Estimate of an economic benefit from investment in improved indoor air quality in an office building

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ABSTRACT

Life-cycle costs of investments for improving air quality in an office building were compared with the resulting revenues from increased office productivity; benefits from reduced health costs and sickness absence were not included. The building was simulated in a cold, a moderate and a hot climate. It was ventilated by a constant air volume system with heat recovery. The air quality was improved by increasing the outdoor air supply rate and by reducing the pollution loads. These upgrades involved increased energy and maintenance costs, first costs of a HVAC system and building construction costs. But the additional investments were highly cost-effective: productivity benefits resulting from a better indoor air quality were up to 60 times higher than the increased costs; the simple and discounted pay-back time was below 2.1 years; and the annual rate of return was four to seven times higher than the minimum rate set at 3.2%. The present data, although obtained by simulations, constitute a strong incentive for providing indoor air of a quality that is better than the minimum levels required by present standards.

INDEX TERMS

Productivity; Energy; HVAC system; Office building; Life-cycle assessment

INTRODUCTION

Recent experiments showed that improving air quality by increasing the outdoor air supply rate or by reducing pollution sources improved the productivity of office workers and developed the quantitative relationship between the indoor air quality and productivity (Wargocki *et al.*, 2000). This relationship was used in the subsequent cost–benefit analysis of measures to improve air quality in a typical office building which showed that the increase in annual energy and maintenance costs due to improved air quality can be several times lower than the resulting benefits from improved office productivity (Djukanovic *et al.*, 2002), matching the similar estimations of Woods and Jamerson (1989). The objective of the present work was to compare life-cycle costs (LCC) of upgrading indoor air quality in an office building with the resulting revenues from increased office productivity and thus to supplement the previous cost-benefit analysis by including the building construction costs, not considered earlier, and by extending the calculation period from an annual to a building life-time.

METHODS

The operation of a constant air volume (CAV) heating, ventilation and air-conditioning (HVAC) system with rotary heat exchanger was simulated in a typical office building with different levels of air quality. The building was simulated in a cold, a moderate and a hot climate. The structural and architectural layout of the building was adopted from the plans of an existing building. The building construction, lighting and air-conditioning systems complied with ASHRAE Standard 90.1-1999 (ASHRAE, 1999). The main building features are summarized in Table 1.

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Table 1 Description of the main features of the building and HVAC system

Location	Winnipeg, Chicago and Miami
Size	11 581 m^2
Shape	U-shape, floor area 965 m^2
Number of floors	12
Number of occupants	864
Occupancy	0.07 person/m^2 floor
Construction	Walls: heavy construction with 12 cm insulation, $U = 0.4$ W/m^2/K, window (glass + frame) $U = 1.1$ W/m^2/K
Glazing	25% of the wall area
Week schedule	8 a.m.–6 p.m.; 30% occupancy on Sundays and holidays
Thermostat settings	24°C cooling; 21.3°C heating, 13°C night set back
Internal loads	14 W/m^2 lighting; 8.1 W/m^2 equipment; 864 persons
Heating plant efficiency	75%
Cooling plant efficiency	Air cooled, medium efficiency, COP = 3

Different levels of air quality in the building were modelled by defining the percentage of occupants entering a given space who are dissatisfied with the perceived air quality. These levels were obtained by changing the pollution load or outdoor air supply rates. The pollution loads from the building materials, furnishing, equipment and HVAC system were assumed to be representative of a low-polluting (0.1 olf/m^2 floor) and a non-low-polluting (0.2 olf/m^2 floor) building (CEN, 1998). With the occupancy set at 0.07 person/m^2 floor, the total pollution load was, respectively, 0.17 and 0.27 olf/m^2. For the given total pollution load and a given air quality, outdoor air supply rates were calculated using the comfort model of Fanger (1988) (Table 2).

Table 2 Outdoor air supply rates at different levels of air quality

Perceived air quality	Outdoor air supply rate (l/s·person)	
(% dissatisfied)	Non-low-polluting building	Low-polluting building
50	6.3	4
40	9.5	6
30	15.3	9.6
20	27.4	17.2
15	39.6	24.9
10	63.2	39.8

Table 3 Estimates for increase in energy costs

Fixed monthly charge per customer	\$300/month
Demand charges per kilowatts of billing demand	\$12/kW
Energy charges per kilowatt-hour	\$0.078/kWh
Natural gas charges per m^3	\$0.192/m^3

The following costs were estimated: (1) annual costs for energy, based on ASHRAE 90.1 (1999) for Chicago (Table 3) and a series of parametric building energy simulations performed using the DOE-2.1E building energy analysis program developed for the U.S. Department of Energy (DOE) (Curtis *et al.*, 1984); (2) first costs of HVAC, based on outdoor air supply rate and the resulting heating/cooling capacities and air-handling unit capacity (Saylor, 2002a); (3) annual maintenance costs, assumed to be 5% of the HVAC first cost; and (4) the building construction cost without HVAC (Saylor, 2002b). The building construction costs for a low-polluting building were assumed to be 5% higher than for a non-low-polluting building.

The increase in office productivity with improved air quality was predicted using the experimental relationship showing a 1.1% increase in productivity for each 10% decrease in the percentage dissatisfied with the air quality upon entering a space (Wargocki *et al.*, 2000). This relationship is valid when occupants are kept thermally neutral by the HVAC system during the entire season and when the air quality causes between 25 and 70% dissatisfied; it was linearly extrapolated for the air quality levels causing less than 25% dissatisfied. Benefits from increased productivity were converted into annual revenues, assuming an annual salary of $33 523 per person ($19.4/h per person) (U.S. Department of Labour, 2000); a 1.1% increase in productivity resulted thus in an annual economic benefit of $368.75 per person.

The calculated costs and revenues were used to perform LCC analysis. The National Institute of Standards and Technology (NIST) DOE/NIST LCC-2002 software modified to include the benefits from improved productivity, was used. The rules of the Federal Energy Management Program (FEMP) of DOE were followed. The life-time of the building was set at 25 years. The real discount rate reflecting real earning power of money and not the general price inflation was set at 3.2% (as of the year 2002); it is equivalent to the interest rate. Future energy prices were calculated using real energy price escalation rates for Midwest U.S. and for the commercial sector; they are annually projected by DOE. Natural gas was the second fuel. All future costs and benefits were discounted and they are consequently expressed in present value dollars (US$ as of the year 2002).

The final results of LCC were shown as increases in costs and benefits as a result of improving air quality in the building from the reference condition—a non-low-polluting building where 50% of occupants are dissatisfied with the air quality. This level of dissatisfaction was selected as a reference because it was shown to be typical for the 56 office buildings studied in the European Audit project in nine countries (Bluyssen *et al.*, 1996). The results were tabulated to show: (1) net savings—a difference in all life-cycle costs and benefits; (2) a simple and discounted pay-back time—the number of years between the beginning of operation of the building and the time at which cumulative benefits are sufficient to offset the increments in initial costs of the improvements to air quality; (3) a savings-to-investment ratio—the ratio of benefits of improved productivity to increased investment costs required for improving air quality; and (4) an adjusted internal rate of return - an economic performance of the air quality upgrade by providing an annual rate of return of investment which is compared with the minimum acceptable rate of return, equal to the real discount rate set in this analysis at 3.2%.

Table 4 Estimated discounted costs in the non-low-polluting building where 50% are dissatisfied with air quality (the reference condition)

Building location	Energy costs ($/m^2)	Maintenance costs ($/m^2)	HVAC first costs ($/m^2)	Building construction costs ($/m^2)
Cold climate	153.8	109.9	129.0	1168
Moderate climate	147.3	113.9	133.7	1168
Hot climate	157.3	116.6	157.3	1168

RESULTS

Table 4 shows the estimated costs in the building in the reference condition. Tables 5–7 show the increases in costs and benefits resulting from improvements in indoor air quality in the building in the reference condition for a building located respectively in a cold, a moderate and a hot climate. The negative values in the tables for costs indicate savings.

Table 5 Results of LCC analysis for the building located in a cold climate

Building	Air quality (% diss.)	Discounted increase from the reference condition ($\$/\text{m}^2$)					Net savings ($\$/\text{m}^2$)	Simple payback time (years)	Adjusted internal rate of return (%)
		Costs				Benefits			
		Energy	Maintenance	HVAC first	Building	Productivity			
Non-low-polluting	50	Reference condition							
	40	1.8	6.4	7.5	0.0	486.9	471.1	0.3	21.9
	30	8.2	18.0	21.2	0.0	973.7	926.3	0.4	20.1
	20	14.6	43.8	51.5	0.0	1460.6	1350.7	0.6	17.8
	15	17.3	70.1	82.3	0.0	1704.0	1534.3	0.9	16.3
	10	24.6	111.0	130.4	0.0	1947.5	1681.5	1.2	14.7
Low-polluting	40	0.0	-0.6	-0.7	0.0	486.9	429.8	2.0	12.4
	30	1.9	6.6	7.7	58.4	973.7	899.1	1.2	14.9
	20	9.5	22.0	25.9	58.4	1460.6	1344.8	1.0	15.6
	15	14.2	38.5	45.3	58.4	1704.0	1547.7	1.1	15.3
	10	17.3	70.5	82.8	58.4	1947.5	1718.4	1.3	14.4

Table 6 Results of LCC analysis for the building located in a moderate climate

Building	Air quality (% diss.)	Discounted increase from the reference condition ($\$/\text{m}^2$)					Net savings ($\$/\text{m}^2$)	Simple payback time (years)	Adjusted internal rate of return (%)
		Costs				Benefits			
		Energy	Maintenance	HVAC first	Building	Productivity			
Non-low-polluting	50	Reference condition							
	40	–0.2	7.8	9.2	0.0	486.9	470.0	0.3	20.9
	30	2.6	23.8	28.0	0.0	973.7	919.2	0.5	18.8
	20	9.5	56.4	66.2	0.0	1460.6	1328.6	0.8	16.6
	15	12.7	86.1	101.1	0.0	1704.0	1504.2	1.1	15.3
	10	19.5	130.7	153.5	0.0	1947.5	1643.8	1.5	13.9
Low-polluting	40	0	–0.7	-0.8	0.0	486.9	429.9	2.0	12.4
	30	–0.2	8.1	9.5	58.4	973.7	897.9	1.2	14.8
	20	4.2	29.0	34.1	58.4	1460.6	1334.9	1.1	15.1
	15	8.8	49.6	58.3	58.4	1704.0	1528.9	1.2	14.7
	10	12.7	86.5	101.6	58.4	1947.5	1688.2	1.5	13.8

DISCUSSION

LCC showed that improving air quality is highly efficient: the benefits from improved air quality can be up to 60 times higher than investments; the investments can generally be recovered in no more than 2 years; and the rate of return can be up to seven times higher than the minimum acceptable interest rate. Based on the above calculations, improving air quality from the ‘mediocre’ level (50% dissatisfied) to the ‘excellent’ level (10% dissatisfied) will, e.g., in a small-sized office building with 100 employees, result in an annual revenue of approximately \$100 000 over a period of 25 years. The results showed also that similar economic benefits can be obtained in different climatic zones, probably because the benefits from improved productivity become a dominating factor in the LCC analysis and considerably exceed the increased investment costs.

