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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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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 work-places 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

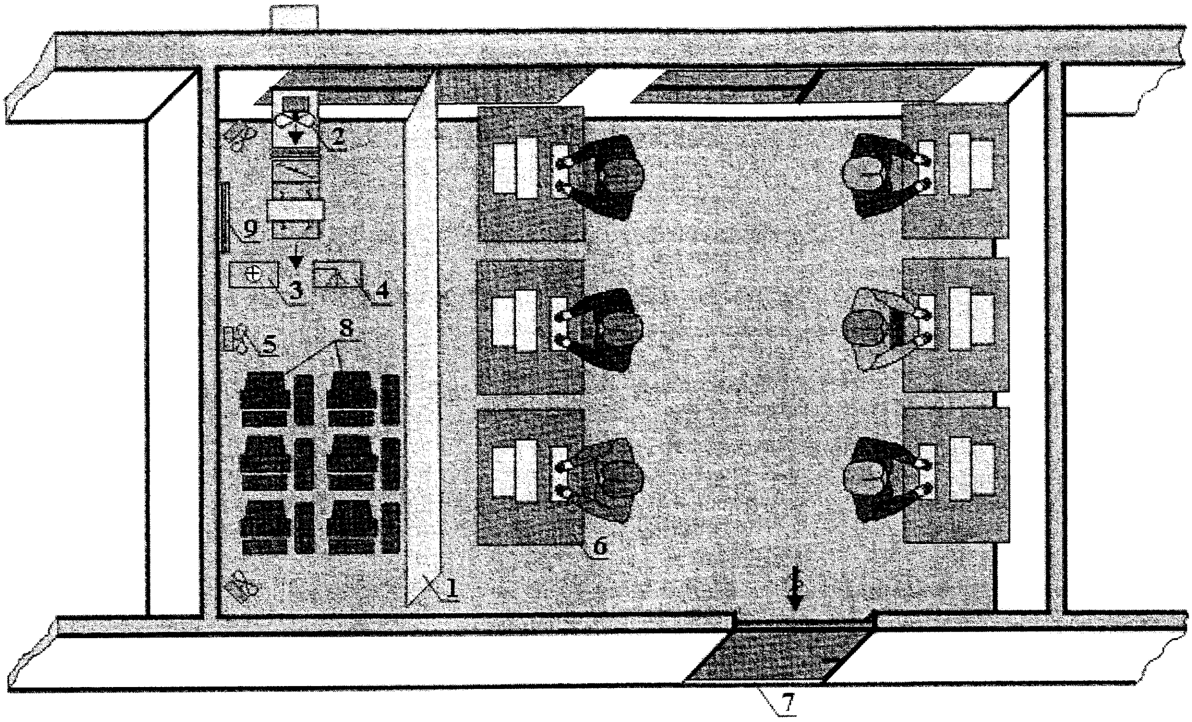

Fig. 1 Experimental set-up in the office where the investigation was carried out: 1, partition; 2, axial fan with damper and silencer; 3, electric heater; 4, ultrasonic humidifier; 5, mixing fan; 6, workstation consisting of a table, a desk lamp and a PC monitor with keyboard; 7, exhaust aperture (a 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

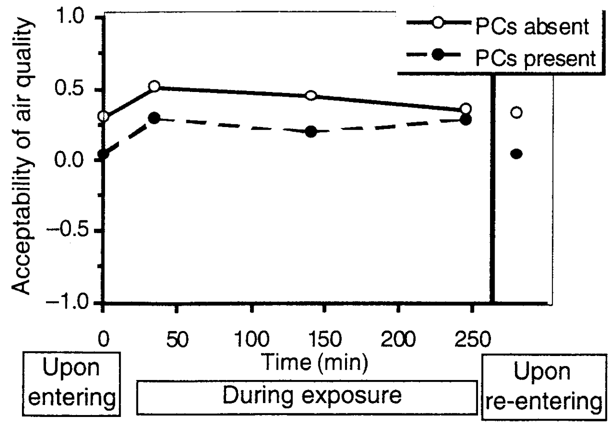

Fig. 2 Acceptability of the air quality as a function of the presence or absence of PCs behind the partition; the scale was coded as follows: −1, clearly not acceptable; 0, just not acceptable/just acceptable; 1, clearly acceptable

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.

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

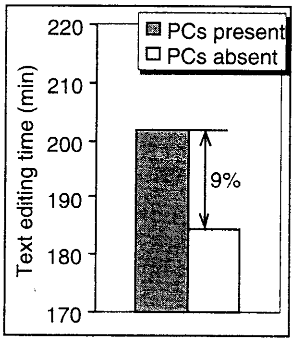

Fig. 3 Estimated time of editing the text (typing, proof-reading and retyping the errors) in the presence or absence of PCs behind the partition

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 ($\mu g/m^3$)	NIOSH RELs ($\mu g/m^3$)	Standardized odour threshold ($\mu g/m^3$)
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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