Human Perception, SBS Symptoms and Performance of Office Work during Exposure to Air Polluted by Building Materials and Personal Computers

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- In memory of my mother -

Preface

The present Ph.D. thesis summarizes the author's research work carried out at the International Centre for Indoor Environment and Energy at the Department of Mechanical Engineering, Technical University of Denmark from January 2000 to July 2004. Supervisors during the Ph.D. study have been Professor P. Ole Fanger, D.Sc. (principal supervisor) and Associate Professor Pawel Wargocki, Ph.D., both from the International Centre for Indoor Environment and Energy, Technical University of Denmark.

I would like to express my sincere gratitude to Professor P. Ole Fanger who invited me in 1999 to his laboratories under a common agreement established between the International Centre for Indoor Environment and Energy, DTU and the Department of Building Services I, Budapest University of Technology and Economics. This invitation has advanced into a research study of almost 5 years with hundreds of hours of exciting experiments, discussions data analyses and interpretation that helped me to explore an extremely multidisciplinary world of science, investigating the effects of the indoor environment on humans. I greatly appreciate his valuable advice and suggestions from his unlimited store of ideas, his open thinking on theoretical issues and pragmatic view on the results.

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Zsolt Bakó-Biró

Summary

The present thesis deals with the impact of polluted air from building materials and personal computers on human perception, Sick Building Syndrome (SBS) symptoms and performance of office work. These effects have been studied in a series of experiments that are described in two different chapters, each of them dealing with one type of pollution source.

Chapter 1, entitled *"Introduction"* gives both a general and a more specific overview of indoor air quality (IAQ) problems investigated in previous studies. After a short historical background and definition of the importance and meaning of good indoor air quality, key issues are briefly presented, such as SBS symptoms, evaluation of IAQ and the related risks of exposures, occurrence of main indoor pollutants and concern in this regard, and the needs and requirements of ventilation. Following a general introductory part, the main focus is given to research studies dealing with the effects and sensory/chemical evaluation of pollution sources that are commonly occurring in various indoor environments. Finally, a review is made of studies emphasizing the necessity of proper source control and adequate ventilation rates, in order to achieve an IAQ set by human requirements, and investigating the effects of IAQ on human performance. This chapter concludes with a description of the rationale and formulation of the objectives of the present work: 1) to evaluate the influence of contaminants emitted from common building products on IAQ and the extent to which such emissions contribute to the prevalence of SBS symptoms and loss of performance of human activities; 2) to investigate whether improving IAQ by means of source control, i.e. reducing the emission of pollutants from indoor sources, is a more effective measure than increasing the rate of outdoor air supply to ventilated buildings; 3) to assess the sensory and chemical pollution load of personal computers (PCs) and the subsequent effects on health, comfort and performance.

Chapter 2, entitled "Impact of emissions from building materials and ventilation rate on PAQ, SBS symptoms and performance of office work", describes an experiment investigating whether an increased level of air pollution, due to the presence of common building-related sources in a low-polluting office, affects the intensity of SBS symptoms and the performance of people. Furthermore, to what extent these effects may be alleviated when improving PAQ by either source removal and/or increasing the outdoor air supply rate in the office. The annual energy use in the office was also simulated for a hypothetical HVAC system that would provide either low or high outdoor air supply rates to the office.

Four air quality conditions were created in an office space (LxWxH = 6x6x3 m) by introducing or removing common building-related pollution sources and by altering the outdoor air supply rate. The building-related pollution sources included linoleum, aged sealant and wooden shelves with books and paper documents. The linoleum was bought for experimental purposes 3 years prior to the experiment and it had never been laid on floors for normal use. The samples of linoleum were attached back to back and hung on a stainless-steel rack. Its size corresponded to the floor area of the office. Sealant was put in an aluminium profile three months in advance of the beginning of the study. The profile had a length corresponding to the total length of the window frames in the office (18 m). Wooden shelves with books and paper documents had a total length of 16 m corresponding to a shelf factor of 0.15 m/m^3room volume. The sources were placed behind a partition when present in the office. In the absence of pollution sources, the office could be characterized as low-polluting, all materials and furnishings being low-emitting. The outdoor air supply rate in the office was altered to provide an air change rate of 1 or 3 h^{-1}, corresponding to 0.83 and 2.5 L/s per m^2floor, or to 5 and 15 L/s per person with the designed number of six persons working at six workstations in the office. All other indoor climate conditions were kept constant. A temperature of 23°C and a relative humidity (RH) of 50% were selected to suit typical thermal conditions for late spring when the experiment was carried out. The air velocity was below 0.2 m/s. The background noise level without occupancy was 35 dB(A).

Thirty female subjects, all students aged between 19 and 30 years old, occupied the office for ca. 2.8 hours in five groups of six people at a time. The groups were exposed to the air quality conditions in the office at random in a balanced order. On each exposure, subjective assessments and chemical sampling on Tenax TA/Tenax GR were made to evaluate the perceived air quality in the office, the intensity of SBS symptoms, and to measure the concentration of VOCs in the office air and outdoors. The subjects have also performed simulated office work comprising addition and multiplication of numbers and text typing. These tasks were used to measure the subjects' performance. The subjective responses were recorded on continuous acceptability and intensity scales for PAQ and horizontal visual analogue (VA) scales were used to register subjects' perception of the indoor environment, symptom intensity and self-estimated work ability. The subjects were instructed to adjust their clothing in order to remain thermally neutral during exposures. Their thermal comfort and the acceptability of the thermal environment were also recorded. The subjects were impartial to the building selected for these investigations and could not see the pollution sources or notice that the outdoor air supply rate was changed.

When the pollution sources were present in the unoccupied office, the percentage dissatisfied with the PAQ upon entering was 35% and 45% at low and high ventilation rates respectively. The quality of air was similarly perceived upon re-entering the office after the exposures when both the pollution sources and bioeffluents were present in the office air; the percentage dissatisfied was 40%-42% at this time. On the other hand, source removal significantly improved ($p<0.0001$) the air acceptability at both ventilation rates regardless of whether bioeffluents were present or not in the office. In the absence of sources at low and high outdoor air supply rates, the percentage dissatisfied with the air quality was 28% and 8.4% or 17% and 7.9% in the office either with or without bioeffluents. Although after the first 30 minutes of occupation the subjects became adapted to the air quality levels in the office, the perceived air quality during exposure was still significantly lower in the presence of sources ($p<0.0005$) compared to the unpolluted office at both ventilation rates. The changes in odour intensity and nose irritation due to the interventions established in the office were consistent with the results obtained for air acceptability, decreasing significantly with source removal, but also with increased ventilation rate. Apparently there was no effect of increased ventilation rate on PAQ when the pollution sources and human bioeffluents were present in the office. However, people considering themselves as more sensitive to poor air quality environment showed that PAQ significantly improved either by source removal ($p<0.008$) or increased ventilation ($p<0.005$). These improvements were still significant ($p<0.02$) for at least half of the subjects (n=16), who reported to have SBS history. The chemical analysis revealed that the presence of pollution sources in the office increased both the concentration of total volatile organic compounds (TVOCs) and the amount of individually measured volatile organic compounds (VOCs) at both outdoor air supply rates. A number of aldehydes and carboxylic acids approaching the human olfactory thresholds (OT) were detected mostly under the condition with sources present and low ventilation rate that may have contributed to the sensory effects observed. Consequently, the source removal in the office with bioeffluents resulted in halving the emission rate of individual VOCs, from ca. 4 mg/h to ca. 2 mg/h at both ventilation rates, whereas the sensory pollution load decreased from 0.34 olf/m^2 to 0.17 olf/m^2 and from 0.99 olf/m^2 to 0.1 olf/m^2 at low and high outdoor air supply rates respectively. Although the increased ventilation rate lowered the concentration of chemical compounds in both offices with and without pollution sources, PAQ improved significantly ($p<0.03$) only in the unpolluted condition. Raising the outdoor air supply rate, in the office with sources present, increased the emission of compounds containing oxygen while the release of hydrocarbons was little affected. Consequently, the total emission of individual VOCs increased by ca. 5% whereas the sensory pollution load was ca. 10 times higher in the office with sources present when the outdoor airflow increased. Most of the SBS symptoms concerning sensation of dryness in eyes and upper airways, and other neurobehavioural symptoms were alleviated in the office with low ventilation rate by source removal. However, the air was perceived less dry and the intensity of nose dryness also decreased with the dilution of air contaminants originating from the pollution sources in question. The objective measures of performance, including both speed and accuracy of the tasks, were generally improved with source removal and/or increased ventilation rate in the office, but significant changes were seldom seen in the absolute values. The air quality improvement obtained by source removal in the office with low ventilation rate was beneficial to lower the error rate of text typing ($p<0.04$) and the absolute decrement in typing performance ($p<0.04$) calculated as the difference in performance between the first and second part of an exposure. Although the effects of increased ventilation in the office with sources present were not reflected in the general results of PAQ, the performance of addition improved ($p<0.05$) as a result of this intervention. The subjects' self-estimated work ability also improved with the interventions established in the office. It grew by ca. 10% ($p<0.05$) when the pollution sources were removed and the outdoor air supply rate increased in the office.

These results indicate that both building materials and furnishing that are commonly used indoors degrade the quality of indoor air i.e., acting as sources of pollution through their emissions that are measurable in both chemical and sensory terms. Although the PAQ may be improved either by source removal or increased ventilation rates, simultaneous application of these methods is advisable. An adequate source control seems to be effective in eliminating the contaminants originating from building materials and reducing the related sensory effects at relatively low outdoor air supply rates. However, the PAQ at a low level of ventilation may still be affected by human bioeffluents and it is difficult to achieve highly acceptable indoor air quality, typically below 10-15% dissatisfied. Although increasing the outdoor air supply rates may be successful in improving PAQ in the case of bioeffluents, it may be less effective if the emission rate of contaminants from various building products is affected by such an intervention. In the present experiment, increased oxidation processes presumably drove the emission of contaminants from the pollution sources inspected, since the emission of compounds containing oxygen and consequently the sensory pollution load increased while more ozone disappeared on the indoor surfaces when the outdoor air supply rate was raised in the presence of sources. Consequently, these processes have counteracted to some extent the beneficial effects of increased ventilation. Furthermore, reducing the sensory pollutants originating from the building materials in the office air by source removal

proved to be a more effective and energy-efficient measure to improve PAQ and lower the intensity of SBS symptoms than increasing the outdoor air supply rate. Although the effects of air quality improvements established in the office on the objective measures of performance were small, it showed excellent correlation with the subjective evaluations of the work ability and with the CO_2 emission rates of people.

Chapter 3, entitled "Effects of personal computers on PAQ, SBS symptoms and performance of office work", includes three consecutive experiments with the main purpose of evaluating the sensory and chemical emission of pollutants emitted from personal computers (PCs), and the effects of such pollution on SBS symptoms and performance during human exposures.

In the first experiment, described in section 3.1, the sensory pollution load of two different brands of PCs were evaluated from the time of purchase up to several hundreds of hours of operation. In addition, the sensory emission rate was measured of another PC brand that was previously used for more than 3 years in the experimental facilities. The new PCs were bought at a local IT company and each type consisted of a unit holding the CPU that was named by the supplier, and a popular but distinct brand of 17" cathode ray tube (CRT) monitor, that is prevalent also on the world market. The PCs of different brands were placed in three adjacent low-polluting office spaces with controlled environment. The air was supplied to each office direct from outdoors at 20 L/s total flow or ca. 7 L/s per PC unit with 3 PCs present in the office space, and conditioned to 22.5°C and 30% relative humidity. A panel of untrained subjects, consisting of students and staff members of DTU, assessed the perceived air quality at regular intervals in each office with PCs either absent or present. Based on these subjective assessments, the sensory pollution loads were calculated for each type of PC, each PC being of a different age. The results showed that the sensory emission rate of PCs is highly dependent on the brand and age of the devices. The newly purchased PCs started to emit 4.3 olf/PC unit and 1.3 olf/PC depending on the brand shortly after turning them on for the first time, whereas the emission of sensory pollutants from the 3-year-old PCs was negligible. Furthermore, the new devices negatively affected the PAQ for several hundreds of hours of operation, while the rate of their emission over time could be approximated using a first order decay model with 347 and 102 hours of half-life respectively.

In the second experiment, described in section 3.2, human subjects were exposed for several hours to emissions originating from PCs in an office-like environment to evaluate the related effects on SBS symptoms and performance. The study was carried out using the facilities presented in Chapter 2. In groups of six, thirty female subjects were exposed for 4.8 h in a low-polluting office to each of two conditions – the presence or absence of three-month-old PCs. The brand and age of PCs used as source of pollution was selected based on the results of the previous experiment in such way as to obtain a mediocre, but not unrealistically low PAQ, at an outdoor air supply rate of 10 L/s per person in the office. The PCs were placed behind a screen so that they were not visible to the subjects. The climatic parameters of 24.5°C and 50% RH in the office were selected to reflect typical conditions for summer, when the experiment took place. All other environmental factors were unchanged. Under each of the two conditions the subjects performed simulated office work including arithmetical calculations, proof-reading and text typing. The typing task was completed on 3-year-old low-polluting PCs, whose sensory pollution load was evaluated in the previous study (described in section 3.1). The subjects also evaluated the air quality and reported SBS symptoms. The presence of PCs increased the percentage of people dissatisfied with the perceived air quality from 15% to 32% ($p<0.01$) and from 12% to 40% ($p<0.0002$) in the office with and without bioeffluents respectively. Consistent with the acceptability ratings, odour intensity and nose irritation were also higher when the PCs were introduced into the office.

The sensory pollution load of each PC was ca. 3.4 olf even after operating continuously for ca. 550 hours, i.e. approximately 3 months of office use. Although there was a lack of strong effects on the SBS symptoms, the typing performance of subjects significantly decreased by 1.2% ($p<0.03$) while the time required for text processing increased by 9% ($p<0.015$) in the office with PCs present compared to the unpolluted condition. The objective measures of performance were little affected in the case of proof-reading and arithmetical tasks.

The third and also the last experiment investigating the sensory and chemical emission from PCs is presented in section 3.3. The chemical measurements were made in a 1 m^3 glass chamber containing three PC units in operation. The PCs were selected randomly from those previously used in the exposure study. However, at this time they had been in use for ca. 2000 hours. The glass chamber was ventilated with 2 h^{-1} air change and located inside a 30 m^3 steel chamber where the outdoor air supply rate was maintained at 500 m^3/h, 24°C and 25% RH. The air leaving the glass chamber was driven to another steel chamber where the pollutants emitted by PCs were diluted in 46 m^3/h outdoor airflow and assessed by a panel of untrained subjects comprising staff members and DTU students who volunteered to take part in the experiment. In addition, the sensory emission from PCs was also evaluated in a low-polluting test office using the same facilities and similar test conditions as in the first experiment presented in section 3.1. The air in the steel chamber where the sensory assessments took place was conditioned to 24°C and 40% RH. The most significant chemicals detected included phenol, toluene, 2-ethylhexanol, formaldehyde, and styrene. Although the concentration of these compounds modelled for the conditions in both the steel chamber and the office where the exposure study described in section 3.2 was carried out, was far below any exposure limits and odour detection thresholds, the presence of sensory pollutants in the steel chamber was still detected with the subjective evaluations, showing that the sensory pollution load of PCs in question was between 0.5 - 0.9 olf/PC unit.

The conclusions from this chapter are that PCs are an important, but hitherto overlooked, source of pollution indoors. They can decrease the perceived air quality, increase SBS symptoms and consequently decrease office productivity. Although the rate of sensory emission decreases over time, the negative effects on PAQ for some PC brands used under daily conditions may persist up to one year, i.e. one third of the life cycle. The time-weighted average sensory pollution load of PCs over ca. 2000 hours of continuous operation (corresponding to ca. 1 year of daily use) may be expected to reach the pollution level of a standard person. Although the chemical compounds identified in the air polluted by the PCs examined were consistent with the results of other investigations, their type and concentration was insufficient to explain the adverse effects observed. This suggests that so-called "stealth chemicals", undetected by the methods employed, and/or mixture effects may have contributed to the negative sensory impacts observed.

Chapter 4, "Discussion" is a concluding chapter of the present thesis outlining implications of the results, limitations of the methodology and recommendations for future experiments. Furthermore, common aspects of the current findings are discussed.

A new relation between PAQ and performance of text typing was developed, integrating the present performance data (Chapter 2 and Chapter 3) with the results reported earlier by Wargocki et al. (2000b; 2000c). It may be applied for a set of typical indoor pollution sources, such as carpets, personal computers, linoleum, sealant and shelves with books and paper, and shows that for every 10% decrease in the percentage dissatisfied with the PAQ, the performance of text typing can be improved by 0.8% (the data applies for the air quality level causing from 15% to 68% dissatisfied). The combined results have also indicated that in laboratory experiments more than 15% change in the absolute level of percentage dissatisfied is required between exposure conditions to be able to see ca. 1% change in performance that can be quantified at the level corresponding to statistical significance of $p<0.05$.

A special emphasis was given to the effects of PAQ on the CO_2 emission rate of people, although this was not the primary objective of this work. There was a systematic indication in the current results that people emit less CO_2 when they are exposed to air polluted by either building materials or PCs. Although this may indicate that during exposure to the polluted conditions the subjects exerted less effort while performing the required tasks, an alternative hypothesis was postulated suggesting that differences in the CO_2 production rate may be due to the changes in people's breathing pattern. To understand the health consequences of shallow or inadequate breathing, pulmonary physiology was reviewed, showing that CO_2 may be retained in the vascular system and may initiate a number of symptoms that are similar to SBS but of a higher intensity. This hypothesis would also be a feasible and simple explanation for the comfort complaints of people exposed to mediocre air quality conditions in "sick buildings", and it should be tested in a series of new investigations by employing non-invasive measurements of a number of physiological parameters such as end-tidal CO_2 level, breathing rate and depth, and possibly cerebral blood flow.

Among drawbacks of the methods used in the present investigations were: relatively short exposures compared to daily work conditions in real environments; lower changes in the PAQ due to interventions compared to those obtained in other studies using a 20-year-old carpet as source of pollution; impact of missing subjects who dropped one or more exposure conditions due to illness on the power of statistical analysis and balance of the exposure conditions for order of presentation; air-scrubbing effect of a SPLIT-type air-conditioner that might have removed some of the pollutants responsible for sensory effects by trapping them in the condensed water leaving the AC unit; parallel registration of indoor and outdoor concentration of ozone could improve the results derived from the ozone measurements. Subject selection was mentioned as an important factor in obtaining a more accurate "instrument" for PAQ evaluations, and for creating a background for better comparison of results obtained from different independent studies. The application of a charcoal filter in the fresh air supply was recommended for future investigations when evaluating emissions from building materials to avoid any unwanted effect of ozone on the sensory/chemical emission rates. Careful study design should be applied to avoid factors that may weaken the investigated effects related to the initial hypothesis, e.g. duration of exposure affecting the development SBS symptoms and the changes observed in performance measures.

The findings of the present work include the following:

(i) Introducing a selection of typical building materials or 3-month-old PCs into a low-polluting office where the outdoor airflow meets the ventilation requirements, negatively affected perceived air quality, increasing the percentage dissatisfied from a background level of 8-17% to 40-45%.

(ii) The time-weighted average pollution of a PC unit with CRT display is approximately the sensory pollution of a standard person (1 olf) in the first year of PC use.

(iii) Increasing the outdoor air supply rate in the presence of building materials sensitive to oxidation processes increased both the sensory and chemical emission rate in the office and counteracted the beneficial effects of ventilation.

(iv) Reduced PAQ in the office increased the intensity of some SBS symptoms and negatively affected the performance of office work. The magnitude of the effects was similar to those obtained in the previous investigations (Wargocki et al., 2000b) where a 20-year-old carpet was used to alter the perceived air quality. A new relation between PAQ and performance was also developed including all data from separate independent studies. It shows that for every 10% decrease in the percentage dissatisfied with the PAQ, the performance of text typing can be improved by 0.8% (the data applies for the air quality level causing from 15% to 68% dissatisfied). Moreover, it was indicated that more than 15% change in the absolute level of percentage dissatisfied is required between exposure conditions to be able to see ca. 1% change in typing performance.

(v) In the presence of pollution sources in the office, the CO_2 produced by people decreased significantly by ca. 5% compared to the unpolluted condition. This effect can be caused by involuntary change in the breathing pattern (shallow breathing) or voluntary reduction of working pace in polluted air. Both changes cause reduction in metabolic rate, and may be a cause for the reduced performance observed. An empirical relation between PAQ and the CO_2 emission rate of people was developed.

Resumé

Nærværende afhandling omhandler undersøgelser af effekten på menneskers komfort, symptomer og produktivitet af kontorarbejde ved eksponering for luft forurenet af byggematerialer og personlige computere. Disse responsfaktorer er blevet undersøgt i en serie af forsøg, som beskrives i to kapitler i denne afhandling - ét for hver type af forureningskilde.

Kapitel 1, "Introduction" beskriver både en generel og en mere specifik gennemgang af indeluftkvalitet som den er beskrevet i en række tidligere undersøgelser. Efter en kort, historisk introduktion argumenteres for vigtigheden og betydningen af god indeluftkvalitet. Nøglebegreber som SBS (Sick Building Syndrome) symptomer, vurdering af luftkvalitet og sammenhængen med eksponeringsrisici defineres, og der gives en kort beskrivelse af kilder til indeluftforurening og ventilationsbehov. Efter den generelle introduktion rettes fokus mod studier af effekter af og sensoriske/kemiske metoder til at måle typiske forureninger i indeluft i forskellige typer indeklima. Den sidste del af litteraturstudiet fokuserer på undersøgelser af betydningen af kildekontrol og ventilation for at opnå en for mennesker acceptabel indeluftkvalitet og på effekten af indeluftkvaliteten på menneskers produktivitet. Kapitlet afsluttes med en beskrivelse af baggrunden for og formålet med dette ph.d-studium: 1) at undersøge betydningen for luftkvaliteten af forurening fra almindelige byggematerialer og hvordan eksponering for emissioner fra byggematerialer påvirker omfanget af SBS-symptomer og menneskers præstationsevne; 2) at undersøge om en forbedring af luftkvaliteten via kildekontrol, d.v.s. ved at reducere emissionen af forurening fra kilderne, er mere effektivt end at øge tilførslen af udeluft; 3) at bedømme den sensoriske og kemiske forurening fra personlige computere og effekten af denne forurening på menneskers komfort, helbred og produktivitet.

Kapitel 2 med titlen " Impact of building materials and ventilation rates on PAQ, SBS symptoms and performance of office work " undersøger om luftforurening, som skyldes almindelige byggematerialer placeret i et lavt-forurenende kontor, påvirker intensiteten af SBS-symptomer og menneskers produktivitet. Endvidere undersøges, om intensiteten af symptomerne bliver mindre og produktiviteten større, når luftkvaliteten forbedres ved at fjerne forureningskilder og/eller forøge mængden af tilført udeluft. Det årlige energiforbrug blev simuleret for et ventilationssystem med både lav og høj mængde tilført udeluft.

Fire niveauer af luftkvalitet blev etableret i et kontorlokale (LxBxH = 6x6x3 m^3) ved at tilføre eller fjerne almindelige bygningsrelaterede forureningskilder og ved at ændre mængden af

tilført udeluft. Forureningskilderne omfattede linoleum, ældet fugemasse og træreoler med bøger og dokumenter. Linoleummaterialet var indkøbt til forsøgsformål tre år før dette forsøg og havde aldrig været lagt på et gulv. Stykkerne hang underside mod underside på en rustfri stålreol. Mængden svarede til kontorets gulvareal. Fugemassen var blevet presset ned i et stålprofil tre måneder før undersøgelsen blev påbegyndt. Stålprofilets længde svarede til den samlede længde af vinduesrammerne i kontoret (18 m). Reolerne med bøger og dokumenter havde en samlet længde på 16 m svarende til en hyldefaktor på 0.15 m/m^3 rumvolumen. Forureningskilderne var placeret bag en skillevæg når de var tilstede i kontoret. Kontoret kunne karakteriseres som lavt-forurenende når kilderne ikke var tilstede eftersom alle materialer og møbler var lavt-emitterende. Mængden af tilført udeluft medførte et luftskifte på enten 1 h^{-1} eller 3 h^{-1} svarende til 0.83 L/s per m^2 gulvareal og 2.5 L/s per m^2 gulvareal eller 5 L/s per person og 15 L/s per person med seks personer beskæftiget ved de seks arbejdspladser i kontoret. Alle andre indeklimaparametre end luftskifte og forureningsbelastning blev holdt konstante. En temperatur på 23°C og en relativ luftfugtighed på 50% blev valgt som repræsentative for det sene forår, hvor forsøgene blev gennemført. Lufthastigheden var under 0.2 m/s og baggrundsstøjniveauet uden forsøgspersoner i lokalet 35 dB(A).

Tredive kvindelige forsøgspersoner, alle studerende i aldersgruppen 19 til 30 år, opholdt sig i kontoret i ca. 2.8 timer i fem grupper á seks personer. Grupperne blev eksponeret for de forskellige niveauer af luftkvalitet i randomiseret, balanceret rækkefølge. Ved hver eksponering blev luftkvaliteten og intensiteten af SBS symptomer vurderet ved subjektive bedømmelser og inde- og udeluftens indhold af flygtige organiske komponenter (VOCer) blev målt med Tenax TA/Tenax GR rør. Forsøgspersonerne udførte simuleret kontorarbejde, der omfattede addition og multiplikation af tal og indskrivning af tekst på PC. Disse opgaver blev udført for at måle forsøgspersonernes præstationsevne i løbet afde forskellige eksponeringer. De subjektive responsfaktorer blev målt på kontinuerte acceptabilitets- og intensitetsskalaer (oplevet luftkvalitet) og horisontale "visual analog" (VA) skalaer blev brugt til at registrere personernes oplevelse af indeklimaet, symptom intensitet og egenbedømt præstationsevne. Forsøgspersonerne blev bedt om at justere deres beklædning således at de var termisk neutrale. De blev også spurgt om deres oplevelse af termisk komfort og acceptabilitet af det termiske indeklima. Forsøgspersonerne vidste ikke, hvilken forsøgskondition, de blev udsat for og de kunne ikke se forureningskilderne eller registrere, at ventilationsraten var blevet ændret.

Når forureningskilderne var tilstede i det tomme kontor var andelen af utilfredse med den oplevede luftkvalitet (ved indtræden i lokalet) 35% og 45% ved henholdsvis den høje og lave luftkvalitet. Luftkvaliteten blev også vurderet ved genindtræden i lokalet efter forsøget når forureningskilder og bioeffluenter havde forurenet luften og andelen af utilfredse var da 40-42%. Fjernelse af forureningskilderne forbedrede acceptabiliteten af luftkvaliteten signifikant ($p<0.0001$) ved begge ventilationsrater uanset om der var bioeffluenter i kontoret eller ej. Uden forureningskilder og med lav og høj ventilationsrate var andelen af utilfredse med luftkvaliteten 28% og 8.4% eller 17% og 7.9% i kontoret med eller uden bioeffluenter. Selvom forsøgspersonerne efter de første 30 min var tilvænnet luften i kontoret, var den oplevede luftkvalitet stadig lavere når forureningskilderne var tilstede ($p<0.0005$) sammenlignet med konditionen hvor de ikke var tilstede ved begge ventilationsrater. Ændringen af lugtintensitet og irritation i næsen, som kunne henføres til interventionerne i kontoret, svarede til den oplevede luftkvalitet og blev forbedret både ved fjernelse af forureningskilderne og forøgelse af luftmængden.

Der var ingen effekt af ventilationsraten på den oplevede luftkvalitet når der var forureningskilder i kontoret og bioeffluenter i luften. Forsøgspersoner der mente, at de var

følsomme overfor dårlig luftkvalitet fandt, at luftkvaliteten blev bedre når forureningskilderne blev fjernet ($p < 0.008$) eller ventilationsraten øget ($p < 0.005$). Disse forbedringer var signifikante ($p < 0.02$) for de forsøgspersoner ($n = 16$), som tidligere havde oplevet SBS symptomer. Den kemiske analyse viste, at med forureningskilderne i kontoret var både koncentrationen af totale flygtige organiske komponenter i luften (TVOC) og koncentrationen af individuelle VOCer højere ved begge ventilationsrater. Relativt høje koncentrationer af forskellige aldehyder og carboxyl syre, der var tæt på lugttærskelen blev målt med forureningskilder i kontoret og den lave ventilationsrate kan have bidraget til de sensoriske effekter, der blev observeret. Fjernelse af forureningskilderne fra kontoret med bioeffluenter resulterede i en halvering af emissionsraten af individuelle VOCer; fra 4 mg/h til ca. 2 mg/h ved begge ventilationsrater. Den sensoriske kildestyrke faldt fra ca. 0.34 olf/m^2 til 0.17 olf/m^2 og fra 0.99 olf/m^2 til 0.1 olf/m^2 ved henholdsvis den lave og høje ventilationsrate. Selvom en forøgelse af ventilationsraten reducerede koncentrationen af kemiske komponenter i luften både med og uden forureningskilderne blev den oplevede luftkvalitet kun signifikant bedre ($p < 0.03$) uden forureningskilderne i kontoret. En forøgelse af ventilationsraten med kilderne tilstede øgede emissionen af oxygenholdige komponenter mens emissionen af kulbrinter kun blev moderat påvirket. Den totale emission af individuelle VOCer blev øget med ca. 5%, hvorimod den sensoriske forureningsbelastning var ca. 10 gange højere med kilderne tilstede i kontoret, når ventilationsraten blev forøget. Intensiteten af de fleste SBS symptomer (tørhed i øjne og øvre luftveje og andre neurologisk relaterede symptomer) blev mindre med den lave ventilationsrate når kilderne blev fjernet fra kontoret. Luften blev oplevet som mindre tør og intensiteten af tørhed i næsen faldt ligeledes med øget fortynding af luftforurening fra forureningskilderne. De objektive mål for forsøgspersonernes produktivitet, som omfattede både hastighed og fejlrate, var generelt bedre, når forureningskilderne ikke var tilstede i kontoret eller med den høje ventilationsrate, men forskellene var sjældent signifikante. Ved den lave ventilationsrate resulterede forbedringen af luftkvaliteten, som blev opnået ved at fjerne forureningskilderne, i en lavere fejlrate ved indskrivning af tekst ($p < 0.04$) og det absolutte fald i præstationen af tekstbehandling ($p < 0.04$) beregnet som forskellen i præstationen mellem den første og anden del af eksponeringen. Selvom effekterne af forøget ventilationsrate med kilderne tilstede ikke afspejlede sig i den oplevede luftkvalitet, blev præstationen ved additionsopgaverne øget ($p < 0.05$) som følge af denne ændring. Personernes egenvurderede præstationsevne blev ca. 10% større ($p < 0.05$) når forureningskilderne blev fjernet og ventilationsraten øget.

Resultaterne af dette forsøg viste, at både byggematerialer og typisk inventar i bygninger forringer luftkvaliteten, d.v.s. forurener luften via emissioner, som kan måles ved både kemiske og sensoriske metoder. Selvom den oplevede luftkvalitet kan forbedres både ved at fjerne forureningskilderne og ved at øge ventilationen anbefales det at anvende begge metoder parallelt. Kildekontrol er en effektiv metode til at eliminere forurening fra byggematerialer og reducere de sensoriske effekter af luftforurening ved lav tilførsel af udeluft. Men den oplevede luftkvalitet ved lav ventilation vil stadig blive påvirket af bioeffluenter fra mennesker, hvorfor det kan være vanskeligt at opnå en acceptabel luftkvalitet, typisk under 10 - 15% utilfredse.

Selvom en forøgelse af udeluftmængden kan være en brugbar metode til at forbedre den oplevede luftkvalitet, er den mindre effektiv hvis emissionen af forurening fra byggematerialer samtidig påvirkes. I disse forsøg blev emissionen af forurening fra byggematerialerne antageligt bestemt af de øgede oxidationsprocesser, eftersom emissionen af forurening, der indeholdt oxygen blev øget og den sensoriske forureningsbelastning forværret samtidig med at mere ozon blev optaget på overflader med den høje

ventilationsrate og med forureningskilderne i kontoret. Derfor kan disse processer i nogen grad have modvirket den positive effekt af øget ventilaton. En reduktion af den sensoriske forureningsbelastning fra byggematerialer var en mere effektiv og energibesparende metode til at forbedre den oplevede luftkvalitet og reducere intensiteten af SBS symptomer end en forøgelse af ventilationsraten. Selvom effekterne af en forbedret luftkvalitet på den observerede præstation af kontorarbejde var små, var der god overensstemmelse med den egenbedømte effektivitet og med emissionen af CO_2.

Kapitel 3 med titlen "Effects of personal computers on PAQ, SBS symptomes and performance of office work" omhandler tre forsøgsserier, som havde til formål at undersøge den sensoriske og kemiske emission fra personlige computere og effekterne af den emitterede forurening på SBS symptomer og præstationen af typisk kontorarbejde.

I det første forsøg, som er beskrevet i kapitel 3.1 blev den sensoriske forurening fra to forskellige typer PC bedømt fra anskaffelsestidspunktet og frem til flere hundrede timers drift. Endvidere bedømtes den sensoriske forurening fra en anden type PC, som havde været anvendt i mere end 3 år. De nye PCer blev købt i en lokal forretning og hver bestod af en enhed, der indeholdt CPUen og en 17" monitor (CRT) der ligesom CPU-enhden er almindeligt forekommende i mange lande. De tre forskellige typer PC blev placeret i tre sammenhængende, lavt-forurenende kontorer, som havde et kontrolleret indeklima. Udeluft blev direkte tilført hvert kontor ved 20 L/s per PC eller ca. 7 L/s per PC med tre PCer i kontoret. Luften blev konditioneret til 22.5 ^{o}C og 30% rh. Efter faste intervaller bedømte et panel bestående af utrænede forsøgspersoner (personale og studerende fra DTU) luftkvaliteten i hvert kontor med PCerne tilstede eller i det tomme kontor. Udfra de subjektive vurderinger af luftkvaliteten blev de sensoriske forureningsbelastninger beregnet for hver type PC efter forskellige driftsperioder. Resultaterne viste, at den sensoriske emissionsrate fra en PC afhænger af fabrikatet og driftstiden. De nyindkøbte PCer forurenede med 4.3 olf/PC henholdsvis 1.3 olf/PC lige efter at de blev tændt for første gang, hvorimod den sensoriske forureningsbelastning fra de tre år gamle PCer var negligibel. Desuden forringede de nye PCer den oplevede luftkvalitet gennem flere hundrede timers drift og emissionsraten kunne approksimeres ved et første ordens henfald med 347 timers og 102 timers halveringstid.

I det andet forsøg, som er beskrevet i kapitel 3.2, blev forsøgspersoner i løbet af flere timer eksponeret for emissioner fra PCer i kontor-lignende omgivelser for at bedømme effekterne på SBS symptomer og præstationsevne. Undersøgelsen blev gennemført i de eksperimentelle faciliteter, som blev beskrevet i kapitel 2. I grupper af seks blev 30 kvindelige forsøgspersoner i et lavt-forurenende kontor i løbet af 4.8 timer eksponeret for to forsøgsbetingelser: med og uden tre måneder gamle PCer i kontoret. PCernes fabrikat og alder var blevet udvalgt på baggrund af resultaterne af de tidligere forsøg, således at en middelmådig, men ikke urealistisk dårlig, oplevet luftkvalitet kune opnås med en ventilationsrate på 10 L/s per person. PCerne blev placeret bag en skærm således at de var gemt for forsøgspersonerne. En temperatur på 24.5 ^{o}C og en relativ luftfugtighed på 50% blev valgt som typiske sommerbetingelser (årstid for gennemførelse af forsøgene). I hver af de to forsøgsbetingelser udførte forsøgspersonerne simuleret kontorarbejde, som omfattede aritmetiske beregninger, korrekturlæsning og indskrivning af tekst. Indskrivning af tekst blev gennemført på tre år gamle, lavt-forurenende PCer for hvilke forureningsbelastningen var blevet bestemt i tidligere forsøg. Forsøgspersonerne bedømte den oplevede luftkvalitet og rapporterede om intensiteten af SBS symptomer. Tilstedeværelsen af PCerne forøgede andelen af utilfredse med den oplevede luftkvalitet fra 15% til 32% ($p < 0.01$) og fra 12% til

40% ($p < 0.0002$) i kontoret med og uden bioeffluenter. I overenstemmelse med acceptabilitetsvurderingerne var også lugtintensiteten højere og irritation i næsen mere udtalt med PCerne tilstede i kontoret. Den sensoriske forureningsbelastning fra hver PC var ca. 3.4 olf – selv efter 550 timers kontinuert drift svarende til tre måneders brug. Selvom der ikke var særligt udtalte effekter på SBS symptomerne faldt præstationen af tekstbehandling med 1.2 % ($p < 0.03$) mens tiden der var nødvendig for at indskrive teksten blev øget med 9% ($p < 0.03$) i kontoret med PCerne tilstede sammenlignet med forsøgsbetingelsen uden PCer. Præstationen af korrekturlæsning og de aritmetiske opgaver varierede kun svagt med forsøgsbetingelserne.

Det tredje og sidste forsøg der undersøgte den sensoriske og kemiske emission fra PCer præsenteres i kapitel 3.3. De kemiske målinger blev gennemført i et glaskammer (1 m^3) der indeholdt tre PCer i drift. PCerne var blevet tilfældigt udvalgt blandt dem, der tidligere blev brugt i eksponeringsstudiet. På nuværende tidspunkt havde de været i drift i 2000 timer. Glaskammeret blev ventileret med et luftskifte på 2 h^{-1} og det var placeret i et 30 m^3 rustfrit stålkammer med en udelufttilførsel på 500 m^3/h, 24 ^oC og 25% rh. Luften fra glaskammeret blev ført til et andet stålkammer, hvor forureningen fra PCerne blev fortyndet med 46 m^3/h udelufttilførsel og vurderet af et panel af utrænede forsøgspersoner bestående af personale og studerende fra DTU. Den sensoriske forureningsbelastning fra PCerne blev også bedømt i et kontor med de samme faciliteter og forsøgsbetingelser som beskrevet i kapitel 3.1. Luften i stålkammeret, hvor de sensoriske bedømmelser blev gennemført, var 24^oC og den relative luftfugtighed 40%. De mest markante kemiske komponenter, der blev identificeret var phenol, toluen, 2-ethylhexanol, formaldehyd og styren. Selvom koncentrationen af disse komponenter i både stålkammeret og i kontoret, hvor eksponeringsstudiet beskrevet i kapitel 3.2 blev gennemført, var betydeligt lavere end eksisterende grænseværdier og lugttærskler, blev deres tilstedeværelse i luften afsløret af de subjektive vurderinger af luftkvaliteten, som viste, at den sensoriske forureningsbelastning for de aktuelle PCer var mellem 0.5 og 0.9 olf/PC.

Konklusionerne fra dette kapitel er, at PCer er en vigtig, men hidtil overset, kilde til forurening af indeluften. PCer kan forringe luftkvaliteten, øge intensiteten af SBS symptomer og dermed reducere produktiviteten af kontorarbejde. Selvom den sensoriske emissionsrate aftog med tiden kan de negative effekter på den oplevede luftkvalitet af nogle typer PC fortsætte i op til et år, hvilket typisk er en tredjedel af PCens levetid. Den gennemsnitlige sensoriske forureningsbelastning af en PC i løbet af 200 timers drift (svarende til omtrent et års daglig brug) kan forventes at nå et niveau svarende til forureningen fra en standardperson. Selvom de kemiske komponenter der blev identificeret i luft der var forurenet af de undersøgte PCer svarede til resultaterne fra andre undersøgelser, var type og koncentration utilstrækkelig til at forklare de observerede sensoriske effekter. En forklaring kan være, at der er skjulte komponenter, der ikke kan identificeres med de anvendte metoder og/eller at tilstedeværelsen af mange komponenter i små koncentrationer tilsammen kan have bidraget til de observerede sensoriske effekter.

Kapitel 4, "Discussion" er et afsluttende kapitel, hvor resultaterne af denne afhandling vurderes i forhold til deres anvendelse, den anvendte metode vurderes og der gives anbefalinger til fremtidige undersøgelser. Desuden diskuteres mere generelle forhold vedrørende undersøgelsens resultater.

En ny relation mellem den oplevede luftkvalitet og præstationen af tekstbehandling blev bestemt ved at integrere de resultaterne fra dette studium (kapitel 2 og 3) og resultater fra tidligere studier af Wargocki et al. (2000b; 2000c). Relationen viser, at for hver 10% reduktion i andelen af utilfredse med den oplevede luftkvalitet øges præstationen med 0.8%.

Sammenhængen kan anvendes i intervallet fra 15% til 68% utilfredse og for forskellige, typiske indendørs forureningskilder som tæppe, PCer, linoleum, fugemasse og reoler med bøger og papir. De kombinerede resultater viste også, at i laboratoriet er en forskel i andelen af utilfredse på 15% point mellem de forskellige eksponeringer nødvendig, for at kunne detektere en forskel på 1% i præstationen svarende til et signifikansniveau på 0.05.

Særlig vægt blev lagt på betydningen af den oplevede luftkvalitet for menneskers CO_2 produktion. Der var en tendens til, at forsøgspersonerne producerede mindre CO_2 når de blev eksponeret for luft, der var forurenet af byggematerialer eller PCer. Selvom dette kan indikere, at forsøgspersonerne anstrengte sig mindre i forurenet luft når de skulle udføre de simulerede kontoropgaver er der også en alternativ hypotese, der foreslår, at forskellen i CO_2 produktionen skyldes et ændret åndedrætsmønster. For at forstå helbredseffekterne af en lav eller utilstrækkelig åndedrætsfunktion blev litteraturen vedrørende respiratorisk fysiologi gennemgået. Gennemgangen viste, at CO_2 kan blive tilbageholdt i det vaskulære system og initiere forskellige symptomer, som svarer til SBS symptomer, men ved en højere intensitet. Denne hypotese ville også være en anvendelig og simpel forklaring på klager over middelmådig luftkvalitet fra personer i ”syge bygninger”. Hypotesen burde afprøves i en serie af nye undersøgelser med ikke-invasive målinger af koncentration af CO_2 i udåndingsluften, åndedrætsfrekvens og om muligt cerebral blodgennemstrømning.

Ulemperne ved den anvendte metode omfatter bl.a. relativt korte eksponeringer sammenlignet med de daglige arbjdsbetingelser i kontorbygninger i praksis; mindre ændringer i den oplevede luftkvalitet sammenlignet med tidligere studier, hvor et 20 år gammelt tæppe blev anvendt som forureningskilde; betydningen for styrken af den statistiske analyse og balanceringen af forsøgsbetingelser at forøgspersoner udeblev fra et eller flere forsøg p.g.a. sygdom; den rensende effekt af klimaanlægget, der kan have fjernet nogle af de forureninger, som ellers ville påvirke forsøgspersonernes sensoriske respons; parallelle målinger af ozon i inde- og udeluft ville resultere i en forbedring af de resultater, der bygger på ozonmålingerne. Udvælgelsen af forsøgspersoner var vigtig for at opnå det mest nøjagtige instrument til at vurdere den oplevede luftkvalitet og for at sammenligne resultater opnået i forskellige, uafhængige undersøgelser. Anvendelse af et aktivt kulfilter i indblæsningsluften anbefales i fremtidige undersøgelser for at undgå uønskede effekter af ozon på de sensoriske og kemiske emissionsrater fra byggematerialer.

Resultaterne af dette studium inkluderer følgende:

(i) At tilføre udvalgte byggematerialer eller tre måneder gamle PCer til et lavt-forurenende kontor, hvor den tilførte udeluftmængde overholdt kravene i eksisterende ventilationsstandarder, havde en negativ effekt på den oplevede luftkvalltet og øgede andelen af utilfredse med luftkvaliteten fra baggrundsniveauet på 8-17% til 40-45%.

(ii) Den tidsvægtede gennemsnitlige forurening fra en PC med CRT monitor svarer omtrent til den sensoriske forureningsbelastning fra en standardperson (1 olf) i løbet af det første brugsår.

