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Impact of Temperature and Humidity on Perception of Indoor Air Quality During Immediate and Longer Whole-Body Exposures

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Abstract Acceptability of clean air and air polluted by building materials was studied in climate chambers with different levels of air temperature and humidity in the ranges 18–28°C and 30–70% relative humidity (RH). The acceptability of the air quality immediately after entering a chamber and during the following 20-min whole-body exposure was assessed by 36 untrained subjects who maintained thermal neutrality by modifying their clothing. The results confirm the significant decrement of the acceptability with increasing temperature and humidity, as shown in a previous study with facial exposures. The odour intensity was found to be independent of temperature and humidity. A linear relation between acceptability and enthalpy of air was again observed by this experiment. No significant difference was observed between the immediate acceptability and the acceptability during the following 20-min exposure, i.e., no adaptation took place. Both the immediate assessment of acceptability and the assessments during the 20-min exposure were independent of the air temperature and humidity to which the subjects were exposed before entering the chamber. The results further indicate that a notable decrement of the ventilation requirement may be achieved by maintaining a moderate enthalpy of air in spaces.

Key words Indoor air quality; Perceived air quality; Temperature; Humidity; Perception; Ventilation.

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Introduction

Previous studies have shown that air temperature and humidity influence the odour perception and perceived quality of indoor air (Kerka and Humphreys, 1956; Cain et al., 1983; Berglund and Cain, 1989). Recently, Fang et al. (1998) found that the acceptability of air decreased significantly with increasing temperature and humidity. A linear relationship between acceptability and enthalpy was observed. At high temperatures and humidities, the perceived air quality was dominated by these two magnitudes rather than by the pollutants in the air. The results of the study by Fang et al. were based on first impressions with only the face being exposed to the air supplied through a diffuser, and the judgements took place in a climate chamber with clean ambient air of 18°C and 30% RH. (The term "clean air" used in this paper refers to air in a climate chamber with no significant pollution sources, the chamber being ventilated by high rates of outdoor air with no significant pollutants). These results need to be further validated.

Assessment of air quality by facial exposure through a diffuser and by whole-body exposure immediately upon entering a space was compared by Knudsen et al. (1993). Using a trained panel, they found that the air quality assessed in a diffuser was no different from the same air assessed immediately upon entering the space. However, their experiment was made at only one level of air temperature (22°C) with uncontrolled humidity. Therefore, the study did not include air temperature and humidity as factors which may influence perceived air quality. The results may not be extended to conditions with different air temperature and humidity.

The perceived quality of air with a given temperature and humidity may change with prolonged exposure due to adaptation to both air pollution and air temperature/humidity. Olfactory adaptation to different odours has been documented in several studies (Cain, 1974; Berglund et al., 1978; Engen, 1991). Cain (1974) studied time-course adaptation to four single-component odorants, 1-propanol, eugenol, n-butyl ace-

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tate and ozone, each tested at different concentration levels. The study found that the time-course of adaptation does not vary in any important way from one substance to another. The general picture is that perceived magnitude decays at a rate of about 2.5%/s from initial perceived magnitude to a steady state-level approximately 40% of the initial value. For ozone, an even higher adaptation was found at a concentration of 1.2 μg/L, where the steady-state level was only 7% of the initial perceived magnitude.

Adaptation of perceived air quality was studied by Gunnarsen et al. (1990). They found that the air quality was perceived as least acceptable immediately after entering a room with air pollution. After some minutes people adapted to the pollution and the air was judged more acceptable. However, this adaptation depended on the type of pollution source. Adaptation to the pollutants from building materials was found to be less compared with the pollution from environmental tobacco smoke and human bioeffluents. Like adaptation of the perception to air pollutants, the perceived air quality may adapt to the thermal environment of the air. The time-course of adaptation of air quality perception with different combinations of humidity was observed by Berglund and Cain (1989). They found that freshness and acceptability of air with different combinations of humidity at 24°C were stable over 60 min; however, in that experiment, the temperature and humidity of the prior exposure air were not reported. The immediate perceived quality of air with a given temperature and humidity may also depend on the temperature and humidity of the prior exposure. As yet, such information is not available.

The present study tested the immediate acceptability of air quality and the acceptability after prolonged exposures to clean and moderately polluted air at different levels of temperature and humidity, using whole-body exposure. The objectives of the study were: (i) to study the impact of temperature and humidity on perception of air quality when people were exposed to the air with their whole body; and (ii) to study whether the perception of air quality will adapt to a given thermal environment and how the previous exposure of air temperature and humidity influences the immediate perception of air quality after a step-change of thermal environment.

