Indoor Air 2004; 14 (Suppl 7): 74–81
www.blackwellpublishing.com/ina

INDOOR AIR

Impact of indoor air temperature and humidity in an office on perceived air quality, SBS symptoms and performance

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Abstract Perceived air quality (PAQ), sick building syndrome (SBS) symptoms and performance of office work were studied in a real office space at three levels of air temperature and humidity and two levels of ventilation rate (20°C/40%, 23°C/50%, 26°C/60% RH at 10 l s^{-1} p^{-1} outside air, and 20°C/40% RH at 3.5 l s^{-1} p^{-1} outside air). Thirty female subjects participated in the experiment. They were exposed to each environmental condition for 280 min. Thermal comfort was maintained at different thermal environments by self-adjustment of clothing. The subjects performed simulated office work throughout each exposure and repeatedly marked a set of visual-analog scales to indicate their perception of environmental conditions and of the intensity of SBS symptoms at the time. The study confirmed the previously observed impact of temperature and humidity on perceived air quality and the linear correlation between acceptability and enthalpy. The impact on perceived air quality of decreasing the ventilation rate from 10 to 3.5 l s^{-1} per person could be counteracted by a decrement of temperature and humidity from 23°C/50% RH to 20°C/40% RH. Performance of office work was not significantly affected by indoor air temperature and humidity. However, several SBS symptoms were alleviated when the subjects worked at low levels of air temperature and humidity, which implies that a longer term exposure to low indoor air temperature and humidity might help to improve the performance of office work.

Key words: Temperature; Humidity; Indoor air quality; Ventilation; SBS symptoms

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Practical implications
The findings of this study indicate the importance of indoor air temperature and humidity on perceived air quality and SBS symptoms. In practice, the required ventilation rate for comfort and health should no longer be independent of indoor air temperature and humidity.

Introduction

Recent studies have shown that temperature and humidity significantly influence the perception of air quality during short exposures. Fang et al. (1998a) and Toftum et al. (1998) studied the impact of temperature and humidity on the perception of air quality using an immediate facial exposure. These studies found that the air was perceived as less acceptable with increasing indoor air temperature and/or humidity. The acceptability of air quality decreased linearly with increasing indoor air enthalpy (see Fig. 1). The earlier study of Berglund and Cain (1989) and the later study of Fang et al. (1998b) confirmed the effect of temperature and humidity on perception of air quality in whole-body exposures of up to 60 min.

All these studies showed that air is perceived as very fresh and acceptable when it is cool and dry, while warm and humid air is always perceived as stuffy and unacceptable even if the air is clean. High temperature and humidity counteract the beneficial effect of increased ventilation rate and degrade perceived indoor air quality. From the perceived air quality (PAQ) point of view, it is therefore beneficial to keep both air temperature and humidity indoors as low as possible, provided that thermal comfort can be maintained. The results revealed a potential for saving energy by decreasing the ventilation rate at lower levels of indoor air enthalpy. However, the results were obtained from laboratory studies with relatively short exposures of less than one hour. It is therefore essential to validate the finding in real indoor space with a longer period of exposure. Furthermore, it is not yet certain that exposure to cool dry air reduces the prevalence of SBS symptoms and increases the performance of office work as well as improving perceived air quality. If so, the required ventilation rate would no longer be independent of indoor air temperature and humidity. A previous study

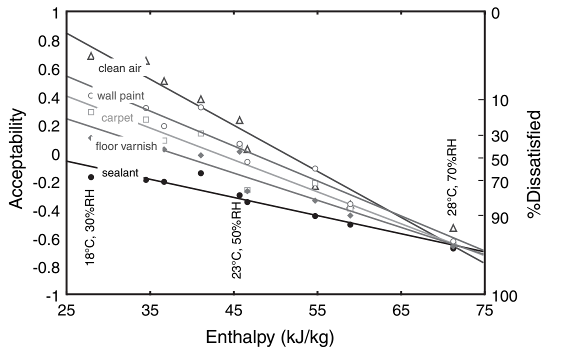

Fig. 1 Linear correlation between acceptability and enthalpy of five air samples—clean outdoor air and air polluted by wall paint, carpet, floor varnish and sealant.

