airflow with minimum horisontal and vertical variation in velocity. Nevertheless, the air velocity profile at the position of the subject was not completely uniform, and it was therefore necessary to control the airflow according to the air velocity measured at a reference point. At horizontal exposure, the mean air velocity was controlled according to air velocity measurements 1.1 m above the floor, at exposure from below according to measurements at 0.1 m, and at exposure from above according to measurements 1.7 m above the floor. The turbulence intensity was not controlled, but varied in the same range independently of the airflow direction, at equal mean air velocity.

Subjects

Forty subjects, 20 women and 20 men, participated in the experiments. The subjects were mainly students who were paid to participate. Each subject participated in 15 experiments. The subjects were told to wear their normal indoor clothing when participating in an experiment. No boots, high-collar sweaters or other garments that would protect the subjects from the air movements were allowed.

Experimental procedure

During the first 45 minutes of an experiment, the air velocity was kept constant at 0.2 m/s, this being the approximate average of the air velocities applied during the remaining 75 minutes (Figure 1). At intervals of 15 minutes during the first 45 minutes, the subjects were asked to assess their thermal sensation on a seven-point scale ranging from cold to hot, and to modify their clothing if they were not feeling thermally neutral. In five successive 15-minute periods, the subjects were exposed to stepwise increased mean air velocities 0.05 m/s, 0.10 m/s, 0.20 m/s, 0.30 m/s and 0.40 m/s. Air velocities in this range are typical in naturally and mechanically ventilated spaces. At each level of air velocity, the subjects assessed their thermal sensation three times by means of questionnaires, and indicated whether they had sensed air movements during the last five minutes, and if so, whether the air movements were uncomfortable and where they were felt.

Data processing

The analysis of the questionnaires regarding discomfort due to draught was mainly based on two questions to the subject: *did you feel air movements during the last five minutes? and, if so, were the air movements uncomfortable?* An air velocity was designated to cause draught when two out of three ratings in any 15-minute velocity period were uncomfortable. Continuous, normally distributed variables with equal variance were compared by analysis of variance. All differences were accepted as significant at the 0.05 level.

Results

Physical parameters

The average mean air velocity in each of the five 15-minute velocity periods is shown in Table 1 for the five airflow directions. For all directions, the measured mean air velocity was close to the planned value, except with airflow from above, where the convective flows above the persons disturbed the mechanically generated flows at low planned mean air velocities.

Planned mean air velocity (m/s)	Measured mean air velocity (m/s)				
	Below	Above	Behind	Front	Side
0.2	0.21	0.21	0.20	0.20	0.20
<0.1	0.05	0.16	0.07	0.06	0.07
0.1	0.11	0.16	0.12	0.11	0.11
0.2	0.21	0.22	0.20	0.19	0.20
0.3	0.30	0.31	0.29	0.30	0.31
0.4	0.41	0.41	0.39	0.40	0.40

Table 1. Planned mean air velocity and corresponding measured mean air velocity in all 15-minute velocity periods at the five airflow directions. At horizontal airflows, air velocities measured at 1.1 m above the floor are shown, from below at 0.1 m and from above at 1.7 m.

The ranges of the turbulence intensities measured for each direction is shown in Table 2. The turbulence intensities were lowest at airflows from below and slightly higher at airflows towards the back, front and side. The turbulence intensities measured at airflows from above were relatively high due to mixing of the rising, convective flow and the countercurrent airflow from the inlet in the ceiling.

Turbulence intensity range (%)				
Below	Above	Behind	Front	Side
3-6	16-29	5-16	10-23	9-20

Table 2. Ranges of measured turbulence intensities at each of the five applied airflow directions.

Overall thermal sensation

Figure 3 shows the average of the subjects' thermal sensation vote as a function of time elapsed at the temperatures 20, 23, and 26°C, respectively. The thermal sensation votes decreased during the last 75 minutes of the experiments concurrently with the increase in air velocity. Particularly at 20°C, the thermal sensation votes decreased to between slightly cool and cool at the end of the experimental period. On average, the subjects voted between neutral and slightly cool at 20°C (-0.2 to -1.3), between neutral and slightly cool at 23°C (0 to -0.6) and between neutral and slightly warm at 26°C (0 to 1). No significant effect of the airflow direction on the overall thermal sensation vote could be documented.