(iii) Med byggematerialer, som var følsomme overfor oxidationsprocesser, tilstede i kontoret resulterede en forøgelse af den tilførte mængde udeluft i, at både den sensoriske og kemiske emissionsrate blev forøget, hvilket modvirkede den positive effekt af øget ventilation.

(iv) En dårligere luftkvalitet i kontoret øgede intensiteten af nogle SBS symptomer og havde en negativ effekt på præstationen af simuleret kontorarbejde. Dette svarer til tidligere resultater af Wargocki et al. (2000b). En ny relation mellem den oplevede luftkvalitet og præstationen af kontorarbejde, der omfattede alle data fra separate, uafhængige studier, blev også formuleret. Relationen viser, at for hver 10% reduktion i andelen af utilfredse med den oplevede luftkvalitet øges præstationen med 0.8%. Sammenhængen kan anvendes i intervallet fra 15% til 68% utilfredse. Endvidere indikerede resultaterne, at en forskel i andelen af utilfredse på 15% point mellem de forskellige eksponeringer er nødvendig, for at kunne detektere en forskel på 1% i præstationen af tekstbehandling.

(v) Med forureningskilder tilstede i kontoret blev forsøgspersonernes CO_2 produktion reduceret med ca. 5% sammenlignet med ingen kilder tilstede. Denne effekt kan skyldes en ufrivillig ændring i åndedrætsmønsteret eller en frivillig reduktion af arbejdstempoet, når luften var forurenet. Begge ændringer forårsager en reduktion af aktivitetsniveauet. En empirisk sammenhæng mellem den oplevede luftkvalitet og emissionsraten af CO_2 blev bestemt.

Chapter 1

Introduction

1.1 Background

The basic needs for the life of a human being are regular supply of food and water, and an essentially continuous supply of air. The quality and quantity of these fundamental supplies are key factors defining the quality of human life. Since the outcomes were almost instantaneous and more evident, the effects of bad food or inadequate drinking-water on human health were not difficult to identify already in early times. However, to recognize the critical relationship between the quality of inhaled air and human well-being took centuries.

Yet the Greeks and Romans already suspected that polluted air, e.g. in crowded cities and mines, may be detrimental to human health. Hippocrates (460-377 B.C.) believed in the natural healing process of rest, a good diet, fresh air and hygiene. He also recognized that the body must be treated as a whole and not just as a series of parts. Furthermore, he was among the first scientists who accurately described disease symptoms such as epilepsy in children and pneumonia. He noted that there were individual differences in the severity of disease symptoms, and that some individuals were better able to cope with their diseases and illnesses than others were. Through the medieval era little was added to this knowledge. Associations between air pollution and health have gained new importance with the epidemiological findings that working in certain heavily polluted premises (Ramazzini, 1633-1714) or living in crowded cities such as London (Arbuthnot, 1667-1735; Brimblecombe, 1977) may cause fundamental health problems. With the Industrial Revolution and the rise of the cities, awareness of the threat posed by outdoor air pollution was clearly recognized, and this potential was tragically demonstrated in a well-chronicled series of disasters across the twentieth century (Firket, 1936; Mills, 1950, Ministry of Health, 1954). Evidence on the health effects of ambient air pollution has been gathered during the last 50 years and the results are summarized in comprehensive recent reviews (Brunekreef and Holgate, 2002; Abelsohn, 2002; Bascom *et al*., 1996a; 1996b).

Considering that the concentration of many pollutants is often higher indoors than outdoors, and that people spend most of their lives - up to 80-90% - at home and at their workplaces in various buildings, there is a strong belief that poor air quality indoors may pose an even higher risk to human health and comfort than outdoors. Due mainly to a wide-ranging and diverse set of health effects that could be related to poor air quality, indoor air quality in non-industrial buildings has received special attention over the past two decades. The health effects in question include both adverse effects and changes in well-being. Indoor air pollution may exacerbate human illnesses that include cancer, lung disease, asthma, allergies and a wide range of comfort-related complaints. Recent estimates made by the World Health Organization (WHO) rank indoor air pollution among global burdens of diseases secondary to major risk factors such as malnutrition, tobacco, HIV and poor water/sanitation (Smith et al., 2002).

The right to health was recognized as early as in 1946 when the Constitution of the WHO stated that the enjoyment of the highest attainable standard of health is one of the fundamental rights of every human being (WHO, 1946). After more than a half-century, in year 2000, the right that every human being is entitled to breathe healthy indoor air was finally acknowledged by a team of experts convened by WHO. This Working Group agreed on a set of statements on “The right to healthy indoor air” (WHO, 2000b), which were derived from fundamental principles in the field of human rights, biomedical ethics, and ecological sustainability (Mølhave and Krzyzanowski, 2003).

However, it is more complex to define healthy indoor air and when we can speak of highly acceptable air quality. Based on the statement in the WHO constitution, health may be defined as a “state of complete physical, mental and social well-being and not merely the absence of disease or infirmity”. Likewise, healthy indoor air may be defined as the air that does not provide any risk of disease and that ensures comfort and well-being for all occupants (Fanger, 2003).

1.1.1 Sick Building Syndrome symptoms and building-related illnesses

In contrast to the industrial indoor environment, where a number of standards attempt to reduce any industrial health hazard by limiting exposure to different pollutants in the working environment (NIOSH, 2002; ACGIH, 2003), non-industrial indoor settings, such as office buildings, recreational facilities, schools and residences, were for a long time considered as being free of harmful substances that could negatively affect human health. However, especially from the ‘70s, there has been increasing awareness of health symptoms and complaints experienced in certain office buildings and other non-industrial settings. Traditionally, the health consequences of poor indoor environmental quality were classified into two main categories: Building-Related Illnesses (BRI) and Sick Building Syndrome (SBS) symptoms. While BRI are caused by exposures to biological, physical or chemical agents in the indoor environment and clinically can be specifically diagnosed, SBS describes a constellation of symptoms that have no clear etiology and are attributable to exposure to a particular building environment.

BRI can be classified into three groups: (i) airborne infectious diseases, such as Legionnaires’ diseases, Pontiac fever and other airway infections; (ii) hypersensitivity diseases, such as allergic asthma, allergic rhinitis and pneumonitis, and certain skin disorders that result from an abnormal response of the immune system to a substance recognized as foreign to the body; (iii) toxic reactions that involve exposure to contaminants, such as carbon monoxide and pesticides, that may lead to acute disruptions of a variety of organ functions and/or increased risk of chronic diseases, for instance, cancer.

The first attempt to define SBS was made by a group of experts within WHO in 1982 who compiled a list containing the common symptoms being reported in relation to buildings. These symptoms included: eye, nose and throat irritation; sensation of dry mucous membranes; dry, itching and red skin primarily in the face; headaches and mental fatigue; high frequency of airway infections and cough; hoarseness and wheezing; nausea and dizziness; and unspecific hypersensitivity. Since then, the Commission of the European Communities and the American Thoracic Society have also attempted to define SBS. Common to each of the definitions is that SBS involves symptoms of the central nervous system (headache, fatigue, lethargy, feeling heavy-headed, difficulty concentrating) and mucous membranes (eyes, nose and throat).

A few dozen observational and experimental studies have been conducted in the last two decades to evaluate SBS and related risk factors; the findings often present a variety of conflicts and the results are often difficult to interpret. Mendell has made one of the first comprehensive reviews on findings of 32 research works. In the studies conducted between 1984 and 1992, 37 factors were potentially related to office worker symptoms (Mendell, 1993). The author summarized the reported relationships between symptom prevalence and various environmental factors in four main categories: environmental measures, building factors, workplace factors, and job or personal factors. Among these factors, air-conditioning, job stress/dissatisfaction and allergies/asthma were consistently associated with increased symptom prevalence and "mostly consistent" associations were found for low ventilation rate, carpets, occupant density, use of video display terminals (VDT) and female gender. Furthermore, the overview of studies investigating ventilation in buildings showed that ventilation rates below 10 L/s per person are significantly associated with an increased prevalence of SBS symptoms.

Reliable information on SBS symptom prevalence and risk factors may be obtained also from comprehensive cross-sectional surveys conducted by different research groups in the past 15 years in Europe and abroad. They include responses of several thousand occupants from a few hundred office buildings and characteristics of the work environment based on standardized questionnaires and physical measurements.

For instance, the British Office Environment Survey (BOES) conducted in 1986, covers 42 buildings and 4373 office workers in England, Scotland and Wales (Burge *et al.*, 1987). The most common work-related symptoms reported were lethargy, blocked nose, dry throat and headache. The symptom reports were common for all buildings and were higher among women and employees with a clerical job function. Risk factors such as air-conditioning or humidification and cleaning/maintenance of HVAC system were associated with increased symptoms. Mechanical ventilation seemed to increase symptom prevalence vs. natural ventilation.

Another large-scale project was conducted in 14 Danish town halls (Skov and Valbjorn, 1987) including over 4300 employees to examine the prevalence of SBS symptoms, using more extensive environmental measures compared to BOES. The results indicated a prevalence of work-related mucosal irritation in nose, throat and eyes and general symptoms such as fatigue and headache, which varied among buildings. Again, women had higher symptom and complaint rates than men and clerical job function, higher occupancy use of photocopiers, carbonless paper and VDT use were correlated with the symptoms reported. However, no significant differences could be demonstrated in mucosal irritation and prevalence of general symptoms when naturally ventilated buildings were compared to those with mechanical ventilation, although the symptoms were somewhat elevated in the latter case. In a follow-up analysis (Skov et al., 1989) a strong correlation was found between symptom reports among office employees and job or psychosocial factors, such as dissatisfaction with superiors, fast work pace, workload and dissatisfaction related to self organization of the work. A further examination of the results showed an association between the prevalence of SBS symptoms and so-called “fleecy factor” and “shelf factor”, floor dust and carpeting (Skov *et al.*, 1990).

Another work, the Swedish Office Illness Project, surveyed 5986 individuals over 210 buildings (Stenberg et al., 1993; Sundell, 1994; Sundell *et al.*, 1994). Their results indicated that female gender, asthma/rhinitis, VDT and paper work, as well as psychosocial factors contribute to the development of SBS symptoms, including skin symptoms. In addition, a ventilation running time lower than 10 h/workday, outdoor airflow rates less than 13.6 L/s per person, the presence of copy machines, humidifiers and fluorescent tube lighting with metal shields and a low cleaning frequency increased the risk of SBS. It should be noted that the perception of dry air was associated with SBS symptoms but not with the physical air humidity. Finally, higher formaldehyde levels with lower concentrations of the total volatile organic compounds (TVOC) were consistent risk indicators for increased SBS.

Perhaps the largest and most ambitious cross-sectional study in Europe was conducted in winter 1994 as part of the Joule II Programme that was sponsored by the Commission of the European Communities. Fifty-six office buildings were investigated in nine countries with a standardized protocol (Groes, 1995; Levin, 1996; Bluyssen et al., 1996). Questionnaires were provided to at least 100 occupants in each building. According to the results, the most common work-related symptoms were lethargy or tiredness, blocked or stuffy nose, dry eyes, dry or irritated throat and dry skin. High correlation was shown between occupants’ adverse perception of the environment and symptoms. Dryness and stuffiness were highly correlated to mucosal and general symptoms. Personal factors such as gender and nationality were more related to the adverse perception of the indoor environment than building factors. Compared to others, women employees performing clerical work, employees working with VDT units for many hours, and people in high-density offices reported more adverse symptoms and perceptions. Furthermore, buildings with humidifiers or cooling systems and those with recirculated air presented a higher risk for symptom development. The occupants in buildings situated next to busy roads and those in offices with a high background noise level reported higher adverse perceptions and symptoms, too. Unlike the Danish Town Hall study, shelf and fleecy factors could not explain the differences in symptom prevalence among buildings. Significant association of higher symptom prevalence and lower TVOC levels was found, as evidenced earlier in the Swedish study. Although low relative humidity did not affect the sensation of dryness or mucosal irritation, it caused a higher prevalence of skin symptoms among employees (Groes, 1995).

In a more recent German project, Pro Klima und Arbeit, 14 office buildings were investigated in a cross-sectional study between 1995 and 1998, including responses from ca. 120 occupants/building (Bischof et. al., 1999; Brasche et al., 1999, Witthauer et al., 1999). The initial results showed higher prevalence of nose, throat and nervous system symptoms among employees working in air-conditioned rooms. Risks were higher in each symptom category (especially skin symptoms) for women, individuals with acute illnesses (especially nose and throat symptoms), and individuals with low job satisfaction. To work with computers provided with poor software represented a higher risk for symptom development. Among environmental factors, the concentration of volatile organic compounds (VOCs) was associated with mucosal and central nervous symptoms; mouth complaints were linked to exposure to microbial endotoxins, and low operative temperature and eye symptoms were related to nitrogen dioxide levels.

Similar findings to those presented above are generally confirmed by a number of other studies conducted overseas, such as The California Healthy Building Study (Fisk et. al., 1993a, 1993b) and other large-scale surveys sponsored by the National Institute for

Occupational Safety and Health (NIOSH) (Malkin *et al.*, 1996; Sieber *et al.*, 1996) or by the Environmental Protection Agency (EPA) (Wallace *et al.*, 1993; Brightman et al., 1997). In addition, a special effort has been made to identify associations between risk factors such as low-level exposures to certain VOCs (Ten Brinke *et al.*, 1998, Apte *et al.*, 1999) and prevalence of SBS symptoms.

To summarize, SBS is a complex problem with subsequent influence on human comfort and health, resulting from the combined effect of a series of environmental and psychosocial factors. Although the personal and psychosocial aspects are of great importance (Lahtinen et al., 1998), no technical solution may be applied to mitigate the complaints of such origin. The prevalence and intensity of symptoms reported often vary due to gender differences that were commonly mentioned in the above studies. One of the most recent works published on this issue indicates that women suffer more SBS than men independent of personal, most work-related and building factors. These differences are most likely due to gender rather than other factors as women are more sensitive not only regarding the indoor environment but also concerning work-related and psychosocial factors (Brasche et al., 2001). Adopting a better organization of the work environment may diminish the risk of SBS symptoms. Lower occupancy, better ergonomic solutions for acoustics, lighting and workstations may all lower symptom prevalence. SBS also depends on a number of building-related and environmental measures describing the indoor climate. It was associated, in the studies mentioned above, with common building materials (carpets), furnishing (shelves) office machinery (VDT use, copy machines) and air-handling units (air-conditioning, ventilation systems), which may all act as sources of pollutants of chemical and/or microbiological origin. Human exposure to such pollution, likewise, increases the prevalence of symptoms. However, further research is needed to characterize and better understand the close relationship between environmental factors and SBS.

1.1.2 Quantifying Indoor Air Quality (IAQ)

Building surveys are certainly valuable tools to identify occupant complaints, providing useful information and recommendations for managers to operate their building under optimal conditions. However, other evaluation methods are also required to assess IAQ, which may be characterized by its constituents, such as pollutants, and/or comfort and health effects on humans.

The pollutants, which are most frequently discussed in relation to the indoor atmospheric environment, may be classified in two main categories such as gases or vapours and particulate matter (Mølhave, 2003). The first category itself includes a number of well-known compounds such as radon, nitrogen dioxide (NO_2), carbon monoxide (CO), and carbon dioxide (CO_2) as well as formaldehyde, organic compounds including VOCs, and reactive compounds such as ozone (O_3). The particulate group is also subdivided into non-viable matter (particulate matter, biological debris, asbestos, man-made fibres) and viable particles such as moulds, spores, microbes and other organic matter in condensed phase or adsorbed onto particles surface. A total characterization of such complex mixtures and consequently of indoor air in physical and chemical terms is rather difficult. The evaluation is even more complicated when so many compounds interact and cause unexpected comfort and health effects.

The health effects of IAQ were divided into three main classes: priority, secondary and hypothetical health effects (Mølhave, 2003). Priority effects are those for which the causality and the relationship to the exposure are well established. In this case, a compound-by-compound evaluation may be established, i.e. in the case of gases the concentrations of individual compounds are compared with occupational threshold limit values (TLV), which have well-established health effects. In some cases however, insufficient knowledge exists (e.g. accurate measuring method) for setting strict guidelines; therefore recommendations may have to be used instead. For the most important indoor air pollutants a number of guidelines and recommendations exist (ASHRAE, 2001; ACGIH, 2003; WHO, 2000a), but an international set of guidelines is still needed (Levin, 1998). In 1987 the WHO Regional Office for Europe published the "Air quality guidelines for Europe" (WHO, 1987), containing health risk assessments of a limited number of 28 chemical air contaminants, later extended to 35 pollutants found in the outdoor and indoor air (WHO, 2000a). Secondary health effects indoors are less adverse (e.g. SBS), being characterized as reversible (e.g. leaving a complaint building fewer symptoms occur) and the occupants experience no severe consequences. For these effects, the causality may not be known exactly, but an association with IAQ is documented. In this case, a strict compound-by-compound evaluation is not possible (or needed) and recommendation principles or "precaution principles" (i.e. keeping the exposure "As Low As Reasonably Achievable" - ALARA) are needed (Mølhave, 2003). When the causality of certain exposures (i.e. moulds, microbiological contaminants) has not yet been firmly proven but is still discussed in the scientific literature, the health effects are defined as hypothetical. In such cases, the ALARA approach is typically adopted for mitigation of indoor air problems until new evidence and recommendations are set.

In non-industrial environments, exposure to highly toxic airborne agents that may cause irreversible adverse effects, generally are not expected unless resulting from accidental exposures (fire, unvented combustion processes, damaged asbestos materials, etc.). However, there are hundreds or even thousands of chemicals (typically organic compounds) in the air, each in very small concentrations that still may influence humans' sensory perception. These compounds are perceived by humans using the olfactory sense situated in the upper part of the nasal cavity and by the general chemical sense. The olfactory sense is sensitive to odorants. The general chemical sense is located in the mucous membranes in the nose and eyes and it is sensitive to sensory irritants in the air. At this end, the comfort aspect of the human requirement in relation to the IAQ would imply that each chemical should be present at concentrations at which it does not cause odour annoyance or irritation. Unfortunately, this way of characterizing the IAQ is rather complicated for numerous reasons (see section 1.1.3).

A more appropriate way to measure IAQ is to use human judgement directly. The method of using human subjects to evaluate perceived IAQ is not new. Sensory measurements have been used already in the '30s by Yaglou (Yaglou et. al., 1936) and later have been applied by Fanger when he introduced the sensory units expressing the perceived IAQ in "pol" (from lat. pollutio) unit or % dissatisfied, and the sensory pollution load in "olf" (from lat. olfactus) (Fanger, 1988). According to this concept, one "olf" is the rate of air pollutants (bioeffluents) emitted by one standard person (i.e. with a standard hygiene of taking a bath every 1.5 days) at an activity level of 1 met (seated), and being thermally neutral. Consequently, one "pol" is the perceived air quality in a space with a sensory load of one olf, ventilated by 1 L/s. For convenience, the "pol" unit is often expressed in "decipol" (1 decipol = 1dp =0.1 pol). Perceived air quality (PAQ) may be assessed either by untrained human subjects (Fanger, 1988; ASHRAE, 2001) or by trained human subjects (Bluyssen et al. 1989). The main difference between the evaluation methods is that while untrained panels assess PAQ typically on a continuous acceptability scale (Gunnarsen and Fanger, 1992), which can be converted into percentage dissatisfied and decipol, trained panel evaluates PAQ directly in decipol. However, the most common way to assess PAQ is with untrained panels as they are easy to conduct, their precision is reasonably good and a panel of usually 20-40 people can provide significant results for most relevant research investigations. Although the olf-decipol units are based on human bioeffluents, these units are successfully used to evaluate the sensory pollution load from other types of pollution source, by expressing the load in "equivalent standard persons", i.e. "olfs".

1.1.3 Sensory and chemical pollutants in relation to IAQ

As mentioned earlier, secondary health effects are more likely to occur in non-industrial environments, which supports the recommendation that PAQ should be evaluated from the sensory effects of the substances in indoor air rather than from toxic effects. After focusing on formaldehyde as a major indoor pollutant, there has been a considerable interest for about two decades in volatile organic compounds (VOCs), assuming that they may affect PAQ, cause eye and airways irritation and consequently increase the prevalence of SBS symptoms. The definition of VOCs suggested by WHO (1987) includes all organic compounds in the boiling point range with a lower limit between 50-100°C and an upper limit between 240-260°C. Other classes of gas phase organic compounds have also been defined with respect to the sampling media and boiling point as very volatile (VVOC) and semi volatile (SVOC) organic compounds. A great number of studies have been conducted to measure concentrations of VOCs, identifying over 300 compounds in indoor air (Berglund et al., 1986). The concentrations of single VOCs reported were generally below 50 $\mu g/m^3$, with most below 5 $\mu g/m^3$ (Brown et al., 1994). In a recent review, Wolkoff and Nielsen (2001) provide a list of "ubiquitous" VOCs that are major compounds and those most often found in indoor air by a number of investigators (Brown, 1999a; Bernhard et al., 1995; Holcomb and Seabrook, 1995, Reitzig et al., 1998; Girman et al. 1999; Bornehag and Stridth, 2000). A number of exposure studies have also been initiated to evaluate the effects of low-level exposure of VOCs mixtures on humans (Mølhave, 2000). However, most of these studies included a limited number of VOCs, which concentrations were often higher compared to those measured in the field investigations.

The direct exposure/effect connection between VOCs and health outcomes, however, is not so straightforward. The low concentrations of VOCs shown in the field studies cannot explain the sensory effects reported (with some exceptions, e.g. formaldehyde). Yet the exposure in the breathing zone may often be higher compared to the sampling location. For example, there is a wide range of VOCs absorbed onto deposited particles that may reach the breathing zone by re-suspension (Wilkins *et al.*, 1993). After failure to characterize IAQ with the traditionally computed total number of organic compounds (TVOC) (Andersson, 1997; Wolkoff, 1995), which itself was widely misused (Brown et al., 1994), a number of new questions were raised in connection with VOCs. These are shortly described in the following:

The number of identified VOCs in the air is strongly related to the performance of the sampling/analytical methods/instrumentation used by the laboratory. Low concentrations in the field are difficult to identify and those that are measured may not necessarily be responsible for the sensory effects (Wolkoff et al., 1997; Wolkoff and Nielsen, 2001). Uncertainties are also encountered regarding the odour threshold of chemicals that is influenced by the evaluation technique used (e.g. sniffing, dilution and air supply techniques) and the sensory panel, accounting that the odour threshold limits are based on 50% detection of odour by a standardized panel of judges, who may perceive odours with different sensitivities (even order of magnitude). In connection to the sensory behaviour of a mixture should be noted that the combined odour intensity of a mixture is less than the sum of the single odour intensities if the concentration of odorous VOCs in the mixture is above the odour threshold (hypo-addition). However, if the individual VOC concentration is below the odour threshold, the mixture may be hyper-additive (i.e. have stronger intensity). Moreover, above odour threshold levels, the intensity of the strongest VOC alone may govern the perceived total intensity of the mixture (Berglund and Lindvall, 1992; Laing et al., 1994; Cain et al., 1995).

Indoor chemistry involving ozone and nitrogen oxides (NO_x) has received special attention in the last decade. These species are transported indoors through ventilation or infiltration, but they also have indoor sources. Ozone may be emitted from office machines, electrostatic filters and from commercially available ozone generators, while NO_x is mainly produced from gas burning. Although ozone is a powerful oxidizing agent, it reacts slowly with most indoor pollutants. However, there is a subset of unsaturated VOCs (typically terpenes), which react with ozone at a sufficiently fast rate to compete with normal air change rates (Weschler, 2000). The reactions have been demonstrated to produce hydroxyl radicals (OH), hydrogen peroxide (H_2O_2), submicron and ultra-fine particles (Weschler and Shields, 1997, 1999; Weschler, 2001). The products themselves are characterized as being more irritant, but they initiate a series of reactions that generate other radicals and ultimately produce species such as saturated and unsaturated aldehydes, ketones, organic and inorganic acids, that are more likely to cause sensory effects (Wolkoff et al., 2000). Especially unsaturated aldehydes are of interest as they have very low odour threshold (down to ppt levels). Ozone also reacts with NO_x to ultimately form inorganic acids, but NO_x is also involved in a series of other reactions with the radicals mentioned above (Weschler and Shields, 1997).

As a conclusion to the problems encountered in relation to VOCs and for a better characterization of IAQ, a broader definition of the organic compounds was recommended by a number of investigators (Wolkoff and Nielsen, 2001; Bornehag and Cain, 2000). According to the new concept, OCIA (Organic Compounds in Indoor Air) was defined to include all biologically relevant organic compounds (i.e. all organic compounds with molecular weight less than 500-1000 Da), excluding proteins and glucans. Thus, according to the new "OCIA universe", all organic gases and vapours, and the compounds already defined by WHO are included, in addition to organic species (i.e. radicals and ionic species, such as acid salts and ionic surface-active compounds) adsorbed onto particles (Wolkoff and Nielsen, 2001).

Until the newly defined concept of OCIA is better understood and related to IAQ problems in the perspective of future research, it is still possible to look into available data, which can be reanalysed using current knowledge. It is still believed that indoor air pollution, including VOCs, is most likely a cause of health effects and comfort problems (Andersson et al., 1997). However, the TVOC concept is not an effect predictor. It can be used as a screening tool in relation to exposure characterization and source identification, but with considerable caution and well-defined evaluation methods for a specified range of VOCs (Mølhave et al., 1997, Mølhave, 2003). Recent developments in indoor chemistry provide new tools in the search for IAQ indicators. Nowadays, there is a better understanding that low terpenes, ozone or even TVOC levels measured in previous field studies might indicate chemical reactions that could contribute to sensory effects or SBS symptoms. The "lost TVOC" concept (i.e. chemical transformation of the VOCs into more irritating compounds that are not identified by the TVOC procedure) with elevated levels of formaldehyde was already reported (Sundell, 1994; Groes 1995). Indeed, the reaction of O_3 or OH radicals with unsaturated hydrocarbons (e.g. limonene) was shown to result in simple products such as formaldehyde, acetaldehyde, hexanal, nonanal and other more complex species. A number of other studies reviewed in the previous section connected the use of photocopiers and laser printers to increased SBS symptoms, which may indicate the implication of ozone in the indoor chemistry. Finally, the presence of moisture/air-conditioning was also among risk factors in most of the studies reviewed. Elevated water content also initiates a number of reactions in the air and material surfaces (Weschler and Schields 1997, Weschler, 2001) resulting in a number of compounds that affect sensory perception. Water content and temperature of air has a modest effect on the VOC emission from indoor surfaces but has a strong direct influence on perceived air quality (Fang, et. al., 1998a, 1998b, 1999a).

1.1.4 Ventilation of buildings

When a human being created the first shelter and built an environment to protect himself against climatic elements, he was already faced with the problem of ventilation. The air within an enclosed environment is always more polluted from such sources as humans than outdoors. Consequently, the main aim of ventilation is to exchange the polluted air with "fresh" (unpolluted) outdoor air, diluting and removing the pollutants indoors. Recognizing that humans do not emit noxious but smelly compounds (Brown-Séguard and d'Arsonval, 1887), ventilation became primarily a question of comfort and not of health. The view of eliminating body odour and maintaining thermal comfort in non-industrial buildings characterized the ventilation standards from Yaglou's experiments (Yaglou et al., 1936) almost up to the '80s. The CO_2 levels measured were used primarily as indicators of human bioeffluents, according to which the ventilation requirements were set (i.e. keeping CO_2 concentrations below 1000 ppm as recommended already by Pettenkofer (1858) in the mid 19th century). It may not be adequate, however, to ventilate merely to eliminate body odour, when currently thousands of other materials and office equipment emit odorous compounds indoors. The need for better ventilation became an issue only after the health aspect of pollutants such as radon, formaldehyde or dust mites were seen (Swedjemark, 1979; Andersen, 1979; Korsgaard, 1979), and WHO (1983) drafted the risks of IAQ problems. The view to ventilate not only for body odour but also for any other air pollutants that potentially may cause a degradation of PAQ was introduced by Fanger (1988). Thereafter, the new ventilation standards (ASHRAE, 1989) and guidelines (CEN, 1998; ECA, 1992), besides the health aspect (i.e. comparing the concentrations of well-known pollutants at a given ventilation rate to TLV values), adopted the philosophy to ventilate for "acceptable indoor air quality", allowing an additional increase of the ventilation requirements due to the emission from indoor materials. The minimum ventilation rates provided reflect a given air quality level expressed in % dissatisfied, typically established between 10% and 30%. These are 20% according to the US regulations (ASHRAE, 2001), while the European guideline (ECA, 1992) provides three categories of air quality corresponding to 10%, 20% and 30% dissatisfied with the air quality. The first category was later updated to 15% in the CR 1752 technical report (CEN, 1998), leaving the two other categories unchanged. In addition, these guidelines provide alternative methods to determine the required ventilation whenever it is believed that the comfort requirement may not be achieved. Currently, this is possible by adopting the comfort model given by Fanger (1988). According to this model, the total outdoor air supply to a space is calculated as a function of the air quality perceived by impartial human subjects indoors and outdoors, on the total sensory pollution load in the space, and on the ventilation effectiveness (Equation 1.1). A systematic methodology of calculating the required ventilation rates to meet the comfort requirements is given in CR 1752 technical report (CEN, 1998).

$$Q = 10 \cdot \frac{G}{C_i - C_o} \cdot \frac{1}{\varepsilon_v}$$

Equation 1.1

Where:

Q is the ventilation rate required for comfort, in litres per second (L/s);
G is the total sensory pollution load, in "olf" (olf);
C_i is the (desired) perceived air quality indoors, in decipol (dp);
C_o is the perceived air quality outdoors, in decipol (dp);
ε_v is the ventilation effectiveness (-), reflecting that the concentration of pollutants may not be uniformly distributed throughout the whole space.

The evaluations made by the sensory panel are based on immediate perception. Furthermore, it is assumed that the sensory pollution load from different sources, such as ventilation system, building materials, furnishing etc., is additive, i.e. the total sensory pollution load may be calculated by simple addition, since the sensory load of each individual source is expressed in "equivalent standard people" (Fanger, 1988; Wargocki, at al., 1996; Wargocki, 1998).

1.2 Pollution sources in the indoor environment

There is a plethora of sources, such as combustion (gas, wood, tobacco), materials (building materials, furnishing, consumer products), equipment, biological sources (people, plants, fungi, microbial growth, animals and food) and deposited dust (Wolkoff, 1995; Pedersen, 2003) that all contribute with different amounts of pollutants to the degradation of IAQ. Traditionally, the main concern in non-industrial buildings was given to the emissions of VOCs since they affect human perception even at very low concentrations (see section 1.1.3).

Wolkoff (1995) categorized the VOC sources according to their time emission profile into building-, human activity- and outdoor-related sources. Building products represent the largest surfaces indoors, and thus they are considered major VOC sources indoors. Their emissions last for a longer time, typically weeks or years. The sources related to human activities, including household and consumer products as well as various office equipment, also represent major VOC sources, but dominate for shorter durations (minutes, hours) at different locations in a building. Both the building- and human activity-related source categories were shown to be equally important when evaluating their impact on the indoor environment (Seifert et al., 1989; Wolkoff et al., 1991). The outdoor-related emissions dominating typically for hours, depend greatly on the outdoor sources, such as traffic, industry in the neighbourhood.

The investigations of indoor sources with the ambition to characterize the emissions and to evaluate their impact on human health, perception and comfort have a long history. Therefore, the literature review presented through a number of studies in the subsequent chapters is focused mainly on two types of sources, i.e. floor coverings and PCs, that are predominant within their categories and both may act as sources of organic pollutants indoors. While floor coverings are traditional building materials, being subjected in a number of investigations, PCs may be considered as relatively new objects in the palette of electronic equipment in the indoor environment, rarely mentioned as potential sources of air pollutants.

1.2.1 Complaints related to emissions from building products

The reviewed literature in section 1.1.1 revealed a number of building factors affecting the prevalence of SBS symptoms. Most studies associated the presence of carpeting, often described as "fleecy" factor, with an increased prevalence of SBS symptoms (Mendell, 1993). The effect of "fleecy" factor was more evident in a number of intervention studies where the suspected carpet was changed with other floor materials such as PVC, linoleum, polyolefin tiles (van Beuningen et al., 1994; Wargocki and Fanger, 1997, Pejtersen et al., 2001) found to be less emitting from evaluations made in laboratory experiments (Knudsen et al., 1994, 1997). A number of studies reported increased SBS symptoms among school personnel and children too, due to the presence of carpeting and fleecy wall materials. The complaints were diminished in each case when the suspected source was removed (Norbäck and Torgén, 1989; Norbäck, 1995; Mathisen et al., 2002).

Removing carpets from indoor environments might lower the prevalence of symptoms; however, in some cases the installation of other materials in homes and school environments was shown to cause adverse health effects among people, especially children. A Norwegian case-control study indicated that the presence of PVC and other plasticizer-containing surface materials in homes increases the risk of bronchial obstruction during the first two years of life (Jaakkola et al. 1999). In a population-based cross-sectional study of 2568 Finnish preschool children, lower respiratory tract symptoms including persistent wheezing, cough, and phlegm were significantly associated with the presence of plastic wall materials whereas upper respiratory symptoms were not (Jaakkola et al. 2000). In another study conducted in 9 Russian cities among 5951 elementary school children the risks of asthma and asthma-related symptoms were related to installation of new materials such as linoleum flooring, synthetic carpeting, particle boards and new furniture (Jaakkola et al., 2002). The authors emphasized that linoleum in colloquial Russian represents a large heterogeneous group of synthetic floor materials and thus an unknown proportion of PVCs.

Powdering of floor polish on linoleum was associated with increased eye and airways irritations among pupils in a Swedish secondary school (Malmberg et al., 2000). Exposure to rosin (known to be used for linoleum varnish) compounds emanating from linoleum flooring was also linked to facial dermatitis (Karlberg et al., 1997). In a study by Wieslander et al., (1999) increased inflammatory effects were measured, when 57 social workers were moved to a newly redecorated building and powdering from the polish on the new linoleum floor occurred. Though the materials in the new building were claimed to be "low emitting" and the personal outdoor airflow was twice as much as in the old building (22 L/s per person), the move resulted in an increased nasal potency and eosinophilic cationic protein (ECP), and lysozyme in nasal lavage fluid, which suggested an increased inflammatory effect in the new building. However, the change in nasal and ocular symptoms among the occupants was not significant. The authors could not identify the causative agents, specifying that although the VOC and formaldehyde levels were low, the concentration of terpenes (sum of pinene, carene and limonene) were significantly higher compared to the old building.

The results of the above studies suggest a negative effect of the floor polish. However, emissions from linoleum covering and associated chemical reactions on the surface could also create compounds, such as fatty acids and aldehydes that may be responsible for such effects (Jensen et al., 1995a; 1995b; 1996). In addition, high levels of terpenes may indicate a potential for reactions if the ozone level increases in the indoor environment (see section 1.1.3). Consequently, it may occur that a joint mechanism causes the observed effects, even if the polish material was harmless to health. In case of re-suspension due to different indoor activities, the powder, having adsorption capability for various VOCs, would be an excellent carrier of the compounds produced on the linoleum surface to the human upper respiratory system. Furthermore, emissions from linoleum are also known to reduce tear film stability and nasal volume (Kjærgaard et al., 1999). The emission of pollutants from linoleum is even stronger if dampness from the building structure is involved (Wolkoff et al., 1995). This may result in increased upper respiratory complaints, dermal symptoms and a higher incidence of sick leave among office employees (Palomäki et al., 2002).

Often the complaints of SBS symptoms arise after building renovations. Reizig et al., (1998) reported 46 out of 51 cases where building occupants complained of increased symptoms, such as eye irritation and headaches, following renovation of their homes. Furthermore, increased concentrations of well-known terpenes, especially α- and β–pinene, and less common compounds, such as phenoxyehanol and longifolene, were measured. The occurrence of elevated α- and β–pinene levels, that also correlates with the limonene levels (though not reported), were associated with new building materials often claimed as "natural products" of low VOC emission. Their results could be confirmed by showing a relationship between the building materials after the renovations and the chemical compounds detected. Indeed, turpentine spirit, often preferred in natural products e.g. paint thinner, is obtained by steam distillation or other means from wood. Consequently, it contains a number of terpenes that will migrate also into the air. Similarly, longifolene is not a part of turpentine spirit but of colophony, which is produced from pine oleoresin and used in adhesives, surface coaters or in varnish, while phenoxyehanol is used in modern products as a substitute for solvents that are of public concern (e.g. xylene). Compared to traditionally used constituents, each chemical found in natural products has a higher boiling point (i.e. less volatile). Consequently, they are released into the building environment at a lower level (i.e. contribute to a lesser extent to the TVOC level) but on a longer time scale.

1.2.2 PCs and the work environment

In the industrialized world, the use of electronic equipment in the indoor environment has kept pace with technological developments. Personal computers (PCs) - consisting of the unit housing the CPU and a monitor – have become one of the most prevalent items of electronic equipment in indoor settings. According to market research studies, the one billionth PC was sold recently and the number of PCs that are currently in use worldwide has reached 500-600 million units. While it has taken the PC industry approximately 25 years to reach the billion mark, the industry is forecasting to ship the two billionth PC in 2008. According to the yearly data, over 35 and 49 million PC units were sold in Europe and US, respectively, in the year 2000 and the worldwide PC shipment will reach 181 million units by 2005 (Reynolds, 2002).

These reports also show that at least 1 billion people have become familiar with computers in the last two decades. The number of PC users nearly tripled regardless of age, sex and occupation in the past ten years according to a recent survey in Denmark made by the Danish National Institute of Occupational Health. PCs penetrated most workplaces and over a wide spread of job categories are extensively used for more than half of an employee's working hours (Burr, 2000).

The office environment has also changed dramatically in the last two decades as a result of the introduction of PCs. In today's computerized office, it is possible to write and print documents, look up information, read electronic mail, and participate in interoffice conferences without leaving the workplace. These changes have resulted in new work habits and a substantial amount of time spent in front of PCs. Concomitantly, complaints among individuals working with PCs or PC-like display units of unusual fatigue, headaches, eye strain, muscular tension and other SBS symptoms have also increased (Knave *et al.*, 1985; Bergqvist and Knave, 1994; Sundell *et al.*, 1994; Bachmann and Myers, 1995; Kamienska-Zyla and Prync-Skotniczny 1996, Petersen *et al.*, 1999).

For many years, investigators have suspected that electromagnetic fields and radiation from electronic devices have negative effects on human comfort and health. However, research to date has provided no conclusive results supporting that hypothesis (McCann *et al.*, 1998; COMAR reports, 1997; WHO Fact Sheets 201 and 205, 1998). There are some studies showing that static electric fields and electromagnetic radiation from cathode ray tube (CRT) monitors may have slight effects on humans (Skyberg *et al.*, 1997; Clements-Croome and Jukes, 2001). However, the current directives (TCO '99) require manufacturers to produce PC monitors with reduced electromagnetic radiation. Some of the complaints mentioned above are due to poor ergonomic design of both the work place and PC parts such as the mouse or keyboard (Lewis *et al.* 2001; Arås *et al.*, 2001; Cook *et al*, 2000; Swanson *et al.*, 1997).

The pollutants emitted by PCs may also contribute to the observed complaints. However, only a few studies have focused on chemical emissions from PCs and/or CRT monitors. The emissions monitored included volatile organic compounds (VOCs) (Brooks *et al.*, 1993; Black and Worthan, 1999; Corsi and Grabbs, 2000; Wensing *et al.*, 2002; Funaki *et al.*, 2002), particles (Black and Worthan, 1999) and flame-retardants (Sjödin *et al.* 2001; Carlsson *et al.*, 2000; Salthammer *et al.*, 2002). Wensing (1999) also looked at emissions from televisions, which are related to those from CRT monitors.

1.2.3 Sensory and chemical evaluation of indoor sources

1.2.3.1 Emissions from building materials

A substantial effort has been made to characterize building materials according to their sensory and chemical emissions. After the olf/decipol unit was introduced (Fanger, 1988), a number of laboratory studies investigated the sensory emission rate of building materials (Lauridsen et al., 1988, Bluyssen and Fanger, 1991; Knudsen et al., 1994; van Beuningen et al., 1994; Knudsen et al., 1997). The implementation of the results aiming to predict the perceived air quality at the recommended ventilation rates in newly designed buildings however, required a number of further investigations. The new studies revealed that the sensory evaluation of materials is affected by a number of factors, which must be considered when human subjects are used to assess PAQ. To solve the discrepancies observed between the assessments of trained-untrained panels when evaluating perceived air quality, Wargocki (1998) developed a transfer model, allowing the comparison of the two assessment methods. Fang et al., (1998a; 1998b, 1999a) demonstrated in a series of experiments that human perception is greatly affected by the enthalpy of the inhaled air and adjustments should be made. The sensory emission rate of some materials may also be different when evaluating on a small scale (i.e. exposing the sensory panel to air extracted from small chambers through a diffuser) or full scale (the polluted air is assessed in a room at first impression upon entering). This was shown also by several experiments (Fang et al., 1998b, Knudsen et al., 1998; Wargocki et al., 2002a), which reveal that the sensory pollution load depends on the nature of the building materials, which determines the emitted chemicals.

Comparing to the sensory evaluation methods, the evaluation of emission rates from materials at the level of VOCs, the exposure/response mechanisms are more complex (see section 1.1.3). On the other hand, characterizing the materials in terms of VOC emission will make it easier to estimate their impact on IAQ and will lead to a better understanding of the sensory effects. Building materials emit a variety of different VOC classes such as alkanes, alkenes, aromatics, aldehydes, ketones, and fatty acids resulting from primary and secondary emissions (Wolkoff, 1995; 1999). To characterize the chemical emission of a building product, it is important to distinguish between primary and secondary emissions. Primary emissions are free (non-bound) VOCs, generally with low molecular weight originating from solvent residues, additives and non-reacted raw products. The mechanisms involved are evaporation from the surface, diffusion within the material or both. These emissions will generally decay within a year from initially high levels (order of mg/h) following presumably a first order decay model (i.e. exponential). Secondary emissions are compounds that are not originally present in the material, but are formed as a consequence of chemical transformations of original constituents. These are emitted or formed by different processes under special chemical or physical conditions, e.g. dampness of underlay structure (hydrolysis of phthalates), increased temperature (degradation of polymer constituents), oxidation and sorption processes (presence of ozone). The magnitude of such emissions is generally lower (order of μg/h) but the time scale is longer (typically years).

Thus, considering the lifetime of a material, primary emissions will dominate only the first few months, after which secondary emissions will play a major role in the sensory and chemical evaluations. Consequently, the characterization of new materials even with advanced measuring techniques is mostly limited to the primary emissions, and the impact of building materials on IAQ in a real environment is difficult to predict. The results of a recent evaluation of common building materials on a longer time scale (Knudsen et al., 1999) show that building products continue to affect perceived air quality, even when the concentration of primary VOCs is well below their respective odour thresholds. Therefore, it was suggested that odour indices (defined as a ratio of the mean weighted concentration of a compound to the odour threshold) even lower than 0.1 may not guarantee that a building product has no impact on PAQ. The authors emphasized, that a better understanding of the secondary emission processes is essential. Secondary emissions gain even more importance when degradation of materials or other ozone-induced reactions occur e.g. ozone and carpets (Weschler et al., 1992), water damage and linoleum (Wolkoff et al., 1995), ozone and linoleum (Jensen et al., 1996).