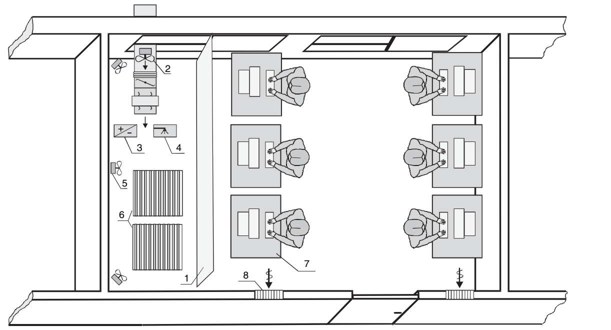

Fig. 2 Experimental set-up in the office in which the field study was carried out. 1. Partition, 2. Ventilation fan with silencer and damper, 3. Heater and air-conditionar, 4. Steam humidifier, 5. Mixing fan, 6. Carpet used as pollution source, 7. Work-stations, 8. Exhaurt ventillation grills.

in which subjects were clothed for comfort at two different air temperatures (Wyon et al., 1975) found no such effect.

This paper presents the results from a field experiment in which the effects of temperature and humidity on perceived air quality were investigated in 280-minute exposures in a real office space. The intensity of SBS symptoms and the performance of tasks simulating office work were recorded while the subjects worked at three different levels of indoor air temperature and humidity with 10 l s^{-1} p^{-1} outside air. The coolest condition was repeated at 3.5 l s^{-1} p^{-1}.

Methods

The experiment was conducted under four different environmental conditions—three levels of indoor air temperature and humidity: 20°C/40%, 23°C/50% and 26°C/60% RH at a normal ventilation rate of 10 l s^{-1} per person of outdoor air and 20°C/40% RH at a low ventilation rate of 3.5 l s^{-1} per person of outdoor air. This design made it possible to examine the impact of enthalpy (combining with both air temperature and humidity) on PAQ, SBS symptoms and performance of office work. The design also made it possible to compare the impact of enthalpy and ventilation rate on these dependent variables.

The experiment was carried out in a 25-year-old office room. The office has a floor area of 36 m^2 and had been renovated three years previously, at which time low-emitting polyolefin floor tiles were laid and new paint was applied to the brick walls and the ceiling. To ensure a moderate level of indoor air pollution, 36 m^2 of tufted bouclé carpet was placed in the office. The carpet was 20 years old and was taken from an office building with a history of occupant complaints. The carpet was not placed on the floor: strips of it were stapled back to back and hung on stainless steel racks behind a partition, where they could not be seen by the subjects.

The office was equipped with a ventilation and air-conditioning system that can maintain constant temperature, humidity and ventilation rate with a stability of (0.3°C (3% RH and (5%, respectively. Figure 2 shows a plan view of the experimental office. The right side of the office was equipped with six workstations and occupied by six subjects at a time; the left side of the office, behind a partition, was used as a technical space where ventilating, heating, air-conditioning and humidification equipment were installed, and where the racks holding the carpet strips were located. The ventilation air was delivered to the occupied space from both above and below the partition. There were several mixing fans in the technical space to ensure complete mixing of conditioned air with the pollutants emitted from the carpet and the air from the occupied space.

Thirty female subjects with an average age of 23 years participated in the experiment. They were divided into five groups of six subjects. Each group participated in the experiment on the same weekday of four successive weeks. On each experimental day, one group of subjects was exposed to one of the four indoor environmental conditions. Each of the five groups encountered the four conditions in a different order, to minimize any bias caused by order of presentation.

During the experiment, the subjects performed simulated office work and were asked to assess the air quality, thermal comfort and different SBS symptoms. The simulated office work tasks were text typing, proofreading, addition and creative thinking (Wargocki et al., 2000). The average number of characters typed per minute, average number of correctly completed arithmetical calculations per hour and average number of lines proofread per minute were used as measures of performance. Creative thinking was evaluated by scoring answers to open-ended questions in terms of their originality in the sample, using information theory to express each subject's accumulated "C-score" in bits (Wyon, 1996).