Methods

Experimental Design and Facilities

The investigation comprised two experimental series. The first series was designed to study the impact of temperature and humidity on the acceptability of clean

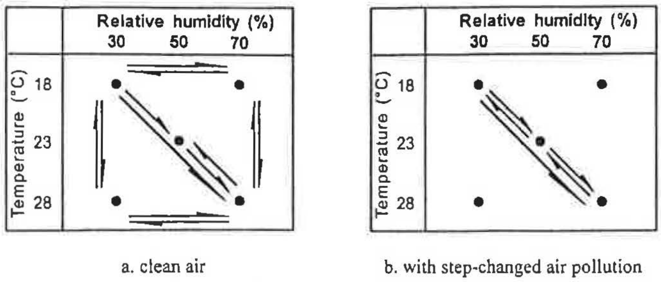


Fig. 1 The step-change of temperature and humidity used in the experiments. (The prior exposure air was always clean)

air during a 20-min whole-body exposure following a step-change of air temperature and/or humidity. Figure 1a shows the step-changes of temperature and humidity tested in this series. The second experimental series had the same assessment procedure as in the first series, except that a constant elevated level of air pollution was introduced together with the step-changed air temperature and humidity. The step-changes of temperature and humidity tested in this series are shown in Figure 1b. The experiments as designed make it possible to observe the impact of temperature and humidity on perception of air quality after immediate and prolonged exposure to two levels of air pollution.

During the experiments, the subjects should maintain thermal neutrality in different thermal environments. This was achieved by their self-adjustment of clothing. In line with the acceptability of air quality assessment, the thermal sensation of the whole body was observed to check whether their whole-body thermal neutrality was achieved or whether the thermal sensation of the whole body may have an influence on the perception of air quality. The odour intensity was also assessed in the second series of experiments.

The experiments were conducted in two identical adjacent climate chambers designed for air quality studies (Albrechtsen, 1988). The climate chambers were made of stainless steel with a volume of 3.6×2.5×2.55 m^3 for each (see Figure 2). To obtain good air quality, the air change rate for each chamber can reach 60 h^{-1} of outdoor air. The air in each of the twin chambers can be conditioned independently, and two different levels of air temperature and humidity in the two chambers can thus be established simultaneously. The control accuracy of the air temperature and humidity in the chamber was ±0.1°C and ±0.25 g/kg, respectively. The door between the two chambers makes it possible to go directly from one chamber to the other; therefore, a step-change of air temperature, humidity, as well as air pollution, can be obtained upon entering one chamber from the other.

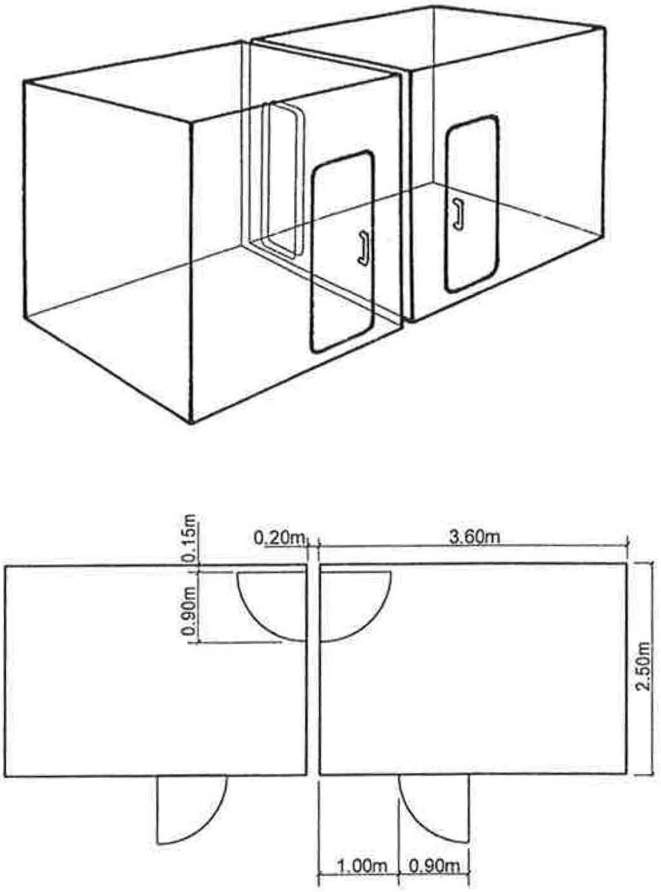


Fig. 2 Perspective view and plan of the two adjacent climate chambers

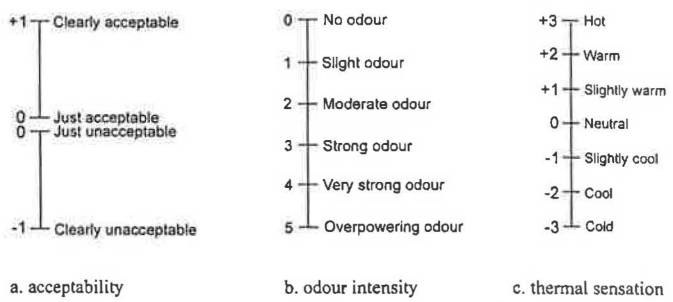


Fig. 3 Scales used in the experiment for assessing acceptability and odour intensity of inhaled air as well as thermal sensation of the whole body