Many studies focused on chemical characterization of building materials. Wolkoff (1995) summarized more than 40 studies reporting typical VOC emissions from different materials in indoor use. The methods of evaluating VOC emissions from different sources are becoming more and more standardized (Wolkoff, 1999), creating a link between the occurrences of chemical compounds in the indoor environment and related sources. Most available data refer to carpet (Hodgson et al., 1992; 1993), linoleum (Jensen et al. 1995a; 1995b), PVC flooring (Lundgren et al., 1999), textile floor coverings (Sollinger et al., 1994), latex paints (Sparks et al., 1999; Chang et al., 1999; 2002), PVC coated wall coverings (Uhde et al., 2001), furniture coatings (Salthammer, 1997), wood, wood-based products and office furniture (Brown, 1999b; Jensen et al. 2001), cork products (Horn et al., 1998), and various building products (Hodgson et al., 2002). At the same time, building investigations reveal the concentrations of a wide list of compounds that are commonly measured indoors (Brown et al., 1994; Bernhard et al., 1995; Reitzig et al., 1998; Wolkoff and Nielsen, 2001). As a conclusion of a comprehensive literature survey comprising 22 field investigations, Wargocki (1998) created a list of 133 VOCs occurring in 582 offices in 209 office buildings. As part of the work presented in the current thesis, the list provided by Wargocki was further developed, associating the individual chemical compounds to the related sources reported in the literature. The compounds on the list were prioritised according to the reported occurrence and concentrations in the buildings studied (i.e. how often were high concentrations detected) and to the odour index. The complete data on VOCs and related sources is presented in Appendix 1.

1.2.3.2 VOCs emitted by PCs

Table 1.2.1 gives an overview of the compounds commonly measured by earlier studies investigating the chemical emissions from various electronic devices. One of the earliest investigations made by Brooks *et al*., (1993) reported 14 major VOC compounds emitted by computers and CRT monitors. The fugitive VOC emissions arise from plastics, solvent coatings, adhesives, and encapsulants associated with manufacture. Emission rates of TVOC were observed to peak after 48 hours of operation at values of 180 μg/h with a subsequent decay in emission to 5-10 μg/h after two weeks.

Table 1.2.1 Chemical compounds emitted from PCs and TV sets commonly measured in previous studies

Study:	Brooks *et al.* (1993)	Black and Worthan (1999)	Corsi and Grabbs (2000)	Wensing *et al.* (2002)	Funaki *et al.* (2002)	Wensing (1999)
Electronic Equipment:	towers/ monitors	PCs	PC towers	PC monitors	PC portable	TVs /Video
Ethylbenzene	x	x	x		x	
Phenol	x	x		x	x	x
Styrene			x		x	x
Toluene	x	x	x	x	x	x
Trichloroethene			x			x
Decane			x		x	
Undecane			x		x	
Dodecane			x		x	
Xylene	x	x	x		x	x
2-Ethyl-1-hexanol		x			x	
n-Butanol	x				x	
2-Butoxyethanol	x				x	x
Formaldehyde						x
Cresol	x					x

In another study of Black and Worthan (1999), TVOC and particle emissions ranging from 0.05 to 24.2 and 0.027 to 0.12 mg/hour, respectively, were measured for six operating PCs. The VOCs identified were alcohols, esters, phenol, and aromatic solvents that could represent a source of odour at low levels. These were likely to originate from residual solvents and plastic construction materials that were heated in the inner part of the PC. The monitoring of emissions was completed over four hours for each computer but dynamic variations in emissions, the age and type of the devices were not reported.

Corsi and Grabbs (2000) reported VOC emissions from packaged and active computers (PCs without any display unit). The initial emission rates of TVOC for active computers varied from 0.6 to 1 mg/h followed by a rapid decay in the emissions to 0.1 mg/h in the first four days of continuous operation. A total of 48 VOCs were identified during the experiments. Thirteen VOCs among the identified compounds were found in each computer test and 12 additional compounds were identified in the off-gas of 2 out of 3 computers tested. Based on the data obtained, TVOC and toluene best-fit exponential emission models were also determined. These emission models were used in conjunction with a simple well-mixed room model to predict concentrations associated with 10 new PCs operated in a 63 m^3 room with 0.5 h^{-1} air-change rate. The simulated TVOC and toluene concentration profiles for continuous and 8 h/day (i.e. office use) operation over 72 hour "start-up" have been characterized, pointing out the differences between the two operational modes.

VOC emissions from 19 different computer monitors and 14 laser printers in normal operation were quantified and compared under standardized test conditions in a 1 m^3 emission test chamber by Wensing *et al*. (2002). Device-specific emission rates of TVOC (36÷11099 μg/h), toluene (1÷1045 μg/h) and phenol (7÷223 μg/h) were used to simulate the concentrations in a model room. Toluene and phenol were identified as major compounds in the emission of every monitor over a longer period of time since toluene is a typical solvent used in the manufacture of electronic devices, while phenol originates from circuit boards on phenol resin basis. The VOC emissions of the computer monitors revealed clearly defined exponential decay behaviour over time. New devices had noticeably higher emission levels compared to older devices. However, the decay behaviour for phenol was not as strongly distinct as for other VOCs due to a diffusion-controlled emission process from the circuit board. The individual VOC compounds were found to be similar to those reported in an earlier investigation made on television sets and video recorders (Wensing, 1999) that included a broad number of chemical compounds from different classes such as aromatic and halogenated hydrocarbons, phenols, aldehydes, ketones, fatty acids, esters, alcohols, etc.

Funaki et al. (2002) measured 25 VOCs originating from a brand new portable computer in operation, with a total emission rate of ca. 170 μg/h·unit. Their results also show that, although the device is turned off, some of the compounds are still emitted at low levels (24 μg/h·unit). Moreover, the emission of a 9-month-old portable computer was still at a measurable level with 7.5 μg/h·unit when turned off. The major compounds measured are similar to those reported earlier, including alcohols, aldehydes, ketones, esters, halocarbons, terpenes, aromatic hydrocarbons and alkanes.

1.2.3.3 Flame-retardants emitted by PCs

Flame-retardant (FR) chemicals are most frequently used to improve the fireproof performance of different materials, particularly of wood and wooden products, polymers, and textiles. Generally, they either reduce ignition susceptibility or lower flame spread once ignition has occurred, thus increasing the escape time in case of fire. There are obvious benefits in using flame-retardants, since they save many human lives and property from fire, but it is often not taken into consideration that during the burning process, toxic products can be produced due to thermal decomposition of flame retardants. These can contribute to the contamination of the atmosphere or form persistent sediments. The flame-retardants may be physically blended with the host polymer (additive FR) or chemically bonded to it (reactive FR). Flame-retardants and their decomposition products may also be released in the indoor environment under normal living conditions, particularly when they are used as additives in the materials to be protected.

There are three main families of flame-retardant chemicals: inorganic compounds (metal hydroxides), halogenated compounds (based primarily on chlorine and bromine) and organophosphorus products (primarily phosphate esters). The first group represents about 50%, the second and third groups 25-25% of the worldwide flame-retardant production by volume.

Several types of flame retardant used in plastic components of electronic goods, such as polybrominated diphenyl ethers (PBDE), organophosphate esters and other brominated flame retardants were detected in the indoor air samples from a plant engaged in recycling electronics goods, a factory assembling printed circuit boards, a computer repair facility, and offices equipped with computers (Sjödin *et al*. 2001). The highest values were detected in the air of the dismantling hall at the recycling plant, where the average concentration of decabromo-diphenyl ether (BDE-209), tetrabromobisphenol A (TBBPA), and triphenyl phosphate (TPP) were 36, 55 and 58 pmol/m^3 (36, 30 and 19 ng/m^3). Tetrabromo diphenyl ether (BDE-47) was the most abundant PBDE congener detected in the air in the computer teaching hall with 0.72 - 0.8 ng/m^3. BDE-209 . TBBPA was also detected in the office air with computers at low levels of 0.083 and 0.036 ng/m^3.

TPP was also identified in a computerized indoor environment (Carlsson *et al*., 2000) where a PC equipment with brand-new CRT monitor was in continuous operation. The initial concentration of TPP in the office raised up to 100 ng/m^3 in one day, then decreased by 50% in one week, and further decreased to approximately 10 ng/m^3 in the next 183-day period. The source of emission was found to be the PC monitor. TPP was found in the plastic material of the PC monitors' outer cover in 10 out of 18 monitors tested. Since TPP has a documented contact allergenic effect on humans, the authors claim that the utilization of this compound as an additive in PC monitor-covers may affect human health. Although TPP levels are far below the current workplace exposure limits (0.224 ppm) used in all developed countries (Beard *et al*., 2001), and although the toxicological data surveys indicate that TPP has relatively low impact on health (Danish EPA, 2000), these low levels of TPP may induce skin sensitization and contact dermatitis in some people.

1.3 Source control and required ventilation rates

The concentration of pollutants in an enclosed space depends mainly on the emission rate of the indoor sources and the rate at which the contaminants are removed (diluted) by ventilation. Consequently, good or acceptable air quality may be provided with an adequate control of both emission and ventilation rates indoors. Pettenkofer and other researchers of his era within the field of building hygiene stated already in mid. 19th century that source control is a prerequisite for good hygiene. Similarly, among indoor researchers it is generally assumed that a low-emission building product is "better" than a high emission product for the environment. Source control has gained much higher importance in the last decade, reflected in the conclusions of the European Audit Project (Bluyssen et al., 1996). The average outdoor airflow rates found in 56 office buildings were 1.9 L/s·m^2 or 25 L/s per person, but in spite of this generous ventilation that meets any requirements set by standards, 30% of the occupants and 50% of the visitors found the air unacceptable. Similarly, 30% to 50% of 6537 people complained about dryness and various SBS symptoms, and the complaints showed a fairly good correlation with the perceived air quality of the occupants. The average level of CO_2 measured in these buildings was 673 ppm, which is far below the recommended levels, indicating clearly that human bioeffluents were less important pollutants than the emissions from other sources. Consequently, the significant pollution sources in the audited buildings were the materials, furnishing, ventilation system and other activity-related sources in the offices. The fact that perceived air quality correlated with the outdoor air supply rates but not with the energy consumption of the buildings, indicates that good indoor air quality may be achieved even at low energy use. Thus, improving indoor air quality without consuming more energy is very attractive if an adequate source control can be applied. The beneficial effects of an improved indoor climate was also shown in another Danish study (Pejtersen, 2001). However, it was also indicated, that the improvements in human response were not as significant in the offices where only the ventilation was improved as in the offices where both the floor covering and the ventilation were changed.

A strategy of developing materials with reduced chemical emissions (VOCs) was adopted already in the '80s on the principle of ALARA (Andersen et al., 1982; WHO, 1989), as little information was available at that time on the emission mechanisms from materials and related effects on humans. Since then, major achievements were seen in understanding the health and comfort impact of indoor air pollutants and also in the development of methods for emission testing and standardization. Nowadays, there are six national and two international labelling schemes in Europe (Maroni and Lundgren, 1998; Wolkoff, 2003) with the ultimate goal of characterizing VOC emissions and labelling building products. However, about half of the schemes are concerned mainly on reporting TVOC and only a few are focused on detailed characterization of emissions in terms of sensory and chemical evaluations. Furthermore, these schemes are also limited when characterizing primary emissions (see section 1.2.3.1). Nevertheless, it is still believed that lowering the primary emission of pollutants will have a positive effect on secondary emissions too, decreasing the probability of a reduced IAQ that is often perceived in various indoor environments. Using the current knowledge will also make it possible for product manufacturers to produce new materials not only with low emissions but also more "ozone resistant" and less sensitive to water damage.

Source control has also gained attention when a number of experimental and intervention studies have failed to show that increasing ventilation rate will have positive effects on SBS symptoms. In the review by Mendell (1993), the studies conducted on the topic of ventilation and health effects showed no significant improvements in symptom prevalence when increasing the ventilation rates typically in the range from 10 L/s per person up to 20-30 L/s per person. This reflects that the scientific evidence to recommend minimum ventilation rates for acceptable indoor air quality when setting standards is rather limited and raises several questions concerning the ventilation rate required to establish a healthy indoor environment.

Godish and Spengler (1996), reviewing the literature on the relationship between ventilation and IAQ, emphasize a number of complex factors that should be considered when using general ventilation to mitigate building-related health complaints. These factors include the following: study design, accuracy of ventilation rate measurements, inadequate mixing, source strength and concentration of contaminants either in the ventilation system or indoors, dynamic interaction between sources and ventilation rates. The authors conclude that limited information is available to support that ventilation increased up to 10 L/s per person may be effective in reducing symptom prevalence and % dissatisfied with PAQ, and a further increase in the ventilation rates may not be effective.

Recent review (Seppänen et al., 1999) applying a precise selection criteria, reviewed 20 cross-sectional investigations conducted mostly in office buildings that reported associations between ventilation rates and human health/comfort. Based on the significant findings of the studies included, the authors concluded that in office buildings or similar spaces an increase in ventilation rate between 0 and 10 L/s per person will significantly reduce occupant symptoms and improve perceived air quality. In addition, the increase in ventilation rates above 10 L/s per person up to ca. 20 L/s per person may further reduce symptoms and improve air quality, although the benefits are less certain based on the available data.

Up to date, the consensus about ventilation rates is that outdoor ventilation rates lower than 25 L/s per person increase the risk of SBS symptoms and short-term sick leave, and decrease productivity in offices. Possibly, the same applies for schools and other non-industrial environments. In addition, air change rates above 0.5 h^{-1} in homes reduce the degree of infestation of house dust mites. These findings are derived from the report of a multidisciplinary group of scientists called "EUROVEN" (Wargocki et al., 2002c) after a thorough review of 105 papers published in peer-reviewed scientific journals on the subject of ventilation and human health or comfort. This report also supports the other two reviews (Mendell, 1993; Seppänen et al., 1999) mentioned above that, compared with naturally or mechanically ventilated buildings, those with air-conditioning systems may present an increased risk of SBS symptoms for several reasons, such as improper maintenance, design and functioning of the air-conditioning system. Nevertheless, the review also reflects that pollution sources other than humans are of high importance indoors. Consequently, a proper source control is needed as much as the required ventilation rates to be established on all pollution loads present indoors. This is why many ventilation and indoor air quality guidelines (ECA, 1992; FISIAQ, 1995, CEN, 1998) advocate reducing pollution sources indoors and designing low-polluting buildings because this will reduce ventilation requirements and at the same time improve air quality.

On the other hand, increasing the outdoor airflow from 10 L/s per person to 25 L/s per person in order to achieve acceptable indoor air quality would imply an increased first costs and energy costs of the ventilation system that will elevate the running costs of a building. Eto and Meyer (1988) evaluated the costs of increased ventilation rates according to the changes established in a newer standard compared to an older one. They estimated that increasing minimum ventilation rates from 2.5 L/s per person (ASHRAE, 1981) to 10 L/s per person (ASHRAE, 1989) would increase energy operating costs of a variable air volume (VAV) ventilation system with an economizer by no more than 5% and first costs by no more than 1%. In addition, according to another energy simulation (Eto, 1990), it was shown that the annual energy operating costs for small- and medium-sized offices situated in different outdoor climates would increase on average by 14% and 9% respectively. Thus, increasing the ventilation rates from 10 L/s per person to 25 L/s per person would imply roughly 15-20% increases in the HVAC energy.

By using the comfort equation of Fanger, the improvements in indoor air quality can be directly calculated when increasing the ventilation rates (Equation 1.1). In a low-polluting building with a typical occupancy of 0.07 person/m^2 (landscape office) the total sensory pollution load (people and building) would be 0.17 olf/m^2. Consequently, the perceived indoor air quality would be 2.5 dp (or 30% dissatisfied) and 1 dp (15% dissatified) when ventilation rates are 10 and 25 L/s per person. According to the relation provided in section 1.4 (Wargocki, et al., 2000b; 2000c) between IAQ and productivity, the related benefits of an improved indoor climate from 2.5 dp to 1 dp would increase the productivity by 1.65%. This means that such an improvement would justify an increase of 165% on the energy side, assuming a factor 100 between the costs of human resources and the expenses of buildings (see section 1.4).

The ventilation requirements discussed above are actually in good agreement with the recommendations of CR 1752 technical report (CEN, 1998). The report specifies that the targeted air quality levels (15%, 20% and 30% dissatisfied) may be achieved at different ventilation requirements if the building is "low-polluting" (≤0.1 olf/m² floor) or "non-low-polluting" (0.2 olf/m² floor or more). The design criteria accounting for the sensory pollution from building materials specify an additional ventilation rate of 1 L/s m² and 2 L/s m² respectively for low- and non-low-polluting buildings on top of the minimum ventilation rates set for people (10 L/s per person). Thus, in the case of open-plan offices (0.07 person/m²), the total airflow required to achieve the requirements of an air quality category "A" (15% dissatisfied) is 1.7 L/s m² (24 L/s per person) for "low-polluting", and 2.7 L/s m² (34 L/s per person) for "non-low-polluting" buildings.

In conclusion, the optimum ventilation rates for a particular building will always depend on indoor pollutant emissions, outdoor pollutant levels, the requirements of the building occupants and on energy considerations.

1.4 Productivity and IAQ

The quality of the indoor environment potentially affects not only the health outcomes of the building occupants but also their work productivity. Several routes may explain this linkage. The health effects of poor environmental quality resulting in increased absenteeism from work of various durations, or in the longer term, a premature work disability, i.e. shorter productive lifetime, will cause a 100% productivity loss. The productivity, however, may be negatively affected to a smaller extent by a number of environmental factors and inadequate workplace ergonomics. Many research activities have been addressed earlier to study the relationship between noise, temperature and lighting on the performance of workers, as these factors could be easily measured, were not difficult to control and the outcomes were more evident (Weinstein, 1974; Wyon, 1974; Wyon et al., 1979; Boyce et al, 1989, Banhidi et al., 1996).

The effects of indoor air quality on productivity became an issue only in the last decade, as a result of extensive research and an understanding of the strong connections between factors such as ventilation, air-conditioning, indoor pollutants and adverse effects on health and comfort. The complexity of a real environment makes it very difficult to evaluate the impact of a single parameter on human performance, mostly because many of them are present at the same time and as a consequence, act together on each individual. In addition, worker motivation affects the relationship between performance and environmental conditions (e.g. highly motivated workers are less likely to have reduced performance in an unfavourable environment; however they may become more tired that may also affect performance). A common approach, to evaluate the influence of climatic factors on human performance could be to measure the extent to which the SBS symptoms occur, as these symptoms are known to cause distraction from work or even short-term absenteeism. However, this link is not well established yet and must be better understood and recognized. A possible mechanism may be described as follows: (1) inadequate ventilation or superfluous emissions from different sources increase the concentration of pollutants, which negatively affect perceived air quality; (2) reduced air quality negatively affects the central nervous system, increasing SBS symptoms such as headache, difficulty in concentration, tiredness; (3) these symptoms will cause distraction from work and decreased work ability, i.e. productivity loss. Nevertheless, indoor pollution may also exacerbate the sensation of dryness and irritation of eyes. As a consequence, a higher blinking rate and watery eyes will negatively affect visual skills and decrease the performance of visually demanding work.

There is limited information in the literature showing a direct relationship between SBS symptoms and worker productivity. Analysing the data of BOES (see section 1.1.1), Raw et al., (1990) found that people reporting more than two symptoms on the SBS list are likely to have reduced performance ratings, and a linear relationship exists between SBS and self-estimated productivity. Based on his data, Fisk and Rosenfeld (1997) estimated an average decrement in the self-reported productivity of 2%. Raw and his colleagues emphasized that the responses evaluated on a 9-grade subjective scale reflect the responder's belief, regardless of whether that belief is correct, and the actual productivity was not assessed. Mucous and work-related symptoms were also found to affect self-reported productivity (Hall et al., 1991), but no further validation on the accuracy of self-reports related to the actual productivity loss were made by other field investigations. Measured data in a field experiment (Nunes et al., 1993) indicate a relationship between SBS symptoms and worker performance. As part of an SBS study of 3 weeks, in which the outdoor air supply was experimentally varied, 47 employees undertook two computerized neurobehavioral tests (Baker et al., 1985) at their workplace. The workers presenting with more SBS symptoms were found to respond 7% longer in a continuous performance task and to have 30% higher error rate in a symbol-digit substitution test. As correlations were found also with temperature but not for the measured pollutants, it is more likely that the effects observed were not only due to air quality factors.

There is growing evidence that poorly perceived indoor air quality is likely to have a negative effect on work performance. This effect was demonstrated by Wargocki et al. (1999) when he exposed impartial female subjects in a realistic office environment to the emissions from a carpet. The study showed that by improving perceived air quality, the SBS symptoms were reduced and performance of typical office tasks increased. These findings were later confirmed by two other independent investigations conducted in Denmark (Wargocki et al., 2000a) and Sweden (Lagercrantz et al., 2000) using the same type of pollution source, but different subjects. The quantitative relationships were developed based on these results and show that for every 10% increment in % of dissatisfied in the range 25-70%, a 1.1% decrement in performance can be expected, or increasing the air quality level by 1 decipol in the range 2-13 dp can cause 0.5% loss in work performance (Wargocki et al., 2000b).

It is natural to ask whether such an improvement in the air quality level to obtain only a small increment on the productivity side will justify any investment to improve the indoor air quality, especially when there are no obvious complaints, and knowing that thermal conditions even within the thermal comfort zone may reduce performance by 5-15% (Wyon, 1996). The salaries of workers in typical office buildings exceed the building energy and maintenance cost by approximately a factor of 100. The same applies for the salaries and annual construction or rental costs (Woods, 1989; Skåret, 1992). Thus, even a 1% increase in productivity should be sufficient to cover any expenses related to doubling of energy or maintenance costs or other large investments involving construction costs or rent. In view of the fact that a good IAQ also reduces the prevalence of SBS symptoms, considerable gains and savings may result in health care costs, involving billions of dollars nation-wide in the US (Pillgram, 1991; Fisk and Rosenfeld, 1997; Fisk, 2000; Milton et al., 2000).

The review of Wyon (1996) on the published literature showed that the payback time for general upgrading of currently unhealthy office buildings (representing 40% of the building stock) would be as low as 1.6 years if only a 0.5% increase in the overall productivity is achieved. Moreover, the cost-benefit simulation made by Djukanovic et al., (2002) showed that the annual increase in productivity was worth at least 10 times as much as the increase in annual energy and maintenance costs, when improving PAQ in office buildings, specifying a pay-back time of no more than 4 months due to the productivity gains achieved. Thus, it seems that there is great potential in investigating the effects of indoor air quality on human health, comfort and productivity.

1.5 Rationale

Previous studies (Wargocki et al., 1999; 2000a; Lagercrantz et al., 2000) showed negative effect of reduced ventilation and increased pollution load on perceive air quality, SBS symptoms and performance. They were done using one type of pollution source and the interventions, i.e. source removal and changing the ventilation rate, were made independently in separate investigations. Although a 20-years-old carpet, used in these studies, represents a significant source of primary and secondary emitted pollutants (Weschler et al., 1992), it may not be representative for many buildings. Moreover, the emissions from a number of other floor coverings, furnishing, office equipment and other materials contribute to the total pollution load of a non-industrial environment. Consequently, these studies require generalization for other typical building-related sources and it would be valuable combining the interventions to examine their relative impact on PAQ, human comfort and performance. The expertise should include pollution sources of different types including building products and electronic equipment that are prevalent and commonly used in various indoor settings. The selected sources should have fairly stable emissions of VOCs that are expected to degrade perceived air quality. With these assumptions, the following materials and electronic equipment were selected: linoleum floor covering, sealant and wooden bookshelves with books and papers, and PCs.

In the previous sections, linoleum was mentioned several times, either in connection with sensory effects or in connection with ozone, as stimulating reactions. Linoleum is often claimed to be a "natural" product and it is preferred as an alternative to many synthetic materials. However, linoleum was shown to emit odorous compounds and VOCs, such as aldehydes and organic acids, which are difficult to characterize as primary emissions since many of them result from the oxidation processes. Consequently, the secondary emissions of linoleum will affect indoor air quality not only for years but also perhaps for a whole lifetime (Wolkoff et al., 1991; 1995; Jensen et al, 1994; 1995a; 1995b; 1996). Furthermore, linoleum also emits a number of compounds with low odour index that are commonly measured indoors as is shown in the evaluation list of VOCs and related sources (Appendix 1).

Based on the results of the Danish Town Hall study, which showed associations between prevalence of SBS symptoms and the shelf factor (Skov *et al.*, 1990), wooden shelves with books and papers may also be considered as a source of pollutants affecting human comfort and health. It is also well known that wooden products emit not only terpenes that are mostly responsible for the characteristic odour of wood, but also other VOC groups, such as alcohols, ketones, aldehydes and carboxylic acids that may also cause sensory effects and irritation among people (Chang and Guo, 1992; Brown, 1999b; Mølhave et al., 2000, Jensen et al., 2001). Furthermore, depending on the composition of toner powder used in different printing applications (Wolkoff et al., 1993a), the emissions from processed papers also represent a wide range of VOCs.

Sealant is a building material frequently occurring indoors. Sensory and chemical evaluations were made in a number of investigations (Bluyssen and Fanger, 1991; Wolkoff et al., 1993b; Nielsen et al., 1997, Fang et al., 1999a). Another recent evaluation carried out for 50 days indicated that the sensory effects of emissions from a waterborne acrylic sealant might persist over a longer time scale, mainly due to secondary emissions from the material (Knudsen et al., 1999).

VDT work was systematically associated with increased SBS symptoms in a number of building investigations (section 1.1.1). It is also known from the literature that PCs are not only basic equipment in indoor environments, but represent also a substantial source of pollution in the near vicinity of people by increasing the concentrations of several chemical compounds in their surroundings (see section 1.2.3.2). The possibility that emissions from PCs may negatively affect people has been anecdotally mentioned by Brooks *et al*. (1993), but has never been systematically evaluated.

The quality of air polluted by such sources should be assessed preferably at different ventilation rates and evaluated in chemical terms, by measuring the types and concentrations of volatile organic compounds (VOCs), and in sensory terms, by using subjective evaluations. Similar to the concept successfully applied in previous studies (Wargocki; 1999, 2000a; Lagercrantz 2000) the experiments should be carried out taking advantage of a well-designed and well-controlled indoor climate, using exposure of female subjects on a longer time scale and under realistic conditions.

1.6 Objectives

The objectives of the present thesis are as follows:

1. To evaluate the influence of contaminants emitted from common building products on IAQ and the extent to which such emissions contribute to the prevalence of SBS symptoms and the loss of performance of human activities (Chapter 2).
2. To investigate whether improving IAQ by means of source control, i.e. reducing the emission of pollutants from indoor sources, is a more effective measure than increasing the rate of outdoor air supplied to a ventilated building (Chapter 2).
3. To assess the sensory and chemical pollution load of PCs and the subsequent effects on health, comfort and performance (Chapter 3).

The objectives defined above will be tested in a series of experiments especially designed for this purpose.

Chapter 2

Impact of emissions from building materials and ventilation rate on PAQ, SBS symptoms and performance of office work

2.1 Methods

2.1.1 Experimental plan

The air pollution level in an office space with low-polluting floor and finishing materials was modified using two methods: by placing a sample of common building products behind a partition and/or by changing the ventilation rate in the office space. All other indoor climate conditions were kept constant, independent of these interventions. The experimental matrix is shown in Table 2.1.1.

Table 2.1.1 Experimental conditions

		Pollution load	
		low	high
Ventilation rate	low	I	II
	high	III	IV

Thirty impartial female subjects occupied the office for ca. 2.8 hours, being kept blind to interventions. The subjects were asked to assess perceived air quality, indoor climate and SBS-symptoms upon entering the office and on several occasions during the experiment. To estimate their performance under different conditions of the experiment they performed several tasks simulating office work. The subjects remained thermally neutral by adjusting their clothing during the experiment. Following the occupation period, subjects left the building for outdoor refreshment and re-entered the office within a short time to evaluate again the perceived air quality.

2.1.2 Facilities and equipment

2.1.2.1 Office characteristics

The study was carried out in an office space (Figure 2.1.1) situated on the second (top) floor of a 25-year-old office building with a flat roof at the Technical University of Denmark. The office occupies two modules in the building structure, each being 3 m wide. The office has a total floor area of 36 m^2 and a volume of 108 m^2 (LxWxH=6x6x3). The external wall with two windows in a wooden frame has an area of 9 m^2 and face east. All other interior walls in the office were adjacent to indoor spaces. A few years prior to the experiment the office was renovated: the walls had been painted and the existing felt carpet was replaced with low-polluting polyolefine floor tiles. The office is divided by a partition made of laminated wooden panels into a smaller "technical space" where all the technical equipment was placed and a larger "working space" occupied by the subjects. The height of the partition was 2 m so the air between the two spaces could easily be mixed and at the same time a barrier was created, preventing people occupying the workspace from seeing what was placed in the technical area.

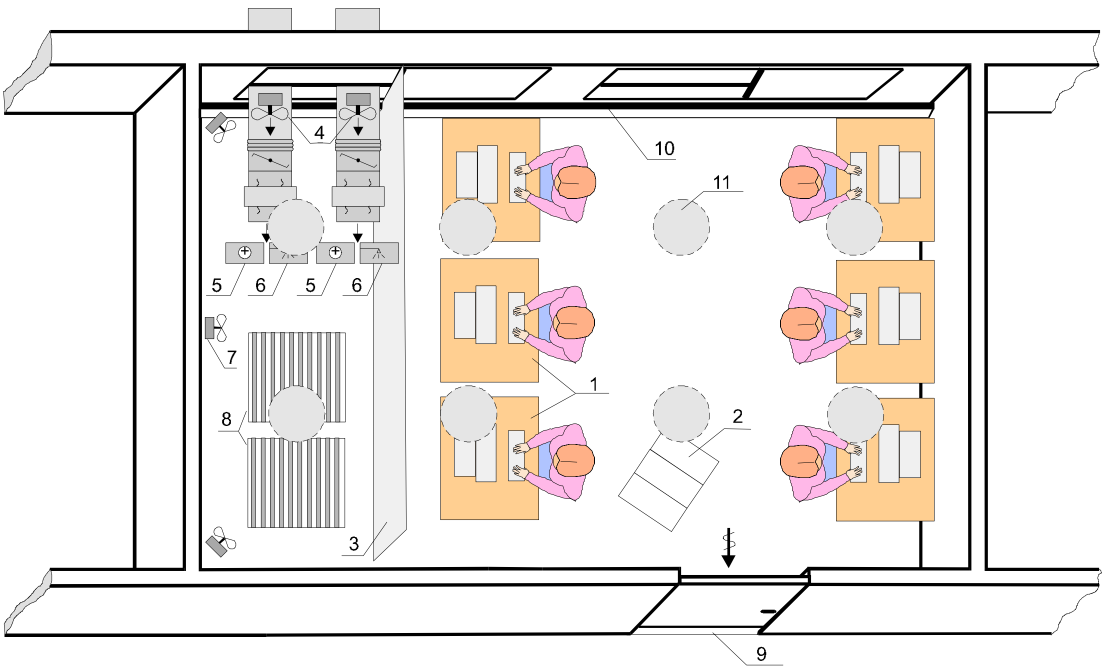


Figure 2.1.1.Experimental set-up in the office with 6 subjects sitting at individual workstations (1) consisting of a table, a chair, a desk lamp and a personal computer (PC) and (2) wooden stairs used by subjects for a step exercise located on one side of the 2-m-high partition (3), and a set of axial fans with dampers and silencers (4), electric heaters (5), ultrasonic humidifiers (6), mixing fans (7) and pollution sources (8), items 4-8 being located on the other side of the partition and thus not visible to subjects; the air left the office through a slot under the entrance door (9). Convectors (10), being a part of a central heating system, are located under the windows on both sides of the partition, as well as 8 illumination fixtures (11) attached to the ceiling, each with a fluorescent bulb of 38 W

The partition was placed perpendicular to the windows so that both the technical and working area had daylight illumination. In the space occupied by the subjects six workstations were set up, each consisting of a table, a desk lamp with low-energy bulb, a chair, and a 15″ CRT monitor and keyboard, each connected to a tower holding the CPU. The PC towers were placed either behind the partition (3 unit) in the technical area or outside the office (3 unit) to lower the noise level in the occupied space and to avoid any risk of pollution that could be emitted by such devices (see section 1.2). For the same reasons, the CRT monitors on the workstations were turned on only for the time required to work with PCs. Nevertheless, these PCs were ca. 3 years old and were shown to have low sensory pollution (see chapter 3.1, PC type C). Three tables were placed along the partition and three along the wall. A camera monitored the occupied area so that the experimenter could verify anytime the subjects' activity from the control room. The technical space was used to accommodate all technical equipment used to control the environmental conditions in the office. All furnishing materials present in the office (e.g the top panel of tables) were selected to be low-polluting materials. Consequently, when no other sources are introduced, the office may be considered as a low-polluting space that was also shown in an earlier experiment (Wargocki et al., 1999), with a sensory pollution load of 0.14 olf/m^2 floor. A two-step wooden stair is also located in the occupied space, aiming to elevate subject's activity level when they were asked to do light exercise during the exposures.

2.1.2.2 Ventilation

No conventional HVAC system was used to ventilate the office where the experiment took place. In the technical area two axial fans, mounted in the window, provided the outdoor air without filtration, considering that the building was situated in a rural area with good outdoor air quality, and filters may also act as a source of pollution. Each fan was connected to a damper and a silencer in order to obtain the required airflow rates and low noise level in the office. The air was exhausted naturally to the adjacent corridor through a slot under the entrance door. Several mixing fans were running in the technical area, pushing the air gently above the partition to obtain good mixing in the whole room, but avoiding creating a draught risk for people sitting at the workstations.

2.1.2.3 Air-conditioning

A SPLIT type air-conditioning (AC) unit and electric oil heaters were used to condition the air to the required temperature. Ultrasonic humidifiers with distilled water provided the required air humidity inside the office. The heaters and humidifiers were controlled by a PID-controller together with the calibrated temperature and humidity sensor (Vaisala Humitter 50Y) placed in the middle of space occupied by the subjects. The AC unit was set only for cooling, i.e. the air was driven through a cooled surface. The filter of the AC unit was removed to lower the risk of pollution.

2.1.3 Subjects

Thirty female subjects were recruited to participate in the experiment among 44 applicants replying to an advertisement distributed in colleges, universities and student hostels in the Greater Copenhagen area. Questionnaires were sent to all applicants to collect information on age, occupation, smoking habits, general health status, and SBS history. The selection criteria included subjects' acquaintance with a PC, non-smoking habits, and absence of chronic diseases as well as absence of asthma, allergy or hay fever. No medical examination of the subjects was made since the information above was obtained from the questionnaires mentioned. Some characteristics of subjects are presented in Table 2.1.2. All subject were students except one engineer. Due to the lack of non-atopic applicants, one person was recruited with a history of hay fever and allergy. Based on the questionnaires, among subjects recruited 10 people considered themselves to be more sensitive to IAQ, 7 subjects often experienced dry air at home/work or reported to have sensitive skin and 22 subjects had two or more SBS symptoms occurring at least twice per month or more.

Table 2.1.2 Characteristics of subjects participating in the experiment. The data were obtained from the preliminary questionnaire containing personal characteristics filled in by the subjects.

Age	19-30 years old (mean 23)
Height	161-183 cm (mean 169)
Weight	50-85 kg (mean 61.6)
Average DuBois body surface	1.70 m^2
Number of non smokers (never-smokers)	24 (21)
Number of asthmatic subjects	0

On the week preceding the experiment the subjects received 3 hours of training to become familiar with their task and to reduce any possible learning effects. They were also instructed on how to complete the questionnaires having different scales to measure subjective responses. The subjects were not informed that the training session was only for practice; furthermore they were not informed about any details regarding the experiment.

To test subjects' ability to distinguish different odour intensities and different types of odour, they took an olfactory test comprising a ranking test with n-butanol, at four concentrations 10, 80, 320 and 1280 ppm (vol/vol) and a matching test with n-butanol, 2-butoxyethanol and 2-butanone, each compound being at a concentration of 640 ppm (vol/vol) and a "blank" exposure with no chemical compound according to ISO (1988) and ISO (1993a). Subjects had on average 84% correct ranking and 72% correct matching. None of the subjects were rejected due to the results of ranking and matching tests.

The 30 people recruited were divided into 5 groups, each comprising 6 subjects. The training session was carried out for each of the five groups separately, one group of 6 people occupying the office at a time (Figure 2.1.1).

Unfortunately, during the investigation period of one month, seven subjects missed one or two experimental conditions due to illness, thus only 23 subjects participated in all four experimental conditions (Table 2.1.3). Whenever a subject could not participate, the experimenters sat at his/her workstation to maintain the same occupancy in the office.

Table 2.1.3 Subjects who missed one or more sessions during the investigation period of one month due to illness.

Groups	Low outdoor air supply rate		High outdoor air supply rate	
	Source present	Source absent	Source present	Source absent
Group 1				Subject 3, 4
Group 2			Subject 7	
Group 3				
Group 4	Subject 20		Subjects 22, 24	Subject 22
Group 5		Subject 26		

The subjects recruited were paid for participation at an hourly rate of approximately 100 DKK. As a source of motivation, they were also paid a bonus of up to 10% of the total salary according to their participation at each experimental condition and their performance.

2.1.4 Experimental conditions

2.1.4.1 Pollution sources

The materials used for the sample of common building-related pollution sources were a combination of linoleum, sealant and wooden shelves with books and papers. The rationale for material selection is described in section 1.5. The linoleum of a normal type with coloured patterns, available on the commercial market was bought three years before this study for experimental purposes, and had never been used on interior floors. The samples of linoleum were attached back-to-back, protecting the edges with aluminum tape to avoid any exposure of the reverse during the experiment. The samples were hung on a stainless-steel rack when placed in the office. The surface area of linoleum was 36 m^2 corresponding to the floor area of the office. The other component of the pollution sources was a colourless sealant, two months old. It was filled in aluminium profiles having a length corresponding to the total length of the window frames in the office (18 m). The books and printed papers were collected from the local library and archive of the department and loaded on wooden shelves. The books were selected to have different bindings and book cloths while the printed papers were kept in assorted folders. The total length of the shelves was 16 m corresponding to a shelf factor of 0.15 m/m^3room volume, a value typical for offices (Skov *et al.*, 1990).

2.1.4.2 Ventilation rates

The experimental conditions with pollution sources present and absent were repeated first when the air-change rate was low (1 h^{-1}) and second when the air-change rate was high (3 h^{-1}), corresponding to a total outdoor air supply of 30 and 90 L/s in the office or 0.83 and 2.5 L/s per m^2floor. With 6 people at a time in the office this is equivalent to 5 and 15 L/s per person. These outdoor airflow rates were selected with special care to cover the range recommended by CEN (1998) for landscape offices with A and C category requirements.

2.1.4.3 Air pollution levels in the office

Four different air quality levels were created in the office. At first, the pollution sources were placed either in the technical space behind the partition (Figure 2.1.1) or removed from the office. In this way, two exposure conditions were created at a specific ventilation rate: office with pollution source absent comprising the building materials, furnishing, workstations and technical equipment in the office, and office with pollution source present comprising the office as described above plus the pollution sources. These experimental conditions will later be referred to as office with “sources absent” and “sources present”. The concentration of pollutants in both cases was modified by altering the outdoor air supply rates, creating in this manner two additional air quality conditions in the office to which the subjects were exposed. These conditions are later referred to as low/high ventilation rates or office with low/high outdoor airflow rates. The concentration of pollutants emitted by the building-related sources was in equilibrium when the subjects entered the office. However, the concentration of bioeffluents increased during exposure, reaching equilibrium (99% of the steady state) after ca. 1.5 hours at a high ventilation rate and 95% of the steady-state levels after ca. 2.8 hours of exposure at a low ventilation rate.

2.1.4.4 Thermal parameters, Noise and Illumination

A temperature of 23°C and a relative humidity of 50% were selected to suit typical thermal conditions for late spring when the experiment was carried out. These values are in the range required for thermal comfort of people performing sedentary office work (ISO, 1993b) assuming that operative temperature did not differ considerably from air temperature. The subjects maintained their thermal neutrality during exposures by adjusting their clothing when they felt it necessary. The designed temperature and relative humidity were kept constant in the office, independent of the four experimental conditions. The air velocity at the workstations was designed to be at or below 0.2 m/s.

The supply fans, the mixing fans and the cooling fans of the computer's power unit placed in the technical area have all contributed with small amounts to the noise level in the office that reached 42 db (A) in the previous experiments (Wargocki et al., 1999, 2000a). In order to reduce this level to 35 db(A), given by CEN (1998) for a buildings of Category A, the small mixing fans were changed to larger fans that could operate with the same effectiveness but at lower speed and less noise, and new supply fans of higher capacity were mounted in the windows. Since the amount of fresh air was adjusted with the dampers, the noise level was unchanged even when the office was ventilated at a high rate.

The illumination level in the office was not controlled. The office was illuminated by daylight through the windows with a glazing surface of 6 m^2. During the afternoons, when the experiments were carried out, there was no direct sunlight in the office, since the windows faced east. The subjects according to their preferences could adjust the illumination level locally at each workstation using the desk lamps with energy-saving bulbs attached to the tables.

2.1.5 Measurements

2.1.5.1 Physical Measurements

Several physical parameters of the indoor environment were measured continuously or intermittently in the office during the experiments. The temperature and relative humidity of air was continuously registered with calibrated temperature and humidity sensors (Vaisaala HMP 131) that were placed close to the breathing zone of the subjects, in the middle of the occupied space and outside the building in near vicinity to the office. These data were collected via a HP-VEE data acquisition system with an interval of 30 seconds and stored on a computer. Operative temperature and air velocity were measured with Brüel&Kjaer 1212 Thermal comfort meter and a Brüel&Kjaer 1213 Indoor Climate Analyser respectively. The sensors were located centrally in the occupied space at a height of 1.2 m above the floor and connected to the instruments outside the office. The data were manually registered every 20 minutes during the exposures.

Every experimental day the ventilation measurement in the office started prior to the session with subjects. Using the constant concentration method, the outdoor air supply was measured by a Brüel&Kjaer Multi-Gas monitor Type 1302 connected with a Brüel&Kjaer Multipoint Sampler and Doser Type 1303. A tracer gas (SF_6) was dosed at the fresh air inlet and the concentration was maintained at 1 ppm at one of the workstations. At the remaining five workstations the concentration of SF_6 was monitored only to ensure that in the room there was good mixing and that every subject received a similar exposure. Based on the amount of tracer gas dosed into the office, the outdoor air supply rate was calculated by the instrument. The air for measurements was sampled close to the breathing zone of each subject.

During experiments, the concentration of CO_2 and toluene equivalent TVOC were continuously measured in the office and outdoors, using the same instruments and sampling tubes as in the case of tracer gas monitoring. Outdoor air was sampled at the inlet of the axial fans supplying the fresh air to the office.

The noise level in the office was measured occasionally using a Brüel&Kjaer Sound Level Meter Type 2218, located in the occupied space close to the subjects.

The ozone concentration was measured alternately with 20 minutes' interval indoors and outdoors using a Seres OZ2000 ozone analyser. The outdoor air was sampled at the inlet of one supply fan while the indoor air was taken from the middle point of the occupied zone. The ozone data were manually recorded according to the measured values displayed by the analyser.

The lighting level was measured at each workstation on two occasions before and after the experimental session by placing a hand-held Hagner EC1 lux meter on the top of the tables corresponding to the standard work plane of 0.85 m above the floor.

All instruments except the sound level meter were placed in a control room adjacent to the experimental office, allowing for permanent monitoring of the measured values.

2.1.5.2 Chemical measurements

Volatile organic compounds were sampled (adsorbed) on Tenax TA and in addition on Tenax GR for identifying the typical odorous compounds. The trapping capacity of graphitized Tenax matrix (Tenax GR) is better for very volatile compounds, which usually were odorous, than the capacity of Tenax TA. Also the retention volumes of Tenax GR for very volatile compounds are better than for Tenax TA due to the carbon content of Tenax GR, which includes 23 % graphitized carbon.

Samples were taken in the middle of the room at a height of ca. 1 metre and outdoors in the direct vicinity of the air inlet on duplicate Tenax tubes that were assembled within a distance of 15 cm from each other. The sampling period started a few minutes in advance of the subjects entering the office and finished at the end of the exposures when the sampling tubes were disconnected from the tube line and both ends were sealed tightly using screw cap fittings with PTFE ferrules. Thereafter the tubes were stored in a freezer at –10°C and sent for analysis 2 weeks after the experiment.