Air quality, thermal comfort and SBS symptoms were assessed by the subjects upon entering the office

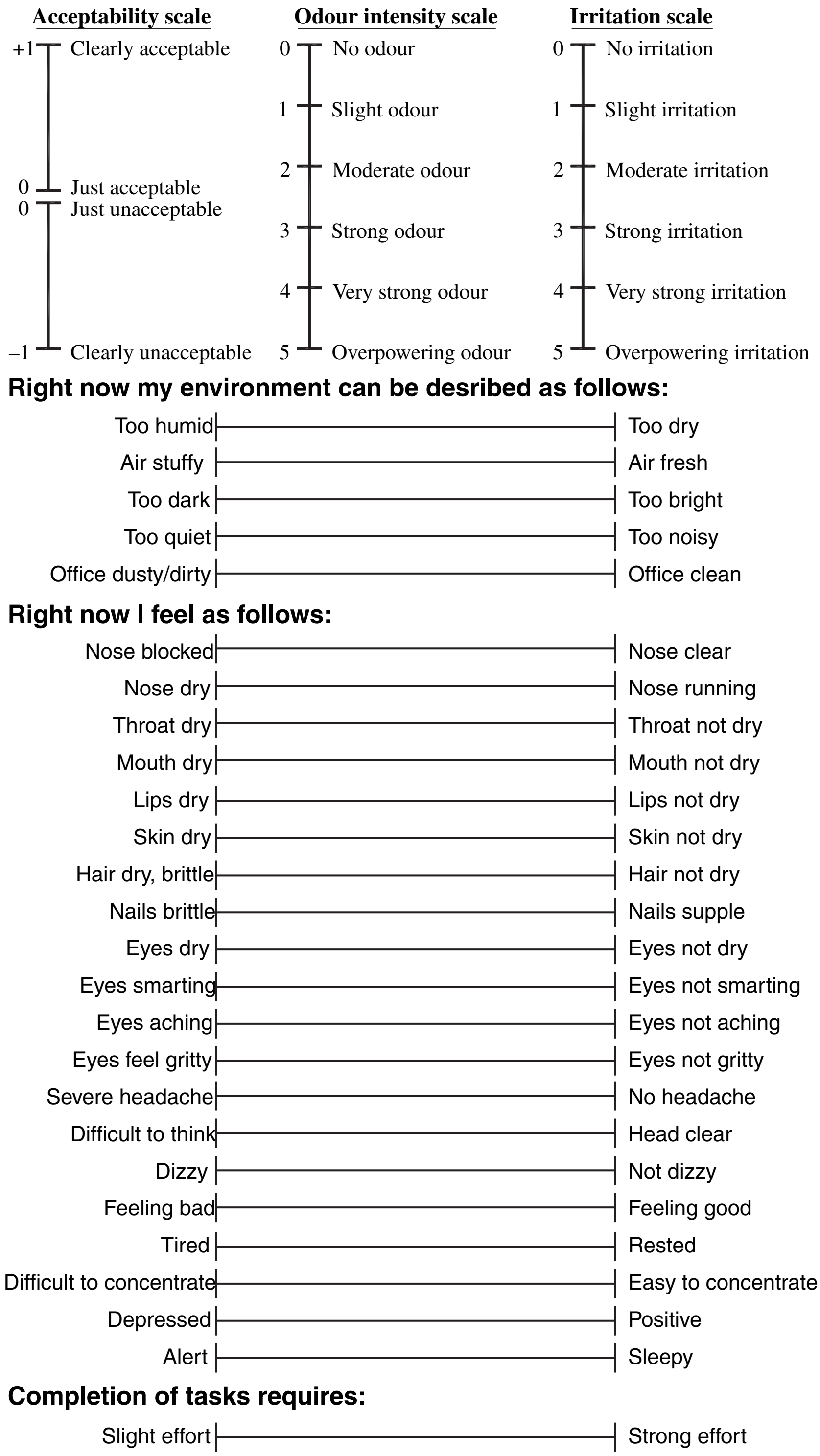

Fig. 3 Questionnaire scales used in the experiment to rate perceived air quality, perception of the environment and SBS symptoms. (a) Scales on which the subjects used to assess the perceived air quality, odor intensity and irritation of eyes, nose and throat. (b) Visual analog scales on which the subjects indicated their general perception of the environment (the 5 initial scales), the intensity of their specific and general SBS symptoms, and effort they exerted. Note that the final scale was found to be interpreted ambiguously by subjects and has been replaced in subsequent research at ICIEE by a 0–100% scale of self-estimated performance.

and after the completion of each task, throughout each 280 min exposure. The subjects were reminded at intervals to adjust their clothing in order to maintain thermal neutrality throughout the whole occupation period. The questionnaire used to obtain subjective sensations included questions on perceived air quality, thermal comfort, general perceptions of the environment and both specific and general SBS symptoms.