Table 7 Results of LCC analysis for the building located in a hot climate

Building	Air quality (% diss.)	Discounted increase from the reference condition ($/m^2)					Net savings ($/m^2)	Simple pay-back time (years)	Adjusted internal rate of return (%)
		Costs				Benefits			
		Energy	Maintenance	HVAC first	Building	Productivity			
Non-low-polluting	50	Reference condition							
	40	2.7	8.2	9.6	0.0	486.9	466.3	0.3	20.6
	30	7.2	24.1	28.3	0.0	973.7	914.1	0.5	18.7
	20	16.0	57.9	68.0	0.0	1460.6	1318.7	0.8	16.4
	15	23.3	90.4	106.2	0.0	1704.0	1484.2	1.1	15.0
	10	31.6	141.1	165.7	0.0	1947.5	1609.0	1.6	13.5
Low-polluting	40	–0.3	–0.8	–3.8	0.0	486.9	433.3	1.9	12.6
	30	2.8	8.5	7.1	58.4	973.7	897.0	1.2	14.9
	20	8.8	29.6	32	58.4	1460.6	1331.8	1.1	15.2
	15	14.3	51.2	57.2	58.4	1704.0	1522.9	1.2	14.7
	10	23.5	90.9	103.9	58.4	1947.5	1670.8	1.5	13.7

The pay-back times estimated in the present simulations are similar to the pay-back of 1.4 years suggested by Dorgan *et al.* (1998). In the earlier simulations, Djukanovic *et al.* (2002) reported pay-back times of investments ≤4 months because they were calculated using the old construction costs (Saylor, 1987) to link them to simulations by Eto and Meyer (1988), and included only the first costs of the HVAC system comprising an increase in boiler and chiller capacity. In the present simulation, the first costs of the HVAC system, comprising all costs related to an increase in air-handling unit capacity and the building construction costs, were used to calculate the pay-back times.

The building construction costs for a low-polluting building were assumed to be 5% higher than in a non-low-polluting building. The simulations for increases in building costs ≥10% were also carried out. However, they showed that the net savings were in some cases lower than the net savings resulting from increasing the outdoor air supply rate, especially when the % dissatisfied with the air quality was reduced from 50 to 40% and to 30%. Since it was felt that high investments in building costs are not justified if higher net savings can be achieved with lower investments in a HVAC system (energy and first costs), a 5% increase in building costs was used.

The present results were obtained by carrying out the simulations and depend upon the set of assumptions provided. They do not include benefits resulting from reduced health costs and reduced absenteeism; lower absenteeism from an increased outdoor air supply rate can result in annual savings of $400 per employee (Milton *et al.*, 2000). The simulations were performed for a medium-sized office building, but the size of the building is not considered to have a strong impact on the findings. The air quality was the only parameter that was changed and assumed to influence productivity; other factors such as noise and thermal conditions were supposed to be constant. However, these factors can also affect productivity. Thermal discomfort can, for example, reduce office productivity by up to 15% (Wyon, 1996), which is nearly three times the maximum effect of 5.5% assumed in the present simulations, but these effects were not considered in the present work. The estimates of increased productivity were obtained from the results of experiments in normal office spaces where subjects performed office work at different indoor air quality levels (Wargocki *et al.*, 2000). There are no comparable data from studies in actual workplaces, but similar estimates were used by others (Fisk and Rosenfeld, 1997; Dorgan *et al.*, 1998). Despite salary levels being taken from U.S.

sources and energy prices being applicable at only one location - Chicago, it is expected that the present result can be applied generally to most other countries of the developed world.

CONCLUSION AND IMPLICATIONS

The present results provide rough estimates of the probable revenues resulting from improving the air quality in office buildings in developed parts of the world, and constitute a powerful argument and strong incentive for providing indoor air of a better quality than the minimum levels required by present standards.

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Effects of pollution from personal computers on perceived air quality, SBS symptoms and productivity in offices

Abstract In groups of six, 30 female subjects were exposed for 4.8 h in a low-polluting office to each of two conditions – the presence or absence of 3-month-old personal computers (PCs). These PCs were placed behind a screen so that they were not visible to the subjects. Throughout the exposure the outdoor air supply was maintained at 10 l/s per person. Under each of the two conditions the subjects performed simulated office work using old low-polluting PCs. They also evaluated the air quality and reported Sick Building Syndrome (SBS) symptoms. The PCs were found to be strong indoor pollution sources, even after they had been in service for 3 months. The sensory pollution load of each PC was 3.4 olf, more than three times the pollution of a standard person. The presence of PCs increased the percentage of people dissatisfied with the perceived air quality from 13 to 41% and increased by 9% the time required for text processing. Chemical analyses were performed to determine the pollutants emitted by the PCs. The most significant chemicals detected included phenol, toluene, 2-ethylhexanol, formaldehyde, and styrene. The identified compounds were, however, insufficient in concentration and kind to explain the observed adverse effects. This suggests that chemicals other than those detected, so-called 'stealth chemicals', may contribute to the negative effects.

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Key words: Personal computers; Perceived air quality; Productivity; Sensory pollution; SBS symptoms; Chemical emissions.

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Practical Implications

PCs are an important, but hitherto overlooked, source of pollution indoors. They can decrease the perceived air quality, increase SBS symptoms and decrease office productivity. The ventilation rate in an office with a 3-month-old PC would need to be increased several times to achieve the same perceived air quality as in a low-polluting office with the PC absent. Pollution from PCs has an important negative impact on the air quality, not only in offices but also in many other spaces, including homes. PCs may have played a role in previously published studies on SBS and perceived air quality, where PCs were overlooked as a possible pollution source in the indoor environment. The fact that the chemicals identified in the office air and in the chamber experiments were insufficient to explain the adverse effects observed during human exposures illustrates the inadequacy of the analytical chemical methods commonly used in indoor air quality investigations. For certain chemicals the human senses are much more sensitive than the chemical methods routinely used in indoor air quality investigations. The adverse effects of PC-generated air pollutants could be reduced by modifications in the manufacturing process, increased ventilation, localized PC exhaust, or personalized ventilation systems.

Introduction

The use of electronic equipment in the indoor environment has increased dramatically in recent decades. Personal computers (PCs) – consisting of the unit housing the CPU and a monitor – have become one of the most prevalent pieces of electronic equipment in indoor settings. According to market research studies, the one billionth PC was recently sold, and the worldwide number of PCs that are currently in use has reached 500–600 million units (Reynolds, 2002). PCs have penetrated most workplaces and, for a wide range of job categories, are used for more than half of an employee's working hours (Burr, 2000). The office environment has also undergone major changes in the last two decades as a result of the introduction of PCs. These changes have led to new work habits and to a substantial amount of time spent in front of a PC. Concomitantly, complaints of unusual fatigue, headaches, eyestrain and other Sick Building Syndrome (SBS) symptoms among individuals working with PCs or PC-like display units have also increased (Bachmann and Myers, 1995; Bergqvist and Knave, 1994; Kamieńska-Żyła and Prync-Skotniczny, 1996; Knave et al., 1985; Sundell et al., 1994). Light and electromagnetic radiation from PCs were suspected for some time to cause negative effects on people. However, research to date has provided no conclusive results supporting that hypothesis [Committee on Man and Radiation (COMAR), 1997; McCann et al., 1998; WHO Fact Sheets, 1998a,b]; only a few studies have shown that static electric fields and electromagnetic radiation produced by cathode-ray tube (CRT) monitors may have slight effects on humans (Clements-Croome and Jukes, 2001; Skyberg et al., 1997). Complaints can also be due to poor ergonomic design of both the workplace and PC parts such as the mouse or keyboard (Arås et al., 2001; Cook et al., 2000; Lewis et al., 2001; Swanson et al., 1997). But despite better ergonomic design of the workstations and issuance of the current directive (TCO '99, 1998) that requires PC monitors to be manufactured with reduced radiation, the complaint rates of people working with PCs is still high. The reason for this could be the pollutants emitted by PCs. However, only a few studies have focused on chemical emissions from PCs and/or CRT type PC monitors and none, except for anecdotal reports (e.g., Brooks et al., 1993), have investigated the effects of these emissions on humans. The chemical emissions measured have included volatile organic compounds (VOCs) (Black and Worthan, 1999; Brooks et al., 1993; Corsi and Grabbs, 2000; Funaki et al., 2002; Wensing et al., 2002), particles (Black and Worthan, 1999) and flame-retardants (Carlsson et al., 2000; Salthammer and Wensing, 2002; Sjödin et al., 2001). Wensing (1999) has also looked at emissions from television sets, which are related to those from CRT monitors.

A number of studies have shown that emissions from building materials and furnishing can degrade perceived air quality, increase the prevalence of SBS symptoms among building occupants, and may negatively affect human performance (Pejtersen et al., 1999; Wargocki et al., 1999, 2002). Accepting the hypothesis that poor indoor air quality has a negative impact on humans, it is reasonable to expect that emissions from PCs, if negatively affecting perceived air quality and increasing SBS symptoms, will negatively affect productivity. The objective of the current study was thus to evaluate the impact of air pollutants produced by PCs on perceived air quality, SBS symptoms and performance of office work.

Methods

Approach

The air pollution level in a low-polluting office was modified by introducing or removing operating PCs. All other environmental parameters remained unchanged. Female subjects were exposed for 4.8 h to both conditions in a balanced design. The subjects assessed perceived air quality, indoor climate and SBS symptoms upon entering the office and on several occasions during exposure. They were unaware of interventions as the PCs were placed behind a partition. During each exposure the subjects performed simulated office work. Subjects were asked to adjust their clothing to remain thermally neutral whenever they felt too warm or too cold during exposure. Under both experimental conditions the air in the office and outdoors was sampled for subsequent chemical analysis. Supplementary air sampling from a 1-m^3 glass chamber containing PCs was made to more fully characterize the emissions.

Facilities

The experiments were carried out in an office described in detail by Wargocki et al. (1999) (Figure 1). The building materials and furnishing in the office are low-emitting (CEN CR 1752, 1998). The office is divided by a 2-m-high partition into a space where PCs and the equipment used to supply and condition the outdoor air are placed, and a space where the subjects are exposed. An axial fan mounted in the window supplies the outdoor air and several small fans provide good mixing within the office.

The air in the office is heated by electric oil-heaters or cooled by a SPLIT-type air-conditioner, and humidified by ultrasonic humidifiers. No traditional heating, ventilating and air conditioning system (HVAC) is in operation. During experiments, to avoid any loss of pollutants from the air, the condensate from the air-conditioner is re-vaporized with ultrasonic humidifiers. The space used for exposure has six workstations, each consisting of a table, a chair, a desk-lamp and a 6-year-old PC with CRT monitors. The PCs at the workstations are used during experiments to perform office tasks and are turned on only for this purpose. The sensory pollution of these PCs is negligible; this was shown by sensory evaluations carried out prior to the present experiment.