The air was sampled using suction pumps located in the room adjacent to the office in order not to introduce an additional noise source in the office. The pumps were connected with the sampling tubes using PE tubing. The sampling flow rate used was 73±18 ml/min. It was registered at the beginning and the end of each sampling period using a rotameter. Before sampling, the tightness between the rotameter and the pump was checked by closing the open-end of the test tube and checking whether the rotameter was showing no flow. The sampling volume was on average 12.6±5.3 L, depending on the flow rate established through each tube.

The samples were directly introduced into a gas chromatograph after thermal desorption. Individual VOCs were separated using capillary columns. The gas chromatography was equipped with a flame ionisation detector (FID) and a mass selective detector (MSD). The desorption temperature was 260°C, desorption time was 6 min and Tenax TA was used as a cold trap sorbent. Single VOCs were identified from the MSD total ion chromatogram using Wiley 138 Library. The concentrations were calculated from the corresponding FID-chromatogram using a toluene response factor. The identifications were not confirmed with pure standards. The detection limit of the analytical method for single VOCs was 5 ng per sample; thus, considering the sampling volumes, the detection limit was between 0.2 and 1.1 $\mu g/m^3$. The total amount of VOCs (TVOC) was calculated from the total area of the FID-chromatogram.

2.1.5.3 Subjective measurements

In the experiments, several questionnaires were used to gather information about perception of the indoor environment and subjective wellbeing. Before entering the experimental office, the subjects filled out regularly a questionnaire regarding personal hygiene, their activities in the morning before the experiment, and wellbeing on that day (entrance questionnaire). During an exposure session the subjects filled out on several occasions questionnaires about perceived air quality, general perceptions of the environment, SBS symptoms, thermal comfort, draught sensation and self-performance. At the end of the exposure, just before leaving the office, the people were asked to fill out a "clothing questionnaire" concerning the type of clothing worn during the experiment.

Aspects of perceived air quality were recorded on continuous scales regarding acceptability of air, odour intensity as well as irritation of eyes, nose and throat (Figure 2.1.2).

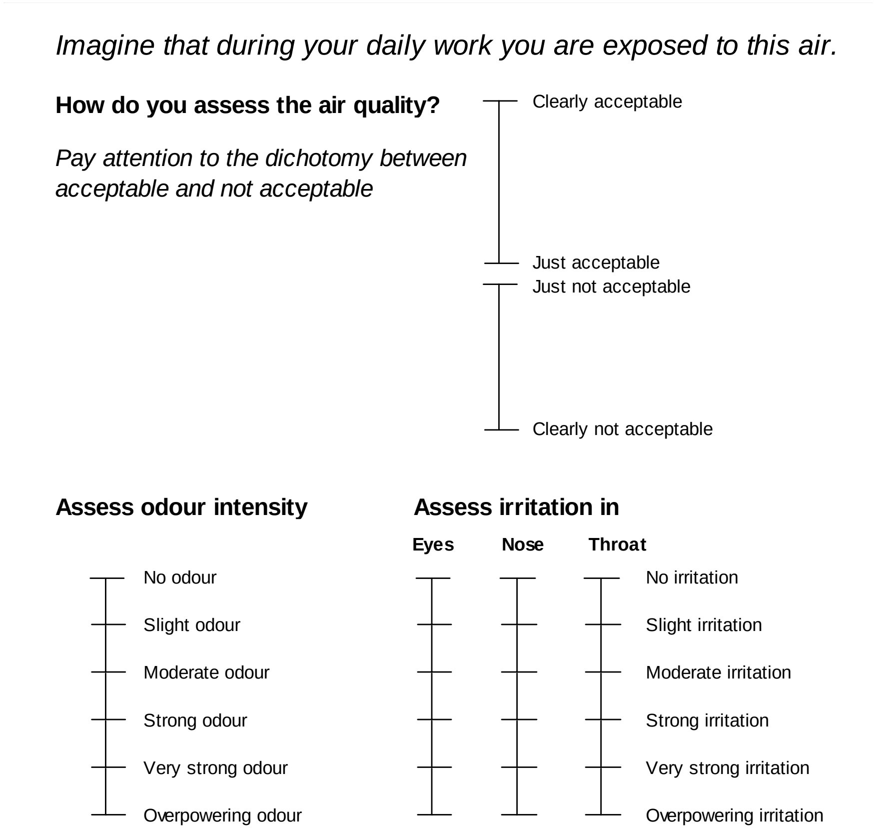


Figure 2.1.2 Questionnaire used to assess the perceived air quality in the office.

The subjects marked their opinion on the related questions at any place between the endpoints given by the relevant scale. To evaluate the acceptability of air, a continuous scale separated in two regions was used, such as the one introduced by Gunnarsen and Fanger (1992). The scales with five labelled marks for measuring the perceived odour intensity and irritations are similar to those used by Yaglou (1955).

Visual analogue scales (VA-scales) were used (Kildesø et al., 1999) to assess general perceptions of the indoor environment, specific symptoms and self-estimated ability to work (Figure 2.1.3). The scale is 100 mm long on a horizontal line without gradation with two vertical lines marking the extreme points of the scale. The subjects put a mark on the scale, more to the left or right side of the line, depending to what extent they agreed with the statement of the symptom in question, labelled on the left and right end of the scale. A set of 14 visual analogue scales was used, each scale representing a perception or symptom: air dryness, air freshness, illumination, office noise, nose, throat and eye dryness, headaches, difficulty in thinking, dizziness, fatigue, difficulty in concentrating, sleepiness and ability to work.

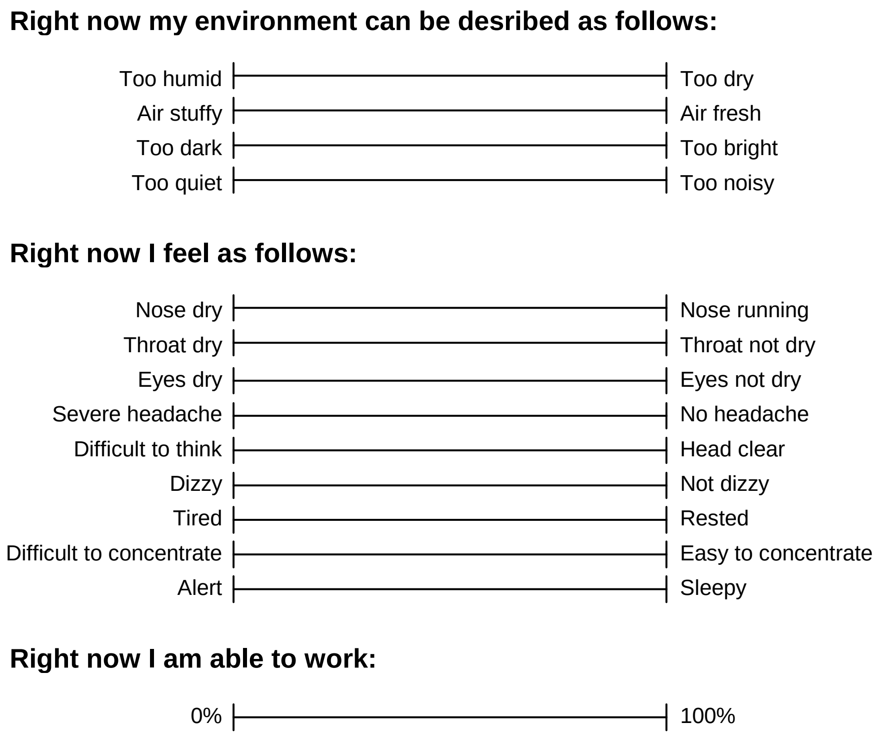


Figure 2.1.3 Visual-analogue scales used to measure general perception of the environment, SBS symptoms and self-estimated ability to work.

To assess the thermal environment in the office, the subjects filled out questionnaires regarding thermal sensation and air movement. Thermal sensation was recorded using a 7-point PMV scale (ASHRAE Handbook, 1997). Furthermore, people were asked to vote whether the thermal climate and the air movement around their body was acceptable or not. These scales were similar to that used during evaluation of the perceived air quality. In this way the percentage of dissatisfied people regarding thermal comfort and due to draught could be estimated.

2.1.5.4 Measurement of performance

Two different methods were used to estimate subjects' performance during occupation under the air quality conditions created in the office: objective measure of subjects' performance when executing simulated office work and self-estimated work ability on VA scales.

Simulation of office work. Simple performance tests of different duration were used to simulate office work. In general, office work covers a wide range of different tasks, among the most common to most office workers are: text typing, reading, proof-reading, paper handling, working with PC, calculations of different kinds, creative problem-solving, etc. Because of the limited time available during one session only two tasks, text typing and arithmetical calculations, have been selected to evaluate subjects' performance, considering that these tasks were shown to be one of the most effective productivity measures in the studies previously carried out by Wargocki et al. (1999, 2000a).

Word processing
Articles of a popular Danish science magazine were re-typed by the subjects into a PC during the text-typing task. The texts were presented to the subjects on paper, printed with 12 point Times New Roman font and with double line spacing. Four different versions of text with similar difficulty were prepared with a length that was impossible to finish in the time available for typing. In each experimental condition a subject used only one of the four texts prepared in randomized order. The subjects typed the texts at their own pace. During an experimental session they had 100 minutes to type each text with a short break after the first 50 minutes of typing. To complete this task, Microsoft Word for Windows version 6 software program was used with default settings, the automatic spell-checker being disabled during text-typing. The performance was measured using the number of characters typed per minute and the error rate (accuracy) of typing expressed as the total number of errors related to the number of words and punctuation marks typed. The total number of errors was calculated by summing up the typing errors (i.e., misspellings and punctuation errors) and the number of words skipped. The number of characters typed was automatically recorded in the text editor. Moreover, to improve analysis of results, a macro module in Windows was developed to count the number of words and punctuation marks typed by the subject and to compare the typed and original documents, detecting any discrepancy between the texts. The counting of total errors was semi-automated.

Arithmetical calculations
Two different tasks were given to the subjects regarding arithmetical calculations: addition and multiplication of numbers (Wyon et al., 1975). Subjects added five two-digit numbers, excluding zeros, printed in a column one below the other. In the multiplication task the subjects multiplied two three-digit numbers, being permitted to use their own way to perform the calculations, but without using a PC or a calculator. The task was to complete as many of the addition or multiplication units as possible in the time available for the tasks. Four different sets of addition and multiplication tasks with similar difficulty were prepared for each experimental condition. Two measures of performance were used in both tasks: the number of units completed per hour (speed) and the percent of correctly executed operations (accuracy).

Self-estimated ability to work A VA-scale was used to evaluate subjective measurement of performance. The subjects were asked to mark on the scale their work ability from 0 to 100% upon completing the multiplication and text-typing task. The scale was included on the same page used to evaluate other SBS symptoms (Figure 2.1.3).

2.1.6 Procedure

The procedure of this experiment is in many aspects similar to those followed in earlier investigations evaluating the effects of IAQ on human comfort, health and performance (Wargocki et al., 1999, 2000a; Lagercrantz, 2000). The study was carried out in May and June 2000 on five consecutive weeks including training sessions, from Monday to Friday.

The preparations to obtain the desired experimental conditions in the office started each morning at 7 a.m. The pollution sources, when necessary, were placed in the office and the ventilation rate was set to the required level. The blinds on the windows were shut to avoid overheating the office due to sunshine. The data collection of climatic parameters in the office and outdoors, except chemical sampling on Tenax TA and GR, has started at 12 a.m. when the concentration of pollutants originating from the building materials and pollution sources had reached steady-state levels in the office. The data collected prior to arrival of the subjects were used to characterize the conditions in the office without bioeffluents. During this time, no one was allowed to enter the office. After exposures, the pollution sources were removed to a separate room and the office was ventilated up to 6 h^{-1} air change rate until the next morning to eliminate any pollution that may have adsorbed on the interior surfaces.

On each experimental day a separate group of six people was exposed for about three hours from 2 p.m. to 5 p.m. Each group was randomly assigned to a day of the week to avoid any interaction of condition with weekday. During the period of the experiment there were three national holidays and no exposures took place on those days. Therefore, these sessions were moved to the same weekday on the preceding or following weeks. Thus, every subject participated on the same weekday in the four experimental conditions and training sessions, with at least one-, but on three occasions a two-week break between the exposures.

The exposures for the 5 groups were randomized in the office. The tasks simulating office work were also randomized for order of presentation to the subjects in order not to confound task versions with the exposure conditions. The randomization of experimental conditions for each group and of performance tasks is presented in Appendix 3.

For every group, the first session was devoted to training, the subjects receiving general information about the experiment, instructions on how to use and fill in the questionnaires and to perform the tasks. The procedure of the training session was similar to the procedure of the real experiment but of shorter duration to allow time for an olfactory test described in section 2.1.3.

The subjects were instructed to perform their normal activities in the morning on the days of the experiments, but to avoid strong perfumes and drinking coffee before the exposures and any other habits and activities that may influence their perception during the experiment (i.e. eating spicy food, garlic etc.). Each experimental session consisted of a pre-exposure, an exposure in the office and a post-exposure, described in the following sections.

2.1.6.1 Pre-exposure

On arrival, the subjects assembled in a naturally ventilated meeting room located close to the entrance of the building. The meeting room was also used to complete the questionnaires given to the subjects about their activities and exposures prior to the experiment. After the subjects had spent about 10 minutes in the meeting room, they assessed the perceived quality of outdoor air by leaving the building. This procedure was repeated every time for each group to ensure that all subjects received similar pre-exposure before entering the office, where one of the four experimental conditions was already prepared.

2.1.6.2 Exposure in the office

The subjects entered the office and stayed there for 2 hours and 45 minutes (165 minutes). During this period, the subjects were not allowed to leave the office except when they went to the restroom in the break time. Upon entering and several occasions during the exposure, the subjects made a subjective evaluation of the indoor environment. They also completed several tasks simulating office work as described above throughout the occupation. The procedure followed the schedule presented in Table 2.1.4.

Table 2.1.4 Schedule of subjective assessments and completed tasks during one experimental session

Exposures	Clock time	Exposure time	Subjective assessments	Performance tasks
Pre-Exposure	14:00		Entrance questionnaire	
	14:05		Air quality rating: outdoors	
Exposure in the office	14:10	0	Air quality rating in the office upon entering	
	14:13	3		Multiplication task (20 min)
	14:33	23	Comfort questionnaire 1 + walking over steps	
	14:38	28		Text typing (50 min)
	15:28	78	Walking over steps (short break)	
	15:29	79		Text typing (50 min)
	16:19	129	Comfort questionnaire 2 + walking over steps	
	16:24	134		Addition task (30 min)
	16:54	164	Clothing questionnaire	
Post-Exposure	16:56		Air quality rating: outdoors	
	16:59		Air quality rating in the office upon re-entering	

Immediately after entering the office, the subjects were shown their workstations and before taking a seat they assessed the acceptability of air, odour intensity and eye, nose and throat - irritation. They were than allowed to sit down and prepare themselves to complete the first task of simulating office work. For the first 20 minutes the subjects worked on a multiplication task. After that, they were asked to complete a more detailed subjective questionnaire regarding perceived air quality, SBS symptoms, self-performance and thermal comfort. Following this evaluation, the computer monitors were turned on and the subjects began the first part of the text-typing task for 50 minutes. After the first typing session they had a short break but were not allowed to leave the office unless they had to use the restroom. The typing task was than continued for another 50 minutes. After this task the computer monitors were turned off, to minimize the heat and possible pollution load in the office, and the subjects were asked to fill out a second detailed, subjective questionnaire, similar to the first one. Finally, the subjects performed the addition task for 30 minutes. The subjects were asked to complete the first comfort questionnaires when they were already adapted to their work environment. The timing of the second comfort questionnaire was earlier than the end of exposure to avoid any interaction of a positive mood change in anticipation of the end of the session on the results (Wargocki, 1999).

At the end of the exposures the subjects recorded their clothing on special questionnaires. They were instructed to bring extra clothing and to wear several thin layers allowing small adjustments of clothing insulation value. During occupation, the subjects were asked and reminded to adjust their clothing, so that they felt thermally neutral all the time in the office.

In order to obtain an average activity level typical for office work (1.2 met), avoiding only sedentary occupation, the subjects were asked each time they completed a subjective questionnaire to perform a step exercise by walking over four steps towards a box where the questionnaires were collected (Wargocki, 1998). On the way to the box and back to the workstations, the subjects walked two steps up and two steps down; each step was 0.2 m high. When the subjects felt thirsty or hungry during occupation, they were allowed to drink plain (non carbonated) spring water and to eat digestive biscuits provided at each workstation.

2.1.6.3 Post-exposure

After 165 minutes of exposure, the group left the office and walked out from the building to a backyard to refresh their senses and assess the outdoor air quality. After 3-5 minutes' refreshment, the subjects re-entered the experimental office and assessed the perceived air quality immediately upon reaching their workstations, as they proceeded upon entering at the start of exposure. At this time the office air contained pollution not only from the building materials and the prepared material samples - if present, but also emissions from people (i.e. bioeffluents) occupying the office and CO_2 above outdoor levels.

2.1.7 Data analysis

2.1.7.1 Coding of subjective ratings

In order to perform the data analysis for subjective ratings, the linear scales were coded as following:

<u>Acceptability scale:</u> "clearly acceptable" = +1; "clearly not acceptable" = -1; "just acceptable/just not acceptable" = +0.01/-0.01; the maximum reading error from the scale was less than 0.025.

<u>Odour intensity scale:</u> "no odour" = 0; "slight odour" = 1; "moderate odour" = 2; "strong odour" = 3; "very strong odour" = 4; "overpowering odour" = 5; the maximum reading error from the scale was less than = 0.05.

<u>Irritation scales:</u> describing irritation of eyes, nose and throat: "no irritation" = 0; "slight irritation" = 1; "moderate irritation" = 2; "strong irritation" = 3; "very strong irritation" = 4; "overpowering irritation" = 5; the maximum reading error from the scale was less than = 0.05.

<u>VA-scales:</u> the endpoints of visual analogue scales were 0 (left end of the scale) and 100 (right end of the scale); the maximum reading error from the scale was less than 0.5.

<u>ASHRAE thermal sensation scale:</u> the 7-point scale was coded as follows: "cold" = -3; "cool" = -2; "slightly cool" = -1; "neutral" = 0; "slightly warm" = +1; "warm" = +2; "hot" = +3; the maximum reading error was less than 0.05.

2.1.7.2 Calculation of the Perceived Air Quality

The percentage of dissatisfied and perceived air quality expressed in decipol are calculated as a measure of the perceived air quality in the office, as follows:

The mean ratings of acceptability are transformed to % dissatisfied using Equation 2.1 based on data by Gunnarsen and Fanger (1992):

$$PD = \frac{e^{-0.18-5.28 \cdot ACC}}{1+e^{-0.18-5.28 \cdot ACC}} \cdot 100$$

Equation 2.1

where:

PD = percentage dissatisfied with the air quality, %
ACC = mean vote of air acceptability

Using this value of PD the perceived air quality expressed in decipol is calculated with Equation 2.2 given by Fanger (1988):

$$C = 112 \cdot [\ln(PD) - 5.98]^{-4}$$

Equation 2.2

where:

C = perceived air quality, decipol;
PD = percentage dissatisfied with the air quality, %.

2.1.7.3 Calculation of sensory pollution loads

The sensory pollution loads in the office for all four experimental conditions were calculated both when subjects were both present and absent in the office, using the following procedure: the sensory assessments made by the subjects on acceptability of air upon entering, re-entering and outdoors were converted first to percentage of dissatisfied then to perceived air quality expressed in decipol unit. Using the comfort model (Equation 1.1) given by Fanger (1988) with the measured ventilation rates and considering that a perfect mixing was achieved, the total sensory pollution load in the office was calculated as follows:

$$G = 0.1 \cdot Q \cdot (C_i - C_o)$$

Equation 2.3

Where:

G = is the total sensory pollution load in the office (olf);
Q = is the outdoor air supply rate in the office (L/s);
C_i = is the perceived air quality inside the office (dp);
C_o = is the perceived air quality outdoors (dp).

2.1.7.4 Calculation of metabolic rate of people

The metabolic rate of a person can be estimated using the relation below (ISO, 1990):

$$M = 5.88 \cdot \frac{0.23 \cdot RQ + 0.77}{RQ} \cdot \frac{G_{CO_2}}{A_{DU}}$$

Equation 2.4

where:

M [W/m²] = metabolism of a person performing typical clerical work in the office. The activity level of sedentary occupation may be estimated to 1.2 met (ISO, 1993b), which is 1.2 · 58.6 = 69.8 W/m²,

G_{CO2} [L/h] = production rate of carbon dioxide (CO_2) by one person calculated from the CO_2 concentration in the office above outdoors in the presence of 6 people at a given outdoor air supply rate

RQ = respiratory quotient, estimated at 0.85 (ISO, 1990)

A_{DU} = DuBois body surface area calculated with the following formula:

$$A_{DU} = 0.202 \cdot W^{0.425} \cdot H^{0.725}$$

where:
H [m] = height of a person,
W [kg] = weight of a person.

2.1.7.5 Calculation of ozone surface removal rate

The concentration of ozone in a ventilated space under steady-state conditions is defined by the sources introducing ozone into the air, and the sinks removing ozone from the air. Thus, the indoor ozone may originate from outdoors, i.e. the outdoor ozone is brought in through ventilation, and from different indoor sources, such as electronic devices that may emit ozone. The major sinks are surface removal, indoor-to-outdoor transport, and reaction with other chemicals in the air. Assuming that there are no O_3 sources in the office and that no chemical reaction of ozone would occur in the office air, the indoor concentration of ozone may be expressed as follows (Weschler, 2000):

$$I = \frac{n \cdot O}{k_d \left(\frac{A}{V} \right) + n}$$

Equation 2.5

where:

I = is the concentration of ozone in the office (ppb);

O = is the outdoor ozone concentration (ppb);

$k_d(A/V)$ = is the ozone surface removal rate constant (h^{-1}) given by the ozone deposition velocity (k_d; [$m \cdot h^{-1}$]) and the ratio between the total surface area in the office (A; [m^2]) and the volume of the room (V; [m^3]);

n = is the air exchange rate in the office (h^{-1}).

Since both the indoor and outdoor ozone concentrations are measured during the experiment, the ozone surface removal rate constant may be calculated from Equation 2.6. Hence the ozone removal rate on the interior surfaces in a given space may be calculated as the product between the ozone concentration in the space and the ozone surface removal rate constant.

$$k_d\left(\frac{A}{V}\right) = n \cdot \left(\frac{1 - I/O}{I/O}\right)$$

Equation 2.6

The I/O concentration ratio of ozone was calculated on each experimental day with and without subjects in the office. Multiple data were collected from outdoors and indoors before and during exposures considering that changes in the outdoor ozone levels during exposures may substantially affect indoor concentrations.

2.1.7.6 Calculation of VOC emission rate

The emission rate of a VOC in a ventilated space under steady-state conditions and complete mixing may be calculated using the following relation:

$$E = Q \cdot (c_i - c_o)$$

Equation 2.7

where:

E = is the emission rate of the chemical compound (mg/h);
Q = is the outdoor air supply rate in the office (m^3/h);
c_i = is the indoor concentration of the chemical compound (mg/m^3);
c_o = is the outdoor concentration of the chemical compound (mg/m^3);

2.1.7.7 Analysis of performance

Subjects' performance in the arithmetical calculations and text typing were calculated on each exposure day for the results describing both speed and accuracy. To see the effect of air pollution on performance, these results were grouped according to the four different experimental conditions, i.e. office with/without pollution sources present at low/high ventilation rates, and compared with each other. Since the subjects executed the text-typing task twice during exposures, the performance changes within each condition could be calculated and compared accordingly.

Regardless of the experimental conditions, and considering the order in which the tasks of different versions were presented to the subjects, possible learning effects were also calculated for the whole period of the experiments i.e. comparing the first version completion (day-1) with the second (day-2), third (day-3) and fourth (day-4).

2.1.7.8 Statistical Analysis

All data obtained from questionnaires and the performance results were tested first for normality using the Shapiro-Wilks' W test with the rejection region of $p<0.01$. For normally distributed data, one-way analysis of variance (ANOVA) or paired t-test was applied to evaluate differences between the conditions. Data not normally distributed were analysed using Friedman two-way analysis of variance by ranks or Wilcoxon matched-pairs for related samples. Whenever increasing trends in a data set were seen, the Page test for ordered alternatives was also considered, under the assumption that higher airflow and lower pollution load have a positive effect on the results. Unless indicated, all p-values are for a one-tailed test, i.e. under the assumption that the presence of pollution sources and/or reduced outdoor air supply rate has a negative effect on IAQ, SBS symptoms and productivity. The rejection region for significance was set to be $p>0.05$.

2.2 Results

2.2.1 Conditions of Indoor Climate inside the Office

The values of general parameters that describe indoor climate inside the office and during exposures are shown in Table 2.2.1 for each condition of air quality. Unless specified, mean values of continuous measurements are indicated for 5 groups of 6 subjects for each condition. Some selected parameters of outdoor air are also indicated.

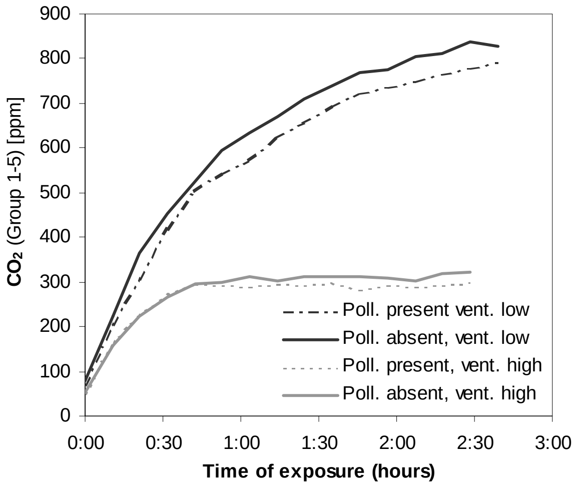
Table 2.2.1. Results of physical measurements describing the office environment under different experimental conditions (average values ± SD).

Measured parameter	Ventilation rate n = 1 h^{-1} (low)		Ventilation rate n = 3 h^{-1} (high)	
	poll. sources present	poll. sources absent	poll. sources present	poll. sources absent
Air temperature [°C] [1]	23.2±0.2	22.8±0.1	23.0±0.3	23.1±0.3
Relative humidity [%] [1]	49±5.0	49±3.3	46±2.0	48±3.6
Operative temperature [°C] [2]	23.8±0.6	23.4±0.4	23.4±0.3	23.3±0.6
Air velocity [m/s] [2]	0.07±0.03	0.15±0.05	0.06±0.03	0.12±0.03
Outdoor air supply [L/s]	28.5±1.8	28.2±1.1	90.7±3.4	89.6±1.1
Carbon dioxide above outdoors [ppm] [1,3]	809±65	842±47	296±15	316±31
TVOC tol. equiv. above outdoors [ppm] [1,3]				
Office without bioeffluents	0.26±0.08	0.17±0.06	0.21±0.11	0.20±0.01
Office with bioeffluents	0.34±0.1	0.25±0.1	0.24±0.1	0.21±0.07
I/O ratio for ozone [4]				
Office without bioeffluents	0.34±0.03	0.39±0.04	0.63±0.03	0.70±0.05
Office with bioeffluents	0.24±0.03	0.21±0.02	0.50±0.02	0.55±0.02
Air temperature outdoors [°C]	19±7	15±4	15±4	20±6
Relative humidity outdoors [%]	60±21	80±15	62±23	50±4
CO_2 outdoors [ppm]	421±11	410±10	400±8	406±5
Ozone, outdoors [ppb] [5]	36±24	26±7	29±8	47±22

[1] Average of measured values at each workstation; [2] measured at the central point of the occupied area; [3] concentration after steady-state level was obtained at 3 h^{-1} and when 95% of the steady-state level was reached at 1 h^{-1}; [4] measured alternately with 20 minutes' interval indoors and outdoors; [5] average outdoor levels during exposures.

The measured values of climatic parameters inside the office did not deviate to a large extent from the designed values. The air temperature during exposure in the office increased by ca. 1 degree Celsius compared to the initial value of 22.5°C on entering, due to the additional heat load produced by 6 people. The relative humidity and outdoor air supply rate were generally constant, presenting only small fluctuations between exposure days. The concentration of tracer gas (SF_6) measured at each workstation was at 1 ppm with 0.01 standard deviation, showing that the air was well mixed in the office.

The carbon dioxide concentration increased to ca. 800 ppm and ca. 300 ppm above outdoor levels in the office ventilated with 1 h^{-1} (low) and 3h^{-1} (high) respectively. At the low air change rate this concentration corresponds to 95% of the steady-state levels. It may be observed that at both ventilation rates the concentration of CO_2 was generally lower in the presence of pollution sources compared to the conditions with pollution sources absent, as is shown by the time profile of average CO_2 concentrations measured at each workstation (Figure 2.2.1 left). This difference remains unchanged after breaking the data for each group. It is shown in the CO_2 emission rate of subjects that was calculated from the steady state (or 95% of the steady state) CO_2 concentrations in the office at the actual ventilation rates measured on each exposure day.



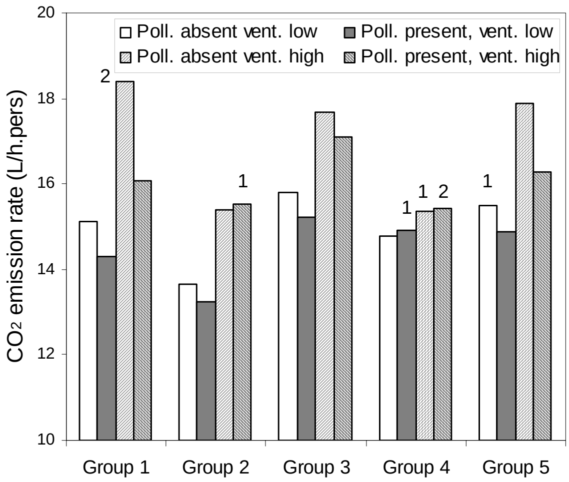


*Figure 2.2.1 **Left:** Time course of carbon dioxide (CO_2) concentration in the office above outdoor levels; **Right:** Carbon dioxide emission rates for groups of 6 people; average data are represented, recorded at each workstation on each exposure day according to 4 experimental conditions created; the numbers on the figure indicate the number of subjects missing in a particular exposure day; the groups were completed by other persons, typically staff members (experimenters), in order to maintain the same occupation rate.*

Consequently, the CO_2 production of 5 groups of subjects (Figure 2.2.1 right) showed a tendency ($p<0.06$) towards a lower emission rate in the office with sources present at a low ventilation rate, and a reduced CO_2 emission rate when sources present in the office were also observed at a high ventilation rate, but only for 3 groups of subjects. Furthermore, it should be noted that whenever a subject could not participate in the experiment, the groups were completed with other people, typically from staff members (experimenters), whose body characteristics and activity level, i.e. CO_2 production rate, were presumably different from those of the subjects they substituted.

Using the CO_2 emissions of people, the average metabolic rate of subjects during 2.8 hours of occupation in the office was calculated (Equation 2.4) in Table 2.2.2.

Table 2.2.2. Average metabolic rate of subjects in groups of 6 people calculated from the carbon dioxide emission rates during occupation of 2.8 hours in the office.

Activity level [W/m²]		Group1	Group2	Group3	Group4	Group5	Average
Low ventilation	Source absent	62	56	59	59	62*	60
	Source present	59	55	56	59*	60	58
High ventilation	Source absent	75**	63	65	60*	71	67
	Source present	65	63*	62	60**	64	63

In the case of missing subjects, the group was completed: * with another person; ** with two other people.

Assuming 1.2 met or 69.8 W/m² for typical office activities (ISO, 1993b) the average metabolic rate of subjects for the experimental conditions was slightly lower, compared to this level, by 5-18%. Further analysis and discussion related to the CO_2 emissions and metabolic rate of subjects exposed to different air quality levels in the office are presented in section 4.3.

In the office without bioeffluents, the indoor ozone concentration on average was lower by 64% and 33% compared to the outdoor ozone level at low and high air change rates respectively, not considering that the pollution sources may affect indoor ozone removal. However, should be noted that the indoor-outdoor concentration ratio (I/O-ratio) of ozone was systematically lower in the presence of sources in the office at both low and high ventilation rates ($p<0.014$). Increasing the outdoor air supply rate in the office caused the I/O-ratio to increase by ca. 1.8 times both with sources present and absent in the office.

The presence of people in the office has substantially affected the I/O concentration ratio; it was on average by 29±11% lower with people present at both low and high ventilation rates compared to the conditions without subjects in the office. After the subjects had entered into the office the changes in the ozone levels occurred within the first hour of exposure, i.e. the indoor ozone concentration reached steady state in the presence of bioeffluents in the second part of the exposures, unless the outdoor levels were not altered. In the office with bioeffluents and high ventilation rate the I/O ratio of ozone increased slightly ($p<0.03$) when the pollution sources were removed. On some exposure days, when the outdoor ozone was low, the indoor concentration of ozone in the office with a low ventilation rate and presence of bioeffluents fell to only a 1-3 ppb; this may have interfered with the sensitivity of the measurement. Consequently, the I/O ratios in these exposures may not be accurate and therefore no statistical comparison between the conditions with/without pollution sources in the office with low ventilation was made.

The ozone surface removal rate constant ($k_d \cdot (A/V)$) was calculated based on the available I/O concentration ratios prior to the exposures (with subjects absent) and at the end of exposures (with subjects present), and the measured ventilation rates on each exposure day (Equation 2.5). The average values are shown in Figure 2.2.2 as a function of the experimental conditions and the presence of bioeffluents in the office.

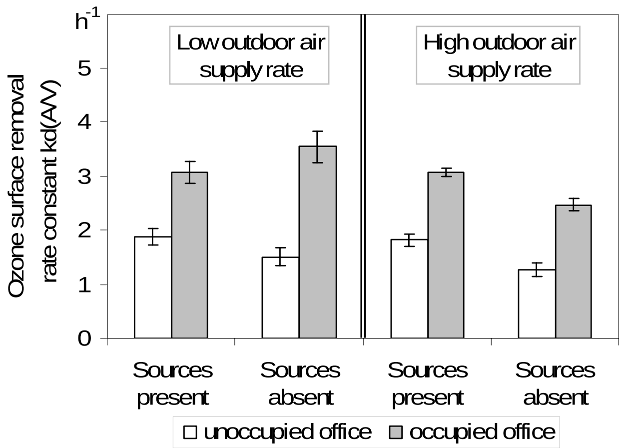


Figure 2.2.2 Ozone surface removal rate constant ($k_d \cdot (A/V)$) for different experimental conditions with and without bioeffluents in the office; the bars indicate standard error.

Although the Innova 1302 Brüel&Kjaer instrument has a rather high detection limit for toluene equivalent TVOC (0.04 ppm or 150 μg/m³), it still provides general information about the concentration of chemical compounds in the office (Table 2.2.1). The TVOC-toluene equivalent levels were highest in the office with a low ventilation rate and presence of pollution sources compared to the other conditions. Furthermore, it was generally higher in the office with pollution sources present compared to the conditions with pollution sources absent at both ventilation rates with and without bioeffluents in the office.

Similar indications (but at reduced levels with one order of magnitude compared to those measured with the Innova 1302) were obtained from the chemical analysis of Tenax TA and Tenax GR sampling media. At this time the TVOC is given from the total area of FID-chromatogram (Figure 2.2.3). Since the chemical sampling was carried out only when the subjects were present in the office, these results include emissions from building materials and pollution sources under steady-state conditions, and emissions from people that reached equilibrium after ca. 90 minutes and 95% of the steady-state levels after 165 minutes of exposure respectively at high and low ventilation rates in the office.

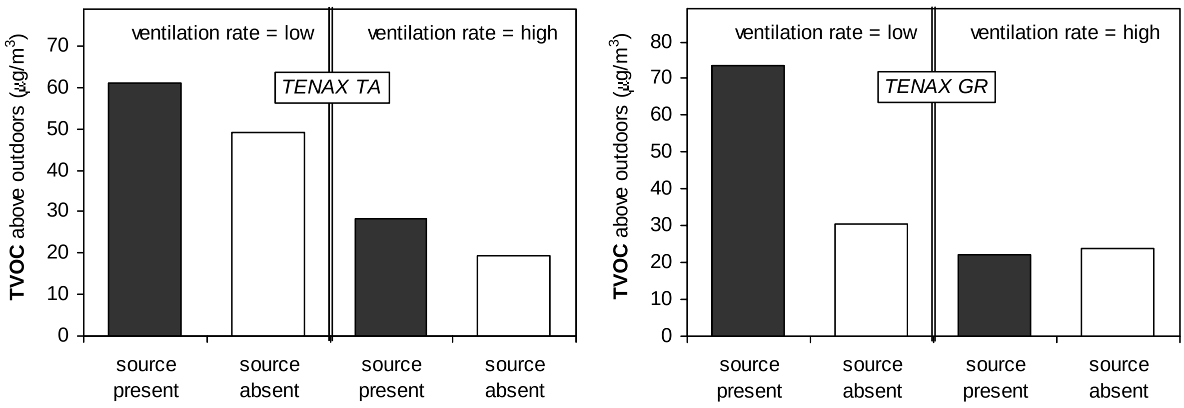
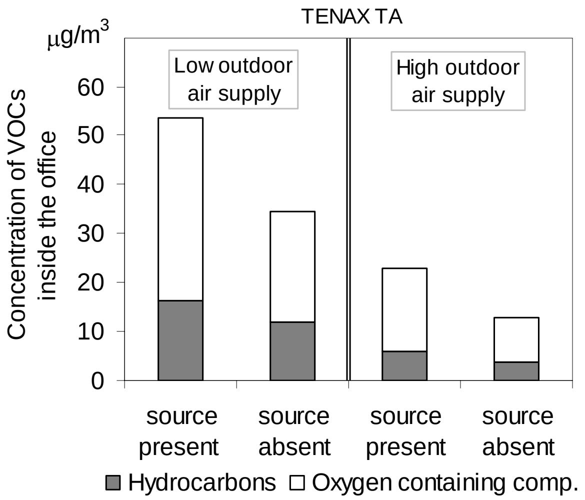


Figure 2.2.3 The total amount of VOCs (TVOC) above outdoors measured during each exposure condition in the office by sampling the air on Tenax TA (left) and Tenax GR (right) tubes

The GS/MS analysis revealed more than 300 different VOC compounds that were captured on the Tenax TA or GR sorbent from the air samples taken indoors for 4 different exposure conditions in the office with subjects present, and outdoors. However, most of these VOCs were reported only for one condition above the detection limit or in traces (below the calculated detection limits). To identify the most representative VOCs in the office air the analyses were made on those compounds that were measured above detection for at least 3 out of 5 groups for one experimental condition. According to this rigorous selection criterion, a total of 57 individual compounds were identified. On average, more than 60% of these compounds were present in both sampling media, 77% in Tenax TA and 86% in Tenax GR. The chemicals are related to the presence of people, and/or primary/secondary emissions of various building materials present in the office. Most of them are simple compounds, such as alkanes (C_7-C_{17}), alcohols (C_2-C_4, C_8), aldehydes (C_2, C_4-C_{10}), ketones ($C_{3\text{-}4}$), carboxylic acids ($C_{3\text{-}4}$, $C_{6\text{-}7}$), and aromatic compounds; however, more complex oxidized and non-oxidized species were also identified. A more detailed list with the concentration of the selected chemicals in the office air is presented in Appendix 2 according to the type of sampling media. The total concentration of these VOCs, calculated by summing up the concentration of each compound identified at the same air quality levels in the office, is shown in Figure 2.2.4. Comparing the results obtained from Tenax TA and GR, in the office with pollution source present, the total concentration of VOCs was exactly the same in both sampling media, i.e. 53±1 μg/m³ and 24±1 μg/m³ respectively at low and high ventilation rates. However, in the office with sources absent the concentrations given by Tenax GR were lower at low ventilation and higher at high ventilation compared to those obtained from Tenax TA. The discrepancy observed may be due to the different sensitivity of the sampling media in relation to the compounds emitted in the low-polluting office.



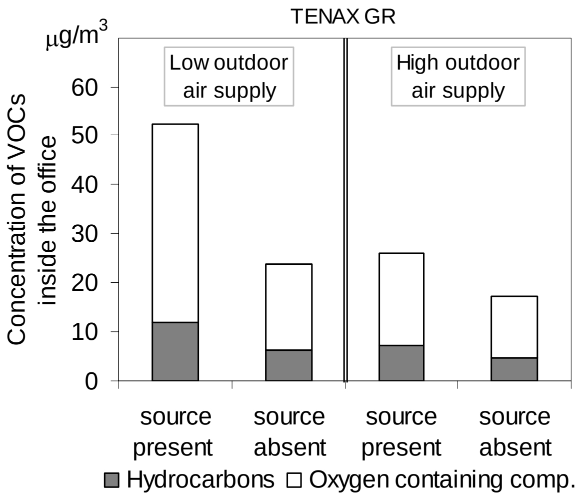


Figure 2.2.4 Concentrations of VOCs inside the office that were identified in Tenax TA (left) and Tenax GR (right) sorbent; The total concentration of individual VOCs was calculated as the sum of hydrocarbons without oxygen and other oxygen-containing compounds (alcohols, ketones, aldehydes, carboxylic acids and other more complex compounds containing oxygen).

Nonetheless, the influence of pollution sources and the applied ventilation rates in the office on the VOC levels is well represented in both figures. The concentrations of individual compounds decreased in the office as a consequence of either removing the pollution sources or increasing the outdoor airflow rates. This was shown already by the TVOC results (Figure 2.2.3) since they are closely related to the total concentrations of single VOCs (Figure 2.2.4). Although the latter values are somewhat lower, such difference was expected considering that the TVOC levels are given by the total area of the FID-chromatogram while the total concentration of individual compounds reflects the sum of the most prevalent compounds identified in the air samples.

Figure 2.2.4 also shows that the fraction of oxygen-containing compounds (alcohols, ketones, aldehydes, carboxylic acids and other more complex compounds containing oxygen) among the individual VOCs is on average two times higher than that for hydrocarbons containing no oxygen (alkanes, terpenes and other aromatics without oxygen content). Oxygen-containing compounds increase in the presence of pollution sources and with the decrement of ventilation rates in the office. This suggests that the pollution sources in the office contribute to the concentration of oxygen-containing compounds by either primary and/or secondary emissions.

Using the concentrations of chemical compounds measured in the office and outdoor air, and the appropriate ventilation rates, the emission rates of the individual VOCs were calculated (Figure 2.2.5 and Appendix 2). Whenever a compound was not detected outdoors, the detection limits were used instead. The results obtained for Tenax TA (Figure 2.2.5 left) show that source removal decreased the emissions both of oxidized and non-oxidized compounds in the office. Consequently, the chemical pollution load in the office with sources absent was lower by 40-50% compared to the office with sources present at both low and high outdoor airflow rates. By increasing the outdoor airflow in the office the emissions of compounds containing no oxygen was reduced by 30-40% in the office both with and without pollution sources.