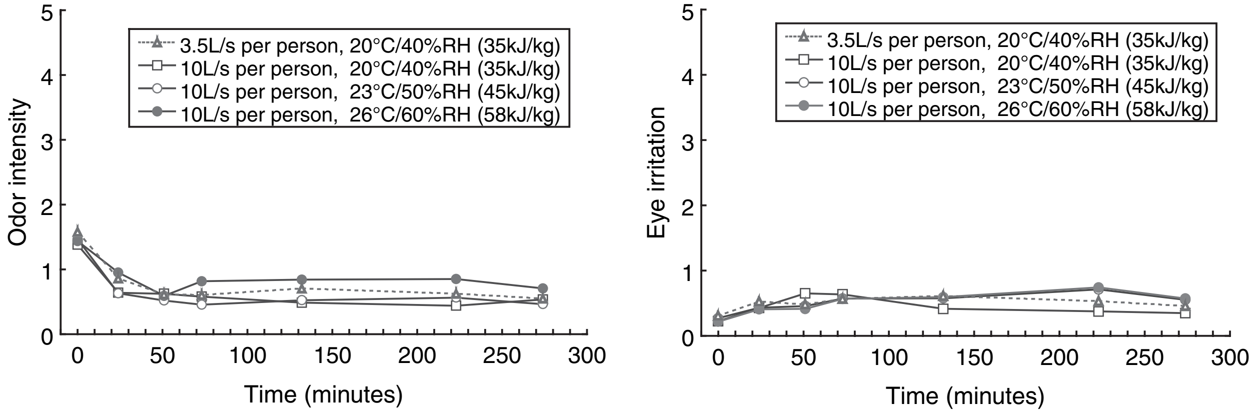

Fig. 4 Time course odor intensity perception and eye irritation under different environmental conditions.

Perceived air quality was assessed using continuous scales describing the acceptability of air, odor intensity and irritation of the eyes, nose and throat, as shown in Fig. 3(a). Thermal sensation was assessed using the ASHRAE 7-point thermal sensation scale (ASHRAE, 2001a). General perceptions of the environment and SBS symptoms were evaluated using DTU's visual-analog scales, shown in Fig. 3(b). Subjects placed a transverse mark on each scale on a printed form. The scale markings were later transcribed to numerical form for analysis. Non-parametric Friedman Two-way ANOVA and Wilcoxon Matched-pairs signed-ranks test were used for testing within-subject effects of enthalpy and ventilation rate on the dependent variables.

Results

During the experiment, subjects attained thermal neutrality at 23°C/50% RH; the mean thermal sensation was slightly cool at 20°C/40% RH and slightly warm at 26°C/60% RH. However, in general, thermal comfort for the subjects was maintained by self-adjustment of clothing. The observed airway irritation was very low and was identical throughout the experiment without being influenced by enthalpy and ventilation rate. Figure 4 shows the time course of perception of odor intensity and eye irritation. The odor intensity assessment did not differ significantly at different levels of temperature and humidity, and there was a clear adaptation of odor intensity perception after 30 minutes' exposure. The observed odor intensity was slightly higher at 26°C/60% RH compared with other conditions with lower levels of temperature and humidity after 1 h exposure. This slight increase of odor intensity is most likely due to a slightly increased emission of bioeffluents. At 20°C/40% RH, a slight increase in odor intensity can also be observed when reducing the ventilation rate from 10 to 3.5 l s^{-1} per person. However, the increased odor intensity due to either increased enthalpy of indoor air or decreased ventilation rate was not statistically significant. Eye irritation increased slightly with increasing enthalpy and decreasing ventilation rate after two hours' exposure. This increase was not significant, and only slight irritation was observed.

A strong effect of temperature and humidity was found on perceived air freshness. Figure 5 shows the time course of air freshness assessments during each of the 4 conditions. The air was perceived as much fresher at low levels of temperature and humidity for both first impression and perception after 280 minutes' adaptation. Adaptation seems to have improved perceived air freshness perception after about one hour, although the improvement was not significant. Friedman Two-way ANOVA shows that the air freshness was significantly improved with decreasing temperature and humidity throughout the whole 280 min exposure period ($p < 0.002$ for the immediate perception and $p < 0.0002$ for the adapted perception). Figure 5 shows that although there was no significant effect of the outside air supply rate on perceived freshness, by the end of the session the rank order was as expected.

As would be expected from the results of the air freshness assessment, the air was judged to be more acceptable as air temperature and humidity decreased.

