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The Effects of Outdoor Air Supply Rate in an Office on Perceived Air Quality, Sick Building Syndrome (SBS) Symptoms and Productivity

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Abstract Perceived air quality, Sick Building Syndrome (SBS) symptoms and productivity were studied in a normally furnished office space (108 m^3) ventilated with an outdoor airflow of 3, 10 or 30 L/s per person, corresponding to an air change rate of 0.6, 2 or 6 h^{-1}. The temperature of 22 °C, the relative humidity of 40% and all other environmental parameters remained unchanged. Five groups of six female subjects were each exposed to the three ventilation rates, one group and one ventilation rate at a time. Each exposure lasted 4.6 h and took place in the afternoon. Subjects were unaware of the intervention and remained thermally neutral by adjusting their clothing. They assessed perceived air quality and SBS symptoms at intervals, and performed simulated normal office work. Increasing ventilation decreased the percentage of subjects dissatisfied with the air quality ($P<0.002$) and the intensity of odour ($P<0.02$), and increased the perceived freshness of air ($P<0.05$). It also decreased the sensation of dryness of mouth and throat ($P<0.0006$), eased difficulty in thinking clearly ($P<0.001$) and made subjects feel generally better ($P<0.0001$). The performance of four simulated office tasks improved monotonically with increasing ventilation rates, and the effect reached formal significance in the case of text-typing ($P<0.03$). For each twofold increase in ventilation rate, performance improved on average by 1.7%. This study shows the benefits for health, comfort and productivity of ventilation at rates well above the minimum levels prescribed in existing standards and guidelines. It confirms the results of a previous study in the same office when the indoor air quality was improved by decreasing the pollution load while the ventilation remained unchanged.

Key words Perceived air quality; IAQ; SBS symptoms; Productivity; Ventilation; Outdoor air change rate; Office.

Practical Implications
Good indoor air quality is beneficial for health, comfort and productivity. It is therefore advisable to ventilate indoor environments at rates above the minimum levels prescribed in present standards and guidelines. Reducing costs and conserving energy by maintaining modest levels of ventilation can easily result in a net loss if productivity is decreased. Increasing ventilation rates above minimum levels can raise productivity and will, in many cases, pay for itself while decreasing the intensity of SBS symptoms and improving perceived air quality. Intelligent use of energy recovery can often minimize energy consumption caused by increased ventilation. As an alternative or supplement to increased ventilation, it will often be beneficial for indoor air quality to eliminate or reduce sources of indoor air pollution or to supply ventilation air close to the breathing zone of the occupants.

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Introduction

The results obtained by Wargocki et al. (1999) indicate that reducing the pollution load on indoor air, as recommended by CEN CR 1752 (1998), is an effective way of improving the perceived air quality, reducing the intensity of some Sick Building Syndrome (SBS) symptoms and increasing some aspects of occupant productivity. In that experiment, a common pollution source was removed from a typical office space, while the ventilation rate and all other environmental parameters were kept unchanged. An alternative way of improving indoor air quality is to increase the ventilation rate and this has always been the main objective of ventilation in indoor spaces (ASHRAE, 1989; ECA, 1992; CEN, 1998). In laboratory and field experiments, increasing the ventilation rate has been shown to be an effective method of improving the perceived quality of air polluted by human bioeffluents (Cain et al., 1983; Fanger and Berg-Munch, 1983; Berg-Munch et al., 1986;

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Iwashita et al., 1990), tobacco smoke (Cain et al., 1983; Clausen, 1988) and building materials (Knudsen et al., 1997, 1998). Field studies have shown that a higher ventilation rate reduces the proportion of people dissatisfied with the perceived air quality in office buildings (Bluyssen et al., 1996; Pejtersen et al., 1999b).

The effects of ventilation on the prevalence of SBS symptoms have been investigated in the field, both in experimental studies in which ventilation rates have been altered to observe their impact on occupants' symptoms, and in cross-sectional studies in which the actual ventilation rates in buildings have only been measured (not altered) and their association with symptoms reported by occupants examined. Higher ventilation rates have been significantly associated with reduced prevalence of SBS symptoms in experimental studies in offices (Jaakkola et al., 1991; Nagda et al., 1991) and schools (Hanssen, 1993), and in cross-sectional studies in office buildings (Sundell, 1994; Groes et al., 1996). On the other hand, no significant effect of higher fresh air supply rates on the prevalence of SBS symptoms could be shown in other experimental studies of office workers (Jaakkola et al., 1990; Menzies, 1991, 1993) or staff at a hospital (Wyon, 1992), or in cross-sectional studies in offices (Jaakkola et al., 1991; Salisbury, 1984) and day-care centres (Routsalainen et al., 1994). The inconsistencies in these experimental studies may stem from the fact that ventilation rates in the buildings investigated were altered in existing HVAC systems, which are often an important source of pollution in themselves if not properly cleaned (Pejtersen et al., 1989; Burge et al., 1990). Increased airflow in such HVAC systems can cause increased emission of pollutants which may reduce or even reverse the positive effect of the increased outdoor air supply (Pejtersen, 1996). The inconsistent results in the cross-sectional studies may also be due to lack of adjustment for potential confounding factors in the statistical analyses, the low number of buildings investigated, the small number of respondents, inaccurate ventilation measurements or the small range of airflow rates (Sundell, 1994).

The reviews of previous studies of the impact of ventilation rate on SBS symptoms have concluded that ventilation rates at or below 10 L/s per person are associated with an increased prevalence of SBS symptoms (Mendell, 1993; Godish and Spengler, 1996; Seppänen et al., 1999). There are benefits of increasing the ventilation rate above 10 L/s per person in relation to SBS symptoms but they are difficult to detect epidemiologically due to the nature of the dose-response curve, as suggested by the most recent and comprehensive review by Seppänen et al. (1999). A log-linear dose-response relationship between the risk of SBS symptoms among office workers and the outdoor air supply rate was observed by Sundell (1994) and a relationship of the same kind had already been observed for perceived air quality (Fanger, 1988).

Little is known as regards ventilation effects on performance (Wyon, 1996). A recent search of the literature did not find a single study in which fresh air supply rate had been shown to affect productivity (Sensharma et al., 1998). Some experiments have indirectly studied the effect of ventilation on performance. Myhrvold et al. (1996) found a significant negative correlation between increasing concentration of CO_2 (range <1,000–4,000 ppm) and the performance of pupils on three psychological tests measuring simple reaction time, choice reaction time and the colour-word test of vigilance. Assuming that the concentration of CO_2 is a good indicator of ventilation rate in occupied rooms, they showed that performance monotonically decreases when ventilation rates are reduced from above 8 L/s per person down to 1 L/s per person. No decrease in the performance of simulated office work had been observed in the classical series of studies performed by the New York State Commission on Ventilation (1923) even though ventilation rates were reduced until the CO_2 concentration had risen to 3,000–4,000 ppm, that is to the highest concentrations measured in classrooms by Myhrvold et al. (1996).

The information summarized above shows that increased ventilation improves the perceived air quality while the benefits of ventilation for human health and productivity require further elucidation. The aim of the present study is to investigate whether the perceived air quality, SBS symptoms and performance of office workers are influenced by changing the ventilation rate from 3 to 30 L/s per person, i.e. in the presently-occurring range of outdoor air supply rates in offices (Sundell, 1994; Womble et al., 1995; Bluyssen et al., 1996; Pejtersen et al., 1999b). The impact of increased ventilation per se is investigated to avoid any simultaneous increase of pollution from the HVAC system itself. Another aim is to extend the results of Wargocki et al. (1999), who investigated the effects of removing indoor pollution sources on health comfort and productivity, to include mitigation by increased ventilation.