Sensitivity to draught

Figure 4 shows the percentage of subjects reporting discomfort due to draught at one or more arbitrary body site at 20, 23 and 26°C, respectively. The draught ratings are shown as a function of the mean air velocity. At exposure from below, the percentage of subjects feeling draught is related to mean air velocities measured 0.1 m above the floor, at exposure from above to measurements performed at 1.7 m, and at airflows towards the front, back and side to measurements performed 1.1 m above the floor. The percentage of subjects feeling discomfort due to draught increased with increasing air velocities and with decreasing air temperatures.

The airflow direction clearly had an impact on the draught rating. At the air temperatures 20°C and 23°C, most subjects felt discomfort due to draught at airflows from below. At airflows

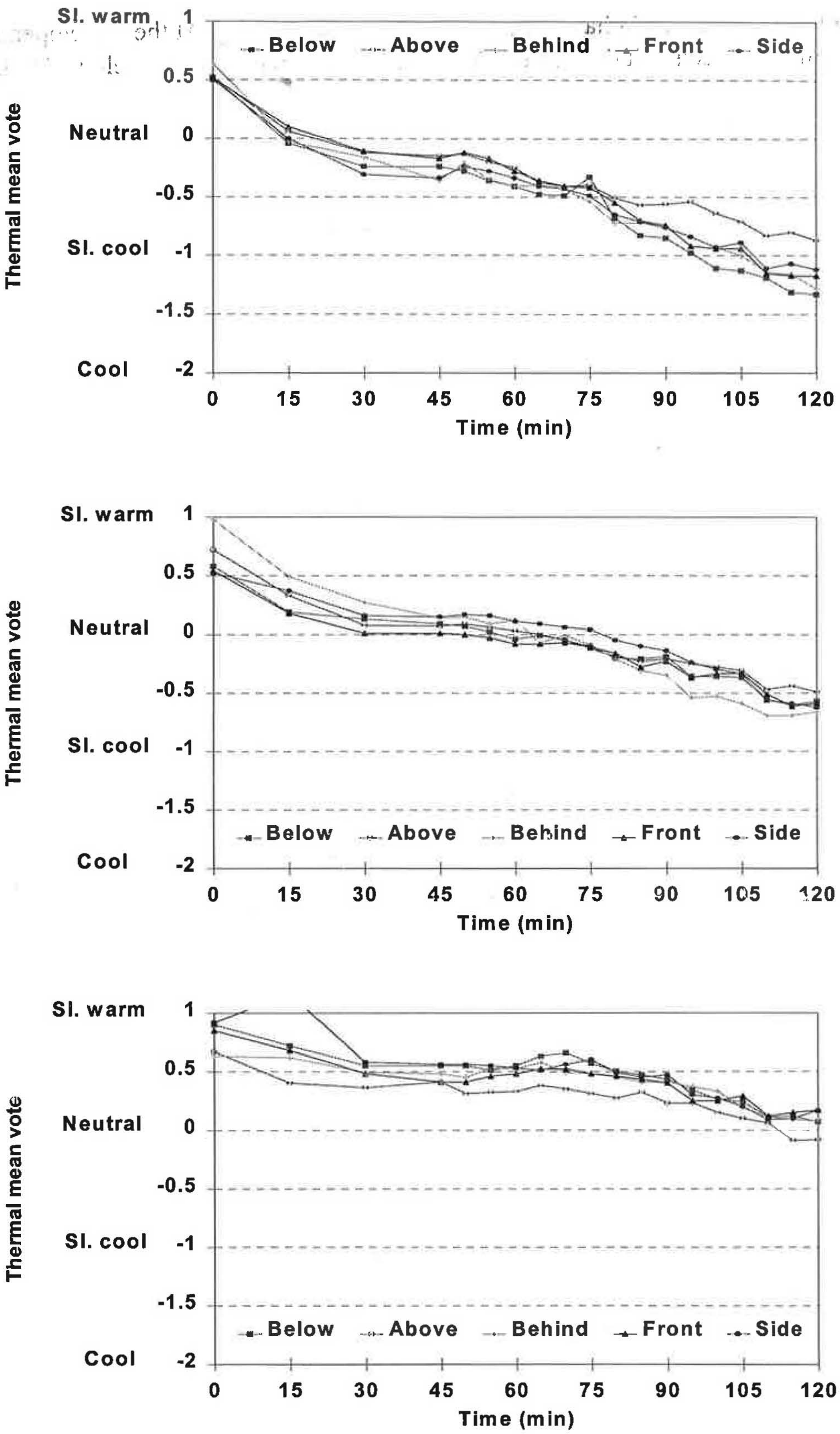

Figure 3. Thermal mean vote (n=40) as a function of time at airflows from five different directions. Top: 20°C; Middle: 23°C; Bottom: 26°C.