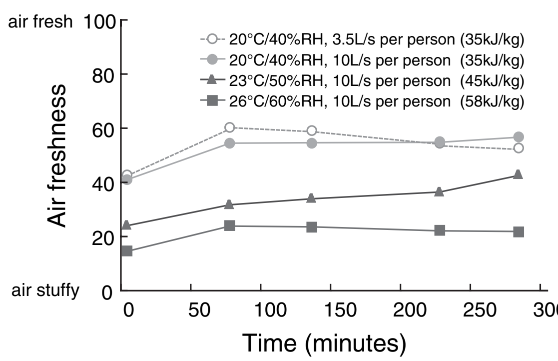

Fig. 5 Time course perception of air freshness under each condition.

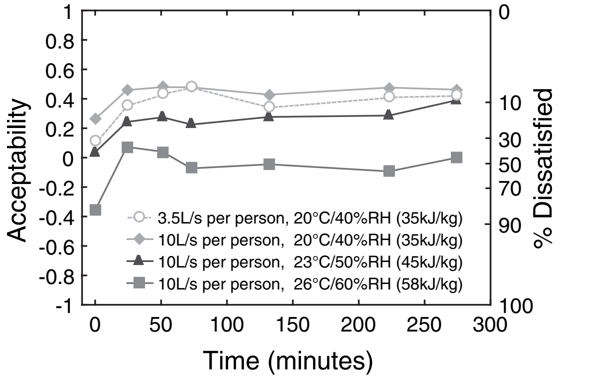

Fig. 6 Time course acceptability of air perceived under different conditions.

Figure 6 shows the time course of the perception of air quality at the three levels of indoor air enthalpy and two levels of ventilation rate. The three solid lines indicate the acceptability of the air with the same level of pollution (e.g., same ventilation rate of 10 l s^{-1} per person) but different levels of temperature and humidity. The results show a significant impact of temperature and humidity on the acceptability of air quality; the air was judged as more unacceptable at the elevated levels of indoor air temperature and humidity. Figure 6 also shows that the perceived air quality improved after 30 minutes' exposure in all four different indoor environmental conditions. This improvement may be due to adaptation. However, it seems that the perception of air quality was more likely to be adapted to air pollution than the enthalpy, since both the acceptability of the first impression and the acceptability after adaptation showed a similar gradient with decreasing indoor air enthalpy. Figures 4 and 5 further confirmed this result. Cooling of mucous membranes probably caused the air to be perceived as fresher and therefore improved the acceptability of air at low temperature and humidity. Since the adaptation had little effect on perceived air freshness, the effect of air temperature and humidity on the acceptability of air could not be removed by adaptation. Adaptation mainly reduced the perception of odor intensity and odor intensity was not affected by air temperature and humidity, as shown in Fig. 4. This may explain why acceptability improved after adaptation while the effects of temperature and humidity persisted.

Analysis of variance of the acceptability data at different levels of enthalpy showed that the effect of enthalpy on acceptability of air was highly significant. Non-parametric Friedman Two-way ANOVA reveals a highly significant ($p < 0.00008$) effect of temperature and humidity on the immediate perception of acceptability and an effect approaching significance ($p < 0.09$) on adapted perception of acceptability. A Wilcoxon Matched-Pairs Signed-Ranks test further shows that both first and adapted perception of acceptability at enthalpy levels of 35 and 45 kJ kg^{-1} were significantly higher than at 58 kJ kg^{-1} ($p < 0.001$). Figure 6 also shows that reducing the ventilation rate decreased acceptability at the first impression ($p < 0.05$ Wilcoxon test) at 35 kJ kg^{-1}, but only slightly decreased acceptability after adaptation. However, even at the low ventilation rate of 3.5 l s^{-1} per person, the air with a low enthalpy of 35 kJ kg^{-1} was still perceived as more acceptable than the air with a higher enthalpy of 45 and 58 kJ kg^{-1} at the higher ventilation rate of 10 l s^{-1} per person.

The linear correlation between acceptability and enthalpy that was found in previous laboratory studies (Fang et al., 1998a,b and Toftum et al., 1998) was also observed in the present field study. Figure 7 shows that the acceptability of the air was strongly correlated with enthalpy both for immediate perception and for perception after adaptation.