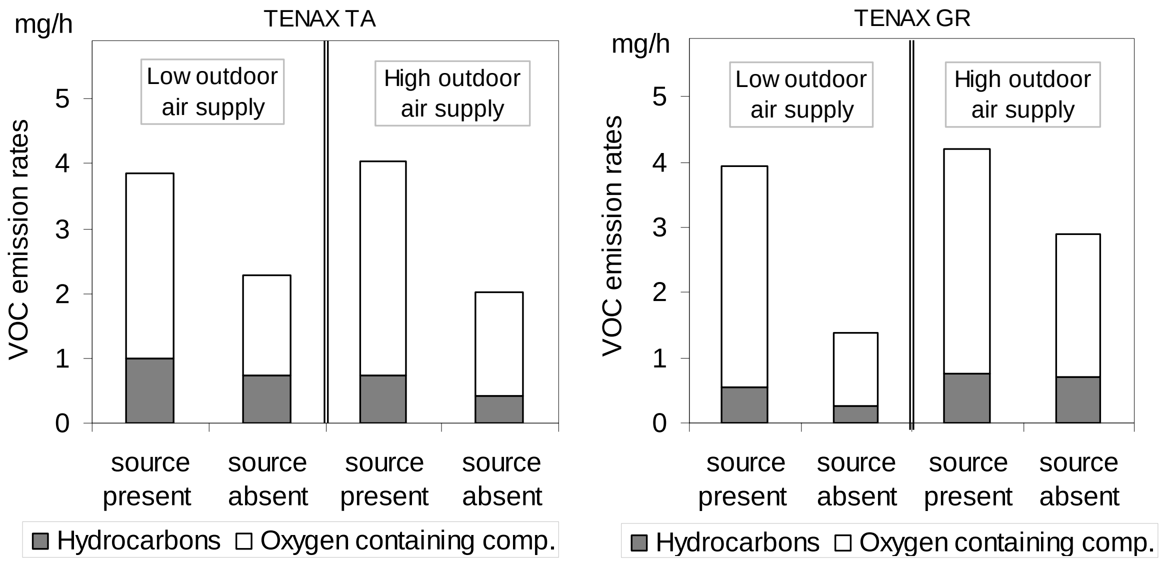


Figure 2.2.5 Emission rates of VOCs as a function of the sampling media and the air quality conditions created in the office i.e., office with/without pollution sources at low/high outdoor airflow rates.

Contrary to this, the higher ventilation rates increased the emissions of compounds with oxygen content. In the low-polluting office this increment was only 3%; in the presence of pollution sources the emissions of compounds containing oxygen increased by almost 20%. This is a clear indication of intensified oxidation processes, which appear to be driven by ozone transported from outdoors to indoors with the supply air. When the outdoor air supply rate in the office was raised the total emission rate of pollutants decreased by 12% in the low-polluting office and increased by 5% in the presence of sources. The results obtained for Tenax GR are similar to those obtained for Tenax TA. The presence of pollution sources intensified the emission of compounds containing oxygen in the office at both ventilation rates. The higher outdoor air supply has also increased the emission of VOCs with oxygen content although in the office without pollution sources such increment in the emission rates was not expected based on the results given by Tenax TA. However, it should be noted that the outdoor ozone levels, and consequently indoor ozone concentrations too, were much higher for the conditions with high ventilation and absence of pollution sources that may have enhanced the oxidation of pollutants being possibly adsorbed on the interior surfaces from the previous exposure days, and considering that the most polluted condition, i.e. office with sources present and low ventilation rate, preceded most of the time the air quality condition with sources absent and high ventilation rate (Appendix 3).

In Figure 2.2.6 the total emission rate of aldehydes are plotted against the ozone surface removal rate (i.e. ozone concentration multiplied by the ozone surface removal rate constant) in the occupied office; each point represents measurements made on a separate day on Tenax TA. The emission rates correlate with the ozone removal rate in a roughly linear fashion ($R^2=0.44$, $p<0.02$ sources present; $R^2=0.57$, $p<0.01$ sources absent). The slope was markedly larger for the condition when sources were present than for the condition when they were absent.

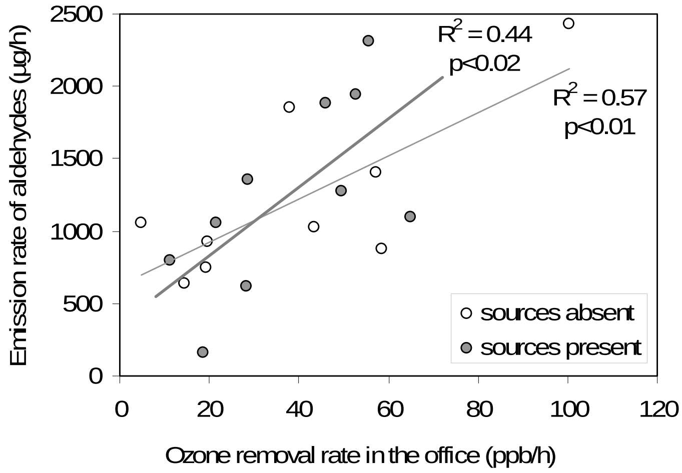


Figure 2.2.6 Emission rate of aldehydes plotted against ozone surface removal rate in the occupied office.

To evaluate the olfactory potential of individual VOCs in the office air, the odour index (OI) was calculated for most of the compounds and it is listed in Appendix 2 based on the available concentrations and the human olfactory threshold (OT) values (Devos *et al.*, 1990). Octanal, nonanal and decanal presented the highest OI over 0.1, which may be assumed high enough for single chemicals to affect odour perception (Wolkoff, 1999; Knudsen et al., 1999). Although the concentration of a number of other aldehydes and carboxylic acids has approached 0.1xOT such as butanal, pentanal, hexanal heptanal, propanoic acid, butanoic acid and hexanoic acid, all other VOCs were identified at concentrations many times below their threshold values.

2.2.2 Perceived Air Quality in the office

2.2.2.1 Perceived Air Quality in the office assessed upon entering

The effect of changing the pollution load and ventilation rate on the acceptability of air in the office upon entering and re-entering is illustrated in Figure 2.2.7. In the office without bioeffluents the acceptability of air significantly increased with source removal at low ($p<0.015$) and high ($p<0.0001$) ventilation rates respectively. Increasing the outdoor air supply rate has also improved ($p<0.03$) the acceptability of air in the office, but only when no pollution sources were present behind the partition. For the office containing bioeffluents plus pollution from the building materials similar results were obtained, except that the improvement of acceptability obtained by source removal at a low ventilation rate did not reach statistically significant levels in the ANOVA analysis. Since ANOVA could be performed only when 23 subjects were present in all four experimental conditions, this comparison was separately repeated with t-test, using all available data (for 28 subjects), this resulted in a significant difference of $p<0.016$ between the conditions with/without sources at low ventilation and presence of bioeffluents. The acceptability of air resulting from source removal at a low ventilation rate was significantly better ($p<0.003$) compared to the air acceptability obtained with an increased outdoor air supply rate in the office with pollution sources present and without bioeffluents. However, this difference was not significant when also bioeffluents were present in the office ($p<0.13$).

The presence of bioeffluents did not significantly affect the acceptability ratings. The only tendency ($p<0.06$) of decreased air acceptability in the office due to the presence of people was obtained in the condition with sources absent and a low outdoor air supply rate, while no significant alteration in the air quality levels were obtained for any of the other conditions.

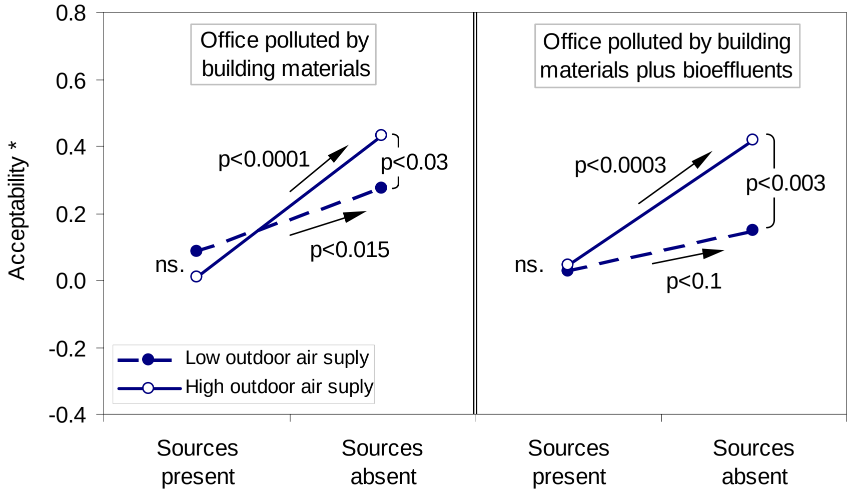


*Figure 2.2.7 Effect of pollution source removal and increasing outdoor air supply rate on acceptability of air as assessed upon entering (office polluted by building materials) and re-entering (office polluted by building materials plus bioeffluents) the office space; p one-tailed values obtained from Duncan's multiple range test; * 1=clearly acceptable, 0=just acceptable/not acceptable, -1=clearly not acceptable*

According to the acceptability votes of subjects present in all four experimental conditions, the percentage of dissatisfied and corresponding levels of air quality were calculated (Table 2.2.3). In the office with source present the percentage dissatisfied with the air quality was in the range 35-42%. Compared to these levels the percentage dissatisfied decreased with source removal to 28% and 17% in the office with and without bioeffluents, which was followed by a further decrease to ca. 8% when the outdoor air supply increased. The percentage dissatisfied with the outdoor air quality was on average 2±0.8% during the all periods of the experiments.

Table 2.2.3 Perceived air quality in the office under different experimental conditions created

	Bioeffluents	Low outdoor air supply rate		High outdoor air supply rate	
		Sources present	Sources absent	Sources present	Sources absent
Dissatisfied (%)	absent	35	17	45	7.9
	present	42	28	40	8.4
Perceived air quality (decipol)	absent	3.2	1.1	4.9	0.48
	present	4.5	2.2	4.0	0.51

Comparable to the acceptability results, odour intensity and nose irritation showed similar effects of the interventions (Figure 2.2.8). Removing the pollution sources, odour intensity was reduced significantly, both in the office polluted by building materials and in the office polluted by building materials plus bioeffluents at low and high ventilation rates.

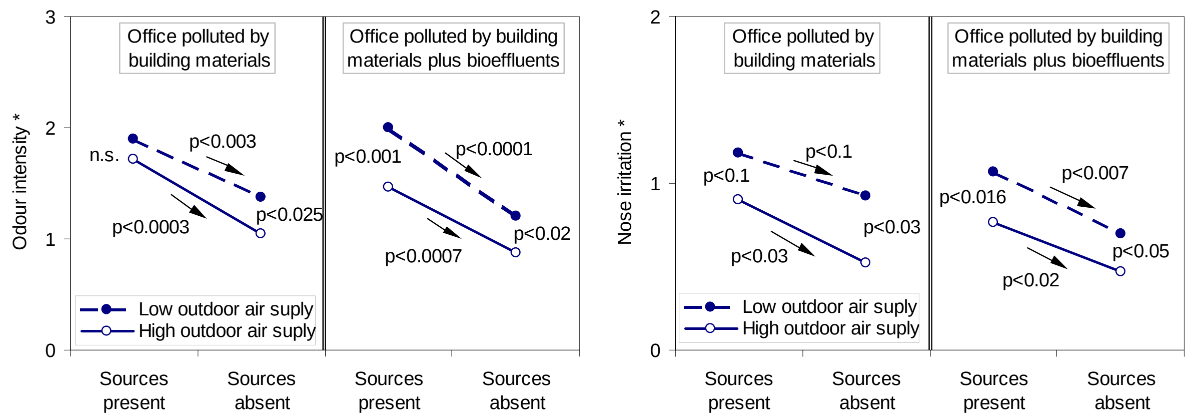


Figure 2.2.8 Odour intensity and nose irritation in the office polluted by building materials and the office polluted by building materials plus bioeffluents, assessed by visitors for the four experimental conditions: source absent/present at low/high outdoor air supply rates; p one-tailed values obtained from Duncan's multiple range test; the scales were coded as follows: 0 – no odour/irritation, 1 – slight odour/irritation, 2 – moderate odour/irritation, 3 – strong odour/irritation, 4 – very strong odour/irritation, 5 – overpowering odour/irritation

Increasing the outdoor air supply rate reduced the odour intensity in the office polluted by building materials plus bioeffluents, both with source present ($p<0.001$) and absent ($p<0.02$), and the office without sources in the absence of bioeffluents ($p<0.025$). Moreover, nose irritation decreased significantly with source removal and with an increased ventilation rate in the office both with/without bioeffluents. Irritation of eyes and throat was not significantly affected by the air quality conditions in the office.

2.2.2.2 Sensory pollution load in the office

The sensory pollution loads in the office were calculated according to the air quality levels presented in Table 2.2.3 and the average outdoor air supply rates within each experimental condition (Table 2.2.4). Removing the pollution sources from the office reduced the sensory pollution load at both ventilation rates. When the outdoor air supply rate was raised the sensory pollution load was almost unchanged in the unpolluted office, but it significantly increased in the presence of pollution sources. These effects of the source removal and the increased ventilation rate can be observed in either the presence or absence of bioeffluents. With people present in the office the sensory pollution load was generally higher, except for one condition, than the initial load when only building materials polluted the office air, but it increased to a lower extent than expected, considering that 6 people, i.e. 6 additional olfs, should have raised the sensory pollution by ca. 0.16 olf/m^2 floor in the office.

Table 2.2.4 Sensory pollution loads in the office (olf/m^2 floor) as a function of the experimental conditions in the absence and presence of bioeffluents

	Low outdoor air supply rate		High outdoor air supply rate	
	Source present	Source absent	Source present	Source absent
Office polluted by building materials	0.25	0.08	1.21	0.09
Office polluted by building materials plus bioeffluents	0.34	0.17	0.99	0.10

2.2.2.3 Air Quality in the office assessed during exposure

Figure 2.2.9 presents the air acceptability votes of subjects and percentage dissatisfied with the perceived air quality upon entering and after they had spent ca. half an hour and ca. two hours in the office. During the first 30 minutes of adaptation, the acceptability of air generally increased compared to the levels upon entering. This increment did not reach significant levels for the conditions with sources absent at a high ventilation rate, where a good air quality level of less than 10% dissatisfied was achieved already upon entering, and in the office with sources present at low ventilation rate, where the subjects' adaptation to the air quality level was presumably longer than 30 minutes. The increment in the acceptability of air in the office with sources present and low ventilation was close to significant ($p<0.06$) in the first 30 minutes, and highly significant ($p<0.004$) after ca. 2 hours of exposure. After the first 30 minutes of exposure no significant changes in the assessments of acceptability of air were measured in either of the experimental conditions created. It is well illustrated in Figure 2.2.9 that the acceptability of air during occupancy was always lower ($p<0.002$ and $p<0.03$ respectively after 0.5 and 2 hours of exposure) when the pollution sources were present in the office, regardless of the outdoor air supply rate applied. Consequently, the percentage dissatisfied with the air quality in the office was in the range 10-19% with source present and only 6-7% with source absent at both ventilation rates. Apparently there was no effect of the increased ventilation rate on the acceptability of air in the office with sources present or absent during occupancy.

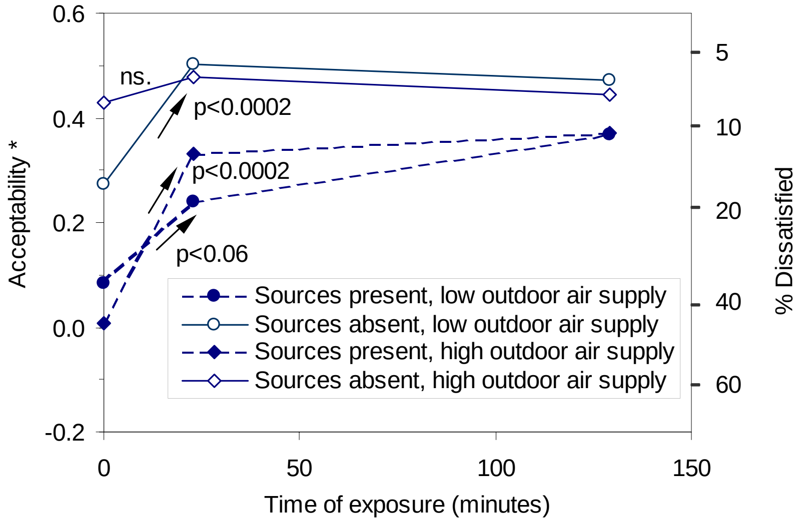


Figure 2.2.9 Acceptability of air and percentage dissatisfied with the air quality upon entering and during occupation as a function of the four experimental conditions created in the office

Odour intensity significantly decreased ($p<0.0001$) below slight odour after the first 30 minutes of exposure under each of the experimental conditions created in the office, as expected. Similarly, nose irritation has also decreased ($p<0.003$), except for the condition with source absent at high outdoor air supply rate, when similar irritation levels were obtained both upon entering and after 30 minutes of exposure. After this period, none of these measures showed significant changes in either the remaining time of the exposures or between the air quality conditions in the office. The irritation of eyes and throat were also no different between the experimental conditions created during exposure.

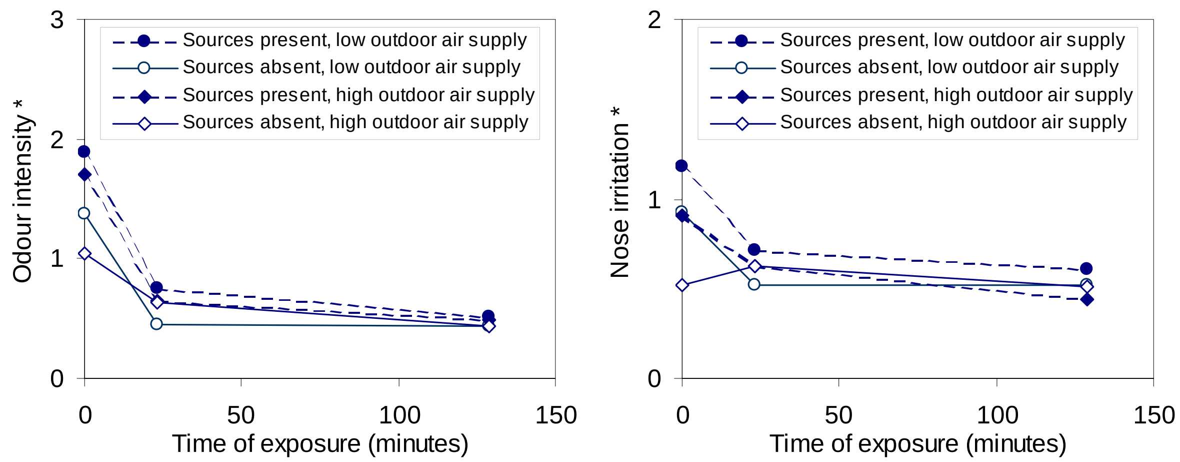


*Figure 2.2.10 Odour intensity (left) and irritation of nose (right) during occupation in the office with sources present amd absent at low and high outdoor air supply rate; * 0=no odour/irritation, 1=slight odour/irritation, 2=moderate odour/irritation*

2.2.3 Assessment of indoor climate and SBS Symptoms

Thermal sensation of subjects during exposures (Figure 2.2.11, left) was close to "neutral" on the "warmer" side of the scale, showing a slight increment ($p<0.03$) with the time of occupation for each condition. This change could be expected, since the air temperature had also increased by ca. 1°C at the end of exposures. The subjects felt significantly warmer in the office with sources present compared to the condition with sources absent at low ventilation rate ($p<0.03$), but the absolute difference was very small (Figure 2.2.11, left). The thermal votes fell always in the same range, between "neutral" and "slightly warm" according to the PMV scale. The percentage dissatisfied with the thermal environment was below 10% for each condition of air quality inside the office that was within the range recommended by standards (ISO1993b).

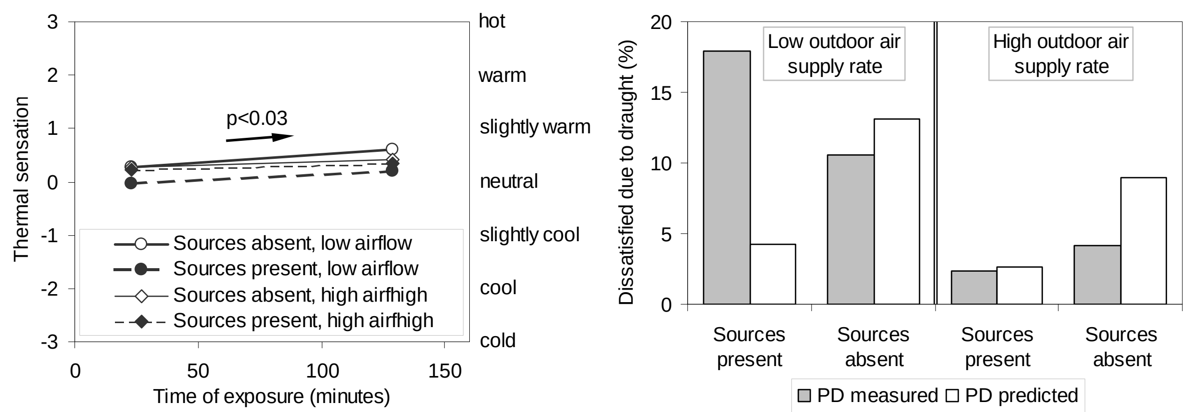


*Figure 2.2.11 **Left**: Thermal sensation of subjects during occupation in the office with sources present/absent at low/high outdoor air supply rates; **Right**: Percentage of people dissatisfied due to draught based on subjective responses or predicted from the measured velocities and air temperatures in the office for each experimental condition*

On average, 50% of the subjects had noticed air movement around their body. The result of their vote was then compared with the predicted percentage dissatisfied (PPD) due to draught (Figure 2.2.11, right) using the results of physical measurements of air temperature and mean air velocities recorded during exposures (Table 2.2.1). The PPD values were in each case below 15%, in accord with the recommended levels (CEN, 1998; category A), while the measured values were generally lower than those predicted, except for the condition with source present at low outdoor air supply rate. This difference is rather unexpected since the actual mean air velocities measured for this condition were lower than in the office without pollution sources at the same ventilation rate. Comparing the subjective votes on air movement, it was significantly less acceptable in the office with source present and low ventilation rate compared to the conditions with high ventilation source present ($p<0.03$) and source absent ($p<0.03$). However, this result is based only on the report of 9-10 subjects and is not representative of the whole group of people occupying the office.

To see whether source removal and/or increased ventilation rates had a significant effect on subjects' perception and SBS symptom intensity, the data were first analysed with Friedman ANOVA. Significant or close to significant changes after 23 minutes of exposure were obtained for air freshness ($p<0.03$), perception of noise (0.07), nose dryness ($p<0.03$), throat dryness ($p<0.04$), eye dryness ($p<0.08$) and intensity of headache ($p<0.08$). According to the second evaluations, after 129 minutes of exposure, the perception of noise level showed the only significant changes between the experimental conditions.

Table 2.2.5 Significant ($p<0.05$) or close to significant ($p<0.10$) effects of source removal on perceptions and symptoms after 23 and 129 minutes of exposure in the office at low and high outdoor air supply rates

Perception or symptom	Time (min)	Low ventilation		High ventilation		Significance of interventions (p-values)			
						Source removal		Increased vent.	
		Sources present	Sources absent	Sources present	Sources absent	low vent.	high vent.	sources present	sources absent
Air dryness	23	38	48	46	48	0.005		0.04	
dry=0; humid =100	129	47	45	44	46				
Air freshness	23	42	53	44	56	0.009	0.04		
stuffy=0; fresh=100	129	42	48	44	43				
Illumination	23	41	43	42	43				
dark=0; bright=100	129	41	41	44	43			0.07	
Noise	23	48	42	43	46	0.02			0.06
noisy=0; quiet=100	129	45	40	44	43	0.04			0.006
Nose dryness	23	32	37	38	41			0.03	
dry=0; not dry=100	129	37	36	41	38				
Throat dryness	23	38	50	50	56	0.03		0.06	
dry=0; not dry=100	129	53	49	57	52				
Eye dryness	23	47	57	48	47	0.04			0.05
dry=0; not dry=100	129	45	45	45	45				
Headache	23	72	78	71	68				
severe=0; no headache=100	129	65	76	68	65	0.02			
Dizziness	23	78	85	82	83	0.07			
dizzy=0; not dizzy=100	129	74	77	79	74				
Tiredness	23	60	70	66	69	0.04			
tired=0; rested=100	129	51	59	46	54	0.10	0.09		
Difficult to concentrate	23	63	68	58	64		0.09		
difficult=0; easy=100	129	51	56	55	57				
Sleepiness	23	69	75	68	71				
sleepy=0; alert =100	129	65	66	55	59			0.05	

Since the Friedman ANOVA test did not show which of the interventions caused the observed differences, pair-wise comparisons (Wilcoxon matched pairs) were used instead. The average votes of subjects present under each condition (23 subjects) and the results of pair-wise comparisons testing the effects of source removal or increasing the outdoor air supply rate in the office are summarized in Table 2.2.5.

According to the first assessments, collected after 23 minutes of exposure, the air freshness significantly increased with source removal at both low and high outdoor air supply rate in the office. Furthermore, in the office with low outdoor air supply and presence of sources, the air was perceived dryer and the sensation of dryness in eyes and throat significantly increased compared to the condition with sources absent. It is also indicated that in the condition with low ventilation rate, the subjects were more tired in the polluted office, although this difference did not reach significant levels at the end of the exposure. In the second assessments, i.e. after 129 minutes of exposure, the only significant change in the SBS symptom severity was seen for headache. It decreased significantly with source removal in the office with low outdoor air supply rate. Tendencies of increased dizziness, as well as tiredness and difficulty in concentrating were also observed as a result of source removal respectively at low and high ventilation rate in the office.

Compared to source removal, fewer symptoms were apparent when increasing the outdoor air supply in the office. When the sources were present the higher outdoor air supply rate was beneficial and decreased significantly the perception of air dryness and sensation of nose dryness, while throat dryness tended to decrease with a low ventilation rate; all these effects were observed only in the first part of the exposure. No apparent reason can be given for growing sleepiness at the end of exposures in the presence of pollution sources when increasing the air change rate in the office. Finally, the changes in the illumination or noise level in the office with the interventions may be considered as environmental "halo" effects (an unconscious tendency to be influenced by a single positive aspect in forming a generally favourable evaluation of an environment), since none of these parameters were changed during this experiment.

*Table 2.2.6 Effect of source removal and/or increased ventilation rates in the office on environmental perceptions and symptom severity of occupants; the arrows show increment (↑) or decrement (↓) in a perception or symptom severity; significance of statistical test: *=0.05<p<0.1; +=0.01≤p<0.05; ++=p<0.01; the number of subjects completing exposures is also indicated.*

Perception or symptom	Source removal		Increased air supply		Source removal and increased ventilation (26 subjects)
	Low ventilation (28 subjects)	High ventilation (25 subjects)	Sources present (26 subjects)	Sources absent (26 subjects)	
Air dryness	↓ ++		↓ +		↓ +
Air freshness	↑ ++	↑ +			↑ +
Office brightness			↑ +		
Office noisiness	↑ +			↓ +	
Nose dryness			↓ +		↓ +
Throat dryness	↓ *		↓ *		↓ *
Eye dryness	↓ +				
Headache	↓ +				
Dizziness	↓ *				
Tiredness	↓ +				↓ +
Difficulty to concentrate	↓ *	↓ *			↓ *
Sleepiness			↑ +		

The pair-wise comparison between the experimental conditions was repeated for all available data, to see whether including more subjects would affect the SBS results previously obtained. Table 2.2.6 gives an overview of the way in which the interventions in the office applied separately or together affect peoples' perceptions and symptoms intensity. The significance of most changes as a result of source removal or increased ventilation showed similar levels as in the case of 23 subjects and stayed within the indicated ranges. When both interventions were applied in the office, i.e. the pollution sources were removed and the outdoor airflow rates increased, the effects on perceptions and symptoms were generally the same as for source removal at a low ventilation rate. In the first part of exposures the air was perceived as less dry and more fresh. The intensity of nose dryness significantly decreased, and the subjects became less tired at the end of exposure. The tendency towards lower throat dryness and easier concentration is also reported as a result of these interventions; no significant changes in the perceptions of noise and light level was observed at this time.

2.2.4 Objective measures of performance

During exposure in the office the subjects were asked to perform several tasks as presented earlier, in section 2.1.5.4. The speed and accuracy of performing these tasks were subsequently used to analyse how the conditions affected subjects' performance.

Although the subjects received one session for instruction and training to become familiar with the tasks, and the exposures of different air quality levels in the office were balanced for the groups for order of presentation, the performance was improved depending on the exposure time (Table 2.2.7). Consequently, these results were analysed with and without applying adjustments for "learning" to evaluate the effects of interventions. When making this adjustment, it may be assumed that the experimental conditions have little effect on learning, as they were balanced on each day of exposure (see Table A-3.1 in Appendix 3). The corrections for learning were made using the following procedure: 1) all data were arranged according to the order of presentation of the exposures, calculating the arithmetical mean values of the performance measures for each day (Table 2.2.7); 2) the means obtained for the second (day-2), third (day-3) and fourth (day-4) exposure days were divided by the mean of the first exposure (day-1) to obtain an average learning index for the whole group 3) each individual data on the second, third and fourth days were divided by the learning index of the respective day; 3) after this adjustment the data were re-arranged according to the exposure conditions, source present/absent at low and high outdoor air supply rates.

Table 2.2.7 Improvement of performance depending on the exposure days in order of presentation; the significance of expected improvements, i.e. increment in speed and decrement in the error rate with the order of exposure days, was calculated with Page test for ordered alternatives.

Exposure time	Multiplication		Addition		Text typing	
	Speed (units/h)	Error rate (%)	Speed (units/h)	Error rate (%)	Speed (char/min)	Error rate (%)
day-1	70.6	25.4	212.8	8.2	156.7	3.5
day-2	73.4	22.5	237.1	6.3	154.8	3.1
day-3	78.4	19.8	237.0	6.1	158.0	2.9
day-4	77.3	18.0	233.6	6.4	158.3	2.9
Page test day 1-4 (p-value)	0.01	0.002	0.002	0.2	0.13	0.04

The analysis of Friedman ANOVA, considering only 23 subjects being present under all four experimental conditions, showed no significant differences in the performance of any of the tasks as a result of the interventions established. Another analysis was performed with all the data available. Due to missing subjects, only a pair-wise comparison could be made to evaluate the effects of interventions in the office on performance. Table 2.2.8 shows the average speed and the corresponding accuracy (error rate) for all subjects who completed exposure, grouped according to the air quality conditions in the office, with and without adjustments for learning. The comparison could be made using 28 and 25 data when evaluating the effects of source removal at low and high ventilation rates respectively, and with 26 data to see the effects of increased ventilation rate in the presence/absence of sources in the office.

*Table 2.2.8 Average speed and accuracy of subjects based on all data available with and without adjustments for learning, indicating significant or close to significant effects between the experimental conditions (* = 0.05 <p <0.1; + = 0.03 <p <0.05).*

Exposure conditions		Multiplication		Addition		Text typing	
Ventilation rate	Sources	Speed (units/h)	Error rate (%)	Speed (units/h)	Error rate (%)	Speed (char/min)	Error rate (%)
Not adjusted for learning:							
Low	Present	75.6 *	24.4	223.9	6.8	155.4	3.4 +
	Absent	73.7	21.9 +	* 228.2 *	6.6	156.9	3.0
High	Present	73.7	17.9	232.2	6.4	157.6	2.9
	Absent	76.4	21.7	235.4	7.4	157.7	3.1
Adjusted for learning:							
Low	Present	71.9 *	28.0	210.1	8.1	155.1	3.7 +
	Absent	69.8	25.7	* 210.2	7.9	157.2	3.4
High	Present	68.8	21.7	214.3	7.7	157.1	3.3
	Absent	71.7	26.2	217.0	9.0	157.3	3.6

*Table 2.2.9 Overall performance of subjects in arithmetical calculations and text typing, i.e. the error-free units or text calculated as the speed reduced by the accuracy of each task; * = 0.05 <p <0.1; + = 0.04 <p <0.05*

Exposure conditions		Overall performance measure		
Ventilation rate	Sources	Multiplication (units/h)	Addition (units/h)	Text typing (characters/min)
Not adjusted for learning:				
Low	Present	59.0	209.0	150.4
	Absent	58.1	+ 212.8	152.3
High	Present	60.6	218.0	153.2
	Absent	61.1	218.4	153.0
Adjusted for learning:				
Low	Present	51.0	193.6	149.6
	Absent	51.8	* 192.4	151.9
High	Present	53.0	197.5	152.1
	Absent	53.4	197.9	151.9

The unadjusted results for learning show that in the case of multiplication the air quality levels in the office did not significantly affect the speed at which the subjects executed this task. The only significant change in the error rate was seen in the office with sources present at low and at high outdoor air supply rate. Although it was lower ($p<0.04$) in the latter condition, no significant difference in the overall performance, i.e. the error-free units calculated as the speed reduced by the accuracy of multiplication (Table 2.2.9) could be observed.

The speed of addition in the office with sources present and a low ventilation rate tended to be lower compared to the conditions with sources present ($p<0.06$) and absent ($p<0.08$) at a high ventilation rate. These changes were also reflected in the overall performance of the addition task (Table 2.2.9), but a significant difference could be seen between the conditions with low and high air supply rates ($p<0.05$) only in the office with sources present.

Analysing the results of text typing, in the office with sources present and a low ventilation rate, the number of words omitted was significantly higher ($p<0.04$) compared to the condition with sources absent (Figure 2.2.12). Consequently, this change has affected the total number of errors, resulting in a significant difference ($p<0.04$) in the error rate between these two conditions (Table 2.2.8). No other significant changes in the absolute values of speed and error rate were observed between the experimental conditions created in the case of text typing.

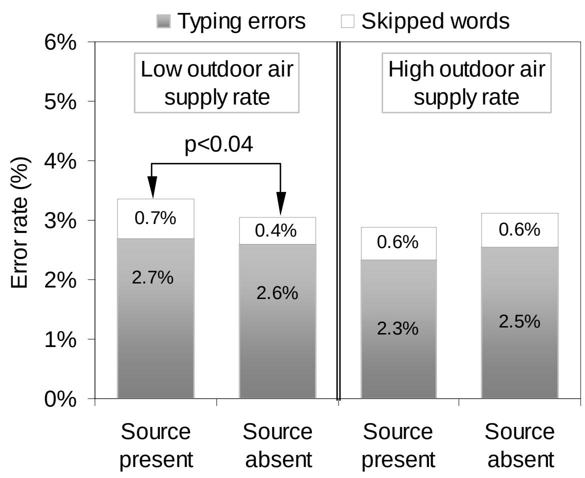


Figure 2.2.12 The error rate of text typing partitioned into typing errors and skipped words as a function of the four experimental conditions in the office with/without sources at low//high ventilation rates.

The results of serial addition and text typing suggest an increasing trend in the overall performance when the sources were removed and the ventilation rates increased in the office. None of these trends reached significant levels when using the Page test, under the assumption that a higher airflow and lower pollution load have a positive effect on people performance; however, this test included only 23 subjects, who completed each exposure.

The adjusted data for learning showed generally a lower speed and higher error rate in the absolute values compared to the unadjusted levels. The effects seen on the performance as a result of interventions for unadjusted data were generally weakened by the adjustment procedure. Consequently, there is no significant difference in the adjusted performance measures between the experimental conditions except in the case of the error rate of text-typing between the office with/without sources and low ventilation rate.

Since the text-typing task was executed in two periods, each lasting for 50 minutes, a more specific analysis was made, by calculating the typing speed and error rate in the first part (28-78 minutes) and second part (79-128 minutes) of each exposure. The unadjusted results for learning are presented in Figure 2.2.13. It shows that the typing speed significantly decreased during exposures in each of the conditions of air quality inside the office. The typing accuracy also decreased, i.e. error rate increased, between the first and second part of the exposures; however, significant differences were seen only in the conditions with high ventilation rate, sources present/absent.

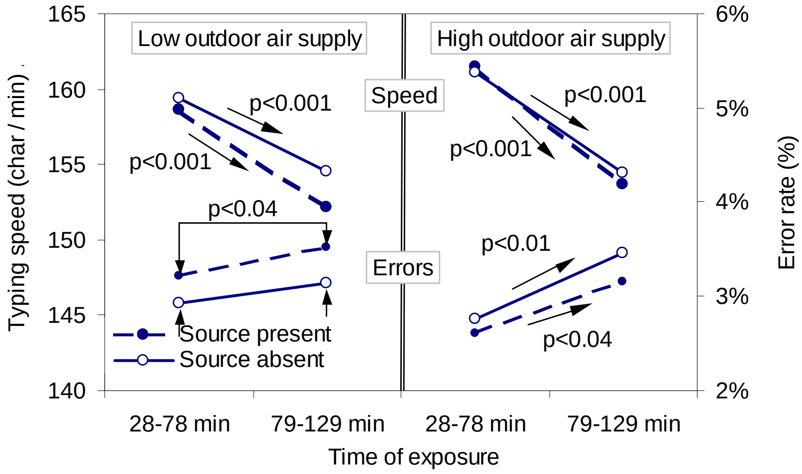


Figure 2.2.13 Results of text typing in the first and second part of the exposure as a function of the experimental condition in the office with sources present/absent at low/high outdoor air supply rates.

To evaluate whether the air quality levels in the office have significantly affected these changes in performance, the absolute differences between the first and second part of the exposures were calculated and compared between the conditions (Figure 2.2.14).

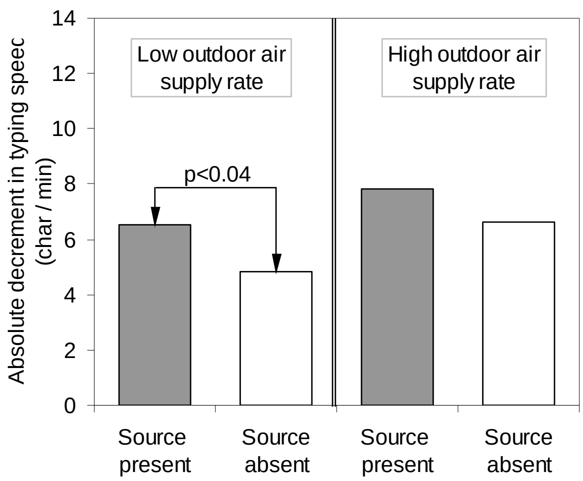


Figure 2.2.14 Absolute changes in the typing speed between the first and second part of the text-typing task as function of the experimental condition in the office

In the conditions with low outdoor air supply rate the absolute decrement in speed of typing was significantly higher (p<0.04) in the office with sources present compared to the office with sources absent. This observation remains valid also for the absolute decrement of the overall typing performance (p<0.04) and the significance of this effect remained unchanged even when adjustments for learning were made. The absolute decrement in the text typing performance was not significantly affected as a result of source removal at a high outdoor air supply rate or due to increased ventilation rates in the conditions with sources present/absent in the office.

2.2.5 Self-estimated ability to work

The analysis of ratings on the SBS questionnaires indicated that most of the symptoms that are expected to have an influence on the self-estimated work ability of subjects and objectively measured performance were affected in the office with sources present at a low outdoor air supply rate (Table 2.2.5). The severity of headache and tiredness were significantly more intense and tendencies towards increased difficulty in concentrating were also observed for this condition, compared to the office with sources absent.

The subjects' self-estimated work ability significantly decreased ($p<0.02$) between the first and second part of each exposure. The magnitude of this change was fairly similar, i.e. it was not significantly affected by the experimental conditions.

The pair-wise comparisons between the conditions of air quality in the office did not show any significant change in the self-estimated work ability of the 23 subjects present in each exposure. This analysis was again repeated for all available data, which showed that during the whole exposure the subject indicated a lower ability to work in the office with sources present and a low ventilation rate compared to the conditions with sources absent ($p<0.05$) or present ($p<0.04$) at a high outdoor air supply rate (Figure 2.2.15). Moreover, the subjects' self-estimated work ability monotonically increased with source removal and increasing outdoor air supply rate when comparing the four conditions with the Page test for ordered alternatives ($p<0.05$).

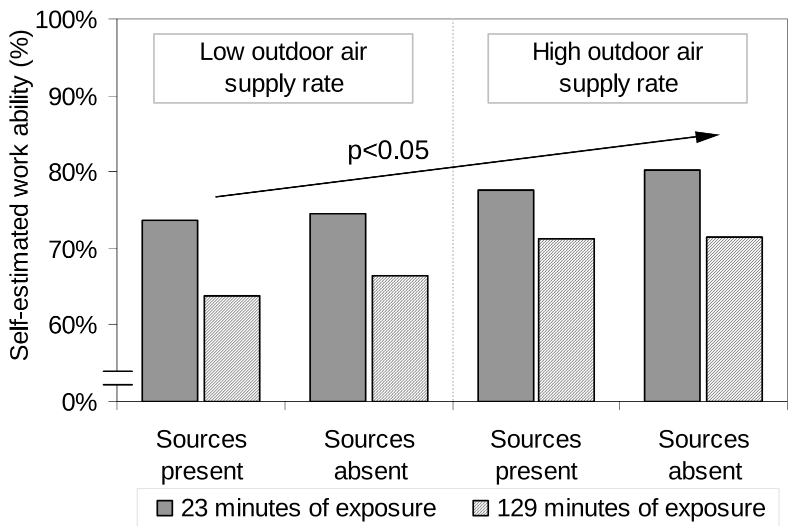


Figure 2.2.15 Self-estimated work ability of subjects during exposures in the office as a function of the experimental conditions: sources present/absent in the office at low/high ventilation rates; Page test for ordered alternatives is applied on the average data between the first and second part of the exposures

2.2.6 Personal factors influencing subjects sensitivity regarding Perceived Air Quality and SBS symptoms

In the previous sections it was not taken account that personal characteristics may influence subjects' assessments of the indoor environment. A separate analysis was carried out to study whether different subgroups of subjects who had a higher sensibility regarding odour perception (based on the olfactory test) or who reported special characteristics in relation to the indoor environment or SBS symptoms would have a different response to the conditions created in the present experiment. Using the results of the olfactory tests and other personal data from the questionnaire completed during recruitment, the subjects were divided into the following subgroups:

1. Subgroup 1: subjects who completed the olfactory test with no more than 1 error on ranking and 2 errors on matching (20 subjects)
2. Subgroup 2: subjects who consider themselves sensitive to IAQ (8 subjects).
3. Subgroup 3: subjects who reported SBS history, having one or more mucous membrane, cutaneous or general symptom occurring at least twice per month in the last year prior to the experiment (16 subjects).

Although subjects who often experienced "dry air" at home or at their workplace, or suffered from eczema when exposed to sunlight were also considered for selection, there were too few subjects fulfilling this criterion.

The percentage dissatisfied with the perceived air quality in the office with bioeffluents is presented in Figure 2.2.16 for all subjects and for different subgroups defined above who participated in each experimental condition.

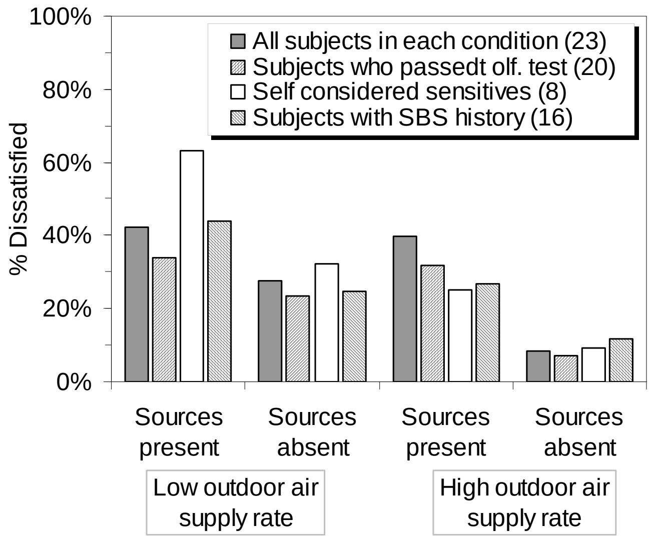


Figure 2.2.16 Perceived air quality in the office expressed in % dissatisfied assessed by all subjects and by different subgroups of people present in each experimental condition in the office with bioeffluents;

Since most of the subjects fulfilled the olfactory criteria, the votes of subgroup 1 were similar to the votes of all 23 subjects. Subgroup 2 reported 63% dissatisfaction with the perceived air quality in the office, showing a substantially higher criticism compared to the whole group of people. On the other hand, each air quality improvement established in the office had a similar effect on their perception: the perceived air quality significantly improved either with source removal ($p<0.008$) or when the outdoor air supply rate was increased ($p<0.005$); however, this group represents only 8 people. The subjects in subgroup 3 also reported that both source removal ($p<0.02$) and increased ventilation rate ($p<0.02$) significantly improved PAQ in the office compared to the condition with sources present and a low outdoor air supply rate. This means that more than half of the subjects completing the exposures considered that the PAQ in the office significantly improved compared to the most polluted condition, as in the case of subgroup 2. It should be noted that in the best air quality condition, i.e. sources absent and high ventilation rate, there was no or very little difference in the perceived quality of air reported by different groups of people.