A total of 36 untrained subjects participated in the experiments. They were mainly university students, with an average age of 25 years. Ten of them were female. The subjects were asked to assess acceptability of the air quality, odour intensity and the thermal sensation of the whole body, using the scales as shown in Figure 3.

Experimental Procedures

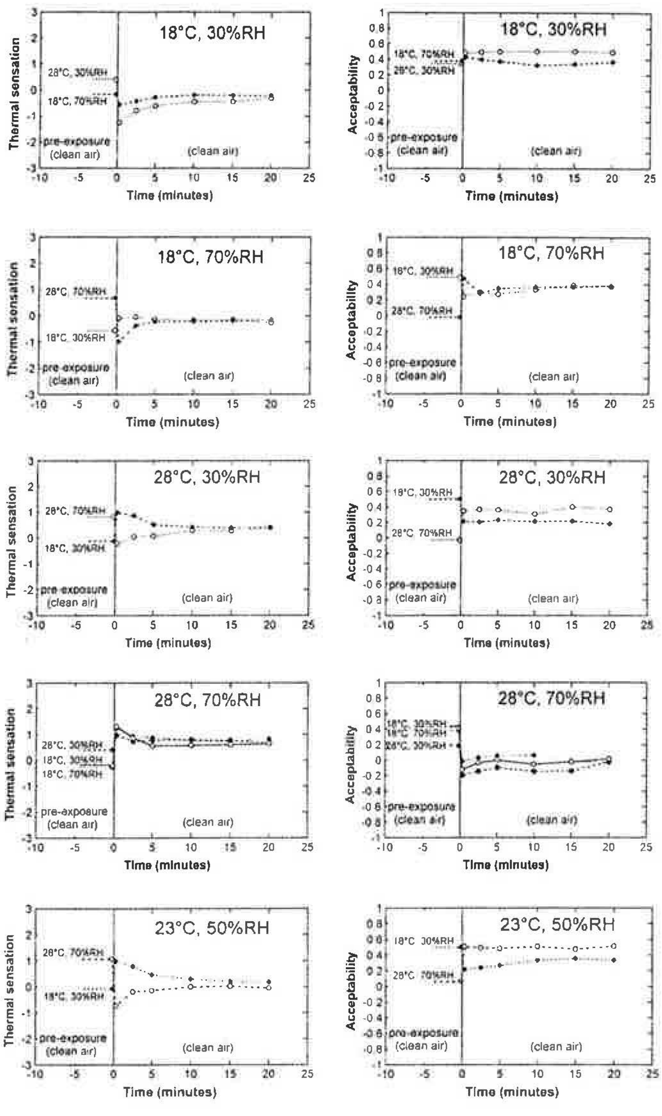
During the first experimental series, the two chambers were kept at different temperatures and humidities with the same ventilation rate of 420 L/s (57 h^{-1}) clean outdoor air. There were no air pollution sources introduced into either chamber except for the slight pollution from the chamber itself and the HVAC system. Therefore, the air in each chamber was clean. The temperature and humidity in the two chambers were changed alternately every 20 min. The subjects were instructed to stay in one chamber for 20 min and were then asked to move to the other chamber. Each time the subjects moved from one chamber to the other, they experienced a step-change of temperature and/or humidity of the air. Their immediate assessment of the acceptability of the air and their assessments after 2.5, 5, 10, 15 and 20 min were made using the scale shown in Figure 3a. Together with the acceptability assessment, the subjects were asked to assess their whole-body thermal sensation using the scale shown in Figure 3c. When the subjects stayed in one chamber, the temperature and humidity in that chamber were kept constant. Meanwhile the temperature and humidity in the other unoccupied chamber was adjusted to prepare for the next 20-min exposure; therefore, each 20-min exposure was also a 20-min prior exposure for the next 20-min exposure.