Test conditions

Six PCs of a popular brand with 17″ CRT monitors connected to mini towers were bought at a local PC supplier. Before the experiments they were unpacked, placed in a ventilated space and turned on for 500 h (corresponding to approximately 3 months of normal office use); this was done to avoid using brand-new PCs

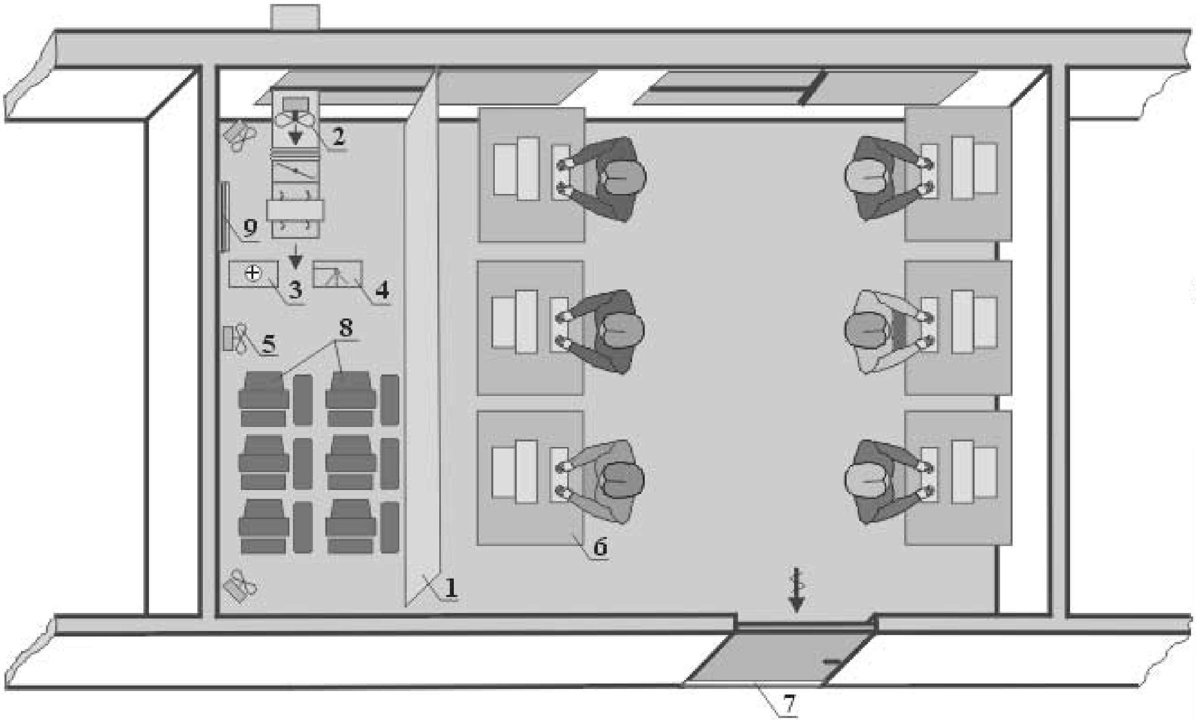

Fig. 1 Experimental set-up in the office where the investigation was carried out: 1, partition; 2, axial fan with damper and silencer; 3, electric heater; 4, ultrasonic humidifier; 5, mixing fan; 6, workstation consisting of a table, a desk lamp and a PC monitor with keyboard; 7, exhaust aperture (a slot under the door); 8, six 3-month-old PCs running in screen saver mode; 9, SPLIT-type air conditioner. In the figure, the subjects are sitting at the workstations and the pollution source is present in the office (six PCs placed behind the partition)

as a pollution source. During experiments the PCs were placed in the office behind a partition or removed from the office. When present in the office, they operated continuously in a screen-saver mode; however, the electric power consumption was the same as if any other program had been running on the PC. Six PCs were used to simulate conditions as if they were in operation at each of the six workstations in the office but were placed behind the screen so that subjects could not see them. The outdoor air supply rate of 60 l/s (corresponding to 2/h or 10 l/s per person with six persons in the office), air temperature of 24.5°C, relative humidity level of 50% and noise level of 35 dB(A) (without subjects in the office) remained constant throughout the experiments. The temperature and relative humidity were selected to reflect typical conditions in early summer when the experiments took place. The office had daylight illumination, but there was no direct sun on the subjects as the experiments were carried out in the afternoon and the windows faced east. Each subject, if needed, could adjust the illumination level by switching on the desk lamp provided at each workstation.

Subjects

Thirty subjects were selected among 51 female applicants to participate in the experiments. They were all students, aged 19–31 years, and were either non-smokers or occasional smokers. None of them had allergy, asthma, hay fever or chronic diseases. One subject was sensitive to dust and two had a history of migraine. This information was obtained from questionnaires completed during recruitment; no medical examinations were performed. In the week prior to the experiments, the subjects received instruction on how to perform tasks simulating office work and how to make subjective evaluations. They also took olfactory tests to evaluate their ability to classify different odour intensities (ranking test) and to identify several odour stimuli (matching test); on average 78% were correct in both tests (ISO, 1988, 1993). The participants were requested not to use strong perfumes, to drink coffee or eat spicy food on the day of their exposure (to avoid influencing their perception).

Measurements and procedure

The subjects were divided into five groups of six persons each. Each group was randomly assigned to a given weekday for exposure in the office with PCs either present or absent in a design balanced for the order of presentation. The subjects assessed the perceived air quality upon entering, during exposure and upon re-entering the office after having left the office for few minutes at the end of the experiment.

Continuous acceptability and intensity scales were used to assess the perceived air quality, odour intensity, and irritation of the eyes, nose and throat (Wargocki et al., 1999). During exposure, the subjects assessed general perceptions of the indoor environment, SBS symptoms and self-estimated ability to work using horizontal visual-analog (VA) scales (Wargocki et al., 1999; Wyon, 1994). They also evaluated thermal sensation on a 7-point PMV scale and acceptability of thermal comfort and draught on a continuous scale. The assessments on VA scales and those related to thermal comfort were made three times in the course of exposure. During exposure, subjects performed simulated office work consisting of text typing, proofreading and arithmetical calculations (addition and multiplication of numbers). These are typical office tasks requiring concentration and in previous studies were shown to be sensitive to changes in air quality (Wargocki et al., 2002).

The outdoor air supply rate and carbon dioxide (CO_2) levels in the office were measured continuously throughout the exposures by a Brüel & Kjaer Multi-Gas monitor Type 1302 (Innova Air Tech Instruments A/S, Ballerup, Denmark) connected with a Brüel & Kjaer Multipoint Sampler and Doser Type 1303. A tracer gas (SF_6) was dosed at the inlet of the fresh air and its concentration was maintained at 1 ppm at one of the workstations. At the remaining five workstations the concentration of SF_6 was at the same time monitored to ensure that good mixing was achieved in the room. Air temperature and relative humidity were measured continuously at each workstation and in the middle of the occupied space with calibrated sensors (Vaisala HUMITTER 50Y, Vaisala Oyj, Helsinki, Finland). The data were collected via an HP-VEE data acquisition system and stored on a computer. Operative temperature and air velocity were measured at a height of 1.2 m above the floor in the middle of the occupied zone, with a Brüel & Kjaer 1212 Thermal Comfort Meter and a Brüel & Kjaer 1213 Indoor Climate analyzer (Innova Air Tech Instruments). The data were manually logged every 20 min during the experiment. The noise level was measured occasionally in the occupied space, using a Brüel & Kjaer 2218 Sound Level Meter. Ozone concentrations were measured alternately indoors in the middle of the occupied space and outdoors in the vicinity of the air intake at 20-min intervals with a Seres OZ2000 ozone analyzer (Seres, Aix-en-Provence, France). The air in the office and outdoors was sampled on XAD-II tubes in series with filters for flame-retardants, and on Tenax TA and silica gel coated with 2,4-DNPH for saturated aldehydes. Following sampling, the tubes were sealed and stored at −10°C in a freezer for 2 months before they were sent to a commercial laboratory. Analyses were performed using (i) a gas chromatograph with an electron capture detector for flame retardants; (ii) a gas chromatograph with a mass selective detector for VOCs and certain aldehydes; and (iii) a high-performance liquid chromatograph with a UV detector for aldehydes. The analytical focus was on aldehydes with relatively low odour thresholds that might be produced by oxidation of various organic precursors. The detection limits ranged from 1.4 to 56 $\mu g/m^3$ for brominated flame-retardants, and from 0.2 to 1.8 $\mu g/m^3$ (for samples on Tenax TA) and from 3.5 to 29 $\mu g/m^3$ (for samples on DNPH) for aldehydes.

To supplement chemical analyses made during exposures in the office, additional measurements were made in a glass chamber. These were carried out after analyses of the exposure study were completed. At that time, the PCs had already been in operation for 2000 h. Nevertheless, in order to link these additional measurements with exposures in the office, it was decided to use these PCs rather than to buy a new batch of the same brand. Three PCs were placed in a 1 m^3 glass chamber ventilated at 2 h^{-1} (0.2 l/s per PC); this was a ventilation rate 50 times lower than during subject exposure in the office. The lower ventilation rate was used so that the resultant concentration of pollutants emitted from the PCs would be higher, improving the likelihood of their detection. The glass chamber was placed in a 30 m^3 stainless steel chamber ventilated at 500 m^3/h (16/h) and maintained at 24°C and 25% RH. The air temperature in the glass chamber increased to 32°C due to the heat load from PCs (ca. 600 W) coupled with the low ventilation rate. The stainless steel and glass chambers were thoroughly cleaned and baked out prior to chemical measurements. The chemical sampling started 6 h after the PCs were placed in the glass chamber and turned on (i.e., when the concentrations in the chamber had presumably reached equilibrium). The air was collected at the inlet of the glass chamber (background) and at the outlet (air containing PC emissions). The sampling protocols used during the office exposures were extended by inclusion of sampling on Tenax TA for VOCs and XAD-II for SVOCs. Following the sampling period, the tubes were sealed and immediately sent for analysis. For the sampling interval employed, the detection limits ranged from 0.1 to 1 $\mu g/m^3$ for VOCs/SVOCs, 8 to 40 $\mu g/m^3$ for aldehydes and 20 $\mu g/m^3$ for brominated flame-retardants.

Data analyses

The subjective responses and performance data were analyzed using either the Wilcoxon matched-pairs test or the paired *t*-test, depending on whether or not the data were normally distributed. A binomial test was used whenever the other two tests failed to show significance. A chi-square test was used to analyze the data in 2 × 2 contingency tables. Reported *P*-values are for a one-tailed test, i.e., in the expected direction that

Table 1 Average values of general parameters of the outdoor air and the office air measured during exposures with humans

	Exposure in the office with PCs			
	Absent		Present	
Parameter	Outdoor air	Office air	Outdoor air	Office air
Air temperature (°C)	23.0	24.2	23.3	24.7
Relative humidity (%)	59	47	52	50
Outdoor air supply (l/s)	–	58.1	–	59.0
CO_2 (ppm)[a]	391	847[a]	390	827[a]
Ozone concentration w/o bioeffluents (ppb)	31.1	19.2	30.9	18.9
Ozone concentration with bioeffluents (ppb)	33.3	15.1	30.2	12.9

[a] After steady-state level was reached.

the presence of PCs has negative effects on air quality, symptoms and productivity.

Results

The air temperature, relative humidity, noise level and the outdoor air supply rate remained close to the intended levels (Table 1). The difference between indoor and outdoor CO_2 concentration, after steady-state levels were achieved, was slightly but significantly ($P < 0.02$) lower when PCs were behind the partition. Indoor ozone levels were comparable among the exposure conditions and were 4–6 ppb lower ($P < 0.004$) when occupants were present.

When PCs were present behind the partition the subjects assessed that the air quality was significantly less acceptable upon entering the office ($P < 0.0005$), during the exposure ($P < 0.015$) and upon re-entering the office ($P < 0.001$) compared with the condition when PCs were absent behind the partition (Figure 2). With PCs present behind the partition, the odour judged upon entering and re-entering the office was significantly more intense, and the air was perceived to be significantly stuffier during the exposure ($P < 0.005$) compared with the condition when PCs were absent behind the partition.