The analysis made on SBS symptom intensity and performance of subjects being part of the subgroups defined above showed little effect of the interventions established in the office compared to the initial findings. Therefore these data were not subjected to detailed presentation.

2.3 Discussion

In the present study a set of common building materials was selected to evaluate its impact on perceived air quality, human comfort and performance. The main hypothesis was that the emissions of such materials negatively affect the quality of indoor air. Furthermore, two methods of air quality improvement, i.e. controlling the emissions of pollutants from indoor sources and/or increasing the ventilation rate in buildings, were directly compared in a common experimental design. It was hypothesized that applying either of these methods would lead to increased IAQ that meets human comfort requirements, resulting in a lower prevalence of adverse sensory effects and other symptoms among people. As a result of improved indoor climate, performance would improve.

These hypotheses were tested in an office where impartial subjects performed simulated office work for approximately 3 hours, under different air quality conditions. Female subjects were selected, as it was shown earlier (section 1.1.1) that they report more SBS symptoms, are thus likely to be more sensitive and would respond even to small changes in the indoor environment. Four levels of air quality were set in the office either by introducing or removing typical building materials, i.e. controlling the emissions, or by changing the outdoor air supply rate, i.e. diluting the pollutants indoors. All other parameters, such as air temperature, relative humidity, air velocity, noise, and lighting were kept constant. Consequently, all changes observed in people's perception or reported symptoms were expected to be caused by interventions resulting in changes in indoor air quality levels.

The office with a high pollution load and low ventilation was the worst condition, where high dissatisfaction with the perceived air quality was reported and the severity of SBS symptoms was stronger compared to the other conditions. To some extent, the negative effects of a mediocre indoor climate were also reflected in people's performance. Though the measurable effects in the objective tasks were small, results showed, as expected, that work performance improved with the interventions established in the office. These results are discussed in detail in the following subsections.

A drawback when evaluating the effects of air quality improvement on people's comfort and performance was that a completely balanced analysis between the four experimental conditions could be performed only for 23 subjects, and this may have decreased the power of statistical comparisons. The pair-wise comparisons between the conditions were also limited to at least 25-28 subjects, depending on how many people were present in each exposure. Most of the subjects dropped out in the conditions with a high outdoor air supply rate, making it difficult to see the effects of increased ventilation, in both presence and absence of pollution sources, and the effects of source removal at a high ventilation rate in the office. This could be one of the reasons why the effects seen for source removal at a low ventilation rate, when the data for 28 subjects are available, were stronger compared to the effects of other interventions. It should be noted that at least 4 significant effects may have occurred simply by chance, considering 5% probability for the null hypothesis and ca. 70 tests performed during the statistical analysis. Nevertheless, in at least 40 tests there were significant effects found between the experimental conditions created.

2.3.1 Effects of source removal and increased outdoor air supply rate on IAQ

The results of the present experiment clearly indicated that building materials and furnishing commonly used in many indoor settings degrade the quality of indoor air i.e., they act as sources of pollution through their emissions that are measurable with both chemical and sensory methods. Whenever such sources were present in the office the concentration of VOCs increased and a greater number of people complained about unacceptable air quality, increased odour intensity and nose irritation on first impression. This effect was consistent at both low and high outdoor air supply rates in the office. Increasing the outdoor air supply rate reduced the concentration of many VOCs and diluted the bioeffluents from humans (as indicated by lower CO_2 concentrations), consequently improving the air quality. However, the positive effect of the increased outdoor air supply rate on PAQ was lower than anticipated in the office with pollution sources present. A possible explanation of this outcome might be that the emission of pollutants from the building materials, which are possibly driven by oxidation processes, have increased, resulting in a persistent odour that would not disappear even at high airflow rates. Consequently, this could have affected some of the subjects who did not vote for higher air acceptability when the ventilation rate in the office with the pollution sources present was increased. This was not, however, indicated by the odour intensity and nose irritation, which significantly decreased with increased ventilation rate when the sources were present.

The air quality ratings on first impression and during exposures were consistent when comparing the effects of pollution sources on perceived air quality. Although the subjects adapted to the air quality conditions in the office, they still voted that air acceptability was lower in the presence of pollution sources, either at high or low airflow rates. At a low ventilation rate the adaptation period to the air polluted by building materials was considerably longer than without sources in the office. This confirms an earlier finding that people's adaptation to the pollutants originating from building materials is smaller than in the case of human bioeffluents (Gunnarsen and Fanger, 1992). In the office without sources the major pollutants were human bioeffluents, which stimulate mainly the olfactory sense and to a lesser extent the common chemical sense. Consequently, in the absence of the pollution sources, high adaptation occurred, resulting in almost no difference in the air quality level during exposures either at low or high outdoor air supply rates. On the other hand, when building materials were the main source of pollution, the improvements in air acceptability due to adaptation were smaller since both the olfactory and chemical senses are stimulated to a higher degree than in the case of bioeffluents. Following the first 30 minutes of exposure, the subjects were not particularly affected by an increased odour intensity or irritation of mucous membranes, as these responses were at a bottom level of the measuring scales even in the office with sources present.

The PAQ in the office was not reduced as expected, due to the presence of bioeffluents. Several factors could influence the panel sensitivity, and may explain this effect. The refreshment period for subjects after they had left the office could have been too short. In order to re-assess the air quality in the office, the subjects went through the building, i.e. cross-adaptation may have occurred, although they followed the shortest way between outdoors and the office. Furthermore, the subjects were "biased", assessing their own bioeffluents after re-entering the office and this could also result in higher acceptability.

The effects of pollution sources examined in this study on PAQ are somewhat lower than those obtained by Wargocki et al., (1999) and Lagercrantz (2000) indicating that carpets may present stronger sources of pollution in indoor environments. Although the triple amount of outdoor air was a successful method to alleviate the effects of pollutants originating from carpets on PAQ (Wargocki et al., 2000b), it may be less effective in the case of other materials that change their emissions at higher ventilation rates. In such circumstances, a higher increment of the ventilation rates may be recommended to obtain a significant improvement of PAQ. It is worth noting that the benefits of an increased outdoor air supply rate for perceived air quality will persist even with reduced pollution sources because the bioeffluents emitted by humans will be diluted. On the other hand, reduction of pollution sources indoors can effectively improve the quality of air without increasing the ventilation requirements.

2.3.2 Compliance with the air quality guidelines

The airflow rates in the present experiment were selected particularly to meet the "low-end" and "high-end" ventilation requirements set by CEN (1998) for low-polluting buildings. The results of the experiments clearly showed that the targeted air quality levels in the "design phase" could be obtained, i.e. when the ventilation rates recommended for air quality categories "A" and "C" were applied, the percentage dissatisfied remained below 15% and 30%, respectively. However, when simulating a typical non-low polluting building, i.e. pollution sources were present, and the higher ventilation rate (90 L/s) was applied in the office, the percentage dissatisfied should fall below 20% (category B) according to CEN (1998); nevertheless, not even the requirement for category C could be fulfilled in this air quality condition when all subjects were included in the sensory panel. This means that in some buildings, where non-low-polluting materials and furnishing are present, the air quality levels aimed at may not be achieved even by applying the airflow rates recommended. These results confirm that the selection of low-polluting building materials and furnishing, as recommended by CEN (1998) and other ventilation and air quality guidelines (ECA, 1992, FISIAQ, 1995), is an effective method for improving indoor air quality without increasing the energy demand of HVAC systems, and it should be considered in the future design of non-industrial indoor environments.

2.3.3 Sensory and chemical pollution load in the office

Removing the pollution sources from the office ventilated at low/high outdoor air supply rates improved the perceived air quality because the chemical and sensory pollution loads in the office were reduced. Increased ventilation should also improve the quality of air by reducing the concentration of pollutants, assuming that their emission rate would not change. Nevertheless, in the office with sources present, both the sensory and chemical pollution load increased with the higher outdoor air supply rate. Although the increment of the total chemical emissions was modest, 5% only, the sensory pollution load was ca. 3 times higher than the load in the office with sources present and a low ventilation rate. Consequently, the increased sensory pollution load could counteract the beneficial effect of an increased outdoor air supply rate on PAQ. On the other hand, when the sources were absent, the sensory pollution load was remarkably constant when altering the outdoor air supply rate in the office. It should be noted that the office was deliberately designed with low polluting materials and had relatively inert surfaces.

One of the reasons, that may explain the higher sensory pollution load is the considerable increment in the emissions of compounds containing oxygen due to intensified oxidation processes on the material surfaces. As a result of such reactions, aldehydes and organic acids are formed with an extremely low odour threshold, possibly causing sensory effects on humans. The correlation found between the emission rates of aldehydes in the office with the ozone surface removal rate is another good indication of the occurrence of oxidative processes initiated by ozone. In addition, a number of radicals, characterized as more irritant, are also produced in such reactions (see section 1.1.3), and are definitely not detected by conventionally applied measuring techniques.

When the sources were present at a low ventilation rate, the odour index of at least 11 compounds was higher than 0.01. Consequently, these compounds could affect the perceived air quality in the office. When measuring such low levels for the odour indices, it is not unusual to have a sensory impact, considering the uncertainty of odour thresholds, large individual differences among people, and sensitivity and hypo-addition of odour thresholds of odorous VOCs in a mixture (section 1.1.3). Chemical compounds with less than 0.1 OI affecting perceived air quality was also observed by Knudsen et al., (1999) when the emissions of 5 building products including carpet, PVC, sealant, floor varnish and wall paint were measured in chemical and sensory terms.

An increase of sensory and chemical emission rates from building products was measured a number of times when increasing the area-specific ventilation rate, but mostly under laboratory conditions, using small-scale test chambers. Knudsen et al. (1994) reported that the sensory pollution load of linoleum markedly increased at higher area-specific airflow rates. They noted that doubling the ventilation causes only half the improvement in terms of decreased % dissatisfied when the pollution originates from linoleum as compared with bioeffluents. However, the ozone content of air used to ventilate the test chambers in that study was not reported and that could also affect their results in relation to the sensory pollution load of linoleum. Gunnarsen (1997) showed that the specific ventilation rate might influence the sensory emission rates in both sensory and chemical terms. At low specific ventilation rates the emissions were proportional, i.e. the chemical and sensory emissions increased with the area-specific ventilation rates. Nevertheless, at higher specific ventilation rates when the chemical emissions stabilized, the sensory emissions continued to increase, especially in the case of carpet and linoleum. Both materials are known to contain constituents that react with ozone at moderately fast rates (Weschler et al., 1992; Jensen et al., 1996). An increase of the sensory pollution load from carpet was also reported in a normal office environment (Wargocki et al., 2000a) when the ventilation rate was changed by a factor of 3, from 0.5 $L/s \cdot m^2$ to 1.7 $L/s \cdot m^2$, but no further increment were seen above this level.

It is known that linoleum has the potential to remove ozone. However, compared with other materials, e.g. unpainted plasterboard or carpets, the deposition velocity is rather small (Klenø et al., 2001). The same was observed in the present experiment, since the I/O ratio was only slightly affected when the pollution sources were introduced in the office. Knudsen et al. (2003) could not show that linoleum exposed to ozone would affect sensory perception.

The higher air change rate in the office normally reduces the time available for gas phase chemical reactions to occur. It is unlikely that reactions in the air have contributed to the concentration of measured compounds, even in the office with sources present and a low ventilation rate, considering the times required for the reactions to occur for most of the indoor VOCs (Weschler, 2000). Limonene, which has one of the highest rate constants for its reaction with ozone compared to other VOCs, was measured on three exposure days above the detection limit in the office with sources present and a low ventilation rate. Its concentration was very low, about 0.5-0.7 $\mu g/m^3$ (0.09-0.12 ppb), whereas the indoor ozone concentrations varied between 4 and 10 ppb, suggesting that no influence of reaction between ozone and limonene would be expected. On the other hand, oxidation processes were seen to occur on the surface of materials, especially if the building product is sensitive to such reactions. Thus the sensory and chemical pollution load in the office is probably due to the emissions and chemical reactions on the surface of materials and is little affected by the reactions occurring in the air.

The findings of the present study provide a further incentive to reduce pollution sources indoors, especially when they emit organic compounds with a strong sensory impact on humans or compounds that, due to chemical reactions, can be transformed into more sensory-potent compounds. It can be anticipated that the advantages of higher outdoor air supply rates are greater when the amount of ozone in the outdoor air is small. The results of chemical analysis suggest additional benefits that may be derived from removing (filtering) ozone from the supply air.

2.3.4 Major VOCs identified in the office air

More than 40% of the prevalent compounds identified in the present study (Appendix 2) are strongly connected to constituents of linoleum and related chemistry, although some of them may also result from the emissions of other materials that pollute the office air. In the manufacturing process of linoleum, linseed oil is thickened by heating or air oxidation; a limited amount of soybean oil or tall oil derived from wood pulp is often added. Thereafter, the thickened material is mixed with pulverized wood or cork particulate matter and other ingredients, such as rosin, chalk and pigments, and then applied to a foundation, usually made of burlap or canvas. In a final process the raw linoleum is hardened in drying rooms for 2-3 weeks at 60-80°C, coatings are applied, and the final product is rolled up.

Considering the multitude of materials used during the manufacture of linoleum, there is great potential for a broad range of VOCs to be released into the air during the product lifetime, by primary and/or secondary emissions. Linseed oil contains glycerides of linolenic, linoleic and oleic acids and hardens by the formation of cross-bonds between these unsaturated acids. However, a variety of aldehydes and fatty acids are also produced during the hardening process and are released into the air by diffusion and/or emitted from later oxidation of un-reacted double bounds. Consequently, the oxidation products of linseed glyceride acids may include propanal, hexanal, nonanal as well as propanoic, hexanoic and nonanoic acids (Jensen et al. 1995a) and four of these compounds were indeed detected in the office air. Wolkoff et al. (1993b) reported that the emissions of hexanal, nonanal and propanoic acid from a section of new linoleum did not allow an adequate decay modelling within a 250 h testing period, perhaps due to the reactions that contributed to the formation of these compounds.

Jensen et al. (1995a) identified 26 major VOCs from headspace measurements of one old and eleven new linoleum samples, and more than half of these compounds were also identified in the current study in the office with sources present. Applying a diffusion model, they were able to fit the emissions of hexanal, nonanal and propionic acid after 24 h decay up to 1000 h; however, in a later experiment Jensen et al. (1996) has shown that the emission of such compounds is not solely a result of migration from the material. In the same study, it was demonstrated that the emissions of hexanal, octanal, nonanal and the related acids were higher when samples of the same linoleum were ventilated with air that contains oxygen and possibly some unspecified amount of ozone, compared to the case when only nitrogen was used for ventilation. Furthermore, when the nitrogen environment was changed to air, then after ca. 500 h of measurements the emissions of each compound increased markedly, which is a clear indication that such compounds are formed from reactions with atmospheric oxygen and/or ozone.

Besides aldehydes and carboxylic acids, a number of alcohols and esthers were detected in the office air, most of them when sources were present and the ventilation rate was low. These species are commonly used as solvents and can be found in a number of building products. 2-Ethylhexanol may originate from sealant (Wolkoff et al., 1993b; Reitzig et al., 1998) but was also detected in the emissions of used linoleum (Wolkoff et al., 1993c). Both 2-(2-ethoxyethoxy)-ethanol and 2-(2-butoxyethoxy)-ethanol are used in cleaning agents or paints (Nielsen et al., 1998). However, they were measured among the emissions of used linoleum, too (Wolkoff et al., 1993c). 2-(2-butoxyethoxy)-ethanol is of special interest due the extremely low odour threshold reported (Nielsen et al., 1998), and therefore its odour index was found to be higher than 0.1 in the office with sources present and a low ventilation rate.

2.3.5 SBS symptoms and perception of the indoor environment

Although the relative humidity was unchanged during exposures, a number of symptoms related to the sensation of dryness in the upper airways were alleviated either by source removal at low ventilation and/or increased outdoor air supply rate in the polluted office (Table 2.2.6). These results agree with the earlier findings that the sensation of dryness has little to do with the relative humidity of air (Sundell and Lindvall, 1993), and is related to the exposure to indoor air pollutants. The present results also show that the sensation of dryness is an important indicator of common SBS symptoms, as reported earlier by Sundell and Lindvall (1993), since most of the symptoms were negatively affected when the sensation of air dryness increased in the office. However, the changes in the air dryness and other mucous symptoms were generally not persistent in the present study, as they were reported mainly in the first part of the exposures. Source removal in the office with low ventilation resulted in stronger sensory improvements, compared to increased ventilation in the presence of sources. This may be a reason why neurobehavioural symptom intensity, such as headache, fatigue, difficulties in concentration and dizziness, in addition to the mucous symptoms, were also alleviated with this intervention but not in the case of altering the ventilation in the office with sources present. The impact on neurobehavioural symptoms, on the other hand, was observed mostly at the end of the exposures, as these symptoms are likely to develop over a longer time scale. Considering that sensation of dryness, being indicator of general SBS symptoms, was also significantly affected by increased ventilation in the polluted office, this intervention may also be considered as having positive effects on SBS symptoms, as shown by Sundell et al. (1994). No further changes in SBS symptom intensity were observed when the second step of air quality improvement, i.e. increase of ventilation rate in the unpolluted office or source removal at high ventilation rate, was established. In the former case, the office had already few contaminants and irritating agents originating from the office surfaces, thus the higher ventilation rate diluted mostly the human bioeffluents that are known to affect mostly the olfactory sense and to a lesser extent the SBS symptoms if the occupation density is not too high. In other words, good indoor air quality in the office was already obtained with source removal at low ventilation rate and although PAQ further improved when raising the ventilation rate, it did not affect SBS. It was seen earlier (section 2.2.6) that the increased outdoor air supply rate in the polluted office resulted in a fairly good PAQ, below 30% for at least half of the group occupying the office, but also in a reduced concentration of the measured VOCs. These improvements may have caused the lower intensity of some symptoms, as indeed was shown in sensation of dryness, but also the chemical exposure. For these reasons, and considering the limitation of statistical analysis mentioned earlier, the SBS symptoms were little affected when further improvement of PAQ, was obtained by an increased ventilation rate.

On some occasions significant differences in the perception of draught, light and noise level were seen between the experimental conditions. Since air velocity, illumination and noise level were not altered during exposures, these changes may be considered as either chance effects or environmental "halo" effects as was shown in earlier studies (Wargocki et al., 1999, 2000a). On the other hand, people may become more susceptible when stress factors, e.g. air quality, occur in the indoor environment. This effect is well illustrated in the complaints concerning draught that were highest in the worst air quality condition in the office, although the measured air velocity was among the lowest in that condition. It should be noted that the presence of sources in the office "obscured" the free air movement behind the partitions, resulting in more uniform and slightly lower velocities in the occupied space, compared to the conditions with no pollution sources present in the office, when the velocities were still below 0.2 m/s.

The effects seen on eye dryness and dryness sensation in the upper airways are in good agreement with other earlier findings that showed that emissions from linoleum increase tear-film stability and have different effects on upper airways (see section 1.2.1). Although the changes in PAQ in the present experiment were smaller than in the case of carpet studies (Wargocki et al., 2000a; 2002b), they still contributed to lower SBS symptom intensity. The intensity of most sensory and neurobehavioural symptoms were reduced in the office by source removal already at low outdoor air supply rates; however, in order to obtain a highly acceptable indoor air quality, a further increase in the ventilation levels may still be justified.

2.3.6 Subjective and objective measures of work performance

As discussed in the previous section, the intensity of neurobehavioural symptoms increased significantly in the office with low ventilation rate and the presence of pollution sources compared to the clean conditions. The subjects reacted accordingly to these symptoms, estimating that their work ability was reduced compared to the other air quality levels in the office. Applying the interventions separately, the subjects' work ability improved by 2.6% and 8.3% respectively with source removal and increased outdoor airflow rates. This increment was the highest (10.3%) when both interventions were established in the office, which is well above the levels reported earlier by other studies on self-reported productivity loss due to poor indoor air quality (see section 1.4). However, these results cannot be compared with those obtained in the carpet studies (Wargocki et al., 2000a; 2002b) where the subjects rated on the exerted effort rather than on work ability.

The air quality conditions in the office were barely reflected in the results of task performance. The relatively small changes in PAQ compared to that reported by Wargocki et al. (1999; 2000a) together with the short exposures and the substantial number of subjects missing one or more exposures weakened the expected effects. Moreover, the order of presentation of experimental conditions was balanced for 30 subjects, to minimize the bias caused by learning, but only 23 subjects participated in all four conditions, which could also contribute to the distortion of the present results.

In the case of text typing there are at least two significant results that may suggest an increase in performance when improving the air quality in the office by source removal at a low ventilation rate. In the presence of sources the error rate of text typing significantly increased by ca. 11%, due to the higher number of words omitted and other misspelling errors, compared to the unpolluted office. This suggests that the subjects were distracted from their work, probably as a result of the increased neurobehavioural symptoms reported. It should be noted that although the number of characters typed was not significantly different in either of the experimental conditions, the text with the higher error rate would probably require longer time for correction. The negative effects of poor air quality were also reflected in the absolute decrement of typing performance during exposures with/without sources in the office and with a low ventilation rate, i.e. the performance between the first and second part of the text-typing task decreased to a greater extent in the presence of sources compared to the unpolluted office at a low ventilation rate. This may indicate that if the subjects work longer and their working pace is sustained as measured in each condition, while their performance decreases at a higher rate in the low air quality condition compared to the more favourable condition, a significant difference in the absolute values of typing performance as a result of this intervention would most probably be seen after a certain exposure period.

The speed and/or the accuracy of addition showed the most significant or close to significant improvements when the outdoor air supply rate was increased in the presence of sources or both interventions were applied in the office. Although the number of units in the addition task tended to increase in the latter case, the overall performance could not show significant improvement due to a slight increment in the error rate. It is remarkable to see that in the office with sources present the performance of addition significantly improved in the case of unadjusted data for learning or tended to improve after adjustments for learning were made, and after ventilation was increased, although the PAQ calculated for the whole group of subjects was rather unaffected and no change in neurobehavioural symptom intensity could be measured. However, as shown earlier, a number of other factors related to sensory perception and SBS, such as odour intensity, nose irritation, air dryness, nose dryness, and self-estimated work ability were significantly improved as a result of this intervention. Consequently, in this particular case, the improvements obtained in the performance measures could not be correlated with changes in PAQ, although it could be expected based on the improvements obtained in other subjective measures. On the other hand, these results agree with the earlier finding of Wargocki et al. (2000a), showing the beneficial effect of increased ventilation on performance.

Small effects of the interventions on the performance of the multiplication task may indicate that in the first 20 minutes of exposure no SBS symptom developed to cause any measurable changes in performance. It may be considered as a "pre-conditioning" period, when the subjects perform demanding mental work to make them more susceptible to their environment. It is suspected that the longer the "pre-conditioning" time, the greater the likelihood of seeing measurable effects in people's performance later on. This could be one of the reasons why the performance of text typing decreased to a smaller extent than expected in the present study. In the previous studies (Wargocki et al., 1999; 2000a; Lagercrantz, 2000) the subjects started the text-typing task after more than one hour of occupation and the effects on performance were seen. It was also mentioned that the air quality improvements obtained in the earlier studies with source removal (Wargocki et al., 1999; 2002b) or by increased ventilation (Wargocki et al., 2000a), where the percentage dissatisfied decreased from 60-68% down to 25-28%, was substantially higher than in the current experiment.

To see whether the finding of Wargocki et al. (2000b), who showed about 0.5% decrement in performance for each decipol, can be confirmed by the present results, the changes in PAQ and objective performance were compared between conditions when there was an indication that effect on performance might approach significant levels. In the case of multiplication, the change in performance approaching significance, obtained between the conditions with low/high ventilation and sources present, unfortunately cannot be correlated with the PAQ, since, due to the reasons discussed earlier, it was not significantly improved by the same intervention. In the office with bioeffluents, source removal and increased ventilation significantly improved the perceived air quality by ca. 4 decipol while the overall performance of addition (adjusted for learning) showed a general improvement of 2.3%, i.e. ca. 0.6% change related to 1 dp. In the case of text-typing, the most significant effects on the performance measures, as already discussed, were obtained with source removal at a low ventilation rate. This intervention significantly improved PAQ by 2.2 dp while the performance of text typing adjusted for learning increased by 1.5%, i.e. 0.7% change for 1dp.

It is striking to see that there is an increasing trend in the results related to the general levels of objective performance, self-estimated work ability and the CO_2 production rate of subjects when the interventions in the office were made separately or together. Figure 2.3.1 shows both adjusted and unadjusted performance of addition as a function of self-estimated work ability and CO_2 emission rate of people in each experimental condition. Using linear regression, it can be seen that the performance of multiplication correlates highly with the self-estimated work ability and CO_2 emission rate. Similar indications may be seen in the case of text-typing performance, but with lower correlation ($R^2 = 0.4$-0.5).

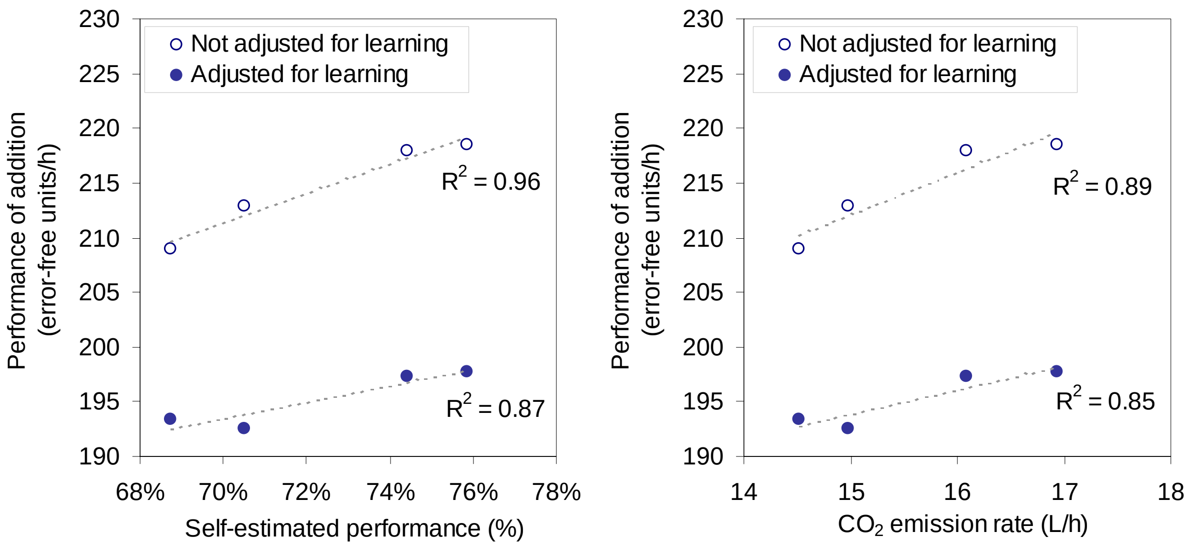


Figure 2.3.1 Overall performance of the addition task, i.e. number of units correctly executed, as a function of self-estimated work ability (left) and CO_2 emission rate of people (right); the conditions with sources present/absent are represented from left to right at low and high ventilation rates respectively.

In conclusion, the present results relating to the subjective and objective evaluation of human performance imply that there is a negative effect when the quality of air is perceived as being unacceptable due to emissions from building materials or inadequate ventilation rates. The effects were seen for both the addition task, simulating the mental performance, and for the text typing task that requires less mental work but more physical effort. The improvements obtained in performance of simulated office work when the perceived air quality was increased are in agreement with previous findings (Wargocki et al. 2000b). Moreover, the objective measures of performance showed excellent correlations with the subjective evaluations of the work ability and with the CO_2 emission rates of people. Two simple methods were involved in estimating peoples' objective performance when working under different environmental conditions. The effects of PAQ on the CO_2 production are further discussed in Chapter 4 of the present thesis.

2.4 Conclusions

From the results of the present experiment that was carried out in an office environment to examine the effects of reducing pollution sources and ventilation rates on indoor air quality, human comfort and activity, the following conclusions can be drawn:

- Removing the pollution sources from the office at both low and high outdoor airflow rates improved perceived air quality significantly. At a low ventilation rate the percentage dissatisfied with source removal decreased from 42% to 28% and from 35% to 17% in the office with or without bioeffluents respectively. At a high ventilation rate these improvements in the perceived air quality were from 40% to 8.4% and from 45% to 7.9% in the office with or without bioeffluents respectively. Also assessments of PAQ during exposure showed that the percentage dissatisfied decreased from ca. 10-19% to ca. 6-7% when the pollution sources were removed from the office, either at high or low ventilation rates.

- In the office without pollution sources, odour intensity and nose irritation were significantly lower and the air was perceived significantly fresher compared to conditions with sources present at both low and high ventilation rates.

- After introducing the pollution sources in the office with low outdoor air supply rates, the air was perceived significantly dryer, eye dryness significantly increased and throat dryness showed a tendency to increase. The relative air humidity and temperature were unchanged.

- The occupants in the office with sources present at a low ventilation rate reported a significant increment in headache and tiredness, and tendencies of increased dizziness and difficulties in concentration compared to the conditions without pollution sources.

- Removing pollution sources from the office was a more effective way to improve perceived air quality and reduce SBS symptoms than diluting the concentration of pollutants by increasing the outdoor airflow rates.

- The perceived air quality in the office without pollution sources improved significantly by increasing the outdoor air supply rate. The same intervention in the polluted office significantly reduced the percentage dissatisfied for people considering themselves more sensitive to IAQ (8 subjects) or people with SBS history (16 subjects), whereas the perceived air quality was not significantly affected when the air quality assessments included all subjects who completed each exposure (23 subjects) regardless of whether they considered themselves more sensitive to IAQ or had SBS history, or not.

- The odour intensity and nose irritation on first impression significantly decreased with the increased ventilation both in the presence and absence of pollution sources in the office.

- When the outdoor air supply rate was increased in the office with sources present the air was perceived significantly less dry and the intensity of nose dryness significantly decreased.

- The self-estimated work ability of subjects was significantly higher in the office with a high ventilation rate and sources either present or absent compared to the polluted office with a low ventilation rate.

- The effects of air quality on performance were small and with some exceptions insignificant. A number of factors, such as relatively small changes in PAQ, short exposures, missing subjects and learning may have been the reason.
- Removing the pollution sources from the office at low outdoor air supply caused significant reduction in the error rate of text typing. The absolute decrement in the typing performance, evaluated as the difference in the performance between the 28-78 minutes and 79-129 minutes of exposure, was significantly higher in the office with sources present compared to the condition with sources absent.
- Increasing the ventilation rate in the office with sources present improved the performance of addition. This effect was significant only when adjustments for learning were not considered.
- As a result of interventions, the performance of multiplication and text typing generally improved and correlated with the improvement in self-estimated work ability and the increment of the CO_2 emission rate of subjects.
- The results of chemical measurements showed that both source removal and increased ventilation rates decreased the total concentration of VOCs and the concentration of single compounds collected by either Tenax TA or Tenax GR in the office air. The VOCs detected in these two sampling media as well as their concentrations were similar.
- Increasing the ventilation rate in the office with sources present increased both the sensory and chemical emission rates from the materials used as source of pollution. No such effect was seen when the ventilation rate in the office with sources absent was increased.
- The increased emission rates due to increased outdoor air supply in the office with pollution sources present counteracted the beneficial effects of higher ventilation and may explain the smaller effects on the perceived air quality and SBS symptoms.
- The reason for the higher emission rates when the ventilation rate was increased in the presence of pollution sources was the substantial increase in the primary and/or secondary emission of compounds containing oxygen. At the same time, the emission rates of hydrocarbons was almost unchanged.
- More than 40% of the chemical compounds detected in the office air were strongly related to the emissions from linoleum containing aldehydes and carboxylic acids that are known to have low odour thresholds.
- In the office with sources present at low outdoor airflow rates the odour indexes of at least 11 compounds were higher than 0.01, which may affect perceived air quality. The odour indices measured for octanal, nonanal, decanal and 2-(2-butoxyethoxy)-ethanol were >0.1, for pentanal and ethyl benzene >0.05, and for hexanal, heptanal, propionic acid, butanoic acid and hexanoic acid >0.01.
- The emission rate of aldehydes correlating with the ozone surface removal rates in the office showed to be another good indicator of oxidative reactions initiated by ozone with indoor materials and/or building occupants.
- In the absence of pollution sources, the office could be classified as a "low-polluting" ($\leq$0.1 olf/m^2 floor) building with an air quality category of "A" and respectively "C" when the air change rates were adjusted to 1 h^{-1} and 3 h^{-1}. In the presence of sources, the

office failed to be categorized in any of the air quality requirements set by ventilation standards and would be considered as a “non-low polluting” (≥0.2 olf/m^2 floor) environment.

- The effects of indoor air quality on human comfort, SBS symptoms and the performance of office work were demonstrated in this study for a mixture of building materials commonly used in indoor settings. Furthermore, these effects were observed for relatively good indoor air quality, causing less than 50% dissatisfied.

Chapter 3

Effects of pollution from personal computers on PAQ, SBS symptoms and performance of office work

The sensory and chemical characterization of emissions from PCs, and the subsequent effects on human comfort and performance were studied in three consecutive experiments. In the first study the main focus was on evaluating the sensory pollution load of different PCs and following the time-course of sensory emissions when such devices are placed in an office environment over an extended period of time. No information was available in the literature on this issue (see section 1.2.3). This study also provided basic information for selecting adequate pollution sources for the next experiment that was intended to evaluate the magnitude of SBS symptoms and performance of subjects exposed for several hours to air polluted by PCs in an office. Although the air in the office was sampled for subsequent chemical analysis, the third experiment was designed particularly to identify the main gaseous pollutants emitted by PCs, interconnecting these data with subjective responses to PAQ.

3.1 Sensory evaluation of emissions from PCs

3.1.1 Methods

3.1.1.1 Experimental plan

A panel assessed the perceived air quality at regular intervals in low-polluting office spaces with a controlled environment where different brands of operating PCs were placed to pollute the air or no pollution source was introduced into the offices. The outdoor air was supplied to each office at a constant rate directly from outdoors and no traditional HVAC system was installed. The PCs were placed in the test offices behind a screen, and were thus invisible to subjects who entered the offices one by one and immediately assessed the air quality (Figure 3.1.1). During sensory evaluations, PCs were in operation.

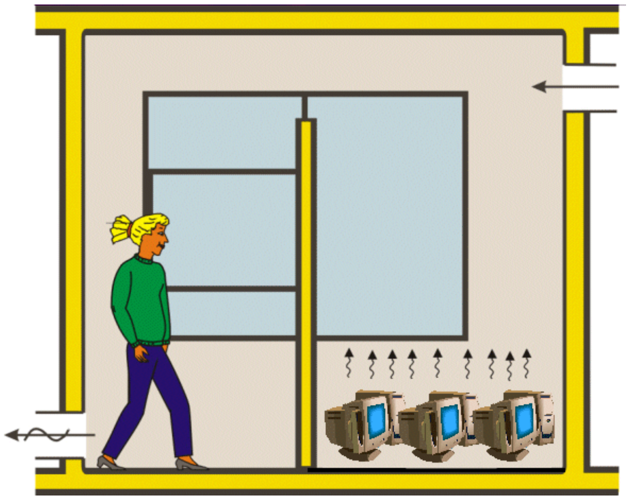


Figure 3.1.1 Experimental setup with PCs were present in the test office. The PCs are placed behind a partition and were not visible to the subjects assessing the perceived air quality in the space.

3.1.1.2 Facilities

The experiments were carried out in three identical and adjacent offices, each being 38 m³ (LxWxH=4.46x2.86x3m). The rooms were used as single offices until one year prior to the experiments; the furnishing was then removed and 2.3 m high partitions were introduced perpendicular to the windows, dividing the offices into two spaces, both having access to a window. The space behind the partition was reserved for the technical equipment and pollution sources, while the space in the front of the partition was kept for the subjects evaluating the air quality in the office. The materials in the offices were low-emitting according to CEN (1998). No traditional ventilation system was in operation in either of these rooms: in each office an axial fan mounted in the window supplied the outdoor air through a damper and a silencer. Electric oil heaters and ultrasonic humidifiers were used to condition the air to the required temperature and air humidity inside the offices. The heaters and humidifiers were controlled from a PC together with the calibrated temperature and humidity sensors (Vaisala HUMITTER 50Y) placed in the middle of each space and used for assessments. The ventilation rate in the offices was measured with a constant concentration method using a Brüel&Kjaer Multi-Gas monitor Type 1302 connected with a Brüel&Kjaer Multipoint Sampler and Doser Type 1303. A tracer gas (SF_6) was dosed at the fresh inlet air and its concentration was maintained at 1 ppm inside the offices.

3.1.1.3 Pollution sources

Three sets of operating PCs, each set consisting of 3 PCs, were used as sources of pollution in the test offices. Six PCs of two configurations were bought at a local PC supplier who was among the first ten IT companies in Denmark. Each configuration had a popular but distinct brand of 17" CRT monitor that is prevalent also on the world market, and one brand of mini tower, named by the supplier, containing a CPU Intel Pentium III; they are called PCs type A and B hereafter.

Another three PCs of a different brand but more than 3 years old (called type C hereafter) were also prepared as sources of pollution. These PCs described in section 2.1.2 were previously used in several exposure studies as part of the facilities where the subjects involved completed different tasks that required the use of a computer.

3.1.1.4 Sensory panel

A group of 24 volunteers participated in the experiments. They were students and staff members of ICIEE. They were either non-smokers or occasional smokers, 50% of them were female and none of them reported a history of allergy, asthma, hay fever or chronic diseases. They were requested not to use strong deodorants or to eat spicy food and drink coffee on the experimental days. On average, 22 people were present in each experimental session.

3.1.1.5 Procedure

Over a two-month period, sensory assessments took place on a given weekday between 10 a.m. and 11 a.m. Before the experiment the test offices were thoroughly cleaned and ventilated at a high ventilation rate for a few days. During the entire experiment the offices were continuously ventilated with a total outdoor flow rate of 72 m^3/h, corresponding to an air change of 2 h^{-1} or 7 L/s per PC unit with 3 PCs present in an office. The air was conditioned to 22.5 °C and a relative humidity of 30% in each office. The sensory evaluations were made in three test offices according to the experimental set-up shown in Table 3.1.1. The first assessments were designed to evaluate the air quality of empty offices. Two days prior to the second assessment, the PCs that were newly purchased were unpacked and introduced in two adjacent offices behind a partition. 3 PCs of type A and B were placed respectively in each office. These PCs were not removed from the offices and were operating in the offices for ca. 1000 h, corresponding to approximately ½ year of office use, assuming 40 operation hours/week. The third office was kept empty for reference exposure except for one condition when the third set of PCs of type C were assessed. The sensory evaluations were regularly repeated when the PCs were at different ages.

Table 3.1.1 Sensory assessment of the air quality in the test offices when they were empty or when PCs of different type and age were placed behind a partition.

Assessment	PC operation time (hours)	Test office 1	Test office 2	Test office 3
1	-	Empty	Empty	Empty
2	46	A	B	Empty
3	163	A	B	Empty
4	330	A	B	Empty
5	576	A	-	Empty
6	721	-	B	Empty
	880	A	-	
7	1047	A	-	C (3 years old)

The assessments were made in a randomized but balanced order of presentation immediately upon entering and approaching the centre of the space, marked on the floor by a cross. Between two assessments, refreshments were taken outside the test rooms in a well-ventilated corridor for at least two minutes. The people entered the office one by one, every two minutes. The air quality was assessed using a continuous acceptability scale described in section 2.1.5.3. The panel was not informed about the type of pollution sources placed behind the partitions.

3.1.1.6 Adjustment of air acceptability votes accounting for panel sensitivity

As specified earlier, the members of the sensory panel were students and staff of ICIEE. This panel has been used regularly in many pilot investigations for sensory evaluations of various indoor sources, and it has been shown that they tend to assess air quality as less acceptable than did a recruited panel of impartial subjects. Consequently their acceptability votes were transformed using a transfer function relating acceptability votes of ICIEE staff and impartial subjects (Baginska, 2002) before % dissatisfied and PAQ were calculated:

$$Acc_e=0.5977 \cdot Acc_p+0.2446$$

Equation 3.1

where:
Acc_p = mean air acceptability of the panel comprising students and staff members of ICIEE,
Acc_e = expected air acceptability of an impartial panel.

3.1.1.7 Calculation of sensory pollution load of a PC unit

The perceived air quality expressed in decipol units was calculated with Equation 2.1 and Equation 2.2. (Fanger, 1988; Gunnarsen and Fanger, 1992). Then using Equation 1.1 and the measured ventilation rates, the sensory pollution loads in the offices with PCs present/absent were calculated and expressed in olfs. Assuming that the sensory pollution is additive (Wargocki, 1998) and each unit would have the same sensory strength, the sensory pollution load of a PC unit was calculated using the following formula:

$$G_{PC} = (G_{PCs} - G_{Bk})/n$$

Equation 3.2

or:

$$G_{PC} = 0.1*Q*(C_{PCs}-C_{Bk})/n$$

Equation 3.3

where:
G_{PC} [olf] = sensory pollution load of a PC unit,
G_{PCs} [olf] = sensory pollution load in an office with PCs present,
G_{Bk} [olf] = background sensory pollution load in an office with PCs absent,
n = number of PC units used to pollute the air inside a test office.

Q [L/s] = measured ventilation rate,
C_{PCs} [dp] = perceived air quality with PCs present in test offices
C_{Bk} [dp] = perceived air quality in an empty test office.

3.1.1.8 Statistical Analysis

The subjective responses of the acceptability of air in the test offices were subjected to analysis of variance in repeated measures design. The assessments of acceptability were analysed for significant differences between the condition with PCs present at different ages or absent using paired t-test. One-way analysis of variance (ANOVA) in a nested design was used to detect whether the brand of PCs or the time of operation had significant effects on PAQ, considering that there is randomization restriction for time of operation.

3.1.2 Results

Mean temperature and the relative humidity of air inside the offices during assessments are shown in Table 3.1.2. They stayed close to the intended levels except for the last assessments when the air temperature reached 24°C in the test offices 1 and 3 due to the exceptional weather conditions. The measured outdoor air rates were 72±2 m^3/h, i.e. 6.7±0.1 L/s per PC unit in each test office.

Table 3.1.2 Mean air temperatures and relative humidities inside the test offices .

Location	Temperature (°C)	Relative humidity (%)
Test office 1	22.7±0.7	29±1
Test office 2	22.4±0.4	29±1
Test office 3	22.2±0.2	30±1

3.1.2.1 PAQ inside the test offices

The sensory panel assessed the acceptability of air in the test offices with an average standard error of ±0.08 (mean standard deviation of ±0.37) on the continuous scale coded –1=clearly not acceptable and +1=clearly acceptable. Table 3.1.3 shows both the original ratings and ratings transformed with Equation 3.1 on air acceptability in the test offices when the PCs, after various operation times, were present or absent behind a partition. In the absence of PCs the PAQ in both test offices was similar ($p<0.65$) and highly acceptable. As the PCs were introduced the perceived air quality significantly decreased in both test offices regardless of how long the PCs were active within the 1050 hours of operation. The analysis of ANOVA showed that the air acceptability significantly improved over time ($p<0.0002$), i.e. with the age of PCs, in both test offices, whereas in the office where PCs of type A were present the PAQ was significantly worse ($p<0.0001$) compared to the other office with PCs of type B.

The acceptability of air in the empty test office designated for reference exposure was on average 0.34±0.04, and did not change significantly during the exposures. Introducing the PCs of type C into this office, the air quality was not significantly affected ($p<0.3$) compared to the empty office.