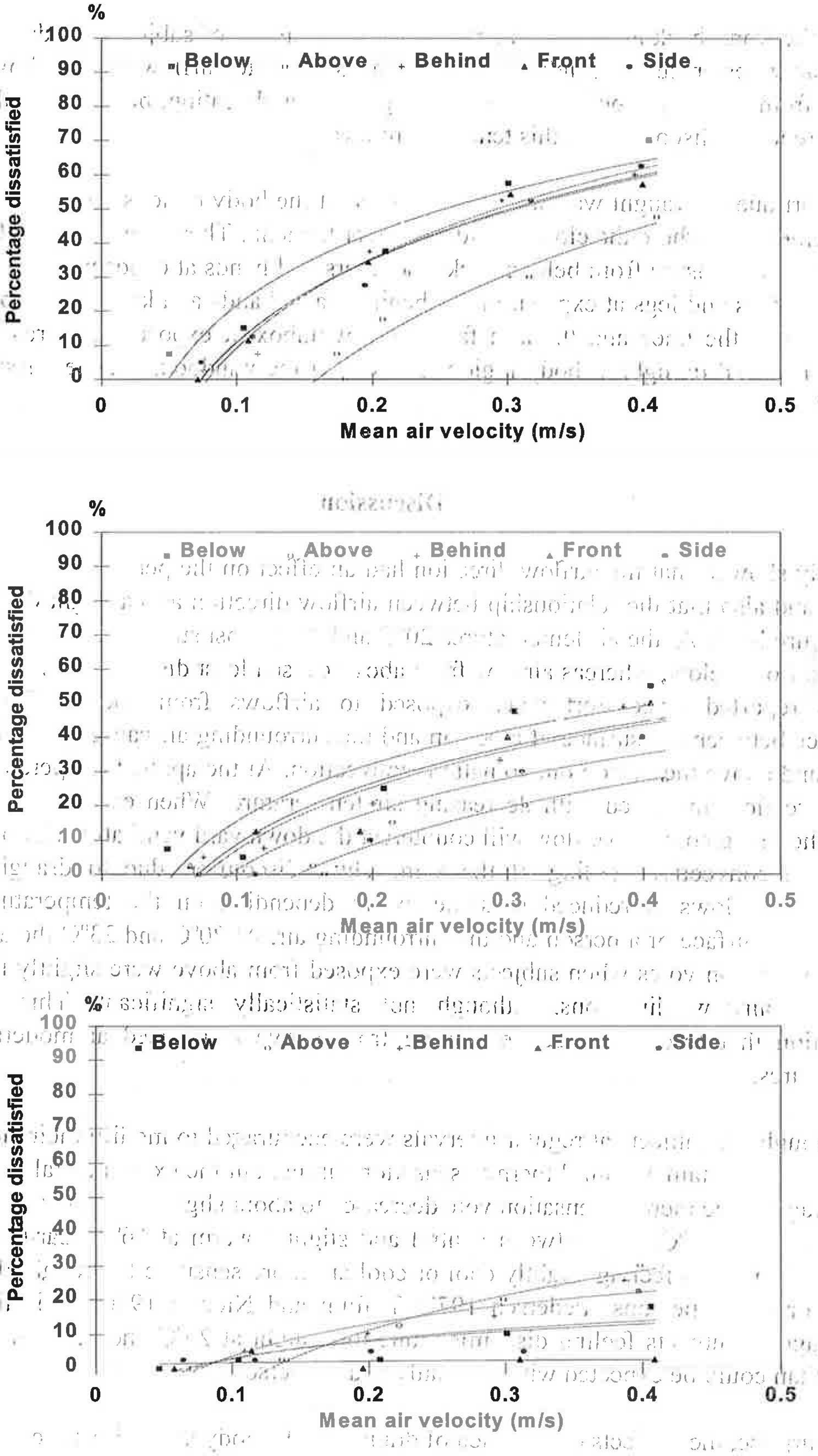

Figure 4. Percentage of dissatisfied due to draught at airflows from five different directions. Top: 20°C; Middle: 23°C; Bottom: 26°C.

towards the front, back and side, an almost equal percentage of subjects felt draught, whereas considerably fewer subjects felt draught when exposed to airflows from above. At 26°C, airflows from above and behind caused the highest draught rating, but in general, only a few subjects reported discomfort at this temperature level.

Discomfort due to draught was predominantly felt at the body regions directly exposed to the air movements or where the clothing did not cover the skin. These regions were feet, legs and lower back at exposure from below; neck, shoulders and hands at exposure from above; neck, back, shoulders and legs at exposure from behind; face, hands and knees at exposure towards the front; and the knee and the arm facing the windbox at exposure towards the side. No subjects reported draught at body regions not facing the windbox, i.e. the chest at exposure from behind.

Discussion

The study showed that the airflow direction had an effect on the perceived discomfort due to draught and also that the relationship between airflow direction and draught depended on the temperature level. At the air temperatures 20°C and 23°C most subjects reported discomfort at exposure from below, whereas airflow from above caused least discomfort. Yet, at 26°C most subjects reported discomfort when exposed to airflows from above. The temperature difference between the surface of a person and the surrounding air causes a layer of rising air around and above the person due to natural convection. At the applied temperature levels, the convective flow increased with decreasing air temperature. When exposed to airflow from above, the rising convective flow will counteract the downward ventilative airflow and reduce the forced convective cooling of the skin. Thus, discomfort due to draught at vertical downward airflows is reduced to some extent depending on the temperature difference between the surface of a person and the surrounding air. At 20°C and 23°C the average of the thermal sensation votes when subjects were exposed from above were slightly higher than at the other airflow directions, although not statistically significant. This supports the assumption that forced convective cooling from above is reduced at moderately low air temperatures.