Table 2 shows the percentage dissatisfied with perceived air quality and the sensory pollution loads calculated using the assessments of acceptability and measured ventilation rates (Clausen, 2000; Fanger, 1988). The presence of PCs behind the partition almost tripled the percentage of dissatisfied and increased the total sensory pollution load by ca. 20 olfs (i.e., each PC behind the partition increased the pollution load in the space by ca. 3.4 olfs).

No significant differences were found in responses on VA scales (the intensity of SBS symptoms and self-estimated ability to work) between the office with PCs present and absent using the Wilcoxon test. These responses were therefore analyzed differently by calculating the odds for a change in a response during exposures in the office. The number of subjects were counted whose responses had changed in the middle and the end of the exposure compared with the responses in the beginning of the exposure; the same was done by comparing the responses in the end and in the middle of the exposure. These various comparisons were made taking into account different latency for change in response. Based on these numbers, 2 × 2 contingency tables were created and odds ratios (OR) ± 95 confidence intervals were calculated. When changes in responses at the end of the exposure were compared with the middle of the exposure, there were significantly more subjects with increased skin dryness (OR = 3.1; [1.1, 9.1] $P < 0.033$) who reported being more sleepy (OR = 3.1; [1.1, 9.1] $P < 0.033$) and who estimated that their work ability was lower (OR = 3.7; [1.1, 11.4] $P < 0.027$) when PCs were present behind the partition compared with the condition when PCs were absent. No other statistically significant changes in responses were found.

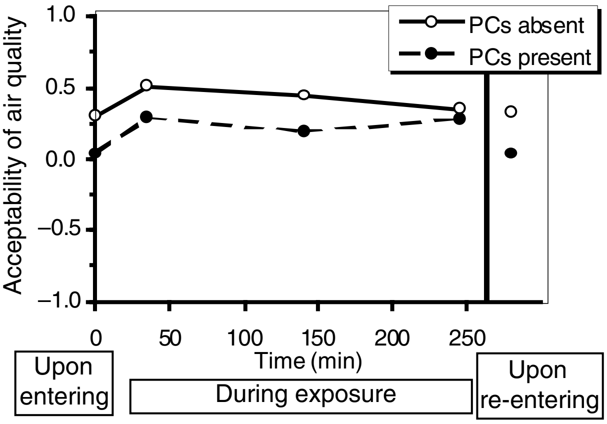

Fig. 2 Acceptability of the air quality as a function of the presence or absence of PCs behind the partition; the scale was coded as follows: −1, clearly not acceptable; 0, just not acceptable/just acceptable; 1, clearly acceptable

Performance of text typing was significantly reduced when PCs were present in the office behind the partition compared with the office with PCs absent (Table 3). The number of errors calculated by summing up the number of words incorrectly typed, punctuation mistakes and the number of words skipped was higher ($P < 0.014$) and the number of subjects who typed less text was higher ($P < 0.03$) although the difference in text typing speed was small. No other significant differences in performance of office tasks between different exposures were found.

Based on the performance of text typing and proofreading (Table 3), the time to edit the text under the two experimental conditions was estimated. This was done by summing up the time available for text typing during exposure, the time required to type the characters by which the text typed was shorter when PCs were present, the time necessary to find all mistakes and the

Table 2 Perceived air quality and sensory pollution loads in the office

Exposure in the office	% Dissatisfied		Sensory pollution load in the office (olf)	
	Office without PCs	Office with PCs	Office without PCs	Office with PCs
Upon entering (without bioeffluents)	14	41	4.9[a]	25.2
During exposure (with bioeffluents)	8	18	–	–
Upon re-entering (with bioeffluents)	13	41	4.2	24.7

[a] < 0.14 olf/m^2 floor.

Table 3 Average performance of text typing and proof-reading

Task	Performance measure	Office without PCs	Office with PCs
Text typing	Typing speed (chr/min)	177.4	176.5
	Number of errors	105	126
Proof-reading	Reading speed (lines/min)	12.2	12.7
	Missed errors (%)	45	46
	False positives (%)	6	5

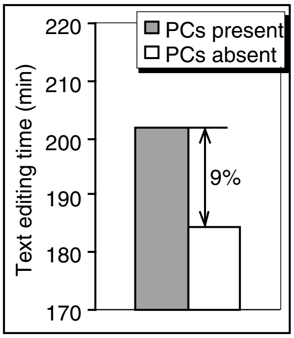

Fig. 3 Estimated time of editing the text (typing, proof-reading and retyping the errors) in the presence or absence of PCs behind the partition

time needed to correct (re-type) them. Figure 3 shows that the estimated overall text processing time with PCs present was 9% longer.

Due to relatively high detection limits, only three aldehydes (hexanal, heptanal, and octanal) were identified in the outdoor or indoor air samples when chemical measurements were made during exposures in the office. The concentration of octanal in the office air was 2 $\mu g/m^3$, i.e., 3.3 times higher than outdoor levels when PCs were present and 1.1 $\mu g/m^3$, i.e., equal to the outdoor concentrations in the absence of PCs. The concentration of heptanal at 0.5 $\mu g/m^3$ was the same indoors and outdoors while hexanal at a concentration of 0.5 $\mu g/m^3$ was only detected outdoors in both experimental conditions.

The additional chemical measurements in the 1 m^3 glass chamber showed that the emissions from the PCs contained formaldehyde, phenol, 2-ethylhexanol, toluene, a series of higher boiling aromatic compounds and several aliphatic compounds. The most abundant individual compounds were phenol and toluene. Using the concentrations of chemical compounds detected in the air supplied to and exhausted from the glass chamber and the measured ventilation rate in the glass chamber, the emission rates of the individual compounds were calculated (Table 4). Based on these, the concentrations that would have occurred in the office at a ventilation rate of 2/h were calculated (Table 4). However, at the time of the human subject exposures the PCs had operated for only 500 h, whereas at the time of the glass chamber emission measurements the PCs had operated for approximately 2000 h. The PC emission rates are expected to have decayed in the intervening 1500 h (Wensing et al., 2002). Consequently, these modeled concentrations are anticipated to be lower than those that actually occurred during the human subject exposures. Depending on the chemical, the actual concentration may have been two or three times higher than the modeled office air concentrations shown in Table 4. Nonetheless, even if the modeled office concentrations are three times higher than those shown in Table 4, they are still much lower than the Recommended Exposure Limits (RELs) established by the National Institute for Occupational Safety and Health (NIOSH, 2002) and the human olfactory thresholds taken from the compilation of Devos et al. (1990).

It is worth noting that formaldehyde, a potential irritant often emitted during thermal oxidation events, was below its detection limit of 6 $\mu g/m^3$ in the office air, consistent with the modeled concentration, and was detected only at low levels in the glass chamber. Brominated flame retardants were not detected, but given the level at which such compounds are expected (Carlsson et al., 2000; Sjödin et al., 2001) and the poor sensitivity of the analytical method (detection limits of 2–50 $\mu g/m^3$), the results are inconclusive regarding flame-retardants.

Discussion

Present results show that PCs can emit pollutants having negative effects on perceived air quality, some SBS symptoms and performance of office work. They can thus be important but hitherto overlooked pollution sources in indoor environments. Even after 3 months of normal operation, the sensory pollution load associated with a PC can be as much as three times the load of a standard person, implying that the ventilation rate would have to be much higher to maintain the level of perceived air quality without PCs. When the pollution load in the office was reduced, i.e., the PCs were absent behind the partition, the conditions in the office improved. Similar effects were seen in the study by Wargocki et al. (1999) in which the pollution load was reduced by removing carpet. Both studies show that reducing pollution sources indoors, as recommended by CEN CR 1752 (1998), can be an effective means to improve health, comfort and productivity.

Table 4 Emission rates of chemical compounds per PC unit based on the concentrations measured in the glass chamber, modeled concentrations of chemicals in the office air, NIOSH RELs and standardized human olfactory thresholds for individual compounds

Compound[a]	Emission rates per PC (μg/h)	Modeled concentrations office air (μg/m^3)	NIOSH RELs (μg/m^3)	Standardized odour threshold (μg/m^3)
Phenol[1,2,4,6]	63.0	1.7	19,000	430
Sum of C_6–C_{10} aromatic compounds	45.9	1.3	–	> 150
Sum of aromatic compounds with high boiling point (toluene equivalent)	58.3	1.6	–	> 150
Sum of isomers of bicyclic aromatic compounds (toluene equivalent)	41.0	1.1	50,000[b]	80[b]
Toluene[1–6]	47.0	1.3	375,000	5900
Styrene[3,5,6]	7.6	0.2	215,000	630
Xylene isomers[1,2,3,5,6]	10.3	0.3	435,000	1400
Formaldehyde[6]	5.2	0.1	20	1100
2-Ethylhexanol[2]	19.6	0.5	–	1300
Branched mono-unsaturated C12	22.3	0.6	–	–
n-Decane[3,5]	11.6	0.3	–	4400
n-Undecane[3,5]	7.6	0.2	–	7700
Sum of other SVOCs (*n*-octane equivalent)	9.4	0.3	–	–
Sum of others VOCs	119.6	3.3	–	–
TVOCs	468.6	13.0		

[a] The numbers indicating previous studies made on emissions from electronic equipments where the chemical compound was detected: (1) Brooks et al. (1993) – PCs; (2) Black and Worthan (1999) – PCs; (3) Corsi and Grabbs (2000) – PC towers; (4) Wensing et al. (2002) – PC monitors; (5) Funaki et al. (2002) – PC portable; (6) Wensing (1999) – TVs/Video.

[b] Values given for naphthalene.

Although the subjects reported decreased satisfaction with air quality in the presence of PCs, there was a lack of strong SBS symptoms. The exposure period may have been too short for the development of such symptoms. Only the severity of skin dryness increased significantly during the exposure period with PCs present in the office, indicating that the work with PCs may exacerbate the development of skin symptoms as suggested by Knave et al. (1985) and Sundell et al. (1994). Nonetheless, human performance was affected; the observed decrease in the performance of text typing in the office with PCs present is in good agreement with the reduced self-estimated work ability and increased sleepiness reported at the end of the exposure. These results suggest that reduced air quality may negatively impact human performance even before the most common SBS symptoms are evident. The negative effects of poor air quality on human performance were also shown by Wargocki et al. (1999, 2000).

It should further be noted that the CO_2 level was slightly but significantly lower when PCs were present in the office, implying that the subjects had a lower metabolic rate under this condition compared to the condition with PCs absent. At the same time, the performance of subjects was reduced when PCs were present in the office. A similar decrease in the CO_2 level and the performance of office work was also reported by Wargocki et al. (1999) when the air pollution level in an office was increased by introducing a 20-year-old tufted bouclé carpet. Both studies suggest that humans may unconsciously slow down their activity and therefore reduce their metabolic rate (avoidance behavior) when air pollution is increased. This effect should be further investigated in future studies.

In the present study, the polluting computers were placed far from the occupants and the pollutants emitted were well mixed with the room air. In real offices, the PCs are placed just in front of each worker who consequently may have higher exposures to the pollutants emitted from the computer. The electromagnetic field and radiation from the PCs were not considered as risk factors for the observed effects in the present study since the PCs were placed behind a partition some distance from the occupants. It should also be noted that for the condition where PCs were present behind the partition, more cooling was required and 20% more water was condensed on the cooling coil, although some of it was re-evaporated by ultrasonic humidifiers. The resultant 'air scrubbing effect' may have removed some airborne pollutants and, if anything, reduced the magnitude of the observed effects on the subjects.