Material and Methods

Approach

The experimental approach and procedures were similar to those used by Wargocki et al. (1999). Instead of introducing or removing a pollution source in an office at constant ventilation, in the present investigation the same source was always present in the office while the outdoor air supply rate was changed to obtain three different ventilation rates: 3, 10 and 30 L/s per person. All other environmental parameters were kept unchanged. Female subjects were exposed to all three ventilation rates. They were unaware of the intervention since the noise level and the air velocity in the occupied zone of the office remained the same at all three ventilation rates. During each exposure, the subjects performed tasks simulating office work and were asked at intervals to assess the perceived air quality, indoor climate, the intensity of their SBS symptoms and thermal comfort. The subjects remained thermally neutral during each exposure by adjusting their clothing.

Facilities

The study was carried out in the room described in detail by Wargocki et al. (1999). The room is an ordinary office with a floor area of $6 \times 6 = 36$ m^2 and a volume of $36 \times 3 = 108$ m^3, divided by a partition that separates the space for the subjects from the space for equipment (Figure 1); the air is well mixed in the entire office. The office can be characterized as "low-polluting" (CEN, 1998); the floor tiles are made of polyolefine which has one of the lowest emissions found among floor materials (Knudsen et al., 1998). No conventional HVAC system components or filters were in operation, to avoid any additional pollution. The air was supplied by axial fans mounted in one of the windows and left the office through a slot under the entrance door. Two fans with silencers were used so that the noise level in the office could be kept constant independent of the ventilation rate. The ventilation rate was changed by turning on or off one or two fans and repositioning the dampers mounted downstream of each fan.

Subjects

Thirty female subjects were recruited to participate in the present experiments, all being familiar with a PC and having no chronic diseases. Table 1 shows the personal characteristics of the subjects obtained from a questionnaire completed by the applicants on recruitment. The subjects were not examined medically. Of the 30 subjects recruited, 29 completed the experimental sessions with the ventilation rates of 3 and 30 L/s per person, while only 27 completed the sessions with

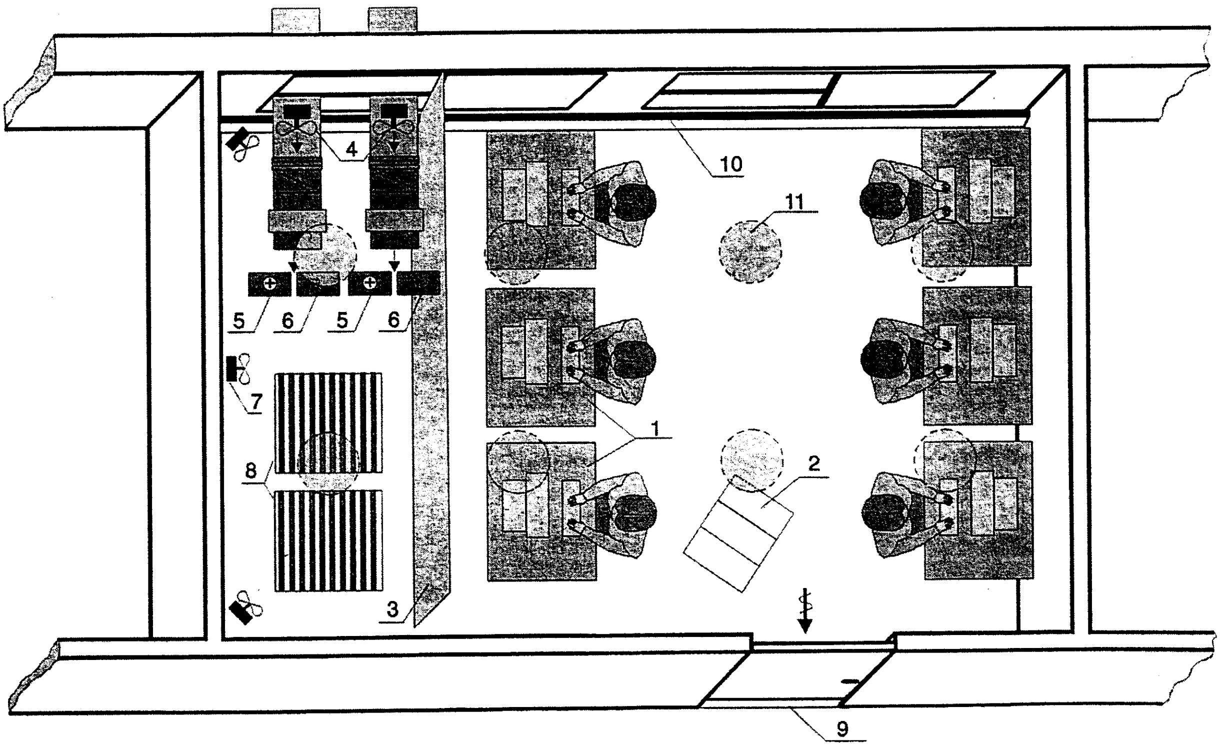

Fig. 1 Experimental set-up in the office showing 6 subjects sitting at individual workstations (1) consisting of a table, a chair, a desk lamp and a personal computer (PC) and (2) wooden stairs used by subjects for a step exercise located on one side of the 2-m-high partition (3), and a set of axial fans with dampers and silencers (4), electric heaters (5), steam humidifiers (6), mixing fans (7) and pollution source (8), items 4–8 being located on the other side of the partition and thus not visible to subjects; the air left the office through a slot under the entrance door (9). Convectors (10), being a part of a central heating system, are located under the windows on both sides of the partition, as well as 8 illumination fixtures (11) attached to the ceiling each with a fluorescent bulb of 38 W

Table 1 Personal characteristics of subjects participating in the present experiment

Total number of subjects	30
Gender	female
Age (range/mean±sd)	18–33/23.5±3.4 years old
Height (mean±sd)	168±6 cm
Weight (mean±sd)	63±9.5 kg
Occupation	students
Number of smokers	5 (smoking <6 cig./day)
Number of atopic subjects (with asthma, hay fever or allergy)	0(2)†
Number of subjects considering themselves as more sensitive than normal to poor air quality	7
Number of subjects with SBS history‡	23

†2 subjects reported that they have hay-fever, but they did not suffer from it at the time of the experiment; ‡those who during the year prior to the experiment experienced one mucosal, cutaneous or general symptom at least twice per month

a ventilation rate of 10 L/s per person. Subjects were paid at a fixed rate for their participation and in order to increase their motivation, they were also paid a bonus of up to 20% of the fixed amount, depending on their performance.

Twenty-seven subjects were familiar with the experimental procedures as they had participated in similar studies in the same room directly prior to the present experiment (Fang et al., 1999; Witterseh et al., 1999). The three other subjects received 1 h of training on the performance tasks and instructions on how to fill out the questionnaires used to obtain subjective responses. All subjects were instructed to abstain from alcoholic beverages, spicy food or garlic from the day before each exposure, not to use strong deodorants or perfume on the day of the exposure and to eat a normal lunch prior to reporting for the experiment. The subjects were not allowed to smoke during the exposures.

Test Conditions

Three different outdoor air supply rates: 3, 10 and 30 L/s per person, were selected for the present experiment to represent a wide range of outdoor airflows, from well below to well above the rates recommended in ventilation standards and guidelines (ASHRAE, 1989; ECA, 1992; CEN, 1998) but still representative of what has been measured in office buildings (Sundell, 1994; Womble et al., 1995; Bluyssen et al., 1996; Pejtersen et al., 1999b); 10 L/s per person was selected to link the present experiment with the study reported by Wargocki et al. (1999). The three ventilation rates correspond to a total outdoor air change rate of 0.6, 2 and 6 h^{-1}. The lowest ventilation rate is close to the typical minimum requirement for domestic environments and is therefore relevant for home offices.