Even though the subjects at regular intervals were encouraged to modify their clothing, it was not possible to attain a neutral thermal sensation throughout the experimental period. At 20°C the average of the thermal sensation vote decreased to about slightly cool, between neutral and slightly cool at 23°C, and between neutral and slightly warm at 26°C. Earlier studies have shown that persons feeling slightly cool or cool are more sensitive to draught than thermally neutral or warm persons (Pedersen 1977; Toftum and Nielsen 1996). It is likely that the percentage of subjects feeling discomfort due to draught at 20°C and 23°C in this study are higher than could be expected with thermally neutral persons.

To no surprise, the subjects complained of draught at the body parts directly exposed to the air movements and not covered by clothing. In agreement with earlier studies, the head region (neck, face and upper back) was one of the regions where draught complaints were most often observed (Pedersen 1977; Fanger and Christensen 1986; Fanger et al. 1988). A large number of complaints of draught were also observed at the feet and lower leg at airflows from below and at the hands at airflows from above and towards the front.

The present experiments may be considered as an extension of the study on which the draught model was based (Fanger et al. 1988). In combination with the results of the present study, the draught model can be further developed to include also the airflow direction in predicting the percentage of dissatisfied due to draught. For thermally neutral, sedentary persons dressed in normal indoor clothing, the draught model predicts the percentage of dissatisfied due to draught at the head region. The model is valid for airflows from behind. The mathematical expression for the model is:

$$DR = (0.37 \cdot Tu \cdot \bar{v} + 3.14) \cdot (34 - t_a) \cdot (\bar{v} - 0.05)^{0.62} \qquad (\%)$$

where DR is the Draught Rating (percentage dissatisfied due to draught),
$\bar{v}$ the mean air velocity (m/s),
Tu the turbulence intensity (%), and
t_a the air temperature

In Figure 5 the percentage of dissatisfied due to draught, predicted by the draught model, is compared with the observed percentage of dissatisfied due to draught *at the head region* at airflows from behind.