The concentration of ozone significantly decreased after people entered the office. This decline of the indoor ozone level may reflect the greater total surface area when subjects are present in the room, increasing the surface removal rate (Weschler, 2000). Some ozone may also be scavenged during respiration or react with unsaturated bioeffluents.

Among the chemical compounds identified in the office air, the indoor/outdoor ratio for octanal was significantly greater than unity (3.3) when PCs were behind the partition, but close to unity (1.1) when PCs were absent, indicating that the PCs may have been a source of this aldehyde or its precursors. However, no such compound was detected later in the glass chamber measurements. The results of chemical analyses of the air from the glass chamber are consistent with previously reported measurements of emissions from electronic equipment (Table 4). Furthermore, the measured TVOC and toluene emission rates fell in the range of those reported by Corsi and Grabbs (2000) and Wensing et al. (2002); however, their results were obtained only during the first 250 h of operation. Aromatic compounds accounted for almost 60% of the organic compounds identified in the PC emissions. The major oxidized compound, which is also the most abundant compound detected, was phenol. This compound, also known as carbolic acid, is a strong irritant to tissue and is odorous at concentrations as low as 430 $\mu g/m^3$ (110 ppb). A potential source of this compound is phenol formaldehyde boards, which are used as substrates for electronic components. Toluene was also among the more abundant identified compounds; it is a solvent often used in the production of electronic devices (Wensing et al., 2002). 2-Ethylhexanol was the only aliphatic alcohol detected at a significant concentration. It is a common hydrolysis product of a number of plasticizers containing '2-ethylhexyl-' substituents [e.g., di(2-ethylhexyl)phthalate or di(2-ethylhexyl)adipate)]. At elevated concentrations its odour is considered objectionable and it is also potentially irritating. However, the calculated concentrations in the office air resulting from PC emissions are much smaller than the compound's reported odour threshold (see Table 4). Formaldehyde was the only low-molecular-weight aldehyde detected. Its estimated concentration in the office was also much lower than that anticipated to have any significant sensory effects.

Although the modeled concentrations of chemicals in the office air fell well below any exposure and odour detection limits (Table 4), the office air in the presence of the PCs was perceived to be less acceptable than the air in the absence of PCs. This does not appear to be simply a consequence of summing the effects of the individual chemicals listed in Table 4. We hypothesize that other chemicals undetected by the chemical analyses employed – so-called 'stealth chemicals' – are responsible for the effects. This highlights the deficiency of the chemical sampling and analysis methods commonly used in evaluating indoor environments. It reaffirms that the organic compounds identified by the analytical methods routinely used to evaluate indoor air (i.e., the chemicals that are easily analyzed) are not necessarily the chemicals responsible for adverse effects (Weschler and Shields, 1997; Wolkoff and Nielsen, 2001; Wolkoff et al., 1997). The present study also shows that the human senses involved in the perception of air (olfactory and chemical) can be more sensitive than chemical analyses. Finally, it should be noted that the present negative effects were seen in a well-ventilated office space where only six PCs polluted the air and the modeled concentrations were low. Nevertheless there are scenarios (e.g., poorly ventilated computer classrooms in schools) in which the measured emissions from PCs may lead to much higher concentrations that may approach RELs and odour threshold limits.

Thermal images of an operating PC were made. They showed that several components on the cathode-ray tube and inside the CRT display reach high temperatures (>60°C). As a consequence of this heat load, plastic accessories and several regions on the printed circuit board were also at elevated temperatures. Such temperatures may increase the release of odorous compounds, plastic additives and flame-retardants from these components. The same mechanism is expected to drive the release of pollutants from PC towers, but to a lesser extent than from CRT monitors, due to the lower operating temperatures of the CPU and its supporting components (Corsi and Grabbs, 2000).

In the present study, only one brand of PC was used to investigate effects. Future studies should include other representative brands and types of computer, including PCs with flat-type PC monitors (TFT or LCD displays) and notebooks.

Conclusions

- Personal computers, represented by one of the most popular brands, were evaluated after they had been in service for 500 h of operation (ca. 3 months of office use). They were found to be strong indoor pollution sources, having a negative impact on perceived air quality, some SBS symptoms and performance of office work. The presence of PCs in a low-polluting office space ventilated at 10 l/s per PC of outdoor air increased the percentage of dissatisfied from 13 to 41% and increased by 9% the time required for text processing.
- The sensory pollution load of each PC was ca. 3.5 olf, i.e., more than three times the pollution of a standard person.
- The chemical compounds emitted by the PCs used in this study were similar to those reported in other studies; phenol and toluene were the major compounds detected.
- The chemical compounds identified were insufficient in concentration and kind to explain the negative effects on humans during exposure to PC emissions. This suggests that chemicals other than those that can be identified by the analytical methods used in the present study, so-called 'stealth chemicals', may contribute to the negative effects.

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POLLUTION SOURCE CONTROL AND VENTILATION IMPROVE HEALTH, COMFORT AND PRODUCTIVITY

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ABSTRACT

Control of indoor pollution sources and ventilation are both means of improving indoor air quality. Three independent experiments have recently documented that removing a pollution source or increasing the ventilation rate will improve perceived air quality, reduce the intensity of several Sick Building Syndrome (SBS) symptoms and improve the productivity of office workers. In these experiments, the performance of simulated office work (text typing, addition and proof-reading, all typical office tasks requiring concentration) improved monotonically as the proportion dissatisfied with the air quality was reduced by either measure. The quantitative relationship was 1.1% change in performance per 10% dissatisfied, in the range 25-70% dissatisfied, or 0.5% change in performance per 1 decipol (dp), in the range 2-13 dp. Significant performance improvements occurred only when the intensity of general SBS symptoms such as headache and difficulty in thinking clearly were significantly reduced, which implies that this was the mechanism of causation. The performance of simulated office work increased monotonically with decreasing pollution load, a 1.6% increase in performance for each two-fold decrease of pollution load in the range 0.3-2 olf/m^2floor, and with increasing outdoor air supply rate, a 1.8% increase in performance for each two-fold increase in the outdoor air supply rate in the range 0.8-5.3 L/s per olf. As these results clearly justify increased initial and operating costs, future developments in HVAC technology may include "personalized air", new ways of improving the quality of supply air (e.g., by filtration), more extensive use of heat recovery from exhaust air and systematic selection of low-polluting building and furnishing materials.

Keywords: Ventilation; Indoor pollution sources; Indoor air quality; SBS; Productivity

INTRODUCTION

It is well documented that thermal conditions within the thermal comfort zone can reduce performance by 5% to 15%, but little is known as regards direct effects of the air quality on human performance in non-industrial environments, especially in offices [1]. Laboratory exposures to toluene (an abundant indoor air pollutant, see Fig. 1 and [2]) at 100 ppm (380 mg/m^3) [3] and to a mixture of 22 common indoor air pollutants at concentrations up to 25 mg/m^3 [4] were shown to reduce the performance of diagnostic psychological tests. However, these two experiments were carried out on selected indoor air pollutants and at concentrations considerably higher than those which typically occur in office buildings [2]. Cross-sectional studies in classrooms in which typical indoor air pollutants from building and furnishing materials and occupants may be presumed to have reached quite high concentrations due to low air change rates that allowed carbon dioxide (CO_2) concentrations to reach levels up to 4000 ppm demonstrated an association between increased CO_2 level and reduced performance of diagnostic psychological tests by pupils >15 years old [5]. The possibility of confounding between classroom air change rates and other factors capable of having caused the observed effects, such as classroom air temperatures or possible socioeconomic differences between the collection areas of different schools, was not addressed. It should also be noted that the dependent variables in all of the above experiments [3,4,5] were diagnostic psychological tests of short duration, which may not predict the performance of typical office work over time. In experiments carried out for the New York State Commission on Ventilation [6] in the 1910's, the performance of simulated office work (including addition and typing) could not be shown to be significantly reduced by low ventilation rates resulting in CO_2 concentrations of 3000-4000 ppm, which were the levels measured in the least well ventilated classrooms in the cross-sectional study cited above [5]. The absence of an effect of low ventilation in the New York experiments could have been due to the presence of sources of pollution in the HVAC system itself, as this would result in a lack of improvement in overall air quality even though CO_2 concentrations and bioeffluents were reduced by the increased ventilation rates used in the control exposures.

It seems reasonable to assume that people who do not feel very well will not work very well. Support for an effect on performance due to the symptoms of distress that are caused by poor air quality is provided by a field investigation in an office building which demonstrated that office workers who had reported any SBS symptoms that day performed significantly less well on diagnostic psychological tests that were administered intermittently throughout the working day by a computer [7], and by the increased SBS symptom intensities that were also associated with high levels of CO_2 in the classroom study cited above [5]. Other possible mechanisms for an effect of poor air quality on performance include distraction by odour, sensory irritation, allergic reactions, or by direct toxicological effects.

The objective of the present paper is to summarize the results obtained in three new and closely related experiments, all of which indicate that poor air quality has a negative effect on the performance of simulated office work and that an increase in the intensity of general SBS symptoms is the causative mechanism, and to discuss the implications of these results for building and HVAC system design.

NEW RESULTS ON THE EFFECTS OF AIR QUALITY ON PERFORMANCE

In three independent field intervention experiments, the air quality in normal offices was altered while the health, comfort and productivity of the occupants were measured [8,9,10]. Air quality was altered by means of one or the other of two types of intervention, either: 1) by decreasing the pollution load, i.e. by physically removing a pollution source without informing the subjects, always maintaining an outdoor air supply rate of 10 L/s per person, which was the intervention used in offices situated in two different countries [8,9]; or 2) by increasing the outdoor air supply rate from 3 to 10 or to 30 L/s per person, thus producing air change rates of 0.6, 2 or 6 per hour in one of these offices, with the same pollution sources always present [10]. A major pollution source in all three studies was the same 20-year-old carpet, present behind a screen in a quantity corresponding to the floor area of the office in which each exposure took place, but the rather innocuous building, floor and furnishing materials, and the bioeffluents emitted by the subjects themselves were of course always present. Although the carpet was taken from a building with a history of SBS problems [11], Fig. 1 shows that the resulting air pollutant concentration levels were typical of those currently found in office buildings worldwide [4]. Temperature, relative humidity, air velocity and noise level were kept constant, independent of the intervention. Ninety female subjects were exposed to different levels of air quality, 30 in each study. They could not see whether the source was present or perceive changes in noise level or air velocity when the ventilation rate was changed, and they remained thermally neutral by adjusting their clothing. In all three studies, subjects performed simulated office work during 4.5-hour exposures to different air quality levels and assessed the perceived air quality and the intensity of their SBS symptoms, in a repeated-measures design balanced for order of presentation. Simulated office work comprised text typing, proof-reading, addition and creative thinking, all being typical office tasks. The performance of these tasks was used to estimate productivity. The perceived air quality in the offices was assessed by asking the subjects to rate the acceptability of the air quality upon entering the office. The intensity of a comprehensive list of specific and general SBS symptoms was indicated by the subjects at intervals throughout each exposure by marking visual-analogue scales (VA-scales).