An air temperature of 22 °C, a relative humidity (RH) of 40%, an air velocity below 0.2 m/s and a noise level of 42 dB(A) (with no occupants or their activity in the office) were kept constant independently of the ventilation rate in the office. To increase the low pollution load in the office to a more common level, an extra pollution source was placed in the office throughout the experiment. The extra pollution source selected was a carpet used in the previous study by Wargocki et al. (1999). This type of material is still found in many existing buildings and the pollutants emitted are typical of those found in many non-low-polluting buildings (Table 2). The air in the office thus contained a typical mixture of pollutants emitted from low-polluting and non-low-polluting materials found in many office buildings. Strips of carpet with a total surface area corresponding to the floor area of the entire office (36 m^2) were suspended on a stainless-steel rack behind the partition where they were not visible to the subjects (Figure 1); they were attached back-to-back so that the backing of the carpet was not exposed to the air during experiments. The office was always illuminated by fluorescent bulbs in fixtures suspended from the ceiling and by daylight through the windows. There was no direct sunlight since the experiments were carried out in the afternoon and the windows faced east. The illumination level could be increased by any subject who felt it was too dark by switching on the desk lamp provided at each workstation.

Measurements

Physical and Chemical Measurements

Measurements of the airflow and the ventilation effectiveness were made regularly at each nominal ventilation rate, using sulphur hexafluoride (SF_6) as a tracer gas and a constant concentration method; the air was sampled at each workstation close to the breathing zone of the subject. The temperature and relative humidity of the air, the concentration of CO_2, and the

Table 2 Data on emission from the carpet used as an extra pollution source in this experiment. The measurements of source strength were made using a Field Laboratory Emission Cell (FLEC) at a temperature of 23 °C, a RH of 50% and an airflow of 250 ml/min. The air from the FLEC was sampled in parallel on a Tenax-TA tube and 25 VOCs with the highest concentration were quantified using gas chromatography/mass spectroscopy (GC/MS) with an accuracy of ±15% (Wargocki, 1998)

Compound	Source strength ($\mu g/m^2 \cdot h$)	Compound	Source strength ($\mu g/m^2 \cdot h$)
benzene	4.25	pentanal	4.95
toluene	24.5	hexanal	22
limonene	5.7	nonanal	6.1
α-pinene	5.0	decanal	1.85
2-butanol	9.2	benzaldehyde	8.2
butyldiglycol	10.4	2-hydroxy-benzaldehyde	3.6
ethanol	9.25	butyldiglycolacetate	8.8
1-ethoxy-2-propanol	12.5	ethylacetate	8.3
2-propanone	18	acetophenone	3.95
2-buten-2-one	11.5	2,2,4,6,6-pentamethylheptane	5.3
acetic acid	65.5	benzothiazol	3.8
benzoic acid	1.5	others (not identified)	21.5
hexanoic acid	3.5	total VOCs	127

toluene-equivalent concentration of total volatile organic compounds (TVOC) were measured continuously at each workstation (close to the breathing zone of the subject) and in the supply air. The ozone (O_3) concentration was measured continuously in the supply air and at the central point of the area occupied by the subjects, where the noise level in the office was also monitored continuously. Duplicate 5-h samples of outdoor and office air were collected on silica gel tubes coated with 2,4-dinitrophenylhydrazin, charcoal and Tenax-TA tubes for measuring, respectively, the concentration of formaldehyde and acetaldehyde, TVOC and C_5 to C_{10} aldehydes. Among all samples collected, three sets were selected for subsequent gas chromatography/mass spectroscopy (GC/MS) analyses, each containing samples of outdoor and indoor air collected at each of the three ventilation rates studied but only from days on which outdoor O_3 concentrations were at similar levels but not less than 20 ppb. The detection limits of the analytical method used were respectively 0.7 $\mu g/m^3$ for formaldehyde and acetaldehyde, 160 $\mu g/m^3$ for TVOC and 0.4 $\mu g/m^3$ for C_5 to C_{10} aldehydes. Concentrations of the measured compounds were analysed with a relative standard deviation of ±10%.

Subjective Measurements

The questionnaires used to obtain subjective sensations were the same as were used by Wargocki et al. (1999). They included questions regarding perceived air quality (Figure 2, left), general perceptions of indoor climate, SBS symptoms and the effort required to complete the tasks (Figure 2, right), and thermal comfort. In addition, the subjects were asked to evaluate the acceptability of the noise level and of the thermal environment in the office using the continuous acceptability scale shown in the top left part of Figure 2.

Measurements of Performance

Throughout the exposure, subjects performed simulated office work consisting of four different tasks: text typing, addition, proof-reading and creative thinking, the first two tasks being those previously used by Wargocki et al. (1999). In the typing task, subjects spent 55 min retyping a printed text onto a PC at their own pace, using the standard text editor. In the addition task, subjects spent 20 min adding units consisting of five two-digit numbers, which were random but excluded zeros, each printed one above the other. In the proof-reading task, subjects spent 20 min checking a printed text in which deliberate mistakes had been inserted (on average about every 4 lines of text but no more than 8 lines of text apart) and highlighted the words which they thought to be wrong without suggesting the exact correction. Each text had four types of deliberate error: spelling errors; two types of grammatical error, one that was obvious in the context of the phrase where it occurred and the other one apparently correct in the context of the immediate phrase but incorrect in the wider context of the text; and logical errors. In the creative thinking task, subjects spent 25 min writing down as many alternative uses as possible for a set of four specified and familiar objects, which were selected at random from among the following eight categories, none being selected twice: dense objects (e.g., brick, book), resilient objects (e.g., eraser, car tyre), long objects (e.g., pencil, needle), flat objects (e.g., newspaper, bedsheet), container objects (e.g., bucket, bottle), hard and/or sharp objects (e.g., knife, spoon), edible objects (e.g., apple, flour) and round (spherical/disk/cone) objects (e.g., football, coin).