Figure 8 shows the average subjective rating of difficulty in thinking clearly. Although there was no significant effect of the outside air supply rate, by the end of the exposure the rank order of conditions was as expected on the basis of earlier research (Wargocki et al., 2000). The intensity of this symptom increased significantly at the end of 280 min of exposure when

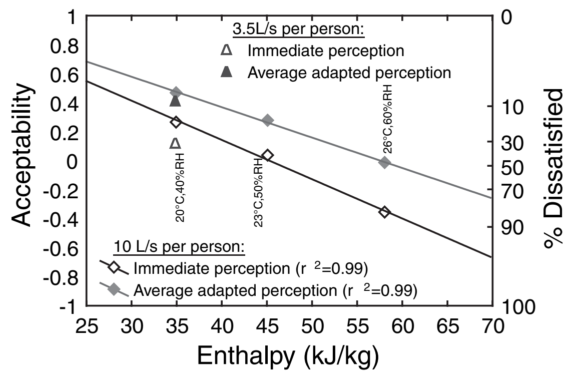

Fig. 7 Linear correlations between acceptability and enthalpy observed in the experiment.

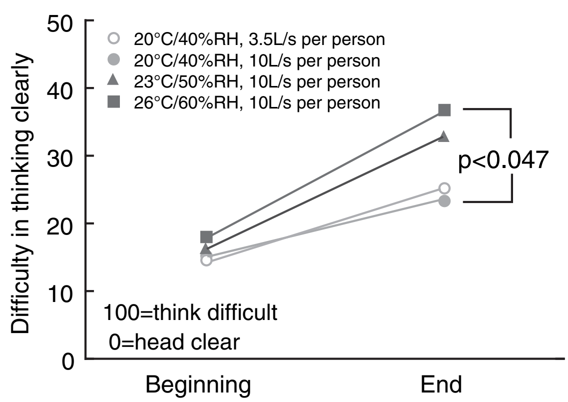

Fig. 8 Difficulty in thinking clearly before and after each exposure.

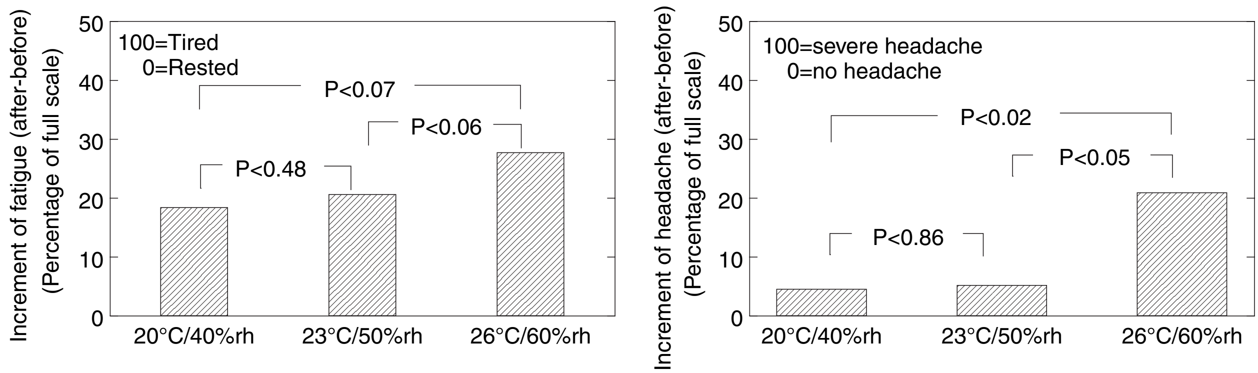

Fig. 9 Mean within-subject change during each exposure for two SBS symptoms.

the subjects worked at 26°C/60% RH compared with when they worked at 20°C/40% RH ($p < 0.05$).

In Fig. 9, the average within-subject changes in fatigue and headache symptom intensity between the beginning and end of each exposure are shown for the three temperature and humidity levels, pooling the two exposures at 20°C/40% RH as the ventilation rate could not be shown to reduce these symptoms significantly. Air temperatures above 23°C with RH above 50% increased the intensity of both of these symptoms. The p-values shown in Fig. 9 were obtained using the non-parametric Wilcoxon Matched-pairs signed-ranks test for within-subject effects.

The increased symptoms of fatigue, headache and difficulty in thinking clearly at the high level of air temperature and humidity may be expected to affect the performance of mental work in a real working situation, but it was not possible to demonstrate any significant effects on the performance of the tasks used in the present experiment.