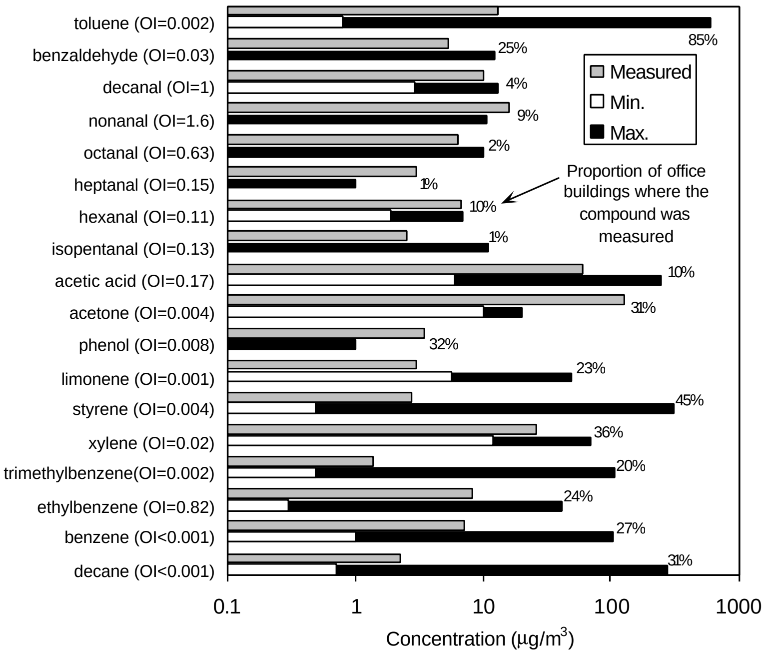

Fig 1. Comparison of concentrations of chemicals measured in the office with pollution source present [8] with the range of concentrations (min.-max.) measured in 22 studies in 209 office buildings when the chemical was detected [2]. Odour index (OI), the ratio of the concentration measured in the experiment to the odour detection threshold concentration [12], is given in brackets for each chemical

The main results of the three studies are presented in Figs. 2 and 3. Fig. 2 shows that removing a pollution source from a space or increasing the ventilation rate significantly improved perceived air quality, significantly reduced the intensity of general SBS symptoms such as headaches and difficulty in thinking clearly, and significantly improved the performance of simulated office work (text typing, addition and proof-reading). Fig. 3 shows that increasing the ventilation rate from 3 to 10 L/s per person had a positive effect on creative thinking. Based on the data presented in Fig. 2, the relationships presented in Figs 4, 5 and 6 were derived. They show that improving air quality, either by reducing the pollution load or by increasing the ventilation rate, improves the performance of office tasks. Air quality in Fig. 4 is expressed either as the % dissatisfied with the air quality or in decipol (dp), which is a quantitative measure of perceived air quality based on sensory assessments [13]. The pollution load in Fig. 5 is expressed in olf units: the sensory air pollution source strength in olf is calculated from air quality levels in decipol and the measured ventilation rate, using the comfort model [13]. The ventilation rate in Fig. 6 is calculated as the reciprocal of the perceived air quality expressed in pol (tenfold dp). The quantitative relationships between air quality, sensory pollution load, ventilation rate and the performance of office work are respectively: (1) a 1.1% increase in performance for every 10% reduction in the proportion of dissatisfied with the air quality, in the range 25-70% dissatisfied, or a 0.50% increase in performance for every decrease of 1 dp, in the range 2-13 dp (Fig. 4); (2) a 1.6% increase in performance for every two-fold decrease of pollution load in the range 0.3-2.0 olf/m^{2}floor (Fig. 5) at a ventilation rate of 10 L/s per person; (3) a 1.8% increase in performance for every two-fold increase of ventilation rate in the range 0.8-5.3 L/s per olf (Fig. 6). It is instructive to note that this range of ventilation rate conditions was achieved when outdoor air of high quality was supplied at the rate of 3-30 L/s per person. The difference is due to the presence of other sources of pollution, in addition to people. As it happens, 5.3 L/s per olf was achieved by removing the extra pollution source while supplying outdoor air at the rate of 10 L/s per person, not by supplying 30 L/s per person with the extra pollution source present.

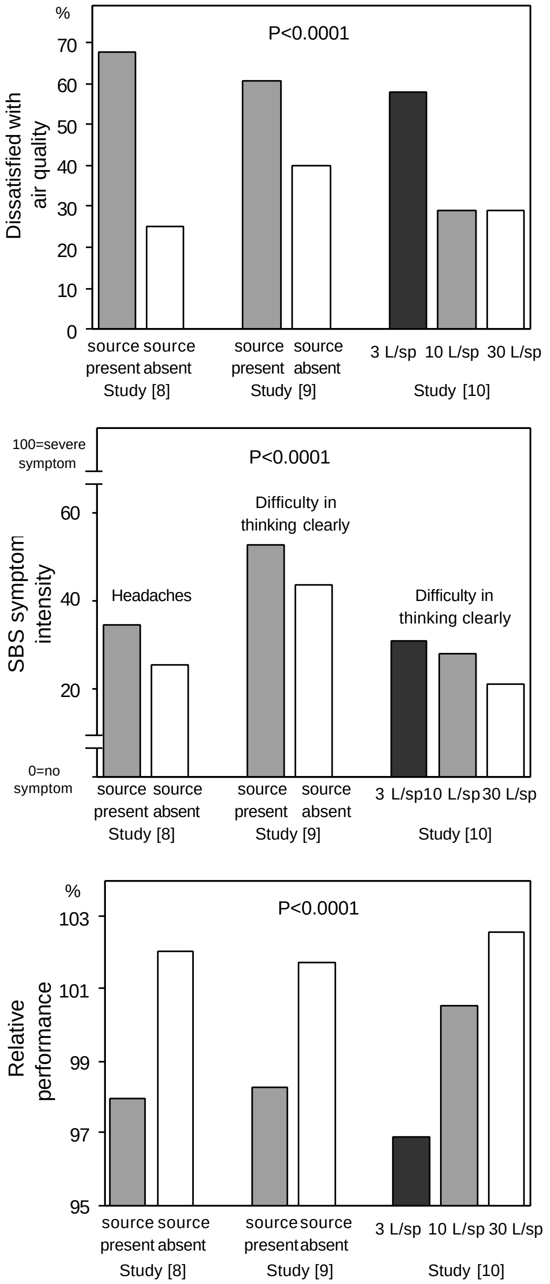

Fig 2. Perceived air quality, intensity of general SBS symptoms and relative performance of office tasks as a function of the presence or absence of the pollution source, or the outdoor air supply rate

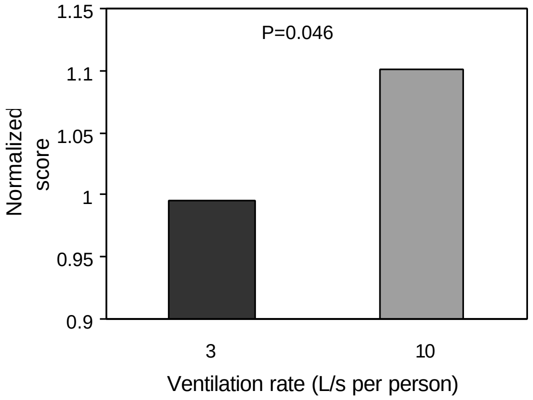

Fig 3. Normalized score on the originality-weighted test of creative or open-ended thinking, as a function of the outdoor air supply rate [10]

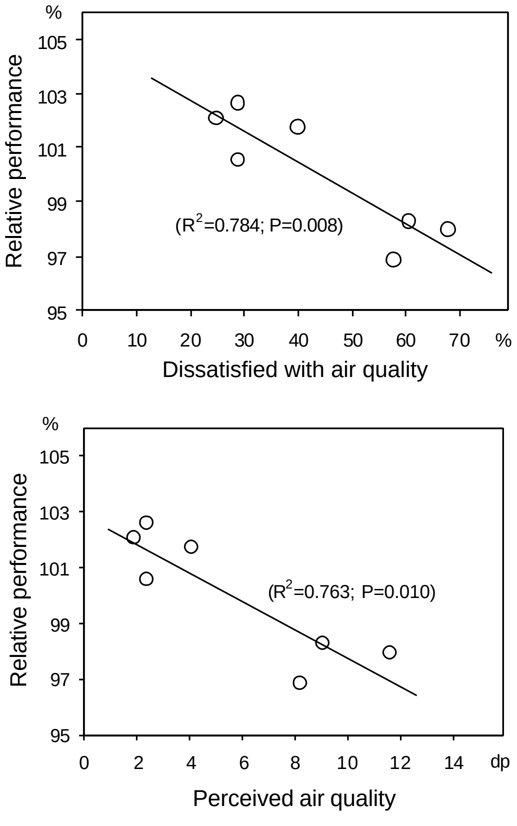

Fig 4. Relative performance of office tasks as a function of the air quality

Figs 2 to 6 indicate that improving air quality by either reducing the pollution load in a space or increasing the outdoor air supply rate has a positive effect on health, comfort and productivity. The possible mechanism of the observed results is indicated in Fig. 2: poor air quality increased the reported intensity of general SBS symptoms (headaches, difficulty in thinking clearly), effects which are expected to reduce the performance of any kind of mental work. Fig. 1 indicates that aldehydes, organic acids and ethylbenzene were present and had odour indices close to 1, i.e. they were present in perceptible concentrations. It is reasonable to assume that these pollutants may be responsible for the observed decrease in perceived air quality when the pollution load was increased. However, as only the 25 VOCs with the highest concentrations were measured, and neither particles nor microorganisms were quantified, this does not amount to support for the hypothesis that SBS symptom intensity and performance were exclusively mediated by odour perception, as other non-perceptible and non-measured pollutants may have contributed to cause the observed effects.

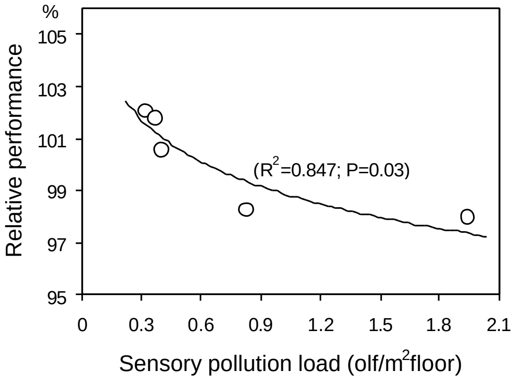

Fig. 5. Relative performance of office tasks as a function of the sensory pollution load at a constant ventilation rate of 10 L/s per person

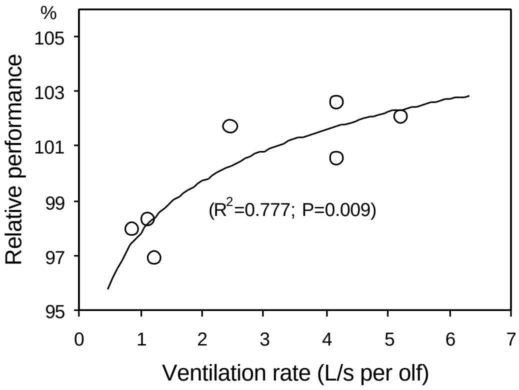

Fig. 6. Relative performance of office tasks as a function of the outdoor air supply rate

IMPLICATIONS FOR BUILDING AND HVAC SYSTEM DESIGN

The effects of air quality on human performance [8,9,10] presented above are similar in magnitude to those observed for the effects of thermal conditions on human performance [1]. They provide a strong economic incentive for designing indoor environments with air of a higher quality than the minimum prescribed by the present ventilation standards. High levels of air quality will not only result in improved productivity but will also promote health and comfort. With intelligent design of the building envelope and the HVAC system, and with careful selection of building and furnishing materials, the provision of good air quality indoors need not necessarily cost more or require more energy. Reducing indoor pollution sources is thus a very efficient way of improving indoor air quality.