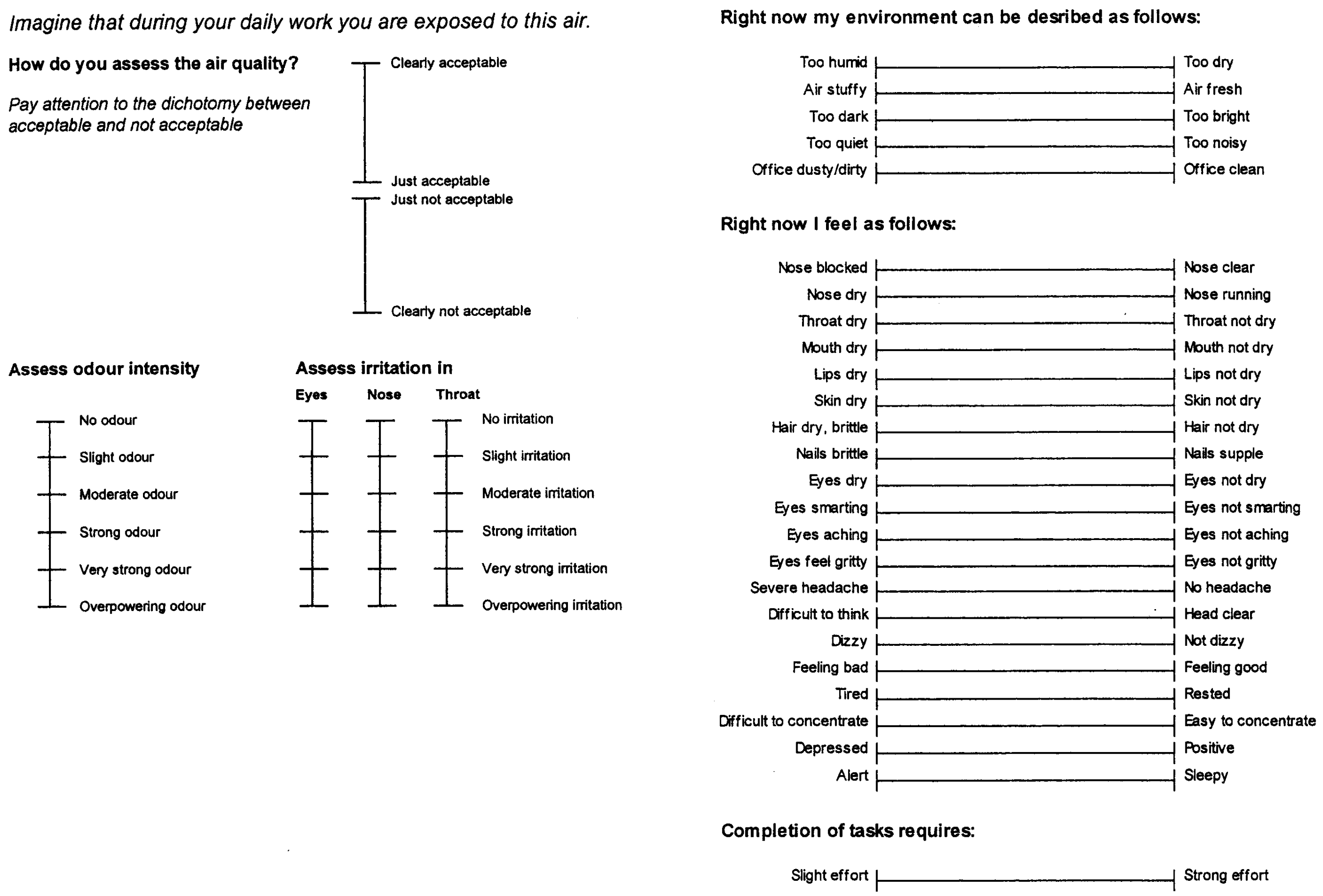

Fig. 2 Questionnaires used to make subjective assessments. Left: Scales used to assess the perceived air quality, odour intensity, irritation of eyes, nose and throat. Right: Visual analogue scales on which the subjects indicated their general perception of the environment (the 5 initial scales), the intensity of their specific and general SBS symptoms (the next 20 scales) and the effort they exerted to perform the office tasks (the last scale)

Six versions of each task, different but of similar difficulty, were administered to subjects, two per exposure. Each version was so long that it was impossible to finish in the time available.

Experimental Procedure

The experiment was carried out during three weeks in February 1999, each week on five days from Monday to Friday, and each day for 5 h in the afternoon, from 13:00 to 18:00. The subjects were assigned to the exposure conditions and the performance tasks completely at random in a balanced design. They were exposed in 5 groups of 6 subjects each, each group being randomly assigned to a weekday, but each group was exposed to the three exposure conditions on the same weekday of three successive experimental weeks. If a subject was missing, the experimenter joined the group so that six persons were present and the source strength of bioeffluents in the office remained the same during each exposure.

Each exposure lasted a total of 275 min and Figure 3 provides the schedule of each exposure. Prior to exposure, subjects assembled in a waiting room for 10 min. In the middle of each exposure, they took a 10-min break during which they stayed in the office and left it only if it was necessary to do so. Following the exposure, subjects returned to the waiting room where they spent 5 min and sampled fresh air, after which they re-entered the office to re-assess the perceived air quality. Following this evaluation, subjects left the building to assess the perceived quality of outdoor air.

All the subjective assessments were made by subjects seated at a workstation except for the assessments of perceived air quality made immediately upon entering and re-entering the office, for which subjects remained standing but approached their workstations. Directly after each subjective measurement (taken upon entering the office and at ca. 71 min, 130 min, 220 min and 270 min of exposure), subjects walked over a set of 4 steps, each 0.2 m high, to simulate physical activity during normal office work (Arens et al., 1998).

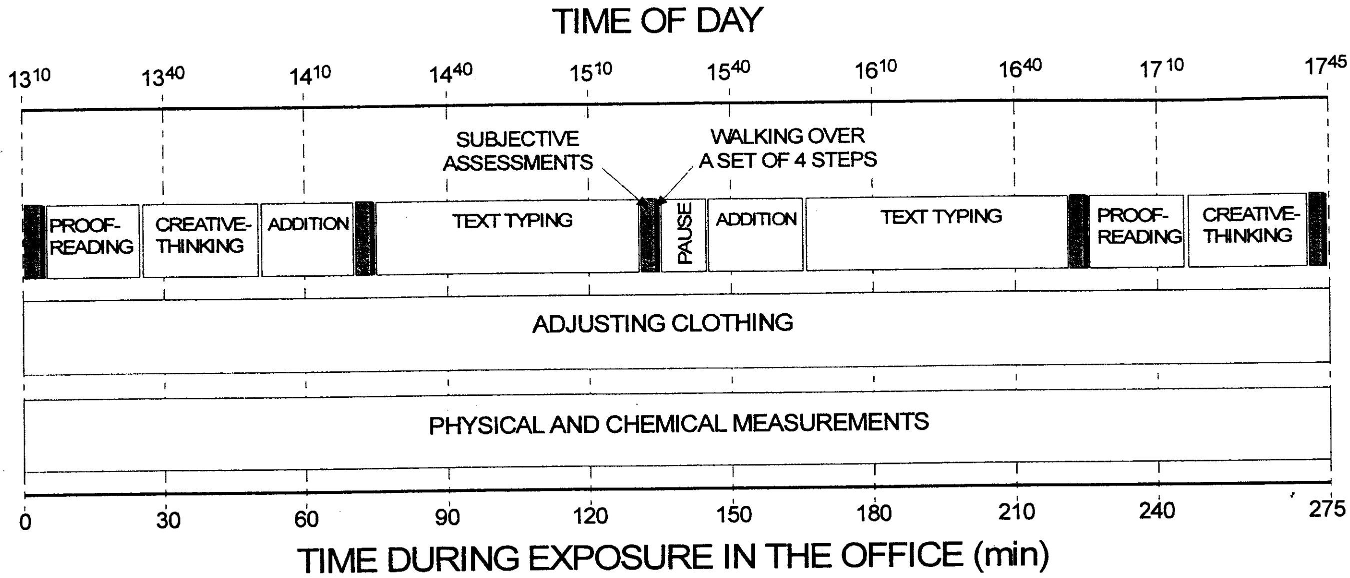

Fig. 3 Schedule of events taking place during each exposure

In order to remain thermally neutral (mean thermal vote=0) throughout the exposure, subjects were reminded to adjust their clothing whenever they felt too warm or too cool. Whenever thirsty or hungry, subjects could consume the non-carbonated water and digestive biscuits which were freely available at each workstation.

Statistical Analyses

Shapiro-Wilk's W test was used to test the normality of the data, with the rejection region set at ($P<0.01$). Normally distributed data were subjected to analysis of variance in a repeated measures design with each subject as her own control, thus excluding any differences in experience, training, intellectual skills, etc.

Table 3 Average (±sd) measured physical and chemical conditions in the office at three different ventilation rates

Parameter	Designed ventilation rate 3 L/(s · p)	10 L/(s · p)	30 L/(s · p)
Outdoor air supply rate (L/s per person)	3.1±0.2	10.6±0.4	30.0±0.4
Total outdoor air change rate (h^{-1})	0.6±0.05	2.1±0.08	6.0±0.07
Air temperature (°C)	22.6±0.4	22.5±0.6	22.1±0.2
Relative humidity (%)	40±0.1	40±0.4	39±0.6
Enthalpy of air (kJ/kg)*	40	40	39
Absolute humidity of air (g/kg)*	6.8	6.8	6.4
Air velocity (m/s)	<0.2	<0.2	<0.2
Sound pressure (dB(A))**	48	48	48
CO_2 above outdoors (ppm)†	1266±68	477±26	195±18
O_3 outdoors/indoors (ppb)††	16/0	18/4	27/16
Toluene equivalent TVOC (ppm)	0.26±0.06	0.20±0.02	0.23±0.02
Formaldehyde above outdoors (µg/m^3)‡	5	3.2	0.8
Acetaldehyde above outdoors (µg/m^3)‡	1.4	1.5	<d.l.‡‡
TVOC above outdoors (µg/m^3)‡	<d.l.	<d.l.	<d.l.
C_5-C_{10} aldehydes above outdoors (µg/m^3)‡	<d.l.	<d.l.	<d.l.