In the second experimental series, the same procedure was used except that air pollution sources were introduced into one chamber to establish a higher pollution level. The ventilation rate in that chamber was decreased to 200 L/s (27 h^{-1}) of clean outdoor air. Apart from acceptability and thermal sensation assessment, odour intensity of the air was also assessed using the scale shown in Figure 3b. Polyvinyl chloride (PVC) and acrylic sealant were used together as pollution sources, as the previous study (Fang et al., 1996) showed that emissions of pollutants from these common materials were almost insensitive to changes in temperature and humidity. To ensure a constant concentration of the pollutants established in the climate chamber during the experiment, the materials used were ventilated for four weeks (three-week ventilation in a previous experiment and one-week continuous ventilation before this study) to achieve a quasi steady-state emission. Several previous studies showed that

Table 1 Material loading used to generate the required air pollution in the experiment

Materials	Area of materials	Sensory pollution load
PVC flooring	60.3 m^2	35.2 olf
Sealant	27.0 m	12.4 olf
Total		47.6 olf

Note: The sealant was applied to u-shaped aluminium profiles with an inner width and depth of 10 mm and 12 mm, respectively



(a) thermal sensation of the air (b) acceptability of the air

Fig. 4 Thermal sensation and acceptability of clean air at five different levels of temperature and humidity for 20-min exposures after step-changes from different temperatures and humidities of prior exposure clean air

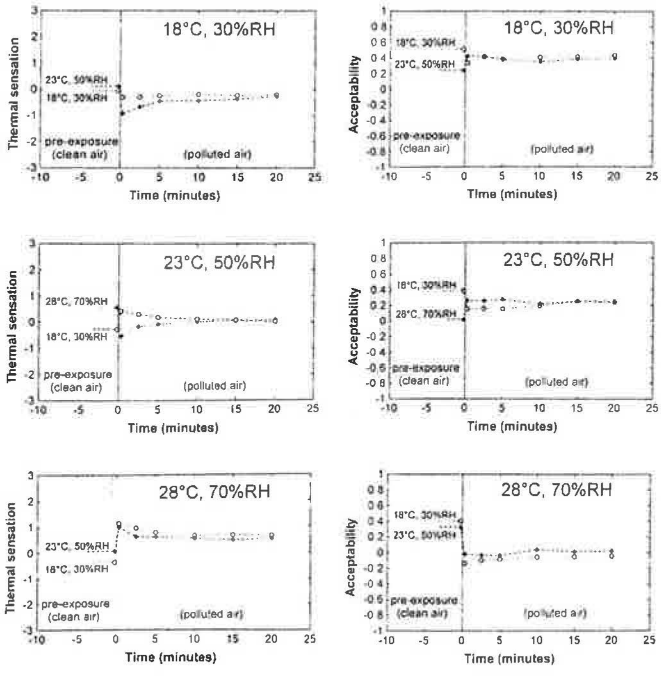
both chemical and sensory emission of these materials tended to become stable after being ventilated for more than two weeks (Tirkkonen et al., 1996; Bluyssen et al., 1996; Knudsen et al., 1996 ; Wolkoff, 1998). The amount of PVC and sealant was selected so as to generate an indoor air quality in the chamber which approximately 30% of the occupants would find unacceptable at 23°C and 50% RH. Table 1 lists the amount of PVC and sealant used in the experiments and the corresponding sensory pollution loads. The materials were placed behind a curtain so that they were invisible to the subjects. To ensure that the subjects were unaware of whether the air in the chamber had been polluted by materials or not, a curtain was also placed in the chamber where no materials were used to introduce pollutants.

During each experimental day, the subjects participated in ten 20-min exposures. The subjects entered the chamber in groups of six and were asked to be seated. During their stay in the chamber, they were permitted to read and were encouraged to adjust their clothing whenever necessary in order to keep themselves in thermal neutrality; however, the clothing adjustments took place after they had voted on their first impression of acceptability and thermal sensation just after entering the chamber. The clothings chosen by the subjects varied from very light clothing (0.3 clo), such as T-shirt and shorts, to heavy clothing (1.3 clo) such as T-shirt, sweat shirt, jacket, shorts, sweat suit trousers and polyester trousers. For each of the 20-min exposures, the thermal neutrality of the subjects could normally be maintained by at most two self-adjustments of clothing.

Results

Thermal Sensations

During the experiments, the air temperature and humidity in the two chambers were controlled at the predetermined values with a stability of ±0.5°C and ±5% RH. The mean thermal sensation votes of the subjects



(a) thermal sensation of the air (b) acceptability of the air

Fig. 5 Thermal sensation and acceptability of polluted air at three different levels of temperature and humidity during a 20-min exposure after step-change from different temperatures and humidities of prior exposure clean air during each step-change of temperature and humidity and during the prolonged exposure in the two experimental series are shown in Figures 4a and 5a. The mean thermal sensation votes showed that the immediate thermal sensation after the step-changes of temperature and humidity depended on the difference of the step-changed temperature and humidity; however, the final thermal sensation of each 20-min exposure was almost independent of the temperature and humidity of the prior exposure. The subjects could always reach thermal neutrality by the end of each 20-min exposure at all the temperature and humidity levels tested. Thermal neutrality was disturbed only by the step-change of temperature and humidity immediately after the subjects moved from one chamber to the other, but it was re-established in the new thermal environment within ten minutes, due to their adjustment of clothing.