Table 3.1.3 Acceptability of air as assessed by the sensory panel (Acc_p) and transformed acceptability (Acc_e) based on which the % dissatisfied was calculated in the test offices as a function of PCs, after different hours of operation, and whether present or absent.

Pollution source	Test office 1 (PC – A)			Test office 2 (PC – B)			Test office 3 (empty / PC – C)		
	Acc_p	Acc_e	PD (%)	Acc_p	Acc_e	PD (%)	Acc_p	Acc_e	PD_e (%)
Empty office	0.385	0.475	6.4	0.427	0.500	5.6	0.353 ‡	0.456	7.0
PCs after 46h	-0.505 *	-0.057	53	-0.186 *	0.134	29	0.270 ‡	0.406	8.9
PCs after 163h	-0.650 *	-0.144	64	-0.015 *	0.236	19	0.356 ‡	0.458	6.9
PCs after 330h	-0.228 *	0.109	32	0.265 *	0.403	9	0.326 ‡	0.439	7.6
PCs after 576h	-0.281 *	0.076	36	-		-	0.368 ‡	0.465	6.7
PCs after 721h	-	-	-	0.265 *	0.369	11	-	-	
PCs after 880h	-0.169 *	0.144	28	-	-	-	0.374 ‡	0.468	6.6
PCs after 1047h	0.028 *	0.262	17	-	-	-	0.276 **	0.317	8.8

* significantly different from empty using t-test; ‡ empty office; ** PCs type C

3.1.2.2 Sensory emission rates of PCs

The calculated sensory pollution load from PCs of types A and B are shown in Table 3.1.4. According to calculations, the sensory emission of PCs type C showed less than 0.1 olf/PC unit; however, this value should be considered only as an indication of a low sensory pollution load, since no significant impact on PAQ was observed due to the presence of these types of device.

Table 3.1.4 Sensory pollution load of a PC unit type A and B at different times of operation

Time of operation (h)	46	163	330	576	721	880	1047
PC – A (olf/PC unit)	4.3	6.6	1.6	1.9	-	1.23	0.54
PC – B (olf/PC unit)	1.38	0.67	0.12	-	0.19	-	-

For both type A and B PCs the strength of emissions decayed with the time of operation. Decay could be fairly well estimated with a first-order decay model (Figure 3.1.2). The half-life of the sensory emissions from a PC was calculated according to the regression lines, and were 347 and 102 hours for PCs of type A and B respectively.

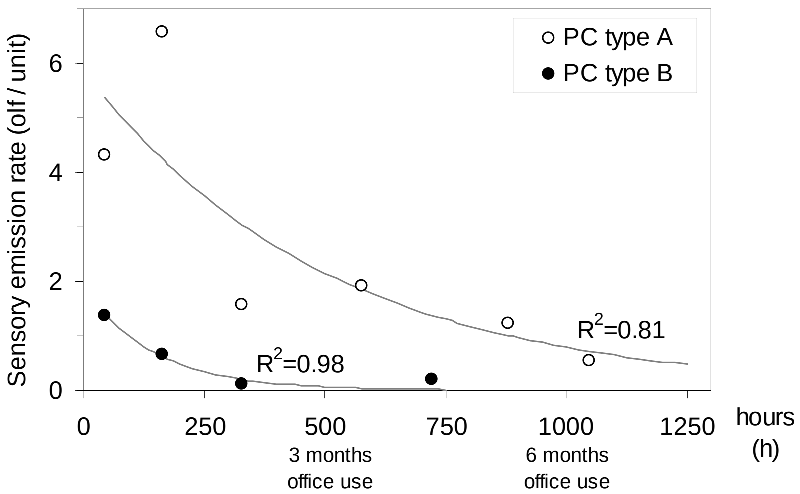


Figure 3.1.2 Decay of sensory emission rates from PCs types A and B estimated by a first order decay model

3.2 Human exposure to air polluted by PCs

3.2.1 Methods

3.2.1.1 Approach

The air pollution level in a low-polluting office was modified by introducing or removing six operating PCs. All other environmental parameters remained unchanged. Female subjects were exposed for 4.8 hours 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 the interventions since the PCs were placed behind a partition. During each exposure the subjects performed simulated office work. Subjects were asked to adjust their clothing in order to remain thermally neutral whenever they felt too warm or too cold during exposure. During both experimental conditions the air in the office and outdoors was sampled for subsequent chemical analysis.

3.2.1.2 Facilities

The experiments were carried out in a low-polluting office previously described in section 2.1.2.1. The PCs used to pollute the office air and the technical equipment providing and conditioning the outdoor air were placed behind a partition. The subjects participating in the experiment were exposed in the space in front of the partition where six workstations were placed, each consisting of a table, a chair, a desk-lamp and a 6-year-old CRT monitor. The CRT monitors at the workstations were connected to mini towers, 3 placed behind the partition and 3 removed from the office. The sensory pollution of these PCs was negligible (<0.1 olf/PC unit) as shown by the sensory evaluations described in section 3.1 (PC type C).

An axial fan mounted in the window supplied the outdoor air and several small fans provided good mixing in the office. The air in the office was heated by electric oil-heaters or cooled by a SPLIT-type air-conditioner, and humidified by ultrasonic humidifiers. No other traditional HVAC system was installed to ventilate the office. During experiments, to avoid loss of pollutants from the air, the condensate from the air-conditioner was re-vaporized with ultrasonic humidifiers.

3.2.1.3 Subjects

Thirty subjects were selected among 51 female applicants to participate in the experiments. They were all students, aged 19-31 years with an average height of 170±5 cm and weight of 61.7±7.1 kg. They were either non-smokers or occasional smokers and none of them had allergy, asthma, hay fever or chronic diseases. One subject was sensitive to dust and two had a history of migraine. Furthermore, 8 subjects considered themselves sensitive to IAQ. 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 86% and 78% were correct respectively in ranking and matching tests (ISO, 1988; ISO, 1993a). The recruited subjects were paid approximately 100 DKK/hour for their participation. A bonus of up to 10% of the total salary was also paid to encourage subjects not to leave any exposure condition and to be focused on the required tasks. During the whole experiment only one subject dropped out due to sickness.

3.2.1.4 Pollution sources

The rationale of PC selection for the pollution source used in this exposure study was based on the results of the previous investigation made on sensory emissions from PCs. The sensory source strength of PCs type A was considerably higher compared to the emissions of other PCs tested, and persisted over a long period. Thus to create a relatively large difference between the exposure conditions PCs type A were used. Consequently, the effects on sensory perception and symptoms were anticipated to be higher and easier to evaluate when human subjects were exposed for a relatively short time to such a pollution load.

Six PCs of type A but of different batches (see section 3.1.1.3) were bought at a local PC supplier. Before the experiments they were unpacked, placed in a ventilated space and turned on for 500 hours (corresponding to approximately 3 months of normal office use); this was done to avoid using brand-new PCs as a pollution source. According to Figure 3.1.2 each PC unit should have a sensory strength of about 2.2 olf.

3.2.1.5 Test Conditions

During experiments, two conditions were created with different pollution loads in the office. In one condition the pollution sources, i.e. 6 PCs, were placed in the office behind a partition. In the other condition the PCs were removed from the office. These two conditions are hereafter referred to as "office with PCs" or "office without PCs". When the PCs were present in the office, they operated continuously in a screen-saver mode; however, the electric power consumption of ca. 180 W was the same as if any other program had been running on them. 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. In both experimental conditions the outdoor air supply rate of 60 L/s (corresponding to 2 h^{-1} or 10 L/s per person with 6 persons in the office), air temperature of 24.5°C, relative humidity level of 50% and noise level of 35dB(A) (without subjects in the office) remained constant. 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 since 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.

3.2.1.6 Measurements

<u>Physical measurements</u>

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 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 only 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). 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 analyser. The data were manually logged every 20 minutes 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-minute intervals with a Seres OZ2000 ozone analyzer.

The temperature of air leaving the casing of PC monitors was continuously measured by data loggers - type HOBO H8 set for temperature and relative humidity - attached at the top grill of each monitor. Additionally, infrared views of the PCs and their major components were taken with an infrared camera to document their normal operating temperatures.

Chemical measurements

During exposures 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 (dinitrophenyl-hydrazin) for saturated aldehydes. The Tenax TA and silica gel tubes were connected to low-flow suction pumps using 20-cm long PE tubing and they were placed into the office before the beginning of each session. These pumps were using reliable stroke counter technology and operated at a low noise level. The sampling period was completed within 1 hour for Tenax TA and 3 hours for silica gel just before the end of the exposure period for subjects at minute flow rates of 105±20 ml. For flame-retardants the air was sampled at a higher flow rate of 2±0.6 L/min using suction pumps located in the room adjacent to the office in order not to introduce an additional noise source in the office. The pumps were connected with the XAD-II tubes using PE tubing and the flow rates at this time were controlled with flow meters. The sampling period for flame-retardants lasted ca. 10 hours. All samples were taken in the middle of the space behind the partition at a height of ca. 1.5 metres and outdoors in the direct vicinity of the air inlet; the sampling tubes were assembled within a distance of 15 cm from each other. Following sampling, the tubes were sealed and stored at –10°C in a freezer for two months before they were sent to a commercial laboratory for analyses. 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 volatile organic compounds 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 (containing 1-8 carbon atoms) 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, from 0.2 to 1.8 $\mu g/m^3$ for aldehydes with 5-8 carbon atoms in Tenax TA and from 3.5 to 29 $\mu g/m^3$ for aldehydes with 1-6 carbons trapped in DNPH.

Subjective measurements

The subjects assessed the perceived air quality upon entering, during exposure and upon re-entering the office after having left for a 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 (Figure 2.1.2).

During exposure, the subjects assessed general perceptions of the indoor environment and SBS symptoms using a set of 25 horizontal VA scales (see section 2.1.5.3), each scale representing a perception of the indoor environment or a symptom as shown in Figure 3.2.1. The subjects also evaluated thermal sensation on a 7-point PMV scale and acceptability of thermal comfort and draught on a continuous scale (see section 2.1.5.3). The assessments on VA-scales and those related to thermal comfort were made 3 times in the course of exposure.

Figure 3.2.1 Visual-analogue scales used to measure general perception of the environment and SBS-symptoms.

Measurement of performance

Two methods were used to measure subjects' performance during exposures to the experimental conditions employed: performance of office work, i.e. performance of subjects engaged in typical office work was evaluated as well as self-estimation of the ability to work on VA scales.

The tasks used to evaluate performance of office work in the present experiment consisted of text typing, proof-reading and arithmetical calculations. Except for proof-reading, these tasks are described in chapter 2.1.5.4 The texts used in proof-reading tasks were re-typed articles from a popular science magazine printed on white paper with double line spacing and a 12 point Times New Roman font. They contained four different types of deliberate errors that would arise from text-typing or other contextual mistakes. With an occurrence of one error per four text lines the errors were approximately evenly distributed between the following categories:

Type I: Misspelled single words as they often occur. These errors are obvious for native speakers and subjects do not need special skills to detect them.

Type II: Grammatical errors. Their occurrence is obvious in the context of the phrase e.g. wrong conjugation of verbs.

Type III Grammatical errors that could appear correctly in the immediate phrase but are wrong in a wider context.

Type IV Contextual errors, grammatically correct in the immediate context but factually or logically wrong in the context of the preceding text.

The subjects' task was to mark the words with errors without any further suggestion of the correct structure. Three measures of performance derived from this task: number of lines read per minute, number of errors found and number of false positives, i.e. the number of correct words marked as errors.

Two versions of the multiplication and addition task, and four versions of texts for typing and proof-reading were prepared with similar difficulty. They were so long that it was impossible to finish in the time available for the individual task. In each experimental condition a subject used a different version of these tasks. The order of presentation was completely randomized among the subjects.

3.2.1.7 Experimental Procedure

The experiment was completed during three consecutive weeks including one week of training in June-July 2001, each week on five days from Monday to Friday. The subjects were divided into 5 groups of 6 persons. 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 order of presentation. Each experimental session lasted ca. 5 hours, from 13:15 to 18:15. The participants were requested not to use strong perfumes, and not to drink coffee or eat spicy food on the day of their exposure (to avoid their possible negative impact on perception). The training sessions were completed in the first week when the subjects received general information about the experimental procedure and instructions about using the subjective questionnaires and various office tasks. They also took the olfactory tests. Each experimental session comprised a pre-exposure, exposure in the office and post-exposure period. The pre-exposure period ensured that all subjects spent ca. 10 minutes in the same environment before entering the office where the experimental conditions were created. The subjects also used this time to complete questionnaires about their activities prior to the experiment and give information about several SBS symptoms that might not be related to the experimental conditions.

Before the exposure in the office, the subjects left the building and assessed the outdoor air quality; afterwards they spent 4 hours and 45 minutes (285 minutes) in the office. During this time they performed different tasks simulating office work and completed subjective questionnaires about perceived air quality, indoor environment, thermal comfort and intensity of SBS symptoms. The schedule of these activities is shown in Table 3.2.1.

Upon entering the office and approaching their workstations the subjects assessed the perceived air quality. At this time the office was polluted only by the building materials and by PCs (when they were placed behind a partition) without any bioeffluents present in the office. Hereafter the subjects were allowed to sit and begin working on the first task. After 30 minutes of multiplication they completed the first set of comfort questionnaires about perceived air quality, indoor environment, thermal comfort and intensity of SBS symptoms. This type of questionnaire was completed on two more occasions after 138 and 243 minutes. Each time, after completion, the subjects were asked to place the questionnaires in a paper box placed in a corner of the office by walking over some steps on their way. This exercise was used to match subjects' activity level to a typical level of office work.

Table 3.2.1 Schedule of subjective assessments and activities during the experimental sessions. The perceived air quality (PAQ) was assessed on a continuous acceptability scale and intensity scales for odour and irritations; the comfort questionnaire included PAQ, SBS and thermal comfort ratings.

Exposures	Clock time	Exposure time	Subjective assessments	Performance tasks
Pre-Exposure	13:15		Entrance questionnaire	
	13:25		Air quality rating: outdoors	
Exposure in the office	13:27	0	Air quality rating in the office upon entering	
	13:30	3		Multiplication task (30 min)
	14:00	33	Comfort questionnaire 1 + walking over steps	
	14:05	38		Proof-reading (45 min)
	14:50	83		Text typing (55 min)
	15:45	138	Comfort questionnaire 2 + walking over steps short break	
	15:50	143		Proof-reading (45 min)
	16:35	188		Text typing (55 min)
	17:30	243	Comfort questionnaire 3 + walking over steps	
	17:35	248		Addition task (30 min)
	18:05	278	Clothing questionnaire	
Post-Exposure	18:12		Air quality rating: outdoors	
	18:15		Air quality rating in the office upon re-entering	

During exposure, the subjects performed the proof-reading and text-typing tasks on two occasions, each time using a different version of the prepared texts. The order of presentation of these tasks was completely randomized for each subject. Though the PC monitors at the workstations were considered low polluting they were switched on during exposure only when it was necessary (during office tasks requiring use of PC, i.e. 2x55 min typing). These measures were used to minimize the interaction of the PCs at the workstations with the designed experimental conditions. Whenever the subjects were hungry or thirsty, they could eat digestive biscuits and drink spring water, which was supplied at each workstation. The subjects worked at their own pace when performing tasks and were not permitted to talk with each other. They were also instructed to adjust their clothing whenever they felt too warm or too cold. At the middle of exposure a short break was allowed, but the subjects were asked to stay inside the office if there was no need to use the rest-room.

After leaving the office, the subjects left the building to refresh their senses and assess again the outdoor air quality. They returned to the office after 5 minutes and upon entering, re-assessed the air quality. At this time the office air contained the emissions from the building materials and PCs (when present) and bioeffluents from the subjects.

3.2.1.8 Data analysis

The scales used for subjective ratings were coded according to the procedure described in section 2.1.7.1. The perceived air quality with or without PCs present in the office and the sensory pollution load of a PC unit were calculated similarly to the method described in section 3.1.1.7.

Subjects' performance, i.e. speed and accuracy of their work, was calculated for both experimental conditions. Learning effects in the case of arithmetical tasks were evaluated by comparing the results when a subject performed the task for the first time (try-1) with the second trial (try 2) regardless of the experimental conditions. In the case of proof-reading and text-typing, according to the order of presentation, try-1 and try-2 were the versions prepared in the first and second part of the first exposure and try-3 and try-4 were the versions prepared in the first and second part of the second exposure. Subjects' performance between the first and second part of the text-typing and proof-reading tasks were also compared within each experimental condition.

The subjective responses and performance data were tested for normality with the Shapiro-Wilks' W test using a rejection region set at $p<0.01$. Normally distributed data were analysed with a paired t-test. Friedman two-way analysis of variance by ranks or Wilcoxon matched pair tests were used when the related samples were not normally distributed. A binomial test was used whenever the other tests failed to show significance. A Chi-square test was used to analyse the data in 2x2 contingency tables. The effects of learning in the performance tests have been evaluated using the Page test for ordered alternatives. Reported p-values are 1-tailed, i.e. in the expected direction that the presence of PCs has negative effects on air quality, symptoms and productivity.

3.2.2 Results

3.2.2.1 Environmental parameters in the office

General parameters describing indoor climate in the office during experiments are presented in Table 3.2.2. These are average values of the measurements carried out during exposures of 5 groups in the office with PCs present and absent. The measured values of these parameters remained close to the intended levels. The air velocity measured in the middle of occupied space during experiments was in the range 0.12-0.14 m/s with a standard deviation of 0.06. Among subjects, 7% were dissatisfied with air movement throughout the exposures. The background noise level in the area of the workstations was at 35 dB(A) in both experimental condition in the absence of subjects.

Air temperature in the office was on average one degree lower when subjects entered the office compared to the intended levels of 24.5°C to compensate the temperature increase during exposure caused by heat load introduced by subjects. However, this difference had only a slight impact on the air enthalpy. It should be noted that during exposure the temperature of air in the office with PCs present was on average 0.5±0.4 °C higher compared to the condition with PCs absent, which is below the measurement error of 0.6°C given for the temperature measurement system used. This difference was consistent throughout the exposures, suggesting that it did not occur by chance. Relative humidity was generally constant during exposures and close to the designed value of 50%.

Table 3.2.2 Average values (±SD) of general parameters of the outdoor air and the office air measured during exposures with humans.

Parameter	Exposure in the office with PCs			
	Absent		Present	
	Outdoor Air	Office Air	Outdoor Air	Office Air
Air temperature (°C)	23.0±1.5	24.2±0.3	22.8±3.1	24.7±0.5
Relative humidity (%)	53±6	51±4	52±13	47±3
Operative temperature (°C)	–	24.8±0.3	–	25.3±0.5
Outdoor air supply (L/s)	–	58.2±0.7	–	57.7±0.9
CO_2 (ppm)	395±3	858±28 *	395±4	835±19 *
Concentration of ozone:				
w/o bioeffluents (ppb)	31.4±6.6	20.6±4.4	29.9±7.1	19.2±4.5
with bioeffluents (ppb)	33.3±5.9	14.3±1.5	31.5±7.7	14.2±4.4
TVOC toluene echiv. (ppm)	1.92±0.2	4.78±0.3 *	1.91±0.2	4.88±0.1 *

* CO_2 and TVOC mean concentrations measured at each workstation and in the middle of the occupied space after steady-state levels were reached after ca. 1.5 hour of exposure.

When the PCs were present behind the partition the temperature of air leaving the casing of PC monitors was on average 30.5±1.6°C during exposures. The power consumption of a PC monitor and tower used to pollute the air in the office was respectively 104 W and 80 W. Consequently the additional heat load in the office with 6 PCs present behind the partition was ca. 1104 W. To keep the air temperature constant, a SPLIT-type air-conditioner was used. It was mounted in the technical space inside the office.

Figure 3.2.2 shows the infrared views of a PC monitor being in operation under the environmental conditions inside the office as a whole unit and with the plastic casing removed. The casing and most of the electronic components are heated to 45-65°C; however, the surface temperatures of some components even reach 65-70 °C under normal conditions of operation.

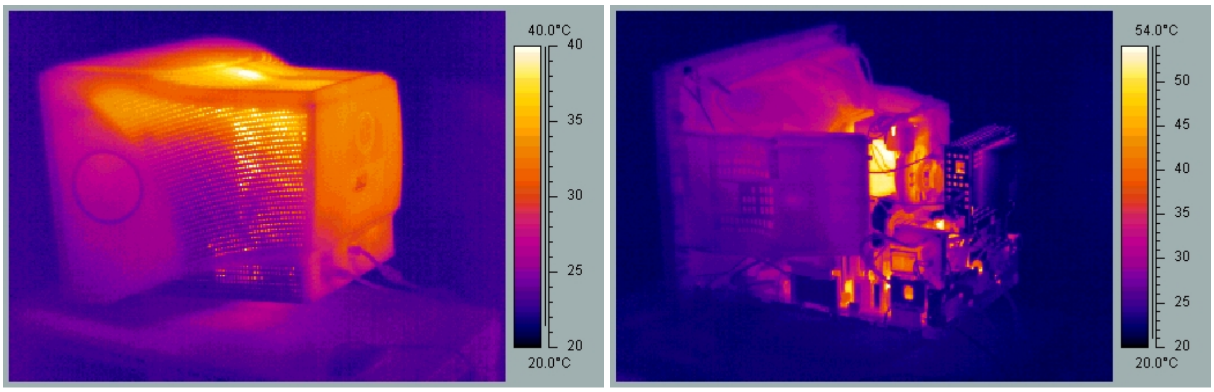


Figure 3.2.2 Infrared views of PC monitors and electronic components under normal operational conditions when they are present inside the office.

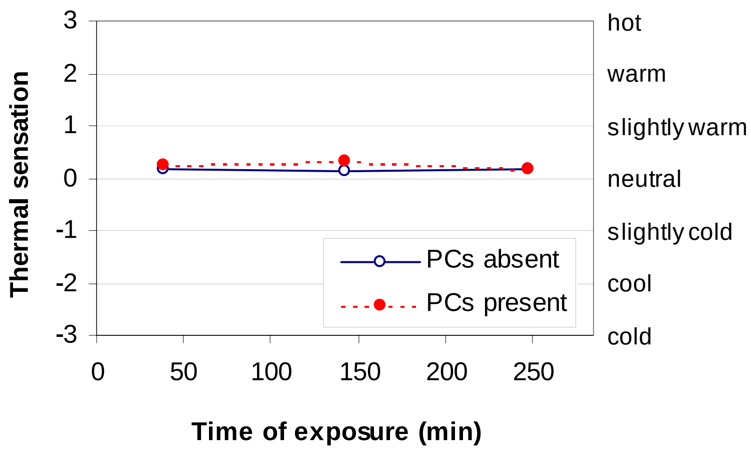


Figure 3.2.3 Thermal sensation of subjects during occupation with and without PCs in the office

The thermal sensation of subjects (Figure 3.2.3) remained constant during exposures, indicating that the subjects adjusted their clothing as instructed. Their thermal votes were not significantly different between the office with/without PCs, and for both conditions were only slightly higher than neutral.

The time profile of CO_2 (Figure 3.2.4 left) represents the average concentrations measured at each workstation and in the middle of the occupied space, which have increased up to ca. 450 ppm above outdoor level during exposures. It can be observed that the CO_2 concentration under steady-state conditions was slightly lower in the office with PCs present. Using the measured ventilation rates in each exposure, the CO_2 production by subjects was calculated (Figure 3.2.4 right) and is shown to be generally lower in the condition with PCs present. The difference was consistent for each of the 5 groups of subjects, showing that the CO_2 emission rate of subjects had decreased on average by ca. 6% ($p<0.03$) from 16.2±0.9 L/h to 15.3±0.7 L/h.

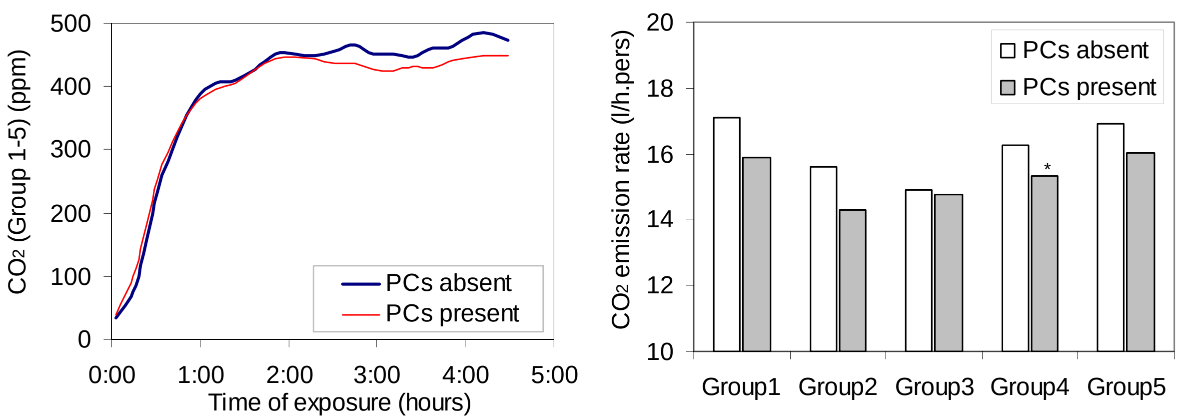


*Figure 3.2.4 Carbon-dioxide concentrations above outdoor levels during exposures and the related emission rates for each group of 6 subjects as a function of the experimental conditions with PCs present/absent in the office; * in the office with PCs present Group 4 was completed with one person due to a missing subject.*

The average metabolic rate of subjects in each subgroup was calculated (Equation 2.4) using the CO_2 concentrations measured in the office after steady-state levels were reached (Table 3.2.3). These levels are slightly higher than the metabolic rate for sedentary occupation of 1 met (58.2 W/m^2) indicating that subjects performed light work during their exposure. Table 3.2.3 also shows that the subjects reduced their activity level on average by 6% when the office air was polluted by PCs.

Table 3.2.3 Calculated activity level of subjects in each group based on the measured CO2 concentrations in the office after steady-state condition was achieved.

Exposure	Activity level (W/m^2)					
	Group1	Group2	Group3	Group4	Group5	Average
PCs absent	65	61	60	64	65	63
PCs present	61	56	59	60*	62	60

* the group was completed with another person due to a missing subject

The measured ozone concentrations indoors, with and without people, and outdoors, were at the same levels in both experimental conditions. Indoor ozone removal was not changed by the presence of PCs in the office. The ratio between indoor and outdoor (I/O) concentration was 65% without occupants in the office and 44% with occupants after steady-state levels were reached; the difference was statistically significant ($p<0.001$). Considering that at the air exchange rate employed in the office no significant reactions occurred between indoor ozone and other indoor pollutants (Weschler, 2000) the ozone surface removal rate constant, i.e. $k_d(V/A)$ was on average 1.1±0.2 h^{-1} without people and 2.6±0.5 h^{-1} with people present in the office.

The measured TVOC-toluene equivalent concentrations showed no significant difference in the office with PCs present and absent. 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 μg/m^3 i.e. 3.3 times higher than outdoor levels when PCs were present and 1.1 μg/m^3 i.e. equal to the outdoor concentrations, in the absence of PCs. The concentration of heptanal at 0.5 μg/m^3 was the same indoors and outdoors while hexanal at a concentration of 0.5 μg/m^3 was detected only outdoors in both experimental conditions.

3.2.2.2 Air Quality in the office assessed upon entering

During the whole experiment, the subjects assessed perceived air quality inside the office on four occasions upon entering to the office and on six occasions during exposure. The air quality was evaluated in terms of acceptability, odour intensity and irritation of the mucous membranes in the eyes, nose and throat.

As visitors the subjects assessed the quality of air upon entering when the office air contained pollution from the building materials or building materials and pollution from PCs and after exposure upon re-entering when the office air contained in addition bioeffluents from the subjects. The results of air acceptability and calculated perceived air quality of these four assessments are shown in Table 3.2.4

Table 3.2.4 Perceived air quality of air in the office as a function of absence or presence of PCs behind the partition with and without bioeffluents.

Exposure in the office	Office without bioeffluents		Office with bioeffluents	
	office without PCs	office with PCs	office without PCs	office with PCs
Acceptability of air (±sd)	0.34 (±0.34)	0.04 (±0.34)	0.29 (±0.37)	0.11 (±0.43)
t-test	p<0.0002		p<0.01	
Percentage dissatisfied (%)	12	40	15	32
Perceived air quality (decipol)	0.8	4.1	1	2.7

The quality of air in the office, both upon entering and re-entering, was significantly less acceptable when PCs were present behind the partition compared to the condition without PCs. Consequently, the percentage dissatisfied with the air quality was below 15% in the office without PCs and ca. three times higher when the office air was polluted by the emissions from PCs. There was no statistical difference between air quality assessments taken upon entering and re-entering either with or without PCs in the office. The perceived air quality of outdoor air did not show significant variations during experiments and caused on average 2% dissatisfied.

The odour intensity with PCs present and absent behind the partition is in good agreement with the results of air acceptability in the office. As seen on the left chart of Figure 3.2.5, with PCs present behind the partition, the odour was significantly more intense upon entering (p<0.001) and re-entering (p<0.002) the office compared to the condition when PCs were absent behind the partition.

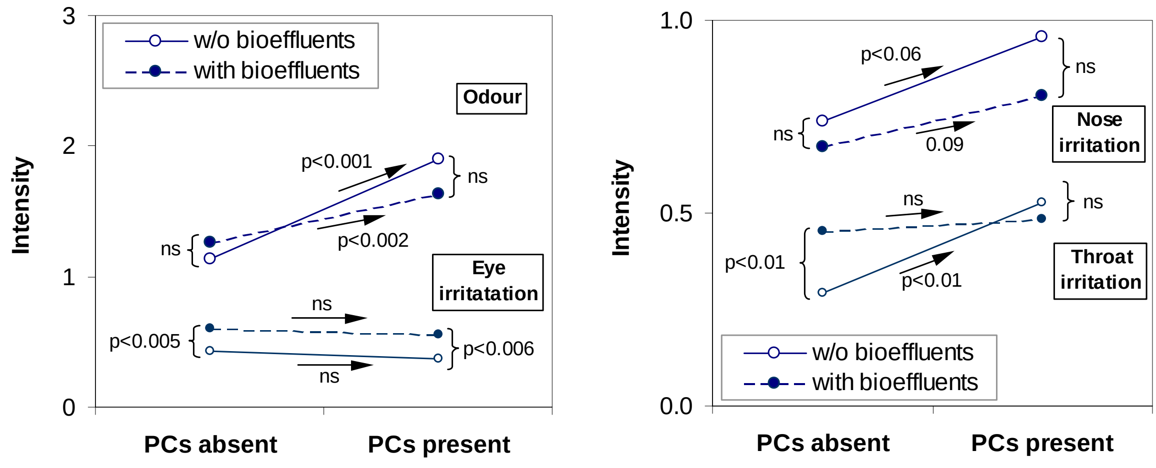


Figure 3.2.5 Change of odour intensity and irritation in eyes, nose and throat as a function of presence or absence of PCs in the office, with and without bioeffluents. The scales were coded as follows: 0 – no odour/irritation, 1 – slight odour/irritation, 2 – moderate odour/irritation, 3 – strong odour/irritation, 4 – very strong odour/irritation, 5 – overpowering odour/irritation

Irritation of nose and throat was similarly affected as odour intensity and acceptability. It was generally higher when PCs were present in the office; however, no significant differences were seen except for throat irritation without bioeffluents (p<0.01). The changes in nose and throat irritation were mainly insignificant also between the assessments taken upon entering and re-entering except for a single case when throat irritation in the condition without PCs was significantly higher in the presence of bioeffluents ($p<0.01$). Irritation of eyes was almost the same between the conditions with and without PCs, but in both conditions it was significantly higher in the presence of bioeffluents.

3.2.2.3 Sensory pollution load in the office

When the PCs were present behind the partition, the sensory pollution load increased in both the office with and without bioeffluents. Table 3.2.5 shows that the total sensory pollution load in the office was higher by 3-6 times when the PCs were present. Thus, with no bioeffluents in the office, each PC placed behind the partition increased the sensory pollution load in the space by ca. 3.4 olf, which is similar to what was expected. As mentioned earlier, the PAQ in the office with PCs present did not change significantly due to the presence of people. Therefore it may be inadequate to calculate the sensory pollution load of PCs based on the assessment when both PCs and bioeffluents were present in the office, since it is not known to what extent PAQ was affected by the emissions of people.

Table 3.2.5 Sensory pollution load in the office as a function of absence or presence of PCs behind the partition with and without bioeffluents.

	Office without bioeffluents		Office with bioeffluents	
	office without PCs	office with PCs	office without PCs	office with PCs
Total sensory pollution load in the office (olf)	3.8	23.6	5.2	15.7
Sensory pollution load related to the floor area (olf/m^{2}floor)	0.10	0.66	0.14	0.44

Without PCs behind the partition the sensory pollution load in the office showed a slightly higher value in the presence of people, with 0.04 olf/m^{2}floor corresponding to only 1.4 olf extra pollution load in the office, which is well below the expected pollution load produced by the 6 subjects. In the absence of PCs and bioeffluents, the sensory pollution load was 0.1 olf/m^{2}floor, showing that the office can be classified as part of a low-polluting building (CEN, 1998).

3.2.2.4 Air Quality in the office assessed during exposure

During exposure the subjects assessed the quality of air on three occasions: at 33, 138 and 243 minutes after they entered the office. The time-course of acceptability and corresponding levels of dissatisfied upon entering and during occupation in both experimental conditions are shown in Figure 3.2.6. In the first 30 minutes of occupation the acceptability of air significantly increased for both conditions ($p<0.015$ without and $p<0.001$ with PCs present) indicating significant sensory adaptation to the conditions inside the office. On average, 20% of the occupants were dissatisfied with the perceived air quality in the office with PCs present; this was significantly higher ($p<0.0005$) compared to only 9% when the PCs were removed from the office. When comparing the PAQ at a given time of occupation it may be observed that the acceptability of air was significantly lower ($p<0.0001$) in the presence of PCs, even after 140 minutes of occupation, compared to the office with PCs absent. Apart from some minor fluctuations, the perceived air quality in the office with PCs present stayed at the same level of ca. 20% dissatisfied during exposure. In the office with PCs absent the air acceptability significantly decreased (p<0.05) in the second part of the exposure, although there is no apparent reason for such a decline, considering that the pollution level was not changed and the bioeffluents had already reached equilibrium. Nonetheless, the percentage of dissatisfied was still below 15% at the end of exposure.

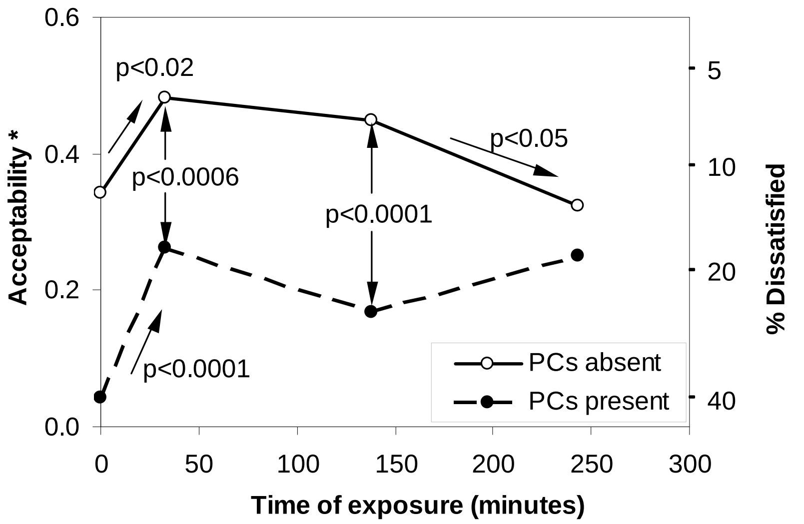


*Figure 3.2.6 Acceptability of air and percentage dissatisfied during occupation in the office with and without PCs behind the partition; * 1=clearly acceptable, 0=just acceptable/not acceptable, -1=clearly not acceptable*

Figure 3.2.7 shows that odour intensity significantly decreased (p<0.001) after the subjects became adapted to the quality of air in the office with or without PCs. Still, the odour intensity assessed by the subjects after 33 minutes of occupation i.e. after adaptation occurred, was significantly higher (p<0.007) when PCs were present compared to the office with PCs absent. After this period, the odour intensity did not change in the absence of PCs but significantly decreased, between 33 and 243 minutes of occupation when PCs were present.

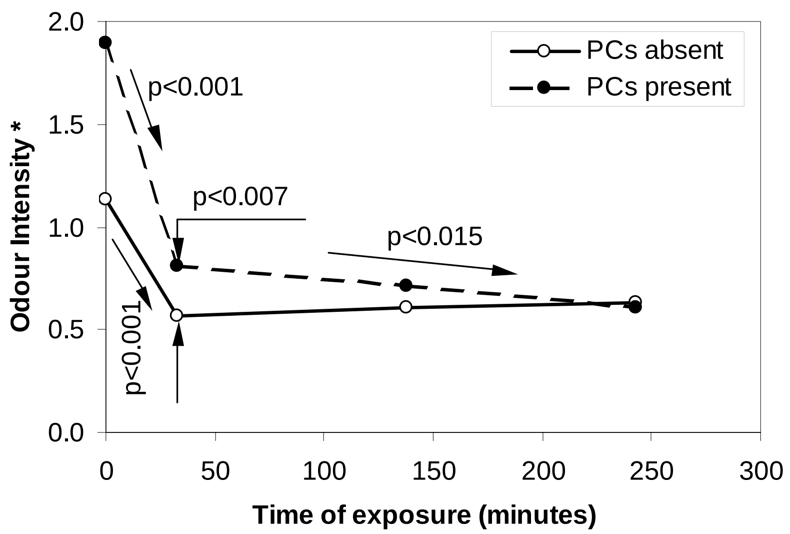


*Figure 3.2.7 Odour intensity during occupation in the office with and without PCs behind the partition; * 0=no odour, 1=slight odour, 2=moderate odour*

Irritation of the mucous membrane in eyes, nose and throat was generally very low, below slight irritation during occupation and no significant difference was found between the conditions with and without PCs in the office. Though irritation of the eyes was at a low level, a significant increase was observed during the exposures in both conditions (Figure 3.2.8 left). This may be caused by the PC monitors at the workstations during the text-typing task due to flickering or other ergonomic factors affecting the visual skills. Irritation of the nose was almost constant when the PCs were absent in the office (Figure 3.2.8 right). When PCs were present, nose irritation significantly ($p<0.002$) decreased during the first half hour of occupation, indicating adaptation, and although it slightly increased ($p<0.04$) during the second part of the exposure, this change was very small in the absolute values. There was no significant effect of exposure on throat irritation.

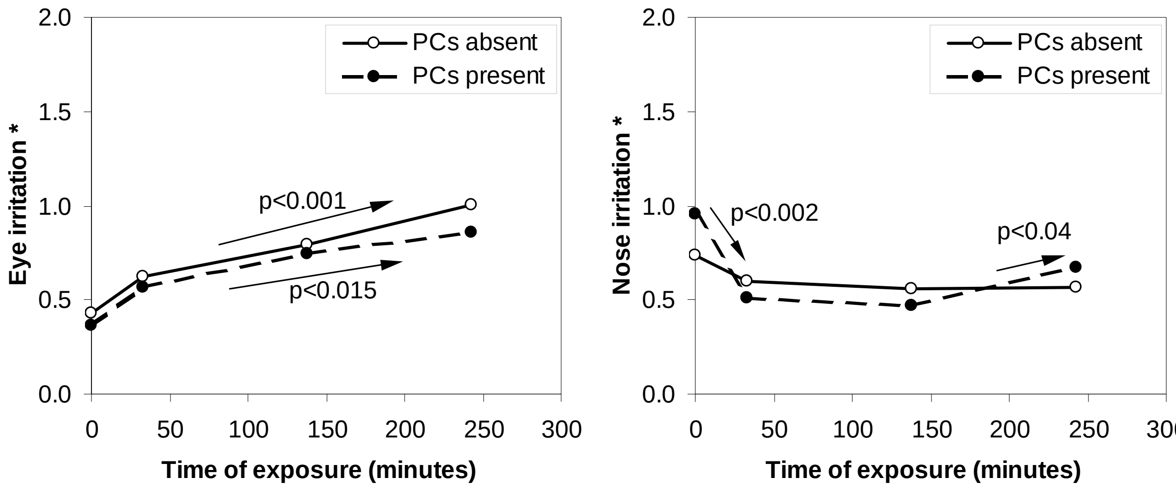


*Figure 3.2.8 Irritation of eyes and nose during occupation in the office with and without PCs behind the partition; * 0=no irritation, 1=slight irritation, 2=moderate irritation*

3.2.2.5 Perception of Indoor Climate and SBS symptoms

General perceptions of the indoor environment and SBS symptoms were assessed on three occasions at 33, 138 and 243 minutes of occupation. These results include 29 subjective votes for each perception or symptom, since one subject dropped out due to sickness in one of the experimental conditions. The votes were analysed for significant differences between each exposure. The results were analysed by calculating the odds for a change in a response during exposures in the office. The number of subjects was 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 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, 2x2 contingency tables were created and odds ratios (OR) ± 95 confidence intervals were calculated.

The indoor environment was assessed on 5 horizontal VA scales, regarding air dryness, air freshness, illumination and noise level, and office cleanliness. Among these factors significant differences were seen for air stuffiness and office cleanliness. Figure 3.2.9 reveals that in the office with PCs present the air was perceived to be significantly more stuffy throughout the exposure ($p<0.001$) compared to the condition when PCs were absent behind the partition.

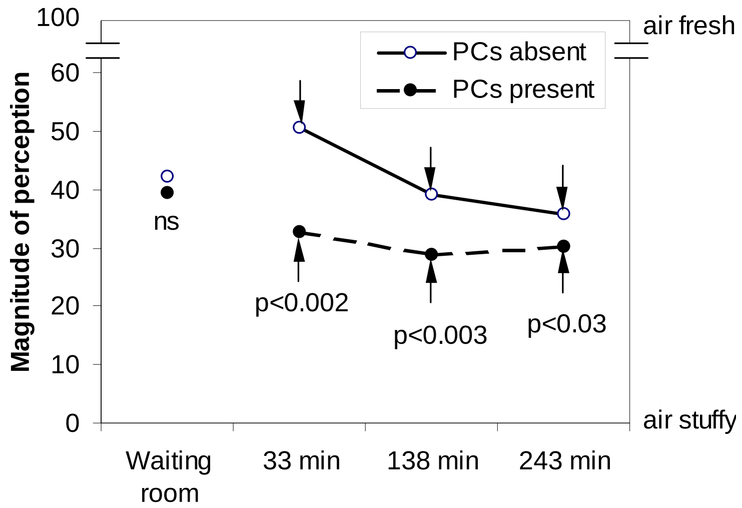


Figure 3.2.9 Air freshness during occupation in the office with and without PCs behind the partition

Table 3.2.6 Significant effects and tendencies on perceptions and symptoms during occupation in the office with PCs present and absent behind the partition

Perception or symptom	Time of exposure (minutes)	Means in office (waiting room)		Statistical test office / (waiting room) p - value	Scale description
		PCs absent	PCs present		
Air freshness	33-243	42 (42)	31 (39)	<0.0002 (<0.3)	0 = air stuffy 100 = air fresh
Noise	138	49 (51)	47 (52)	<0.06 (<0.4)	0 = too noisy 100 = too quiet
Office cleanliness	138-243	65 (67)	71 (73)	<0.005 (<0.01)	0 = office dirty 100 = office clean
Nose dryness	138	33 (36)	25 (35)	<0.08 (<0.4)	0 = nose dry 100 = nose running
Skin dryness	33-138	68 (70)	77 (81)	<0.0003 (<0.01)	0 = skin dry 100 = skin not dry
Nail brittleness	243	72 (76)	81 (79)	<0.01 (<0.05)	0 = nails brittle 100 = nails supple
Eye dryness	243	51 (75)	58 (78)	<0.08 (<0.06)	0 = eyes dry 100 = eyes not dry
Eyes grittiness	243	78 (89)	87 (94)	<0.01 (<0.15)	0 = eyes feel gritty 100 = eyes not gritty
Difficulty in thinking	33	74 (84)	72 (86)	<0.09 (<0.15)	0 = difficult to think 100 = head clear
Dizziness	33	87 (92)	93 (95)	<0.09 (<0.04)	0 = dizzy 100 = not dizzy

The subjects reported that the office was more dirty at the middle ($p<0.02$) and end ($p<0.03$) of exposure with PCs absent compared to the condition with PCs present. They also voted that the waiting room was more dirty (Table 3.2.6) before exposure to the condition without PCs, which may explain this result. It should be noted that the same cleaning procedure was used in the offices both with/without PCs and the waiting room. A tendency towards an increased noise level was observed at the middle of exposure in the office with PCs present; this may be the environmental "halo" effect due to decreased PAQ in the office.