Figure 10 shows the assessment of the air humidity at two levels of ventilation rate with the same enthalpy and at two levels of enthalpy with the same ventilation rate. For the first impression, the air with lower humidity and temperature was felt to be significantly drier than the air with higher temperature and humidity ($p < 0.02$ Wilcoxon test), but the air with the same temperature and humidity was perceived to be equally dry at both ventilation rates. However, after two hours' exposure, the subjects could not distinguish the different humidities at the same ventilation rate, and there was a tendency for the air to be perceived as drier at the low ventilation rate than at the high ventilation rate ($p < 0.07$ Wilcoxon test) although the physical humidity and temperature were the same. This difference might increase after prolonged exposure. This result implies that even though dryness sensation is dependent on humidity at the initial exposure, in longer exposures air pollution is what determines the sensation of dryness.

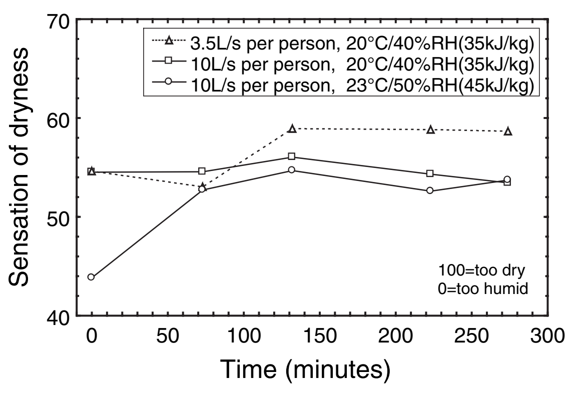

Fig. 10 Time course dry sensation of air with different levels of temperature, humidity and ventilation rate.

Discussion

Ventilation is required in order to obtain a comfortable and healthy indoor environment. In practice, comfort usually determines the required ventilation rate (CEN, 1998). The ventilation rates prescribed in existing ventilation standards (CEN, 1998 and ASHRAE, 2001b) do not include the impact of air temperature and humidity. In ASHRAE standard 62 (ASHRAE, 2001b), the outdoor air requirement for ventilation in office spaces is stipulated as $10\ l\ s^{-1}$ per person. The European Design Criteria (CEN, 1998) suggests a minimum outdoor air requirement of $4\ l\ s^{-1}$ per person to obtain a perceived air quality of 2.5 dp (30% PD). However, results presented in Fig. 6 show that with a ventilation rate of $10\ l\ s^{-1}$ per person, the air was perceived as unacceptable on first impression, with 40% and 85% dissatisfied (PD) at 23°C/50% RH and 26°C/60% RH, respectively. After adaptation, about 50% of the occupants still found the air unacceptable at 26°C/60% RH. At 20°C/40% RH, both immediate and adapted perception of the air quality were improved to 19% and 8% PD, which fits quite well with the European Design Criteria (CEN, 1998). Air freshness also improved at lower levels of temperature and humidity but did not improve when the ventilation rate increased from 3.4

to 10 l s^{-1} per person. Figure 6 shows further that decreasing the ventilation rate from 10 to 3.5 l s^{-1} per person can be compensated for by decreasing indoor air enthalpy from 45 kJ kg^{-1} (23°C/50% RH) to 35 kJ kg^{-1} (20°C/40% RH) so as to maintain perceived air quality. The present study also found that decreasing the ventilation rate from 10 to 3.5 l s^{-1} per person at 20°C/40% RH did not increase irritation symptoms. These results indicate the importance of the indoor air temperature and humidity in determining the ventilation requirement, and the great potential that exists for reducing the ventilation rate by decreasing the indoor air temperature and humidity. Recently, Liu et al.'s case study (Liu et al., 1999) provided data from the field. They found that decreasing peak room relative humidity in an office building from 70% to 55% and simultaneously reducing the total outside airflow by 86% significantly improved the comfort of office workers and saved 27% of the building's energy consumption. The present results further confirm that the effects of temperature and humidity on the perception of air quality can last for a long time and do not diminish after a period of adaptation and that SBS symptoms such as fatigue and headache may also be caused by exposure to air at slightly raised temperature and humidity. This is of course a common experience, but is often attributed to the objective rather than the subjective quality of the air.