Perceived Air Quality

The mean acceptability votes of the 36 subjects for the first experimental series with clean air are shown in Figure 4b. The mean votes for the second experimental series with polluted air are shown in Figure 5b. Each figure shows the acceptability of the air with one combination of temperature and humidity for a 20-min exposure period together with the acceptability of the air in the prior exposure period with different levels of temperature and humidity.

Figure 4b and 5b show that in both experimental series there were no significant differences between the acceptability immediately upon entering a chamber and the acceptability recorded during the following 20-min exposure. There seemed to be no time course adaptation of acceptability at different combinations of air temperature and humidity. The acceptability of the air during each 20-min exposure also seems constant without being influenced by the change of whole-body thermal sensation. Furthermore, the acceptability of air (both clean and polluted) with different temperature and humidity is generally independent of the environmental conditions of the prior exposed clean air. Only the immediate acceptability of clean air at 18°C, 70% RH and 23°C, 50% RH was found to be influenced to a statistically significant degree by the temperature and humidity of the prior exposure.

From Figure 4b and 5b it can also be observed that the perceived air quality was strongly influenced by air temperature and/or humidity; the acceptability decreased with increasing air temperature and humidity.

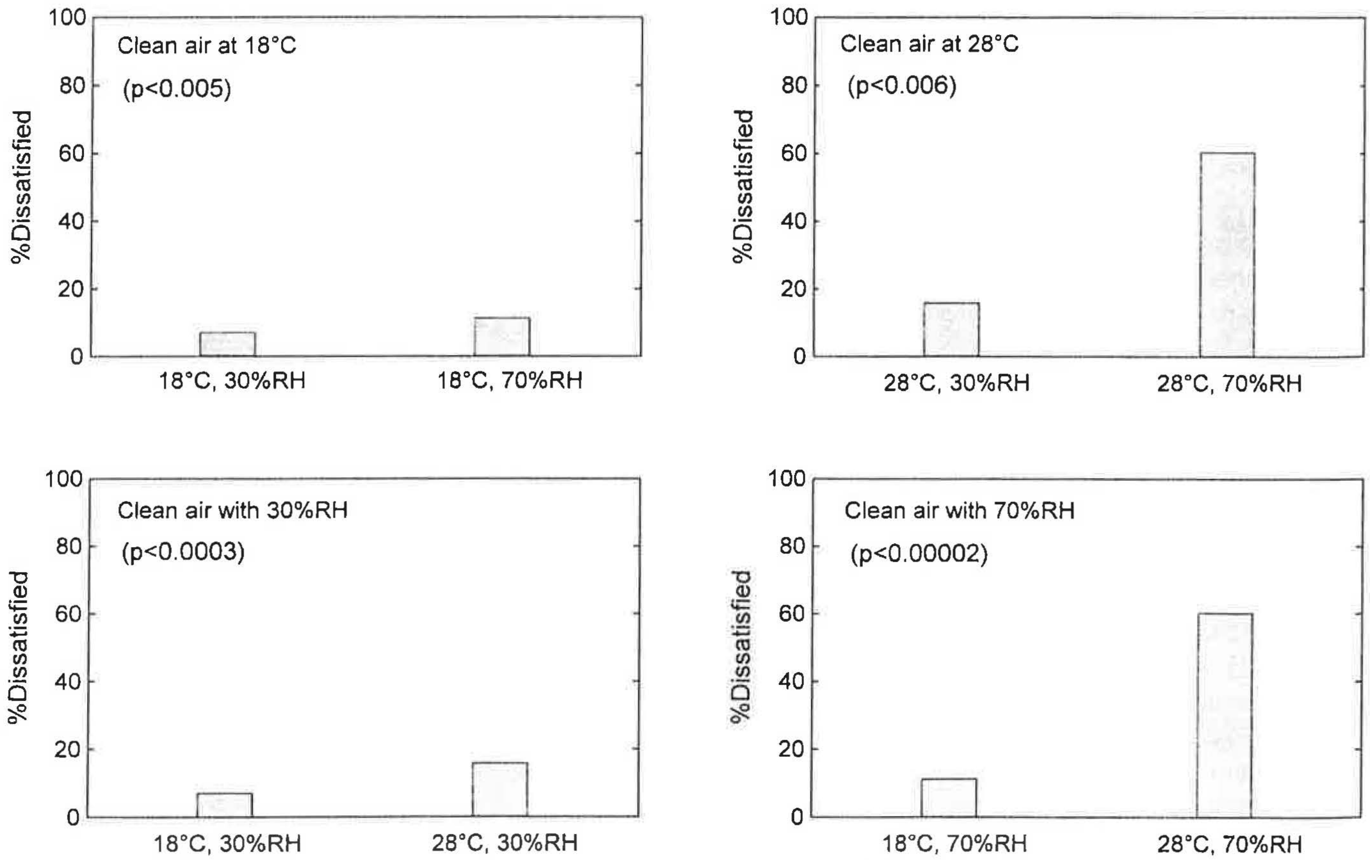


Fig. 6 Comparison of PD for clean air at two different levels of temperature or humidity

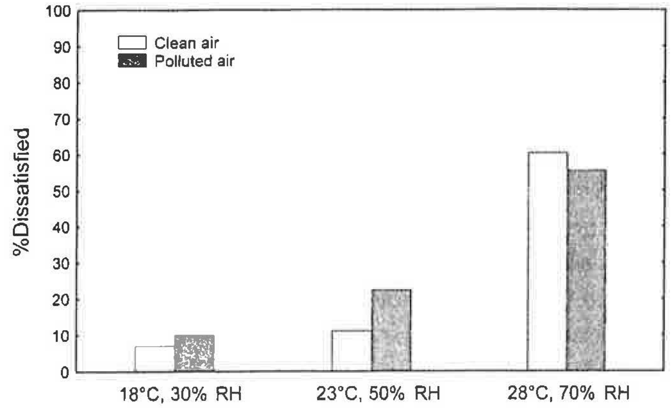


Fig. 7 Comparison of PD between clean and polluted air at three different combinations of temperature and humidity. The impact of temperature and humidity on perceived air quality were significant (P<0.01) for both clean and polluted air