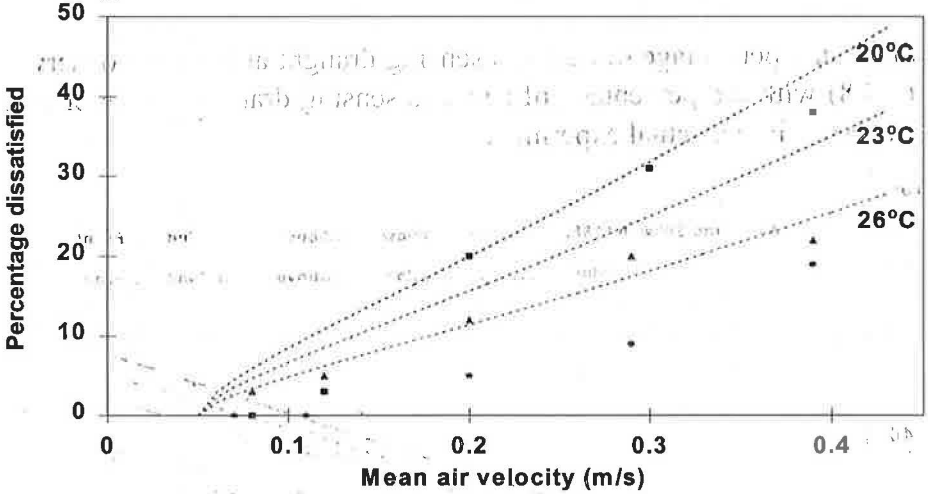

Figure 5. Comparison of predictions made by the draught model and observed draught rating at the head region at airflow from behind.

The figure shows a relatively good correspondence between the observed and predicted percentage of dissatisfied due to draught for subjects exposed to airflows from behind. Yet, at 23°C and 26°C, the model predicts a higher percentage of dissatisfied than was observed. In a subsequent paper, the ratio between the percentage of dissatisfied at an arbitrary flow direction and at airflows from behind will be used to extend the draught model to predict draught rating at arbitrary flow directions.

Figure 6 compares the percentage of subjects sensing draught at the head as observed by Mayer and Schwab (1988) and in the present study. The comparison is made for the face at airflows from below, above and towards the front and for the neck at airflows from behind. In contrast to the present results, Mayer and Schwab observed a high percentage of subjects complaining of draught at the head at airflows from below. Generally, Mayer and Schwab observed a higher percentage of dissatisfied, independent of the airflow direction.

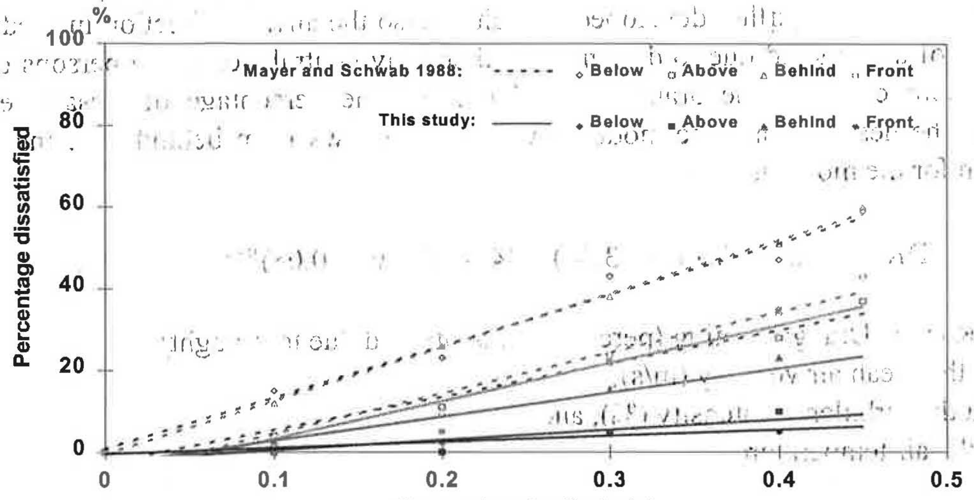

Figure 6. Comparison of draught ratings at the head observed in the present experiments at 23°C and by Mayer and Schwab (1988).