* calculated using the measured air temperature and relative humidity
** time-weighted sound pressure in the office with subjects; sound pressure was ca. 53 dB(A) during typing and ca. 44 dB(A) in the other periods independently of the ventilation rate in the office
† steady-state concentration for 10 and 30 L/s per person and 95% of the steady state concentration at 3 L/s per person obtained toward the end of exposure (measured outdoor concentration of CO_2 was ca. 430 ppm)
†† expected indoor-to-outdoor concentration ratio of O_3 was 0.14, 0.35 and 0.62 respectively for the air change rate of 0.6, 2.1 and 6 h^{-1} (Weschler et al., 1989)
‡ measured using GC/MS analyses when the outdoor O_3 concentration was ca. 25 ppb and the indoor O_3 concentration was 0, 7 and 16 ppb respectively for the ventilation rate of 3, 10 and 30 L/s per person
‡‡ <d.l.=below the detection limits of the analytical method, being 0.7 µg/m^3 for acetaldehyde, 160 µg/m^3 for TVOC and 0.4 µg/m^3 for C_5-C_{10} aldehydes

which can influence performance, and to linear regression analyses (Montgomery, 1991). Data from the scales measuring general perceptions of the environment and SBS symptoms (Figure 2, right) were treated as measures of subjective response at the ordinal level of measurement. These, together with the data that was not normally distributed, were analysed using the non-parametric 1-tailed Page test for ordered alternatives (Siegel and Castellan, 1988), which examines the hypothesis that adverse responses decreased and performance increased monotonically as the ventilation rate increased from 3 through 10 and up to 30 L/s per person.

Results

Table 3 shows the measured levels of the parameters describing the indoor environment in the office. Ventilation rates, temperature, relative humidity, noise level and air velocity were close to the intended levels. Ventilation measurements showed that the air in the office was well mixed. Subjective measurements showed no significant differences in the acceptability of thermal conditions, draught, noise level, illumination or office cleanliness at the three ventilation rates studied. The concentration of CO_2 indoors decreased with increasing ventilation rate. Based on these measurements, the average metabolic rate of the subjects was estimated to be ca. 1±0.1 met, 1.2±0.15 met and 1.35±0.05 met respectively, for the ventilation rates 3, 10 and 30 L/s per person. These values increase systematically with ventilation rate (Page test, $P<0.05$). The highest average indoor and outdoor O_3 concentration was measured at the ventilation rate of 30 L/s per person. The concentration of formaldehyde was lower at higher ventilation rates while the toluene-equivalent TVOC concentration was not affected by the ventilation. Measured concentrations of acetaldehyde, C_5 to C_{10} aldehydes and TVOC (analysed using GC/MS method) were very low, mostly below the detection limits of the analytical method used.

The subjective assessments of perceived air quality made upon entering the office showed that an increased ventilation rate significantly improved the acceptability of the air quality ($P<0.002$) and perceived air freshness ($P<0.05$), reduced odour intensity ($P<0.02$) and tended to reduce nose irritation ($P<0.07$). Upon re-entering the office shortly after the end of each exposure, an increased ventilation rate significantly improved the acceptability of the air quality ($P<0.01$) and tended to reduce odour intensity ($P<0.10$); these were the only two subjective assessments made by the subjects at this stage of the experiment. Monotonic improvements of perceived air quality with increasing ventilation rate were observed for subjective evaluations made upon entering and re-entering the office and were also seen during the ex-

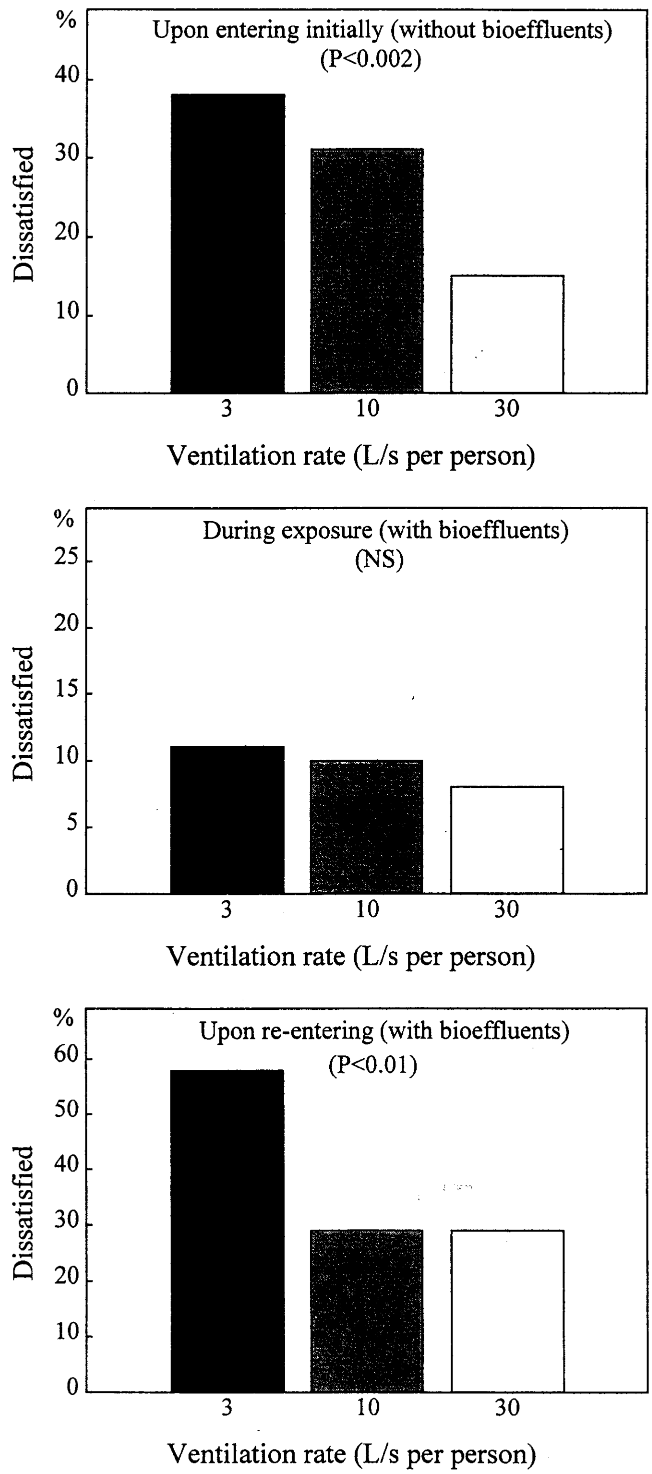

Fig. 4 Percentage dissatisfied with the perceived air quality upon entering the office (top), during exposure in the office (middle) and upon re-entering the office (bottom), as a function of the ventilation rate in the office

Table 4 Sensory pollution loads in the office at three different ventilation rates

	Sensory pollution load (olf/m²floor) at three ventilation rates			
Exposure in the office	3 L/(s · p)	10 L/(s · p)	30 L/(s · p)	Average
Upon entering (without bioeffluents)	0.18	0.45	0.40	0.34
Upon re-entering (with bioeffluents)	0.42	0.40	1.12	0.65

posure. During the exposure, the differences in perceived air quality between conditions did not reach statistical significance, except for throat irritation which increased slightly during the exposure at 3 and 10 L/s per person (P<0.03). The percentages dissatisfied with the air quality, calculated using assessments of the acceptability of air quality (Gunnarsen and Fanger, 1992), decreased monotonically with increasing ventilation rate (Figure 4); less than 3% of the subjects were dissatisfied with the quality of the outdoor air.