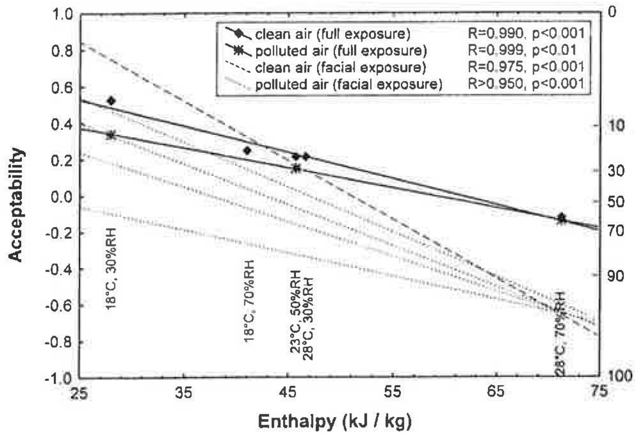


Fig. 8 The acceptability-enthalpy relations obtained from the experiment with whole-body exposure compared with the results from the experiment with facial exposure

To compare the perceived air quality at different levels of temperature and/or humidity during whole-body exposure, the mean percentage of dissatisfied during each 20-min exposure was calculated and compared in Figure 6 according to the influence of temperature or humidity. The percentage of dissatisfied (PD) was calculated from mean acceptability of the assessed air using a logit curve fitted to the relation obtained by Gunnarsen and Fanger (1992):

$$PD = \frac{\exp(-0.18-5.28 \cdot ACC)}{1+\exp(-0.18-5.28 \cdot ACC)} \cdot 100 \qquad (1)$$

where:

PD =percentage of persons dissatisfied with the air quality (%),
ACC=mean acceptability of assessed air.

Figure 6 shows that the perceived air quality decreases with increasing air temperature or humidity; however, the impact of relative humidity is much less at low temperatures than at high temperatures. A similar phenomenon is shown for the impact of temperature. The percentage of dissatisfied for the perception of both clean air and polluted air at three different temperature and humidity combinations is shown in Figure 7. The figure indicates that the perceived air quality can be improved by decreasing the air temperature and humidity instead of increasing the ventilation rate and decreasing pollution load. The assessment of polluted air with 25% PD at 23°C and 50% RH for instance, can be improved to about 10% PD by decreasing the temperature and humidity to 18°C and 30% RH. This would give the same percentage of dissatisfied as clean air assessed at 23°C and 50% RH. At 28°C and 70% RH, the decrease of temperature and humidity will be an even more effective way of improving air quality.