Selecting low-polluting building and furnishing materials will result in decreased pollution load. This method is strongly recommended by CEN CR 1752 [14] as it need not involve extra costs, especially if applied at the building design stage.

Increasing the ventilation rate will incur extra costs. However, the additional costs will be small compared to the economic benefits obtained by the increased productivity that will result, considering that the total operating costs for HVAC are normally well under 1% of labour costs. Efficient energy recovery systems can often minimize the extra energy consumption used to increase ventilation rates. High quality of the breathing air can even be obtained at low ventilation rates by using "personalized air" systems [15,16] instead of traditional HVAC systems which aim to achieve full mixing. In such systems small amounts of fresh and cooled air are supplied directly to the breathing zone of the occupants so that a high quality of inhaled air is obtained. High quality of breathing air can only be achieved by assuring high quality of air supplied by HVAC systems, which sometimes in themselves can be a source of pollution [17,18,19]. Effective maintenance and cleaning of HVAC systems is thus essential. New developments in HVAC technology should include innovative ways of filtering room and supply air and new methods of air-conditioning.

CONCLUSIONS

- The performance of office work has been shown experimentally to be a function of air quality. This effect appears to be mediated by effects on the subjectively reported intensity of general rather than specific SBS symptoms.
- Improving air quality by pollution source control or increased ventilation is economically justified since it is beneficial for human health, comfort and productivity. Consequently, future buildings should be low-energy and low-polluting. This goal can be achieved by proper selection of building and furnishing materials, new ways of filtering the air supplied by HVAC systems, personalized air systems, and efficient heat recovery from exhaust air.

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Subjective perceptions, symptom intensity and performance: a comparison of two independent studies, both changing similarly the pollution load in an office

Abstract The present paper shows that introducing or removing the same pollution source in an office in two independent investigations, one in Denmark and one in Sweden, using similar experimental methodology, resulted in similar and repeatable effects on subjective assessments of perceived air quality, intensity of sick building syndrome symptoms and performance of office work. Removing the pollution source improved the perceived air quality, decreased the perceived dryness of air and the severity of headaches, and increased typing performance. These effects were observed separately in each experiment and were all significant ($P \leq 0.05$) after combining the data from both studies, indicating the advantages of pollution source strength control for health, comfort, and productivity.

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Key words: Perceived air quality; Sick Building Syndrome (SBS) symptoms; Performance; Pollution load; Office; Repeatability of effects; Pollution source control

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Practical Implications
Present results indicate further the benefits of good indoor air quality for health, comfort, and productivity. They also demonstrate that providing good indoor air quality can be achieved effectively by avoiding or reducing indoor air pollution sources and by selecting low-polluting building materials, both being low-cost and energy-efficient solutions.

Introduction

Background and objectives

A number of studies have shown that reducing the pollution load on indoor air by removing sources of pollution decreases the number of people dissatisfied with the air quality (van Beuningen *et al.*, 1994; Wargocki & Fanger, 1997) and the prevalence of sick building syndrome (SBS) symptoms (Norbäck & Torgén, 1989; Pejtersen *et al.*, 2001). In addition to the effects mentioned above, recent Danish experiments have shown that decreasing the pollution load improves the performance of simulated office work (Wargocki *et al.*, 1999). The Danish study was later repeated in Sweden to confirm the results, i.e., in another location and with other subjects, but using the same pollution source and similar methodology (Lagercrantz *et al.*, 2000). The objectives of the present paper are to compare the results obtained in the Danish and Swedish experiments, and to analyze the combined results of the two studies.

Description of Danish and Swedish experiments

The same pollution source was introduced or removed from two normal office spaces, one in Denmark

Table 1 Environmental conditions during the Danish and Swedish experiments

	Experiment	
	Danish	Swedish
Extra pollution source	Carpet (the same in the Danish and Swedish experiment)	Carpet
Extra pollution source loading = office floor area (m^2)	36	65
Office volume (m^3)	108	163
Outdoor air supply rate:		
Per person (l/s per person)	10	9.5
Per m^2 floor (l/s per m^2 floor)	1.67	0.88
Total outdoor airflow rate (l/s)	60	57
Air change rate (h)	2	1.3
Mean[a] temperature (°C)	24.2	22.6
Mean[a] relative humidity (%)	50	30
Mean[a] air velocity (m/s)	0.14	<0.1
Mean[a] sound pressure level (without subjects) (dB(A))	42	Not measured
Illumination	Daylight and artificial	Daylight and artificial
Mean[a] CO_2 concentration indoors (outdoors) (ppm)	959 (407)	867 (393)
Mean[a] ozone concentration outdoors (ppb)	35–40	33–35
Ratio of indoor-to-outdoor ozone concentration in the office with source absent	0.29	0.20
Ratio of indoor-to-outdoor ozone concentration in the office with source present	0.25	0.13
Mean[a] TVOC-Toluene equivalent concentration (ppm)	2.35	Not measured
Month in which the experiment was performed	June	April

[a] Average value in the office with source present and absent.

(Wargocki *et al.*, 1999) and one in Sweden (Lagercrantz *et al.*, 2000), in order to modify the pollution load. The source was a tufted bouclé carpet with 100% polyamide fibers and latex backing of the type that is quite common in existing buildings; it was taken from an office building with a history of SBS symptoms (Pejtersen *et al.*, 2001), where it had been in use for 20 years. Air temperature, relative humidity, noise level, air velocity, and outdoor air supply rate remained unchanged, and were not affected by the intervention (Table 1); the air was well mixed. The air temperature and relative humidity were different in the Danish and Swedish experiments because they reflected typical indoor thermal conditions for the season at the location where the studies were carried out. The outdoor air supply rate per person was kept at the same level in both studies, but the air change rates were different because the volume of each office was not the same. In each experiment, 30 different female subjects (Table 2) were exposed for 4.6 h in the afternoon, in groups of six at a time, to the source present–absent conditions, the design being balanced for order of presentation. They remained thermally neutral by modifying their clothing and they could not see whether the source was present because it was hidden behind a screen. During the exposures, the subjects performed tasks simulating office work. In the Danish study they performed addition, text typing, creative thinking, and psychological tests. In the Swedish experiment proof-reading replaced the psychological tests and the creative thinking task took a new form, while typing and addition remained unchanged compared with the Danish study. Proof-reading was introduced as it is a common task in most office work (Wargocki *et al.*, 2000). The creative thinking task took a new form to provide a better estimate of subjects' creativity (they wrote down as many alternative uses as possible for a set of four specified and familiar objects, Wargocki *et al.*, 2000) while the Danish version of the task was more a test of the knowledge and recall abilities of the subjects (they listed given male or female names for a specified pair of first letters). Duration of the performance tasks and the order of their presentation were almost the same in both studies. In each experiment, the subjects assessed the perceived air quality and intensity of SBS symptoms upon entering the office and during exposures, and re-assessed the perceived air quality upon re-entering the office just after the exposure, following a few minutes spent in a

Table 2 Characteristics of subjects participating in the Danish and Swedish experiments

	Experiment	
	Danish	Swedish
Subjects recruited (completing all exposure conditions)	30 (30)	30 (28)
Gender	Female	Female
Occupation	Student	Student
Age (years): range (mean ± s.d.)	20–31 (24 ± 3)	20–31 (24 ± 3)
Height ± s.d. (cm)	169 ± 7	168 ± 6
Weight ± s.d. (kg)	64 ± 9	64 ± 10
Number of non-smokers	23	30
Number of atopic subjects (with asthma, hay fever, or allergy)	2	1

Table 3 Proportion dissatisfied with the air quality and sensory pollution loads in the office in Denmark and in Sweden

	Experiment			
	Danish		Swedish	
	Source present	Source absent	Source present	Source absent
Dissatisfied with air quality (%):				
Office without bioeffluents (upon entering the office before exposure)	22	15	60	35
Office with bioeffluents (upon re-entering the office just after exposure)	68	25	61	40
Sensory pollution load (olf/m^{2}floor):				
Office without bioeffluents (upon entering the office before exposure)	0.25	0.14	0.77	0.28
Office with bioeffluents (upon re-entering the office just after exposure)	1.92	0.31	0.79	0.35

well-ventilated space. The subjective estimates were made on visual analog scales (VAS), which are continuous lines with marked endpoints representing different responses (Wargocki *et al.*, 1999, 2000). The same scales were used in both studies, except that the end-labels were either in Danish or in Swedish.

The percentage dissatisfied with the air quality and the total sensory pollution loads were not the same in the offices in Denmark and in Sweden (Table 3) because of differences in building materials and furnishings in each office, and in the air temperature and relative humidity.

Methods

To compare the results of the Danish and Swedish studies, the effects of introducing or removing the pollution source in the offices on the subjective assessments of perceived air quality, the intensity of SBS symptoms and the performance of tasks simulating office work were first estimated with paired *t*-tests or Wilcoxon matched-pairs signed-ranks tests carried out on the results obtained separately in each experiment. The Kappa[1] statistic was then used to estimate the agreement between the results of the two experiments by comparing the direction of the effects (Siegel & Castellan 1988).

The statistical significance of the effects after combining the results from both experiments, i.e., regarding the data as being one from a single experiment, was analyzed with paired *t*-tests or Wilcoxon matched-pairs signed-ranks tests. It was also estimated by combining the *P*-values determined separately in the Danish and in the Swedish study (using paired *t*-test or the Wilcoxon matched-pairs signed ranks test), regarding each experiment as an independent test of the same hypothesis: $\chi^2 = -2\Sigma(\ln P)$ with two degrees of freedom for each independent test so combined, i.e., four degrees of freedom in this case (Winer 1970).

Except for Kappa, all statistical tests were one-tailed.

Results

The results of the Danish and Swedish experiments are compared in Table 4. They show reasonably good agreement (Kappa = 0.477, $P = 0.0005$). Five effects were found to be independently significant: the air quality was more acceptable, irritation of the nose decreased, the performance of text typing increased, and the office was judged to be darker when the pollution source was not present in the office, in both experiments, while a scale reporting the effort required to maintain performance was apparently interpreted quite differently by the subjects in the two studies, as discussed in the following section.

Twenty-six effects were statistically significant in at least one of the two experiments, among which as many as seven of nine significant effects in the Danish experiment and as many as 19 of 22 significant effects in the Swedish experiment showed that when the pollution source was not present in the office the subjective responses and performance of simulated office work were improved. Combining the results of the two experiments resulted in 14 significant effects among which 13 showed an improvement of subjective responses and performance of simulated office work when the pollution source was not present in the office; their magnitudes are presented in Table 5.

Discussion

Reasonably good agreement was observed between the results of the two experiments, in terms of subjective responses and the performance of simulated office work. The analysis of the combined results from both experiments further supports this conclusion as it shows that all of the significant effects on combined data were in the same direction as in each of the separate experiments (Table 4). The results of the Swedish experiment thus confirmed the findings of

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[1] A ratio of the proportion of times the results agree (corrected for a chance agreement) to the maximum possible times the results agree; for the complete agreement Kappa = 1 and for no agreement Kappa = 0.