Using the assessments of perceived air quality made upon entering and re-entering the office, and the measured ventilation rates, the total sensory pollution loads in the office were estimated (Fanger, 1988) and are shown in Table 4.

The sensation of dry throat and mouth, difficulty in thinking clearly and the general feeling of wellbeing (feeling good/bad) were all significantly affected by changing the ventilation rate (P<0.001). The magnitude of these symptoms decreased monotonically with increasing ventilation rate (Figure 5). The magnitude of fatigue and depression changed little with ventilation rate, although these symptoms were significantly worse when the ventilation rate was reduced

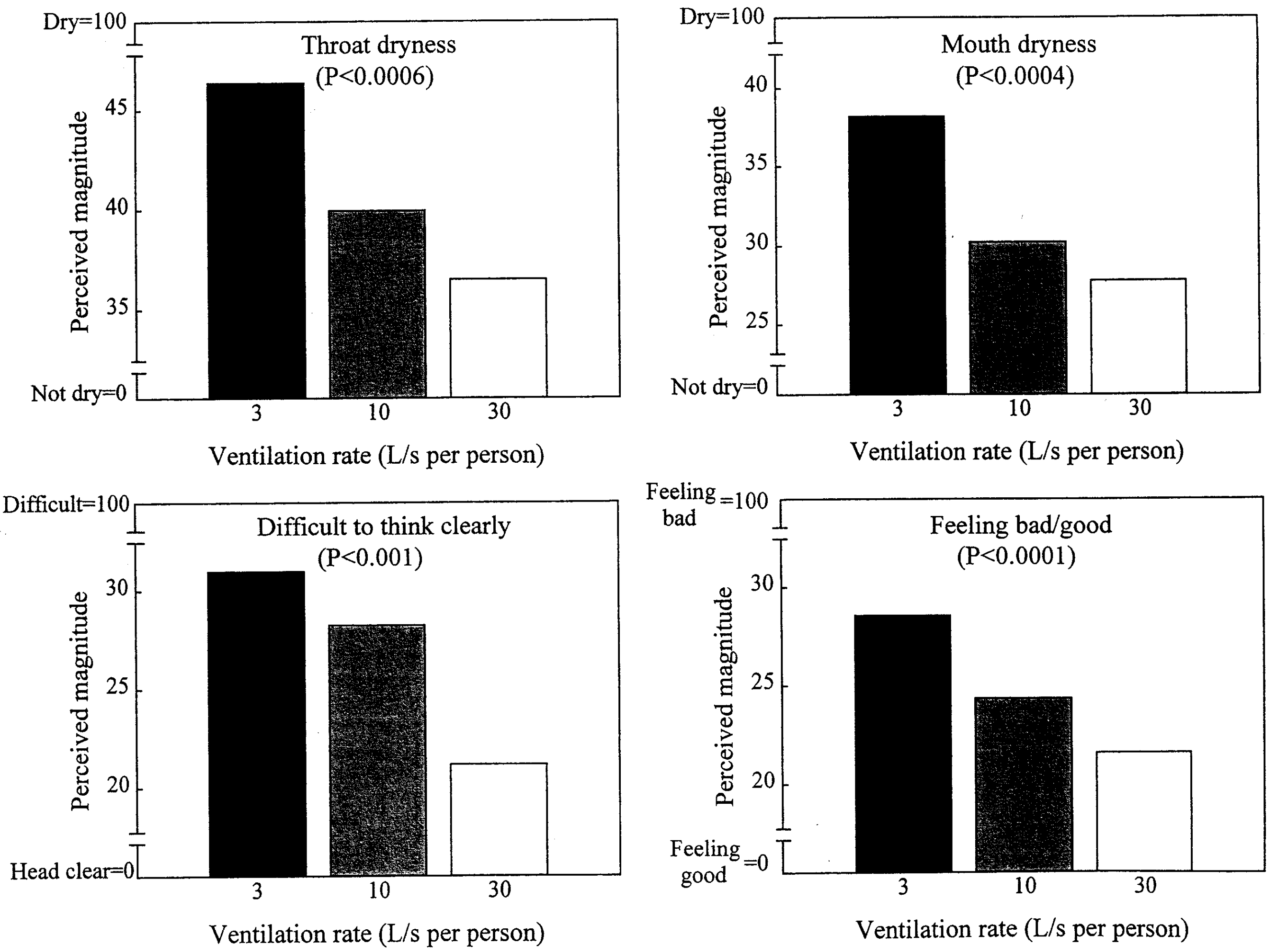

Fig. 5 Perceived magnitude of SBS symptoms as a function of the ventilation rate in the office for those symptoms for which the difference in SBS intensity was highly significant (P<0.001) between the exposure conditions

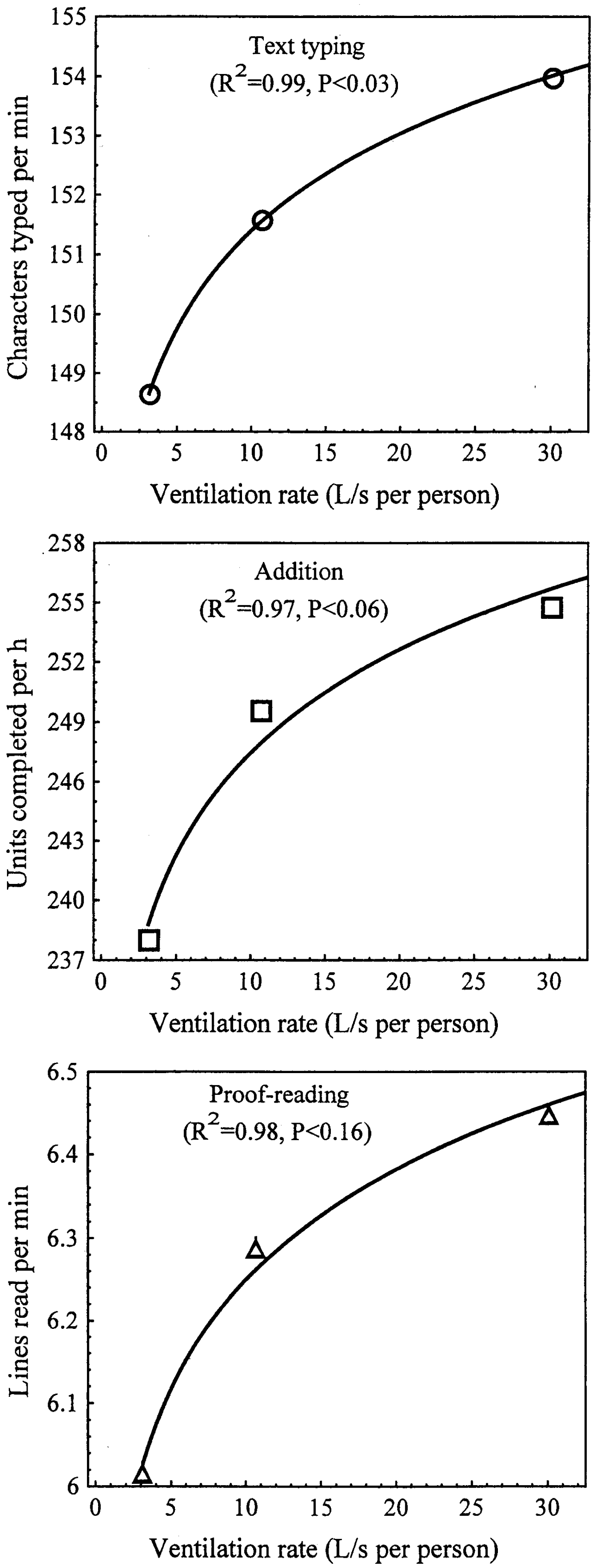

Fig. 6 Performance of a text typing task (top), addition task (middle) and proof-reading task (bottom), as a function of the ventilation rate. Figures show log-linear regression lines fitted to data points describing the overall performance of the tasks (i.e., integrating speed and accuracy) at different ventilation rates. The regression lines imply that for every two-fold increase of the ventilation rate in the range from 3 to 30 L/s per person, performance increased by ca. 1.1% for typing, and by ca. 2.1% for addition and proof-reading

($P<0.04$). Changing the ventilation rate did not significantly affect other SBS symptoms assessed during the exposure. The rating of the effort required to complete the performance tasks showed that the subjects tended to mark the scale closer to the "strong effort" end at lower ventilation rates ($P<0.07$).