To validate the linear relations between acceptability and enthalpy of the air which were found in the previous study (Fang et al., 1998), the acceptability of air obtained from this experiment of whole-body exposure was also correlated with enthalpy of the different environmental conditions (see Figure 8). For comparison, the similar relationships obtained in the previous study are shown in Figure 8 as well. An excellent linear correlation between acceptability and enthalpy was also observed in this experiment at the two levels of air pollution tested; however, the results of the present experiment showed a less pronounced impact of enthalpy on acceptability than the results obtained in the experiment involving facial exposure. But the present study confirmed that the impact of temperature and humidity on acceptability of air is strong and significant. The percentage of dissatisfied with clean air increased from 10% to 60% as the air temperature and

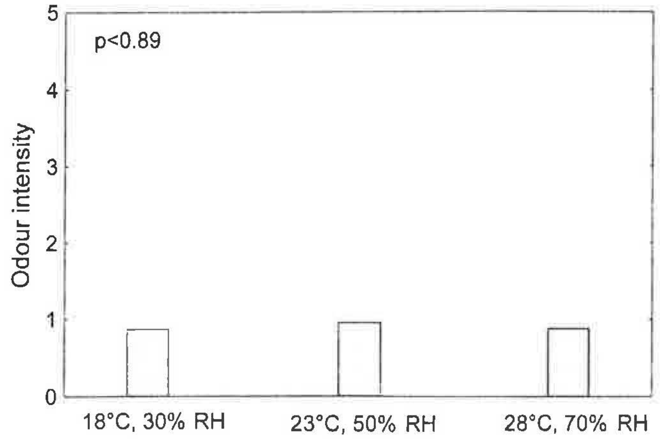


Fig. 9 Mean odour intensity vote of immediate perception to the air polluted by building materials in three different temperature and humidity environments

humidity increased from 18°C and 30% RH to 28°C and 70% RH (Figure 8).

Odour Intensity

The mean odour intensity votes of the air polluted by building materials at three temperature and humidity levels are shown in Figure 9, each with prior exposures to clean air at 18°C and 30% RH. In contrast to the acceptability assessment of the same polluted air, the perceived odour intensity of the air did not change with changing air temperature and humidity. Figure 10 shows the odour intensity assessment of the same polluted air at the three levels of temperature and humidity over the 20-min exposure. Prior to each 20-min exposure, pre-exposures to clean air at two different levels of temperature and humidity were made. Figure 10 also shows that the odour intensity assessment in different temperature and humidity environments was not influenced by the temperature and humidity of the pre-exposure to clean air and little adaptation could be observed during 20-min exposure.