Figure 7 compares the percentage of subjects sensing draught at the head observed by Mayer and Schwab (1988) with the percentage of subjects sensing draught at one or more arbitrary body sites as observed in the actual experiments.

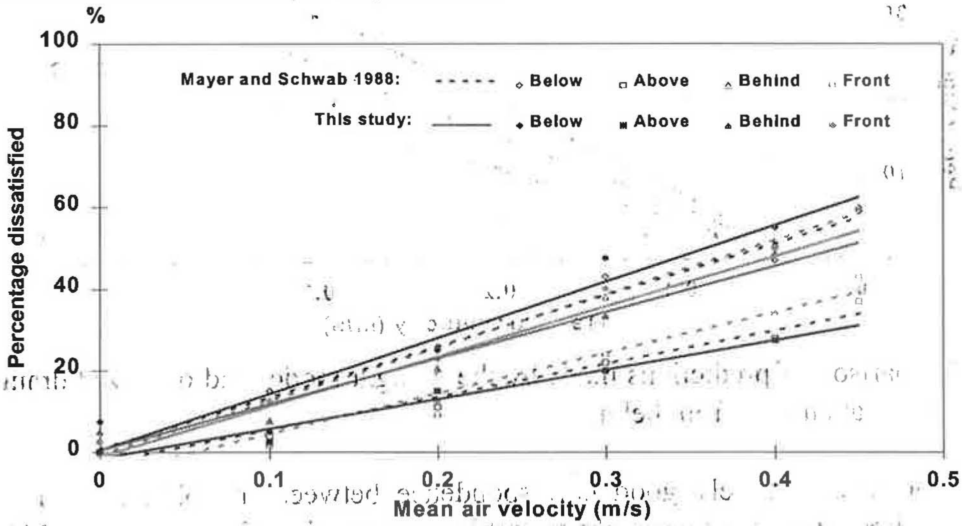

Figure 7. Comparison of overall draught rating observed in the present experiments at 23°C and draught ratings at the head as observed by Mayer and Schwab (1988).

Except at exposure towards the front, Figure 7 shows a relatively good correspondence between the two studies. In fact, this was surprising as Mayer and Schwab based the percentage of subjects sensing draught on the draught rating at the head, whereas in the present study draught rating is included independent of body region. Also, the questionnaire used differed in that Mayer and Schwab asked for sensation and pleasantness of air movement. In the actual experiments, the subjects were asked if they perceived the air movements as uncomfortable. The latter procedure implies that those persons sensing air movements and perceiving these as uncomfortable add to the percentage of dissatisfied. Using the first procedure, the persons not perceiving the air movements as pleasant or comfortable, do not necessarily find the air movements uncomfortable. The basis for calculating the percentage of dissatisfied is therefore different in the two studies. Finally, the procedures for measurement and control of air velocities differed. Mayer and Schwab adjusted the air movements without subjects present, whereas in this study, air velocities were observed and controlled during the experimental period with subjects at the workstations. In spite of the discrepancies in the applied experimental methods, the results from the two studies show a good correspondence.

Conclusions

An effect of the airflow direction on discomfort due to draught was documented. Quantitatively, the effect depended on the air temperature. At 20°C and 23°C, most subjects perceived discomfort when exposed to air movements from below, whereas at 26°C most subjects perceived discomfort at air movements from above.

The study showed that airflow direction had an effect on discomfort due to draught. The current design guidelines for air movements in spaces do not take the airflow direction into account. Thus, it is essential in future guidelines to specify more detailed draught criteria, which include the airflow direction in the evaluation of draught risk in spaces.

Acknowledgment

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