Performance of the text typing, addition and proof-reading tasks was studied by analysing speed and accuracy. Significant learning effects were observed for these tasks at each ventilation rate but they did not alter the effects on performance. The results show that performance improved with increasing ventilation rate, but the difference between conditions did not reach formal significance in the analysis of variance and only approached significance for the number of characters typed per minute ($P<0.08$). These data were subsequently analysed using the non-parametric Page test against ordered hypothesis, which tests the significance of the expected trend with increasing ventilation. The Page test showed that the number of characters typed per minute in the text typing task tended to increase ($P<0.08$) at higher ventilation rates. A similar tendency was seen for the number of units completed per hour in the addition task ($P<0.06$) and the number of lines read per minute in the proof-reading task ($P<0.07$). Parametric tests for linear trend against a log-transformed ventilation rate, as shown in Figure 6, were then applied, integrating speed and accuracy to derive measures of overall performance. The results shown in Figure 6 confirm the results of the Page test and reach formal significance in the case of text typing ($P<0.03$).

Based on the regression lines presented in Figure 6 and considering that the relationship between performance and ventilation follows a logarithmic function, it was estimated that every two-fold increase in ventilation rate above 3 L/s per person would produce a 1.1% increase in overall performance in the text typing task and a 2.1% increase in overall performance in the addition and proof-reading tasks. Hence, every two-fold increase of the ventilation rate in the range from 3 to 30 L/s per person, tended to increase the overall performance of the subjects on all tasks by 1.4% if effects are weighted by the time spent on each performance task, or by 1.7% if an unweighted mean workrate is derived instead.

The results of the creative thinking task show that when ventilation rate was increased from 3 to 10 L/s per person, subjects wrote down more alternative uses of specified objects ($P<0.025$); weighting each answer for its originality in the sample, a significantly higher score was obtained at the higher ventilation rate ($P<0.046$); both P-values are 1-tailed. Increasing ventilation rate further, from 10 to 30 L/s per person, had no significant effect on either of these measures.

Discussion

The results of the present experiment show that increased ventilation rate between 3, 10 and 30 L/s per person, corresponding to a total outdoor air change rate of 0.6, 2 and 6 h^{-1} respectively, the range typically found in office buildings around the world (Sundell, 1994; Womble et al., 1995; Bluyssen et al., 1996; Pejtersen et al., 1999b) improved perceived air quality, decreased the intensity of some SBS symptoms and improved performance. A statistically significant and monotonic decrease in the number of subjects dissatisfied with the air quality and the intensity of sensations of dry throat and mouth, difficulty in thinking clearly and feeling bad/good was observed when the ventilation rate in the office was increased. A monotonic improvement in task performance with increasing ventilation rate was also observed, with remarkable consistency across the different tasks. The observed monotonic trends imply that there is a similar dose-response relationship between ventilation rate and human comfort, as shown in the investigation in 14 office buildings ventilated in the range 0.1–3 h^{-1} (Pejtersen et al., 1999b), between ventilation rate and human health, as shown in the study in 160 office buildings ventilated in the range 2–50 L/s per person (Sundell, 1994), and between ventilation rate and human performance, as shown in the present experiment in an office ventilated from 3 to 30 L/s per person. The relationship observed in the present study implies that doubling the ventilation rate can increase productivity by 1.1% to 2.1%, depending on the task, and on average by 1.7%, the productivity increments being estimated using the performance of subjects on typing, proof-reading and addition of numbers, all common office tasks and all requiring concentration. Increasing ventilation rate also increased originality in a creative thinking task. The present study indicates that ventilation rates well above the minimum rates suggested in existing ventilation standards and guidelines (ASHRAE, 1989; ECA, 1992; CEN, 1998) would be beneficial for human health, comfort and productivity. As no information on how ventilation directly affects productivity has previously been available (Wyon, 1996; Sensharma et al., 1998), further investigations extending the present findings would be useful.

The results of the present study confirm the findings of the previous experiment (Wargocki et al., 1999). Both investigations indicate that improved indoor air quality, achieved either by removing a pollution source (the intervention used in the previous experiment) or by increased ventilation (the intervention used in the present experiment) decreases the intensity of some SBS symptoms and improves perceived air quality and productivity. These results confirm that the source control strongly recommended by the recently-published European guidelines CEN CR 1752 (1998) and ventilation well beyond the rates prescribed in existing ventilation standards and guidelines (ASHRAE, 1989; ECA, 1992; CEN, 1998) are effective methods of improving human health, comfort and productivity. Although the effects achieved by the two methods are quite similar, their principle is different. Removing pollution sources decreases the concentration of pollutants associated with these sources while the concentrations of other pollutants from other indoor sources remain unchanged. Increasing ventilation rate decreases the concentration of pollutants emitted from all indoor sources. Increasing the total outdoor air change rate also reduces the time available for chemical reactions indoors between outdoor ozone and volatile organic compounds (VOCs), which can produce other compounds often more adverse for human health and comfort than their precursors (Weschler and Schields, 2000). In the present experiment, the measurements of C_5 to C_{10} aldehydes, formaldehyde and acetaldehyde, which are expected to be such products, do not confirm that such chemical reactions occurred, due perhaps to low concentrations of ozone especially at the low ventilation rate when the time available for such reactions is the greatest. Increasing ventilation can increase outdoor-to-indoor transport of reactants such as ozone and nitrogen oxides, and by elevating their concentrations indoors may counteract the benefits of higher ventilation. Taking the above considerations into account, the parallel use of source control and adequate ventilation indoors seems to be the preferred approach for improving indoor air quality. The benefits of such an approach have been shown in many practical applications. For example, in a study in an office building, in which the intervention consisting of substituting a polluting material with a low-polluting alternative and a simultaneous increase in the outdoor air supply rate and the ventilation effectiveness, was shown to reduce adverse perceptions and the prevalence of SBS symptoms among occupants (Pejtersen et al., 1999a).

The value of improved productivity is reduced by the higher costs associated with improved indoor air quality. The selection of low-polluting materials during the design of a building may cost nothing extra while increased ventilation may involve extra costs, depending on the climate. Computer simulations by Eto and Meyer (1988) and Eto (1990) using a building energy analysis program (DOE-2.1C), showed that doubling the ventilation rate above 2.5 L/s per person will increase annual energy operating costs of HVAC in office buildings by no more than 3–5%, and total building construction costs due to the increased first cost of the HVAC system by less than 0.5%. Total operating costs of HVAC are normally well below 1% of labour costs (Woods and Jamerson, 1989). The difference between the operating costs of a HVAC system with high and low ventilation rate may therefore be a few promille of the labour costs, which is a minor expense compared to the benefits for productivity, health and comfort. Furthermore, with intelligent use of energy recovery, the extra energy consumption for increased ventilation can often be minimized. The above considerations are based on traditional HVAC systems with full mixing. By using "personalized air" the same quality of inhaled air may be obtained at much lower ventilation rates (Fanger, 2000). This has been shown in studies of task/ambient conditioning systems in which air is supplied from desk-mounted outlets. These have been shown to increase air change effectiveness and pollutant removal efficiency (Faulkner et al., 1999). The provision of a high quality of breathing air may not necessarily cost more or require more energy.