Many previous studies have shown that the sensation of dryness was poorly correlated with physical indoor air humidity. The humidity sensation votes obtained in the present experiment show that decreasing the ventilation rate may increase the sensation of dryness. A tendency can be observed in Fig. 10 for the air to be perceived as drier during longer exposure when the ventilation rate decreased. In contrast, decreasing the humidity did not increase the sensation of dryness after longer exposure. This tendency towards a sensation of dryness due to decreasing the ventilation rate may become even stronger with increasing indoor air temperature, as observed by Andersson et al. (1975). The results of the present study support Bakke and Levy's finding from a field investigation (Bakke & Levy, 1990). They found that complaints of "dry air" were most frequent in connection with the lowest ventilation rate and the highest air humidity tested (about 45% RH). Sundell and Lindvall's field investigation (Sundell & Lindvall, 1993) also showed that the "sensation of dryness" has little to do with physical air humidity. They observed no significant relationship between the prevalence of SBS symptoms and the indoor air humidity in the range 10–40% RH. The present experimental results appear to agree with many previous findings that indicate that indoor air pollutants may contribute to certain symptoms that are similar to a sensation of dryness.

It was not possible to show any significant effect of temperature and humidity on performance in this study, presumably because subjects succeeded as intended in remaining in a state of thermal comfort, but it would be a mistake to conclude that temperature and humidity have no influence on the productivity of office workers in the real world, who frequently do not succeed in remaining in thermal comfort over the range 20–26°C. Wyon (1993) has reviewed many previous studies showing that both heat and cold stress affect the performance of most types of work. In the present study, no heat or cold stress was in fact applied to the subjects because they were able to adjust their clothing to maintain thermal neutrality. In spite of this, their heads were still exposed to moderate heat stress at 26°C and 60% RH. In the long term, this local heat stress plus the perceived stuffiness of air at raised levels of temperature and humidity may be expected to result in some SBS symptoms. The observed increment of fatigue, headache and difficulty in thinking clearly at 26°C and 60% RH indicate that productivity might well be reduced in a real workplace towards the end of a long day's work.

Additionally, the subjects may have been overmotivated in the 5-h experiment, so that they put too much effort into their work and so were able to overcome the effect of moderately uncomfortable environmental conditions and maintain their performance. Tanabe (2003) found a similar phenomenon when he asked his subjects to perform calculations at two very different levels of illumination (3 and 800 lx). His experiment showed that people could maintain their productivity when they worked in an extremely dark environment (e.g., 3lx). However, both subjective and objectively measured fatigue were significantly higher when the subjects worked at 3 lx compared with the symptom measured in the reference condition of 800 lx. In both experiments, performance was maintained at the cost of increasing mental fatigue, which sooner or later may decrease work performance or cause physical disorder. The two experiments covered a range of environmental conditions from mildly uncomfortable to extremely uncomfortable. As productivity in real life is almost impossible to measure, fatigue and some SBS symptoms might be used as indirect indicators of the risk that productivity will be reduced in an uncomfortable environment.

Increasing the ventilation rate from 3.5 to 10 l s^{-1} per person significantly improved the first impression of perceived air quality. However, the improvement was not significant at the end of the 280 min exposure, probably due to adaptation. Similar results were also observed in Wargocki's study (Wargocki et al., 2000) which used the same methodology, i.e., the same number of subjects, the same exposure period, the same indoor air pollution source and the same office work tasks. Wargocki's experiment further demonstrated a significant effect of ventilation rate on both SBS symptoms and performance that was not observed in the present experiment. Wargocki's experiment was designed specifically to observe the effect of ventilation rate on perceived air quality, SBS symptoms and productivity. The experimental design used three levels of ventilation rate as an independent variable in a fully balanced order of presentation that made the statistical analysis more sensitive. The present incomplete design with only two levels of ventilation rate, in which order of presentation of ventilation rate was not fully balanced, was clearly less sensitive than that of the previous comparison of ventilation rate. The present experiment was designed mainly to observe the effect of temperature and humidity on perceived air quality, SBS symptoms and performance, and to compare the effect of temperature and humidity with the effect of ventilation rate. The effect of ventilation rate was only observed at a low level of air temperature and humidity (20°C/40% RH) and only two levels of ventilation rate were studied. The results of this experiment should therefore not be used to conclude that the outdoor air supply rate has no effect on SBS symptoms and productivity.

Conclusions

Perception of air freshness and acceptability improved greatly as temperature and humidity decreased and the effect lasted for several hours. Such an improvement of perceived air quality due to decreased indoor air enthalpy could be used to compensate for the negative effect of reducing the outdoor air supply rate from 10 to 3.5 l s^{-1} per person.

Intensity of fatigue, headache and difficulty in thinking clearly decreased when subjects worked at slightly lower levels of air temperature and humidity.

Acknowledgments

This study was supported by the Danish Scientific and Technical Research Council (SVTF) through its funding of the International Centre for Indoor Environment and Energy (ICIEE).

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