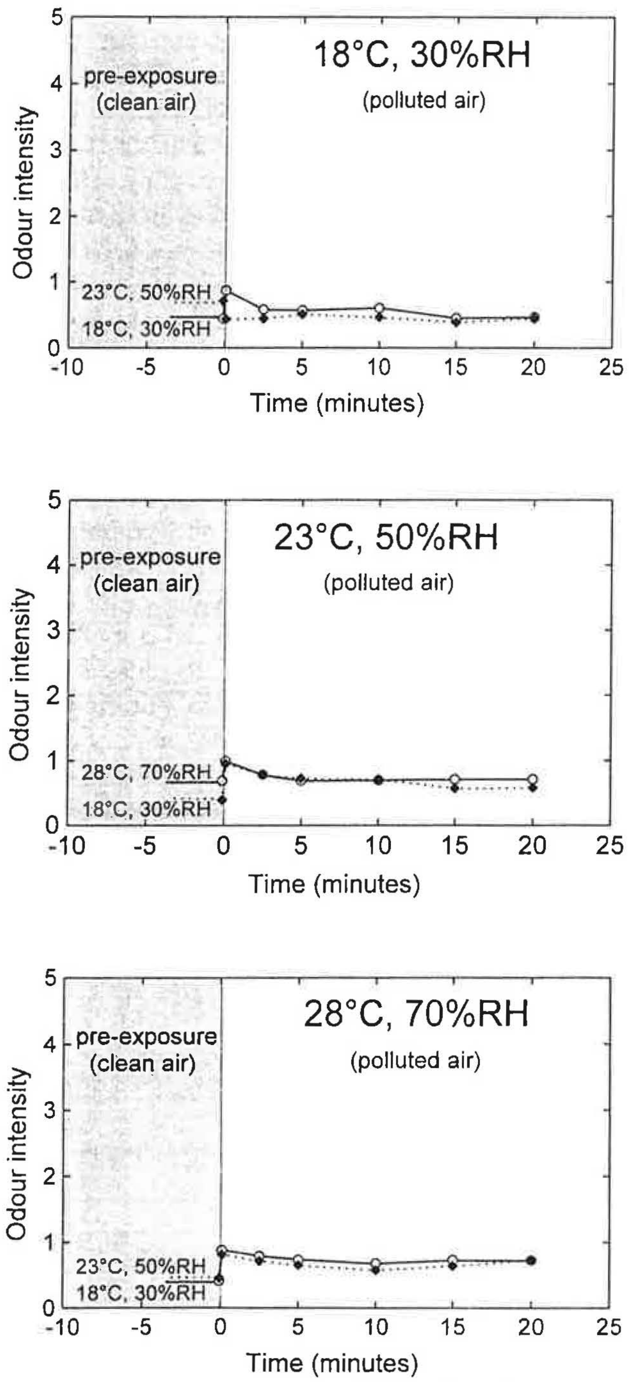


Fig. 10 Odour intensity of the polluted air at three different levels of temperature and humidity during a 20-min exposure after step-change from different temperatures and humidities of prior exposure clean air

Discussion

The present study found a strong impact of temperature and humidity on acceptability of air and little impact on perception of odour intensity. Acceptability of both clean and polluted air was linearly correlated with enthalpy of the air. These results agree with those observed from the previous study using facial exposure (Fang et al., 1998). The present results further confirm that enthalpy, the energy content of inspired air, plays an important role as regards perception of air quality. The energy content of the inspired air does not alter the perception of odour intensity, but a sufficient cooling of the mucosa by the inspired air due to convection and evaporation seems to be essential for the perception of acceptable air quality. Therefore, besides air pollutants, enthalpy of the inspired air should also be considered as a factor which influences perceived air quality.

The present study shows that the acceptability of air at various levels of temperature and humidity is assessed differently during whole-body exposure than during facial exposure by diffusers. This is most likely due to the difference in the exposure procedures rather than to the influence of whole-body thermal sensation, since the present experiment shows that the change of whole-body thermal sensation has little influence on the perception of air quality. For the facial exposure procedure (Fang et al., 1998), the subjects were allowed to compare the assessed air with the favourable background air at 18°C and 30%. This may have contributed to make the assessment of the air quality at elevated temperature and humidity more unacceptable. For the whole-body exposure, the subjects, upon entering a space, had no chance to go back and re-perceive the pre-exposure air. In this procedure the subjects lacked a favourable reference to compare with, and their assessment probably became less critical. The facial exposure procedure was designed to increase the efficiency of the experiments. However, the effect of tem perature and humidity on acceptability of both the assessed air and the ambient air must be considered.

The study of Gunnarsen (1990) found little adaptation of perceived air quality to the air polluted by building materials. This result was confirmed by the present experiment. Moreover, no time course adaptation of acceptability was observed at different levels of air temperature and humidity in this experiment during the 20-min whole-body exposure. This result agrees with the findings of Berglund and Cain (1989). In the present experiment, the acceptability of air quality in connection with different temperature and humidity combinations of prior exposures was also tested. The results showed that the temperature and humidity of prior exposure had little influence on the immediate perception of air quality. Furthermore, the acceptability of air quality was found to be independent of a moderate change in whole-body thermal sensation. Therefore, it may be concluded that the first impression of air quality can be used as an indicator of perceived air quality regardless of the temperature and humidity level of the prior exposure. However, the time course adaptation may be significant when air is highly polluted, especially when it is polluted by human bioeffluents. Moreover, in this experiment, the prior exposure air was always clean. The combined effect of temperature/humidity and cross-adaptation may be further studied.

The results in Figure 7 show that cold and dry air with an elevated pollution level causes the same percentage of dissatisfied as clean air which is warmer and more humid. These results indicate the possibility of lowering the ventilation rate required to provide a certain percentage of dissatisfied by decreasing indoor air temperature and humidity. In practice the emission from many materials is also reduced with decreasing temperatures and humidities (Fang et al., 1996; Wolkoff, 1998). This will further enhance the benefits of a decreased temperature and humidity of the air. Present standards and guidelines for ventilation prescribe the required ventilation without taking account of temperature and humidity (ASHRAE, 1989; DIN, 1994; ECA, 1992). The results of the present study point out the potential that exists for energy conservation by maintaining a moderate indoor air temperature and humidity. Therefore, the impact of temperature and humidity could be considered in future revisions of the standards. Field studies are also recommended to further explore this potential.

Conclusions

- During whole-body exposure, temperature and humidity have a significant impact on perceived air quality. The acceptability of air is linearly related to the enthalpy and decreases with increasing air temperature and humidity.
- The acceptability of air does not change significantly during 20 min compared to the first impression of acceptability after a step-change of temperature and humidity.
- The perceived quality of air after a step-change of temperature and humidity is independent of the previous air temperature and humidity.
- The odour intensity was independent of air temperature and humidity.
- Field validation of the present results is recommended.

Acknowledgements

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