Unlike what may occur in many field investigations, the effects on perceived air quality, SBS symptoms and productivity observed in this experiment were exclusively caused by changing the ventilation rate in the office. The parameters describing the thermal, acoustic and visual environment in the office were not changed by changing the ventilation rate and there was no need to adjust for them in the statistical analysis. Another advantage of the present experiment was that the ventilation rates were carefully measured and the air was effectively mixed under each condition. Lack of proper measurements of ventilation and room air distribution is a limitation in many field investigations, especially when the total outdoor airflows are estimated from measurements in the supply or exhaust ducts without taking into account that the ventilation may be modified substantially by occupants opening the windows. Such improper ventilation measurements may explain why no associations between ventilation rates and the prevalence of SBS symptoms were seen in some of the previous field studies (Jaakkola et al., 1990; Routsalainen et al., 1994).

A unique point of the present design was that no traditional HVAC system was used, since it was feared that this might be a variable source of pollution which could decrease the positive effect of increased ventilation. Several previous investigations have shown that the HVAC system in itself can be a source of pollution leading to a reduction of perceived air quality indoors (Fanger et al., 1988; Pejtersen et al., 1989; Bluyssen, 1993; Hujanen et al., 1991; Pejtersen, 1996) and to increased prevalence of SBS symptoms (Burge et al., 1990; Jaakkola et al., 1993), especially for systems with humidification and air-conditioning (Mendell, 1993). It has been hypothesized that poor maintenance of ventilation systems may explain why no association between the prevalence of SBS symptoms and ventilation rates was found in many field experiments (Salisbury, 1984; Jaakkola et al., 1991; Menzies et al., 1991, 1993; Routsalainen et al., 1994); other possible reasons listed by Sundell (1994) include too few buildings or occupants investigated, insufficient difference between the ventilation rates studied, no adjustment for confounding factors, and as mentioned earlier, inaccurate measurement of the outdoor air supply rate. As the aim of the present study was to investigate the impact of ventilation as such, outdoor air was supplied directly into the office by axial fans mounted in the window, without filtration or air-conditioning. Filtering was not necessary in the suburbs north of Copenhagen where the outdoor air quality is excellent. This was confirmed by the sensory assessments made by the subjects in this study: less than 3% were dissatisfied with the quality of the air outdoors. The air in the office was conditioned to the desired temperature by low-temperature convectors and electrical heaters, and to the desired relative humidity by steam humidifiers. All of the equipment was situated in the office and was thoroughly cleaned before each experimental session to avoid possible air contamination.

In the present experiment, the sensation of dryness of throat and mouth was significantly elevated ($P<0.0006$) by decreasing the ventilation rate in the office, even though the subjects could drink at any time. Throat irritation also increased ($P<0.03$) when the ventilation rate was low. These effects are expected at low ventilation when the higher concentrations of pollutants are likely to occur and produce irritation and a sensation of dryness.

The present results show that the sensory pollution loads from materials may not always be constant, as originally assumed by Fanger (1988), but can increase with increasing ventilation rate, as was implied by the results obtained by Knudsen et al. (1997, 1998). The average sensory pollution load for the office without bioeffluents was 0.34 olf/m^{2}floor and differs little from the load of 0.25 olf/m^{2}floor which was found in the previous study in the same room when the same extra pollution source was present (Wargocki et al., 1999). The total sensory pollution load in the office predicted by the addition of the sensory pollution load from bioeffluents, estimated to be 0.16 olf/m^2floor for six persons in the office (CEN, 1998), and the average sensory pollution load of 0.34 olf/m^2floor from the office, is 0.50 olf/m^2floor. The measured average total sensory pollution load was 0.65 olf/m^2floor, which is slightly higher than the estimate based on addition and much higher than the highest of the two individual loads. The difference between prediction and measurement may either be due to increased emission (from materials or subjects) at higher ventilation rates, or to contribution from PCs and VDUs operating intermittently during the exposures when subjects performed the text-typing task.

The metabolic rates estimated from the measurements of CO_2 agree well with the range of metabolic rates recorded in large field studies in offices (de Dear and Fountain, 1994). Metabolic rates decreased when the ventilation rate decreased. Increased muscle tonus at higher work rates (Wyon et al., 1975) may explain the higher metabolic rate at increased ventilation rate. Another underlying mechanism could be that subjects may unconsciously reduce their breathing rate at low ventilation rates. Breathing shallowly when air pollution levels are high and air quality is poor would lower the metabolic rate. This supplementary hypothesis requires validation in future experiments.

Subjects tended to mark the "necessary effort" scale closer to "strong effort" at lower ventilation rates ($P<0.07$). This would not be remarkable except that in the previous experiment (Wargocki et al., 1999), subjects marked the same scale closer to "strong effort" when the pollution source was absent, i.e. when the air quality was higher, corresponding to very high ventilation rates. This was a significant effect and was interpreted to mean that subjects were reporting the effort they were conscious of exerting. It was suggested that they had exerted less effort when the pollution source was present because it significantly increased their headaches. The effect in the present experiment is in the opposite direction, and it would be facile either to discount this observation because it is not formally significant at the ($P<0.05$) level or to suggest that the subjects in the present experiment had started to use the scale as was originally intended, to assess task difficulty by indicating the amount of effort necessary to maintain performance. The conclusion must be that the task difficulty or "necessary effort" scale is difficult for subjects to use when performance is not maintained, that the interpretation will often be ambiguous and that the scale should therefore not be used in its present form. Future experiments should simply ask subjects to indicate, on a continuous scale from 0 to 100%, how well they have been working in relation to their maximum capacity. This was the approach adopted by Kildesø et al. (1999) and in the field intervention experiment reported by Croxford et al. (2000) and Wyon et al. (2000). In a further analysis of the latter experiment (Wyon et al., 2000) it was possible to show that self-estimated productivity, as indicated on this scale, was significantly increased by a filter change which reduced airborne particle density.

The present investigation is an experimental study with a cross-over design and young female students who were unaware of the intervention. Measurements of noise levels in the office and the subjective assessments of noise acceptability confirmed that noise levels did not differ between conditions. The study was carried out in a real office space with windows and access to daylight. Although every effort was made to provide a natural and typical office environment, it may have been perceived as different from that of a normal workplace. Female subjects were selected since they consistently report more SBS symptoms than males (Mendell, 1993). Subjects were exposed only once to each condition and for a period of ca. 4.6 h, unlike the repeated exposures for 8 h per day and 5 days per week which occur in real workplaces. Future studies may address possible contextual effects, effects in other populations and the effects of recurrent and longer exposures. Field studies including interventions in existing office buildings would be useful to provide supplementary information on the impact of ventilation and indoor air quality on productivity.

Conclusions

- Perceived air quality improved, the intensity of SBS symptoms decreased and productivity increased when the ventilation rate increased in a normal office with otherwise constant and neutral thermal, acoustic and visual conditions, subjects remaining thermally neutral. The present study shows the benefits for human health, comfort and productivity of ventilation rates well above the minimum rates prescribed in existing standards and guidelines.
- Overall productivity increased on average by 1.7% for every two-fold increase in the ventilation rate between 3 and 30 L/s per person.
- To promote human comfort, health and productivity, it is recommended that indoor air quality be maintained at a high level by controlling indoor pollution sources and by ensuring adequate ventilation.

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