Table 4 Comparison of results obtained in the two experiments and the results of an analysis of combined data from both experiments. Pluses (+) indicate that the conditions (evaluated by subjective responses and performance tests) improved in the office with source absent, minuses (–) that conditions improved when the pollution source was present in the offices. Significant effects ($P \leq 0.05$) are marked in bold

	Experiment		
Response	Danish	Swedish	Combined data (Danish + Swedish)
Assessments made upon entering the office:			
Acceptability of air quality	+	**+**	**+**
Intensity of odor	–	**+**	+
Irritation of eyes	–	**+**	+
Irritation of nose	–	+	–
Irritation of throat	–	+	+
Evaluations made during exposure in the office:			
Acceptability of air quality	–	**+**	+
Intensity of odor	**+**	+	**+**
Irritation of eyes	**+**	–	+
Irritation of nose	+	**–**	**–**
Irritation of throat	+	+	**+**
Perceived dryness of air	+	**+**	**+**
Perceived freshness of air	+	**+**	+
Perceived intensity of illumination	**–**	**–**	**–**
Perceived intensity of noise	–	+	+
Perceived level of office cleanliness	+	+	+
Congestion of nose	+	–	–
Dryness of nose	+	**+**	**+**
Dryness of throat	+	+	+
Dryness of mouth	–	–	–
Dryness of lips	–	+	+
Dryness of skin	–	+	+
Dryness of hair	+	+	+
Dryness of nails	+	+	+
Dryness of eyes	–	–	–
Feeling of smarting eyes	–	+	+
Feeling of aching eyes	+	+	+
Feeling of gritty eyes	–	**+**	+
Severity of headache	**+**	+	**+**
Difficult to think clearly	–	**+**	+
Feeling of dizziness	+	**+**	**+**
Wellbeing	+	–	–
Fatigue	–	**+**	+
Difficult to concentrate	+	+	+
Feeling of depression	–	**–**	**–**
Arousal (sleepiness)	+	–	–
Self-estimated effort	**–**	**+**	**–**
Performance of text typing (char/min)	**+**	**+**	**+**
Performance of text typing (% errors)	**+**	+	**+**
Performance of addition (units/h)	+	+	+
Performance of addition (% errors)	–	**+**	+
Performance of proof-reading (lines/min)	Not measured	–	n.a.
Performance of proof-reading (% errors missed)	Not measured	+	n.a.
Performance of proof-reading (% false positives)	Not measured	+	n.a.
Performance of creative thinking task (normalized creativity score)	–	–	–
Performance of creative thinking task (number of repeated answers)	+	+	+
Assessments made upon re-entering the office just after the exposure:			
Acceptability of air quality	**+**	**+**	**+**
Intensity of odor	+	**+**	**+**
Irritation of eyes	+	**+**	**+**
Irritation of nose	**+**	**+**	**+**
Iritation of throat	+	**+**	**+**

the earlier Danish study. The purpose of repeating the Danish study in Sweden was to confirm the existence and direction of the effects, not whether their magnitude would be similar. There were systematic differences between the two studies (Tables 1–3), not least their geographic location and their subjects. In spite of these differences, the analysis of the combined data from both experiments was possible without any adjustments

Table 5 Subjective responses and measures of performance for which significant effects ($P \leq 0.05$) were observed after combining the data from the Danish and the Swedish experiments

Subjective response or performance	Unit of measurement	Experiment	Mean ± standard deviation		Effect of extra pollution source		
						Combined studies*	
			Source present	Source absent	Single study *P*-value	*P*-value (paired *t*-test or Wilcoxon test)†	*P*-value (χ^2-test)‡
Assessments made upon entering the office:							
Acceptability of air quality	Clearly acceptable = 1 clearly not acceptable = −1	Danish:	0.21 ± 0.45	0.29 ± 0.42	0.17	0.009 (t = 2.44; d.f. = 54)	0.01 (χ^2 = 13.3; d.f. = 4)
		Swedish:	− 0.11 ± 0.38	0.08 ± 0.31	0.008		
Evaluations made during exposure in the office:							
Intensity of odor	No odor = 0; slight = 10; moderate = 20	Danish:	7.2 ± 6.5	5.3 ± 5.2	0.05	0.01 (*Z* = 2.22; *N* = 58)	0.03 (χ^2 = 10.8; d.f. = 4)
		Swedish:	6.2 ± 3.8	4.8 ± 3.2	0.08		
Irritation of throat	No irritation = 0; slight = 10; moderate = 20	Danish:	4.1 ± 5.2	3.1 ± 4.2	0.07	0.02 (*Z* = 2.08; *N* = 58)	0.03 (χ^2 = 11.0; d.f. = 4)
		Swedish:	7.5 ± 7.2	6.2 ± 6.6	0.06		
Perceived dryness of air	Humid = 0; dry = 100	Danish:	57.2 ± 17.9	51.8 ± 23.6	0.22	0.05 (*Z* = 1.64; *N* = 58)	0.06 (χ^2 = 9.0; d.f. = 4)
		Swedish:	64.4 ± 17.4	60.3 ± 15.4	0.05		
Perceived intensity of illumination	Dark = 0; bright = 100	Danish:	42.5 ± 15.6	37.2 ± 13.7	0.04	0.003 (*Z* = 2.77; *N* = 58)	0.004 (χ^2 = 15.4; d.f. = 4)
		Swedish:	42.4 ± 13.0	36.8 ± 13.4	0.01		
Dryness of nose	Dry = 0; runny = 100	Danish:	22.5 ± 23.2	25.4 ± 21.7	0.19	0.03 (*Z* = 1.94; *N* = 58)	0.04 (χ^2 = 10.0; d.f. = 4)
		Swedish:	36.3 ± 25.6	45.4 ± 26.8	0.04		
Severity of headache	Severe = 100; no headache = 0	Danish:	33.1 ± 22.6	26.5 ± 23.1	0.05	0.02 (*Z* = 2.12; *N* = 58)	0.03 (χ^2 = 10.8; d.f. = 4)
		Swedish:	32.4 ± 22.9	27.1 ± 23.8	0.10		
Performance of text typing	Characters per min	Danish:	136.1 ± 46.9	145.5 ± 42.8	0.002	<0.001 (*t* = 3.35; d.f. = 57)	<0.001 (χ^2 = 19.6; d.f. = 4)
		Swedish:	135.2 ± 30.3	137.3 ± 29.4	0.04		
Performance of text typing	% errors	Danish:	0.79 ± 0.69	0.67 ± 0.44	0.005	0.03 (*Z* = 1.92; *N* = 57)	0.014 (χ^2 = 12.5; d.f. = 4)
		Swedish:	0.58 ± 0.37	0.54 ± 0.27	0.38		
Assessments made upon re-entering the office just after the exposure:							
Acceptability of air quality	Clearly acceptable = 1 clearly not acceptable = −1	Danish:	− 0.18 ± 0.51	0.18 ± 0.44	<0.001	<0.001 (t = 4.63; d.f. = 57)	<0.001 (χ^2 = 27.0; d.f. = 4)
		Swedish:	− 0.12 ± 0.39	0.04 ± 0.40	0.05		
Intensity of odor	No odor = 0; slight = 10; moderate = 20	Danish:	16.6 ± 9.7	15.0 ± 6.8	0.11	0.001 (t = 3.16; d.f. = 57)	0.002 (χ^2 = 17.5; d.f. = 4)
		Swedish:	18.0 ± 7.4	13.5 ± 8.0	0.001		
Irritation of eyes	No irritation = 0; slight = 10; moderate = 20	Danish:	4.3 ± 4.5	3.7 ± 4.9	0.14	0.02 (*Z* = 2.05; *N* = 57)	0.03 (χ^2 = 10.4; d.f. = 4)
		Swedish:	11.0 ± 19.9	5.4 ± 4.5	0.04		
Irritation of nose	No irritation = 0; slight = 10; moderate = 20	Danish:	10.2 ± 8.6	5.9 ± 6.3	0.004	<0.001 (*Z* = 3.43; *N* = 57)	0.001 (χ^2 = 19.7; d.f. = 4)
		Swedish:	9.2 ± 7.1	6.2 ± 6.6	0.02		
Irritation of throat	No irritation = 0; slight = 10; moderate = 20	Danish:	5.5 ± 6.7	4.7 ± 6.2	0.32	0.05 (*Z* = 1.69; *N* = 57)	0.06 (χ^2 = 9.1; d.f. = 4)
		Swedish:	7.3 ± 7.2	4.9 ± 4.8	0.03		

*Two *p*-values are given for two different statistical tests used to analyze combined data, as follows: † *p*-value of paired *t*-test or Wilcoxon matched-pairs signed-ranks test, regarding the data from Danish and Swedish experiments as being from one single experiment; ‡ *p*-value calculated by combining the *p*-values obtained in each independent experiment to get a χ^2 test (Winer 1970).

because all analyses were made as within-subject designs to examine a change of responses for each subject rather than a group, and because the pollution load on the air in the offices was the only variable changed in either of the two experiments. As the number of observations was doubled from 30 to 60 in the analysis of the combined data, the sensitivity of the analyses increased. This implies that in order to detect small effects of indoor environmental factors on health, comfort, and performance, experimental studies may require a larger number of observations.

In both experiments, the subjects judged the office to be significantly darker when the pollution source was not present in the office. This effect was not caused by the pollution source absorbing any of the daylight reaching the occupants and the mechanism underlying this effect should be further investigated. However, as suggested by Wargocki *et al.* (1999) it may simply indicate that subjects felt more relaxed in the less-polluted condition. In terms of self-estimated effort, the results of the two experiments show a discrepancy. The subjects indicated that they required significantly more effort to complete the performance tasks when the pollution source was not present in the office in the Danish experiment and significantly less effort in the Swedish experiment. This discrepancy may be caused by a different interpretation of the scale: it may be taken by the subjects to indicate task difficulty, as originally intended by Wyon (1994), and used to report the effort that would have been required to maintain performance, or to indicate the effort actually exerted, as suggested by Wargocki *et al.* (1999). The problem is that subjects cannot know whether they have succeeded in maintaining performance. It is thus strongly recommended that in future experiments subjects should simply be asked to indicate how well they have been able to work in relation to their maximum capacity, using a continuous scale from 0 to 100%.

The perception of dry air and dry nose were alleviated when the pollution source was not present in the office, although the relative humidity remained unchanged; also irritation of nose, eyes, and throat evaluated upon re-entering the office decreased in this condition (Table 4). These results imply that the perception of dryness was caused by irritants in the air, as suggested by Sundell (1994). Both experiments show also that nearly all effects on performance showed at least a tendency to improve when the pollution source was not present in the office (Table 4). The mechanism by which air quality affects human performance is unknown but the present results may suggest that poor air quality may induce general SBS symptoms such as headache, dizziness, difficulty in thinking clearly and fatigue, which are all known to have negative effects on human performance.

The results of the Danish and of the Swedish experiment, and the combined results of both studies, support the provision of an incentive to design for low-polluting buildings, as advocated in recent ventilation and indoor air quality guidelines (CEN, 1998, ECA, 1992; FISIAQ, 1995). The underlying aim of these documents is to improve air quality and acceptability, while the present data show that a reduction in total indoor pollution source strength can also reduce SBS symptoms and increase productivity.

Conclusions

Reasonably good agreement was observed between the results of two independent experiments in two countries, using a very similar experimental protocol, and the presence or absence of the same pollution source to modify the pollution load in an office.

Removing the pollution source was shown in both experiments to result in positive effects on health, comfort, and the performance of office work.

The present results provide a further reason to design for low-polluting buildings.

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