Table 3.2.6 shows that the intensity of symptoms of skin dryness, eye dryness, nail brittleness and dizziness was significantly higher on arrival (i.e. in the waiting room) when the subjects were exposed to the condition with PCs absent. This "predisposition" of subjects is reflected also during exposure when significant differences or tendencies could be observed in the intensities of these symptoms. The subjects felt that their eyes were grittier at the end of exposure with PCs absent. This change may also be related to the fact that the subjects had more eye symptoms from the beginning of exposure. Tendencies towards increased nose dryness and difficulty in thinking were seen during exposure with PCs; however, these symptoms did not reach statistically significant levels.

When odds for a change in a response were analysed during exposures in the office, significant changes in the intensities of skin dryness and sleepiness were seen. In the presence of PCs behind the partition, significantly more subjects reported increased skin dryness (OR=3.1; [1.1, 9.1] $p<0.033$) when changes in responses at the end of the exposure were compared, either with the middle or with the beginning of exposure. Furthermore, during the second part of the exposure, there were significantly more subjects who reported increased sleepiness (OR=3.1; [1.1, 9.1] $p<0.033$) when PCs were present behind the partition compared with the condition when PCs were absent.

Finally, it is worth noting that the magnitude of symptoms regarding headache, tiredness, difficulty of thinking and concentrating significantly increased with almost the same slope with the time of occupation in both conditions with PCs present and absent in the office, suggesting that the subjects became equally exhausted when completing their tasks during almost 5 hours of occupation (Figure 3.2.10).

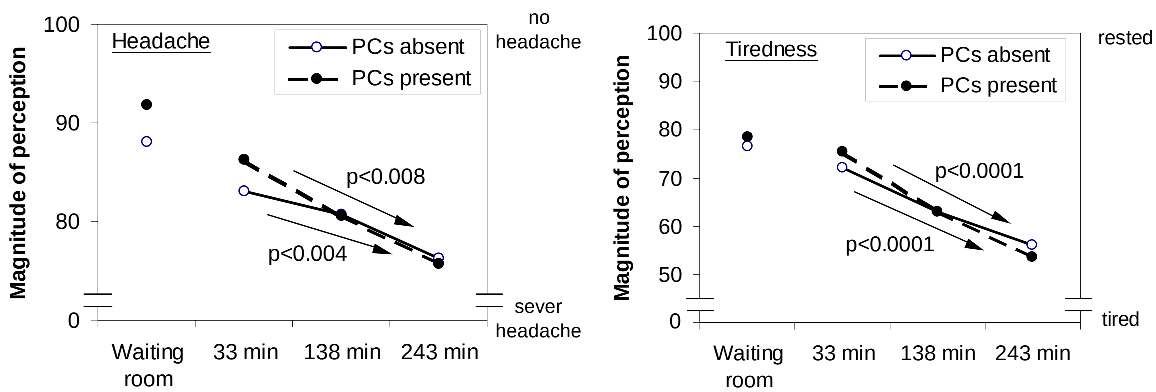


Figure 3.2.10 Time-course of symptoms of headache and tiredness during occupation in the office with and without PCs behind the partition

3.2.2.6 Objective measures of performance

The analyses of performance are based on data obtained from 29 subjects, who participated in both experimental conditions, in the office with PCs present or absent. During occupation the subjects performed typical office work, including multiplication, addition, proof-reading and text typing as described in earlier sections.

Before comparing the performance measures between the conditions (PCs present-absent), learning effects were evaluated for each task, assuming that exposure conditions would have on average a similar effect on learning. Table 3.2.7 shows that significant learning took place in each task when evaluating the results for speed and/or the accuracy measure. Therefore each performance measure was adjusted for learning whenever the effect showed significant levels, i.e. the results obtained for try-2, in the arithmetical tasks, and those for try-2-3-4, in the case of proof reading and text-typing, have been related to the first completion (try-1) similar to the method described earlier (section 2.2.4). Following this procedure, the data were re-arranged according to the experimental conditions. The performance measures of each task adjusted/unadjusted for learning according to the air quality conditions in the office with PCs present or absent are presented in Table 3.2.8 and Table 3.2.9.

Table 3.2.7 Improvement of task performance described by the speed and accuracy depending on the number of trials in order of presentation; the significance of expected improvements was calculated with t-test in the case of arithmetical task or Page test for ordered alternative for proof-reading and text typing; n.s.=not significant.

Exposure time	Multiplication		Addition		Proof-reading		Text typing	
	Speed (units/h)	Errors (%)	Speed (units/h)	Errors (%)	Speed (lines/min)	Errors (%)	Speed (chr/min)	Errors (%)
try-1	82	20.8	240	6.4	12.0	51.6	176.9	3.5
try-2	88	21.2	256	5.1	12.8	51.4	179.4	3.4
try-3	-	-	-	-	12.3	48.3	178.1	3.0
try-4	-	-	-	-	12.8	50.6	181.6	3.0
p level	0.00015	n.s	0.0002	0.02	0.04	n.s.	0.015	0.03

Table 3.2.8 Average speed and accuracy, with and without adjustments for learning effects, as a function of experimental conditions in the office; n.a. = not adjusted for learning when the effect was not significant; n.s.=not significant.

Exposure conditions	Multiplication		Addition		Proof-reading		Text typing	
	Speed (units/h)	Errors (%)	Speed (units/h)	Errors (%)	Speed (lines/min)	Errors (%)	Speed (chr/min)	Errors (%)
Not adjusted for learning:								
PCs present	85.3	19.6	252.3	5.6	12.7	50.5	178.7	3.4
PCs absent	84.0	22.4	243.8	5.9	12.2	50.6	179.3	3.0
p level	n.s.	0.06	0.03	n.s.	0.03	n.s.	n.s.	0.1
Adjusted for learning:								
PCs present	81.5	n.a.	241.9	6.3	12.2	n.a.	177.7	3.8
PCs absent	81.5	n.a.	237.4	6.1	11.8	n.a.	178.7	3.2
p level	n.s.		n.s.	n.s.	0.05		n.s.	0.02

Table 3.2.9 Overall performance of subjects, considering both speed and the error rate at which the tasks were completed ; n.s.=not significant.

Exposure conditions	Multiplication	Addition	Proof-reading	Text typing
	units/h	units/h	lines/min	chr/min
Not adjusted for learning:				
PCs present	67.9	238.1	6.03	172.9
PCs absent	65.4	229.8	5.98	174.3
p level	0.09	0.04	n.s.	0.1
Adjusted for learning:				
PCs present	65.6	226.7	5.80	170.1
PCs absent	63.7	222.9	5.76	172.1
p level	n.s.	n.s.	n.s.	0.03

The results of arithmetical tasks reveal that the speed and error rate (i.e. performance) of these tasks was little affected by the exposure condition but a significant learning effect was observed when the subjects performed the tasks for the first (try-1) and second time (try-2). Apparently, the performance of the addition task was higher when PCs were present; however this was mainly due to a strong learning effect, since 3 groups of subjects out of 5 spent their second exposure in the office with PCs present. After balancing the results for learning, no significant changes were seen in either the speed, error rate or the overall performance of this task. A similar bias caused by learning may be observed in the results of the proof-reading and text-typing tasks, although the effects were lower than in the case of arithmetical calculations. Even though learning affected these results, it can be observed that the tendencies in the error rate and overall performance of text typing were already in the expected direction without adjustment. When the data were adjusted for learning, these tendencies became significant, showing that the air quality condition in the office with PCs present negatively affected the performance of subjects in this task: the error rate significantly increased by ca. 1.2 times (i.e. 20% increment) and the overall performance, calculated as the typing speed reduced by the error rate, significantly decreased by ca. 1.2% in the absolute values.

Since the proof-reading and text typing tasks were presented twice to the subjects during exposure, a more detailed analysis could be performed on these measures. Figure 3.2.11 (left) shows that the subjects increased their reading speed in both experimental conditions when executing the task in the first and second part of the exposures. However, no such increment was observed after adjustment for learning. Similar to the summarized results for all sessions (Table 3.2.8), the reading speed was somewhat higher ($p<0.02$ for unadjusted and 0.05 for adjusted results) in the first part of exposure in the office with PCs present compared to PCs absent. This is most likely due to learning and the fact that the order of presentation of the conditions with/without PCs could not be completely balanced for 5 groups of subjects.

The error rate of proof-reading that includes the number of errors found in the text and false positives vs. the total number of errors hidden in the text, was not affected during the exposures and no significant differences were seen between the conditions with PCs absent/present in the office.

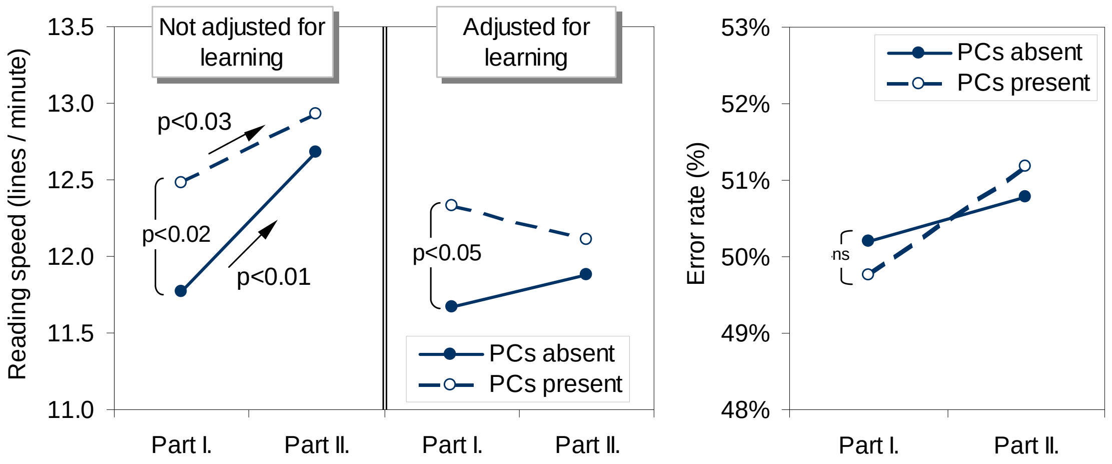


Figure 3.2.11 Speed and error rate of proof-reading in the first and second part of the exposure conditions before and after adjustments of reading speed for learning; the error rate, reflecting the number of errors found and false positives vs. the total number of errors hidden in the text, was not significantly affected by learning and no adjustments were made for such an effect.

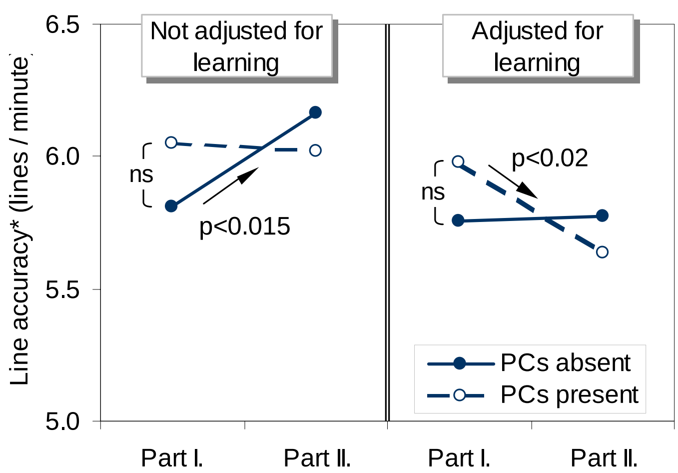


*Figure 3.2.12 Performance of proof-reading in the first and second part of the exposures as a function of PCs present or absent in the office, before and after adjustments for learning; * line accuracy = number of lines proofed without mistakes;*

Before adjustment for learning was made, the line accuracy, i.e. number of lines proofed without mistakes, significantly increased ($p<0.015$) during exposure with PCs absent (Figure 3.2.12). However, no such improvement in the performance of proof-reading was seen in the office with PCs present. Calculating the absolute changes during the two conditions, there was a tendency for greater improvement in the performance of proof-reading ($p<0.075$) in the office with PCs absent compared to the polluted office. A tendency for increased reading performance during exposure with PCs absent was also seen, when odds for a change between the first and second part were analysed (OR=2.34, [0.8, 6.7] $p<0.09$). After adjustments for learning were made, the relative effect on these changes in reading performance during exposures with/without PCs in the office was basically the same (i.e. OR was unchanged). At this time performance remained unchanged in the office with sources absent and it significantly decreased in the condition with PCs present (Figure 3.2.12).

The subjects generally typed more text in the second part of the exposure under both conditions of air quality in the office (Figure 3.2.13) when no adjustments for learning were made. This increment was 2.1% ($p<0.02$) in the office with PCs absent, while the error rate of typing was fairly constant. In the office with PCs present no significant change in the speed of typing was seen. The error rate of text typing was generally higher in both the first and second part of the exposures with PCs present but the difference was significant only in the first part. After adjusting these results for learning, no significant change in either speed or error rate between the first and second part of the text typing was observed, but the difference in the error rate increased between the conditions with PCs present/absent in the office. Furthermore, the overall performance of text typing calculated from these results (Figure 3.2.14) was significantly lower in the second part of the exposure ($p<0.05$) which is consistent with the earlier findings obtained for the general results of text typing (Table 3.2.9).

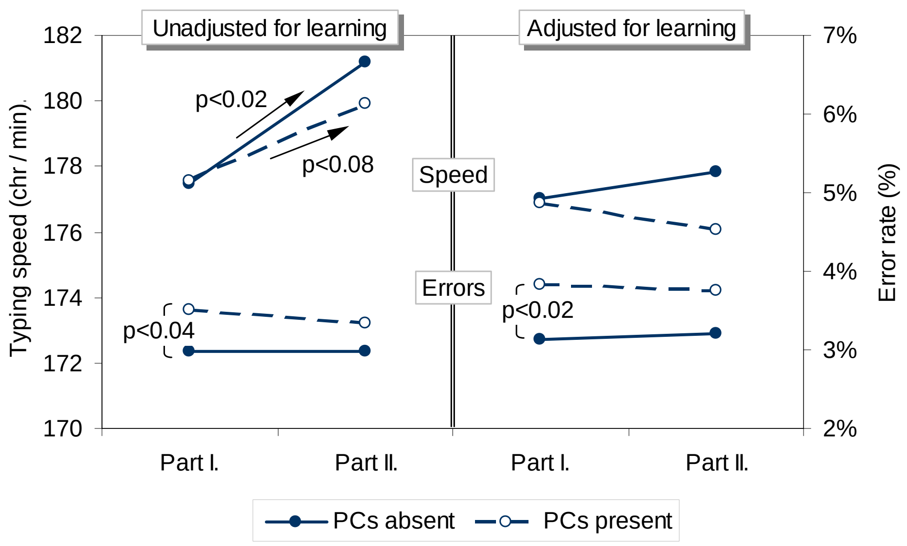


Figure 3.2.13 Speed and accuracy of text typing in the first and second part of the exposure sessions with and without adjustments for learning.

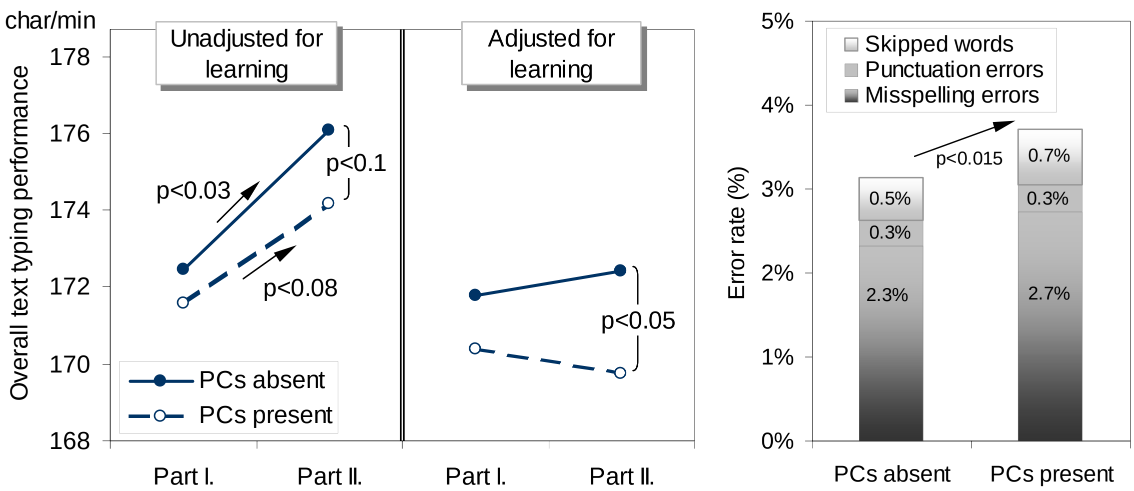


*Figure 3.2.14 **Left**: Overall performance of text typing, i.e. the typing speed reduced by the accuracy, as a function of PCs present or absent behind the partition inside the office; **Right**: Error rate of text typing task consisting of punctuation errors, misspelling errors and skipped words.*

Figure 3.2.14 (right) shows the adjusted error rate of text typing for the whole exposure in the office with PCs present/absent, divided according to the number of words incorrectly typed (misspellings), punctuation mistakes and the number of skipped words related to the total number of words and punctuation marks typed. Although there were no significant changes within these error categories, it can be seen that the subjects generally made more misspellings and skipped more words while executing the text-typing task in the office with PCs present compared to the condition with PCs absent.

Based on the performance of text typing and proof-reading, 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 difference in the amount of text between the exposures with and without PCs (since the text typed in the condition with PCs present was shorter), the time necessary to find all mistakes and the time needed to correct (re-type) them. Figure 3.2.15 shows that in the office with PCs present people would need ca. 17 minutes more time to perform the same quantity and quality of text as in the condition with PCs absent; the difference is significant ($p<0.015$).

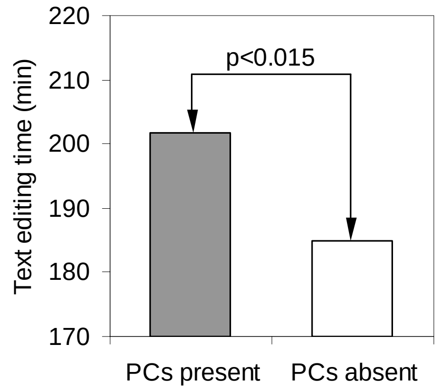


Figure 3.2.15 Estimated time for editing the text (typing, proof-reading and retyping the errors) in the presence or absence of PCs behind the partition.

3.2.2.7 Self-estimated work ability

The analyses of 5 SBS symptoms - headache, tiredness, difficulty of thinking, concentrating and sleepiness that could have an influence on the self-estimated work ability of subjects showed significant changes during the exposures. The self-estimated work ability of subjects decreased during exposures in a similar fashion. This made it difficult to detect significant differences between the experimental conditions.

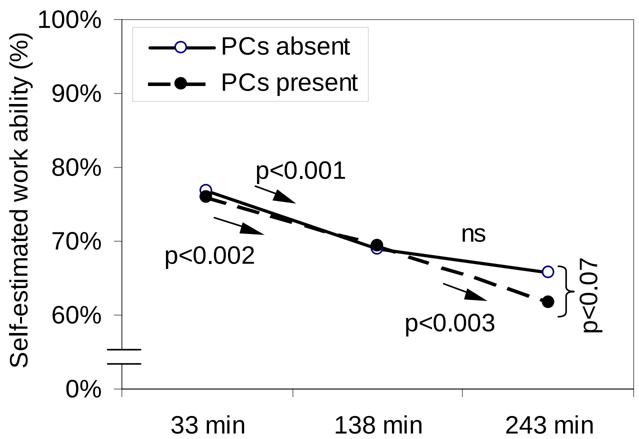


Figure 3.2.16 Self-estimated work ability of subjects during exposures in the office as a function of PCs present and PC absent

Figure 3.2.16 indicates that the air pollution originating from the PCs negatively affects the self-estimated performance. In the second part of the exposure the number of subjects whose work ability decreased was significantly higher in the office with PCs present compared to the condition with PCs absent (OR=3.7; [1.1, 11.4] $p<0.027$), while the absolute value of the self-estimated work ability after 243 minutes of occupation was slightly lower ($p<0.07$) for the condition with PCs present.

3.2.2.8 Personal factors influencing subjects' sensitivity on Perceived Air Quality, and SBS symptoms

Similar to the method described in section 2.2.6, some of the analysis presented for the whole group of subjects (n=29) who participated in both experimental conditions was repeated for different subgroups of people who may present higher sensitivity to different aspects of the indoor environment.

The PAQ in the office, expressed in % dissatisfied, for subjects who passed (n=17), or failed (n=12) the olfactory test is presented in Figure 3.2.17. As described in section 2.2.6 the criteria for passing the olfactory test was to make less than 1 error on ranking and 2 errors on matching. The PAQ was generally worse for subjects who passed the test, and better for subjects failing the test compared to the results obtained for the whole group of subjects. This effect is consistent for each assessment taken upon entering and re-entering the office with/without PCs, and during exposure with PCs present. It should be noted that in the office without PCs the PAQ was fairly similar regardless of which subgroup made the assessment. In the office with PCs present the subjects who passed the olfactory test assessed PAQ significantly worse ($p<0.02$) upon re-entering than subjects who failed the test. No other significant difference was detected when comparing the results between these subgroups.

The PAQ in the office with PCs present was significantly lower compared to the condition with PCs absent when subjects who passed the olfactory test made the sensory evaluation upon entering ($p<0.007$), during exposure ($p<0.007$) and upon re-entering ($p<0.04$). This effect could also be observed for subjects who failed the test, but only upon entering ($p<0.008$) and during exposures ($p<0.007$); upon re-entering it was not significant. In the office with PCs absent, their vote was almost unchanged and no adaptation could be observed.

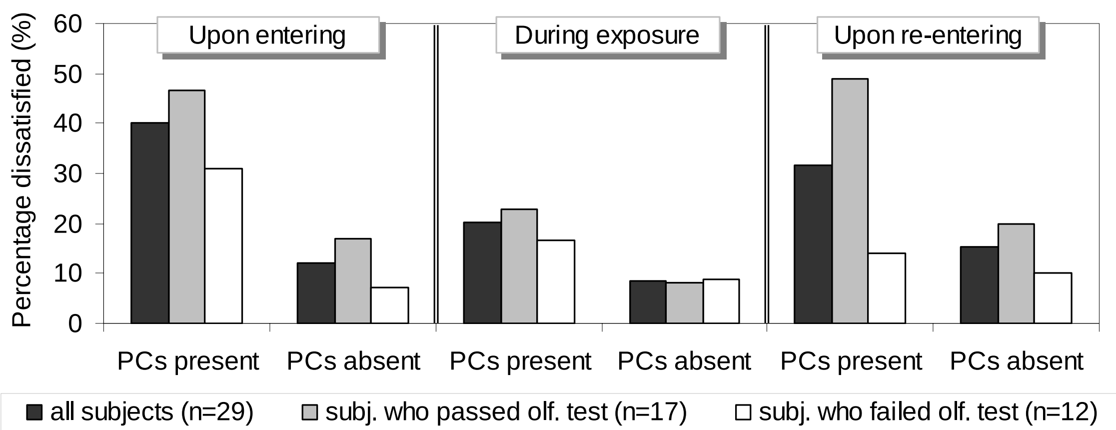


Figure 3.2.17 Quality of air perceived by two subgroups of subjects who passed or failed the olfactory test upon entering, during exposure and upon re-entering the office with PCs present or PCs absent.

The air quality rating of subjects who considered themselves sensitive to IAQ (n=8) did not show any specific alteration compared to the general results (Table 3.2.4) obtained for the whole group.

Table 3.2.10 shows the differences in the intensity of SBS symptoms, perceptions and self-estimated work ability in the office with PCs present and absent for subjects who often experienced "dry air" at home or at their workplace, or suffered from eczema when exposed to sunlight (n=10).

Table 3.2.10 Significant effects and tendencies on perceptions and self-estimated work ability during occupation in the office with PCs present and absent behind the partition – subgroup 2 (subjects experiencing often dry air at home or at work and those whose skin is sensitive to sunlight n=10)

Perception or symptom	Time of occupation (minutes)	Means in office (waiting room)		Statistical test office (waiting room)	Scale description
		PCs absent	PCs present	p-value	
Air dryness	243	58 (44)	45 (47)	0.01 (0.3)	0 = air dry 100 = air humid
Air freshness	33	57 (44)	29 (40)	0.03 (0.2)	0 = air stuffy 100 = air fresh
Office noisiness	33-243	51 (52)	43 (49)	0.006 (0.046)	0 = office noisy 100 = office quiet
Nose dryness	33-243	38 (27)	25 (25)	0.05 (0.3)	0 = nose dry 100 = nose running
Skin dryness	33-243	69 (68)	83 (79)	0.002 (0.12)	0 = skin dry 100 = skin not dry
Eye dryness	243	60 (85)	76 (87)	0.016 (0.06)	0 = eyes dry 100 = eyes not dry
Smarting eyes	33-138	92 (91)	83 (89)	0.08 (0.4)	0 = eyes smarting 100=eyes not smarting
Aching eyes	33	92 (94)	87 (89)	0.05 (0.18)	0 = eyes smarting 100=eyes not smarting
Eye grittiness	33	94 (94)	88 (94)	0.07 (0.4)	0 = eyes feel gritty 100 = eyes not gritty
Headache	138-243	78 (90)	70 (93)	0.002 (0.4)	0 = severe headache 100 = no headache
Well-being	33-243	75 (89)	71 (91)	0.03 (0.3)	0 = feeling bad 100 = feeling good
Mood	33-138	86 (88)	80 (86)	0.02 (0.09)	0 = depressed 100 = positive
Sleepiness	243	64 (88)	56 (83)	0.085 (0.05)	0 = sleepy 100 = alert
Work ability	243	64 (-)	58 (-)	0.05 (-)	0 = 0% 100 = 100%

This subgroup showed more SBS symptoms compared to the whole group. They generally reported more dryness or dryness-like symptoms in the upper respiratory tract, and eye symptoms. Although the intensity of skin dryness was again higher in the absolute value in the office with PCs present, as for the whole group, significantly more subjects reported increased skin dryness (OR=16; [1.8, 143] $p<0.007$) under this condition than in the office without PCs, when the comparison was made for change in a response between the beginning and the end of exposures. "Predisposition", i.e. significant or close to significant differences in symptom intensity before the exposures in the office with/without PCs started, may be seen also for symptoms other than skin dryness. The intensity of neurobehavioural symptoms of this subgroup, such as headache and well-being, increased in the office with PCs present compared to the clean condition. This effect was not seen when the analysis was made for the whole group. The effect on self-estimated work ability was consistent with the indications seen for the whole group and it was significantly decreased by ca. 9% in the office with PCs present compared to the office without PCs.

As regards the effects of conditions (PCs present/absent in the office) on people with SBS-history, they were similar to those observed for the whole group since almost all subjects (23 out of 29) presented some kind of SBS symptoms during the last 12 months prior to the experiment.

3.3 Supplementary study on chemical and sensory emissions from PCs

3.3.1 Methods

3.3.1.1 Approach

Chemical and sensory evaluations of emissions from PCs were made in a glass chamber, a stainless steel chamber and in a low-polluting test office. For the chemical analysis, the air was sampled in the glass chamber where the PCs were placed and ventilated at a low airflow. The air leaving the glass chamber was driven to a steel chamber where the pollutants emitted by PCs were diluted and assessed by a panel of untrained subjects (Figure 3.3.1). In addition, the sensory emission from PCs was evaluated in a low-polluting test office.

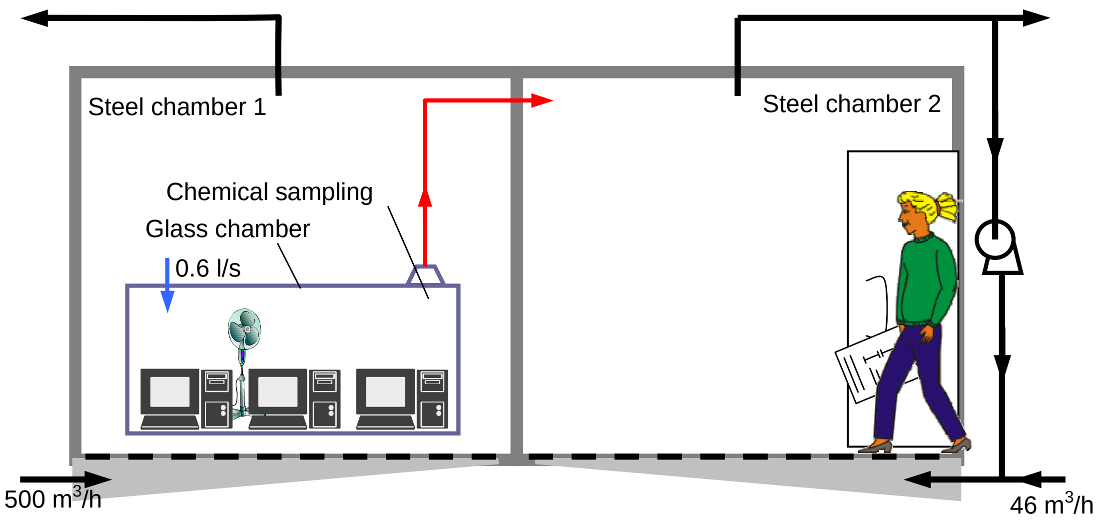


Figure 3.3.1 Chemical and sensory evaluation of pollutants emitted by PCs. The air pollutants emitted from the PCs were diluted into the air of another steel chamber for sensory evaluations.

3.3.1.2 Facilities

The experiments were carried out in stainless-steel twin chambers (chambers 1 and 2), designed especially for indoor air quality studies (Albrechtsen, 1988). Each chamber has a volume of 30 m^3 (including re-circulation ducts) and is served by a completely separate HVAC system. The ducts supplying the outdoor air and the chamber walls are made of stainless steel. The air in the chambers is distributed through a perforated floor, extracted at the ceiling and re-circulated at a high rate if it is necessary to obtain a good mixing of the pollutants emitted in the chamber (Figure 3.3.1). The pressure in the chambers is slightly higher than in the direct vicinity to avoid mixing of the surrounding air with the air in the chambers when subjects enter for sensory assessment.

A glass chamber with a volume of 1 m^3 (LxWxH=1.7x0.6x1 m) fixed in a metal frame was placed in chamber 1. The top cover can easily be removed to arrange the PCs and a small fan that mixed the air inside the glass-chamber. The air from the glass chamber was extracted through a Teflon tube by means of a miniature fan at a rate of 2 m^3/h to chamber 2. The same fan was also used to adjust the required airflow through the glass chamber. The test facilities of the low-polluting office where additional sensory assessments were carried out, in order to supplement the evaluations made in the steel-chamber, are described in detail in section 3.1.1.2.

3.3.1.3 Subjects

Twenty-six people participated in the experiment. They were students at DTU and staff members who volunteered to take part in the subjective evaluations. During recruitment ,smoking was the only exclusion criteria to the admission since no olfactory test was completed. Furthermore, the subjects were requested to avoid using strong deodorants, eating spicy food or drinking coffee preceding the sensory evaluation as that might influence their olfactory senses. The sensory panel included both males and females, 62% of them being males. On average, 20 people made an assessment under each condition created. The subjects were not informed about the experimental conditions or the type of pollution used in the exposures.

3.3.1.4 Pollution sources

Three PCs out of six units used in the study described in section 3.2 were randomly selected for the current experiment. These measurements were carried out after analyses of the exposure study were completed, when the PCs had already been in operation for 2000 hours. Nevertheless, in order to link these additional data with exposures in the office, it was decided to use the same PCs rather than to buy a new batch of the same brand.

3.3.1.5 Measurements

The temperature and relative humidity of air at different locations were continuously measured using data loggers - type HOBO H8. The loggers were mounted on the inner and outer surface of the glass chamber, on the top grill of the monitors and inside the steel chambers. The ventilation rate inside the glass chamber was measured with the tracer gas (SF_6), using the constant dosing method. SF_6 was dosed at the outlet of the glass chamber before the exhaust fan and measured downstream of the Teflon-tube that was leading the polluted air into chamber 2. The ventilation rates in the steel chambers were measured with the same method using the duct systems supplying the outdoor air to the chambers. The outdoor air flow, temperature and relative humidity of air inside the test office were measured similar to the procedure described in section 3.1.1.2. The ozone level in chamber 1 and the glass chamber was measured both with PCs turned on and off, using a SERES 2000 ozone analyzer.

For the chemical analyses 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 (section 3.2.1.6) were extended by inclusion of sampling on Tenax TA for VOCs and XAD-II for SVOCs. For the sampling interval employed, the detection limits ranged from 0.1-1 $\mu g/m^3$ for VOCs/SVOCs, 8-40 $\mu g/m^3$ for aldehydes and 20 $\mu g/m^3$ for brominated flame-retardants. Following the sampling period, the tubes were sealed and immediately sent for analysis.

Upon entering chamber 2 and the test office the subjects assessed the perceived air quality on the continuous acceptability scale (Figure 2.1.2). The scales of subjective ratings were coded (see section 2.1.7.1) and the perceived air quality in chamber 2 and inside the test office with and without pollutants from PCs was evaluated. The sensory pollution load of a PC unit was calculated similar to the method described in section 3.1.1.7.

3.3.1.6 Procedure and test conditions

The glass chamber containing the PCs was sealed with aluminum tape, leaving only a small orifice for the air intake. The pressure inside the glass chamber was slightly lower than in the surroundings to avoid any leakage of pollutants into chamber 1. The air exchange rate inside the glass chamber was adjusted to 2 h^{-1} or 0.2 L/s per PC that was 50 times lower than in the exposure study (section 3.2.1.5). 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 outdoor air was introduced to steel chamber 1 without re-circulation at 500 m^3/h (16 h^{-1}) to achieve a good air quality in the surroundings of the glass chamber and maintained at 24°C and 25% RH. The stainless steel and glass chambers were thoroughly cleaned and baked out prior to chemical measurements. The chemical sampling started 6 hours after the PCs were placed in the glass chamber and turned on (i.e., when the concentrations in the chamber had reached equilibrium). The air polluted by PCs was introduced to chamber 2 and diluted in 46 m^3/h outdoor airflow (4.5 L/s per PC), at which rate the chamber was ventilated. Thus, the concentration of pollutants in chamber 2 where the sensory assessments took place was ca. 24 times lower than in the glass chamber. To obtain a good mixing of the pollutants in chamber 2 the air was re-circulated at a high rate.

The sensory evaluations took place on separate days during early afternoon. The subjects assessed the perceived air quality in chamber 2 on three occasions: when the pollutants emitted by PCs in the glass chamber were diluted into the steel chamber, in the presence of PCs in the steel chamber placed behind a partition and in the chamber without PCs. Furthermore, the quality of air in the test office was assessed on two occasions, when the PCs were placed in the test office behind a partition and in the office without any pollution source. The ventilation rate in the office was at 2 h^{-1} or 7 L/s per PC unit when the PCs were present. The temperature and relative humidity in chamber 2 and in the test office was maintained at 24°C and 40% during sensory evaluations, corresponding to summer conditions when the experiment was carried out. The subjects entered chamber 2 or the test office one by one, with 2-5 minutes' intermission between two assessments. Prior to evaluations the subjects refreshed their senses outside the building.

3.3.2 Results

The general parameters describing the indoor climate (t, RH and air-change rate) in the stainless steel chambers and inside the test office stayed close to the intended levels with minor variations, below 5% compared to the required values. 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 airflow at which the chamber was ventilated.

As the PCs were turned on or off, the concentration of ozone changed inside the glass chamber. The ratio between the ozone levels in the glass chamber and steel chamber 1 was 0.38 and 0.57 respectively when the PCs were in operation or turned off. During the chemical sampling the concentration of ozone in chamber 1 was about 33-35 ppb.

3.3.2.1 Subjective evaluations

Table 3.3.1 summarizes the results of subjective evaluations made in chamber 2 and in the test office when the pollutants emitted by PCs were present/absent in the air. The acceptability of air significantly decreased when the air was polluted by the emissions from PCs, both in steel chamber 2 ($p<0.00005$) and in the office ($p<0.014$) compared to the condition without PCs. No significant difference in the perceived air quality in chamber 2 was observed between the conditions when the pollutants from the PCs were diluted from the glass chamber or emitted directly into the steel chamber, suggesting that the elevated temperature in the glass chamber did not enhance the sensory emission rate. The acceptability votes were transformed in a similar way as in section 3.1.1.6 and % dissatisfied, perceived air quality in decipol and sensory pollution loads were determined. It can be seen that after ca. 2000 hours of operation, which is ca. 1 year of normal operation, the PCs emit about 1 olf, thus corresponding approximately to the pollution load from a standard person. The sensory pollution load measured in the test office is lower compared to that obtained in the steel chamber, which may be due to adsorption on indoor surfaces.

Table 3.3.1 Results of subjective evaluations in chamber 2 and the test office when pollutants emitted by PCs are present/absent in the air.

	Steel chamber			Test office	
	PCs present *	PCs present	PCs absent	PCs present	PCs absent
Acceptability of air [1] (±sd [2])	-0.14±0.46	-0.14±0.42	0.47±0.43	0.05±0.36	0.35±0.44
Transformed acceptability [3]	0.16	0.16	0.52	0.27	0.45
Percentage dissatisfied (%)	26	26	5	16	7
Perceived air quality (dp)	2.1	2.1	0.3	1.1	0.4
Total sensory pollution load (olf) [4]	2.6	2.6	0.2	2	0.6
Sensory emission of PCs (olf/PC)	0.9	0.9	-	0.5	-

* pollution of PCs is introduced from the glass chamber;
[1] scale coded: -1=clearly not acceptable; 0 just not acceptable/just acceptable; 1= clearly acceptable;
[2] sd=standard deviation;
[3] using Equation 3.1 in order to calculate PAQ and sensory pollution load for impartial subjects;
[4] 2% were dissatisfied with outdoor air quality

3.3.2.2 Emission of chemical compounds from PCs

The chemical measurements in the 1 m^3 glass chamber showed that the emissions from PCs contained formaldehyde, phenol, 2-ethylhexanol, toluene, a series of higher boiling aromatic compounds and several aliphatic compounds (Table 3.3.2). The most abundant of these were phenol and toluene. Based on the concentrations of chemicals 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. Using these data the concentration of pollutants could be modelled in both steel chamber 2 and in the office where 30 people had been previously exposed, taking into account that the emissions of PCs are diluted in these rooms depending on the fresh air supply rates applied. To model the office concentrations, it was not considered that the emission rate of chemicals decays with operation of PCs (Wensing *et al.,* 2002), considering that each compound may decay at a different rate. The actual concentrations in the office may have been ca. 6 times higher than the modelled values (Table 3.3.2) if the decay in the sensory and chemical emission rate is similar.

Table 3.3.2 Emission rate of chemical compounds per PC calculated from the concentrations measured in the glass chamber; modelled concentrations of chemicals in the office exposure study (section 3.2) and steel chamber 2; NIOSH RELs, standardized human olfactory thresholds (OT) and the expected odour index (OI) when relating the modelled concentrations to the OT is also indicated for the compounds presented.

Compound *	Emission rates per PC [μg/h]	Modelled concentrations office exp./ steel chamber [μg/m³]	NIOSH RELs [μg/m³]	Standardized odour threshold OT [μg/m³]	Odour Index (OI) office exp./ steel chamber [-] x 10^{-2}
Phenol [1, 2, 4, 6]	63.0	1.7/4.4	19 000	427	0.4/1.0
Sum of C_6-C_{10} aromatic comp.	45.9	1.3/3.9	-	> 150	0.9/2.6
Sum of aromatic compounds with high boiling point (toluene equivalent)	58.3	1.6/4.1	-	> 150	1.1/2.8
Sum of isomers of bicyclic aromatic compounds (toluene equivalent)	41.0	1.1/3.1	50 000**	80**	1.4/3.8
Toluene [1-6]	47.0	1.3/6.4	375 000	5900	0.02/0.1
Styrene [3, 5, 6]	7.6	0.2/1.0	215 000	630	0.03/0.2
Xylene isomers [1, 2, 3, 5, 6]	10.3	0.3/1.2	435 000	1400	0.02/0.1
Formaldehyde [6]	5.2	0.1/4.5	20	1100	0.01/0.4
2-Ethylhexanol [2]	19.6	0.5/1.8	-	1300	0.04/0.1
Branched mono-unsaturated C12	22.3	0.6/1.9	-	-	-
n-Decane [3, 5]	11.6	0.3/1.3	-	4400	0.007/0.03
n-Undecane [3, 5]	7.6	0.2/1	-	7700	0.003/0.01
Sum of other SVOCs (n-octane equivalent)	9.4	0.3/2.5	-	-	-
Sum of others VOCs	119.6	3.3/7.9	-	-	-
ΣVOCs	468.6	13.0/45.0			

* The numbers indicating previous studies made on emissions from electronic equipment where the chemical compound was detected: 1) Brooks, 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.
** values given for Naphthalene

Even if the modelled office concentrations are one order of magnitude higher than those shown in Table 3.3.2, 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 odour index of the most abundant compounds would also be at the limit of 0.1. The human olfactory thresholds were 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 μg/m³ in the office air, which is consistent with the modelled 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.

3.4 Discussion

The effects of emissions from PCs on indoor air quality, human comfort and performance of office work was systematically investigated in a series of experiments involving subjective ratings of more than 70 people and other objective measures. These investigations create strong support for the original hypothesis, showing that such emissions may degrade perceived air quality not only in the first few hours of operation, after the PCs are installed for the first time, but over a longer time-scale up to several hundred hours when they are turned on. Thus, PCs can 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 3 times the load of a standard person, implying that the ventilation rate in an office with such PCs would need substantial increments to maintain the level of perceived air quality as measured without PCs. When the pollution load in the office was reduced, by removing the PCs, the air quality conditions significantly improved for both visitors and occupants of the space. Although in a number of field investigations it was suggested that working with PCs may exacerbate the intensity of SBS symptoms, it was unclear to what extent PCs are the causative factors for such outcomes. It was assumed that electromagnetic radiation or other factors (see section 1.2.2) may cause symptoms. In the present experiments it was shown that exposing people to the pollutants originating from PCs may increase SBS symptom intensity and negatively affect performance. The negative effects on SBS symptoms were stronger for people, who often experienced "dry air" at home or at their workplace or suffered from eczema when exposed to sunlight.

In the present studies, the polluting computers were placed far from the occupants and the pollutants emitted were well mixed with the room air. Contrary to the experimental set-up, 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, depending on air distribution. It should also be noted that in the exposure study for the condition where PCs were present behind the partition, more cooling was required and 20% more water was condensed on the cooling coil, even though 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. In addition, there is a potential that the pollutants in the office could be partly removed by adsorption on the interior surfaces as indicated by the sensory assessments carried out in the stainless steel chamber and the test office. The electromagnetic field and radiation from the studied PCs complying with the current directives (TCO'99, 1998) are low and cannot have influenced the observed effects in any of the present studies, considering that the PCs were placed behind a partition, some distance from the occupants or from the visitors who assessed the perceived air quality in the offices and/or executed simulated office work.

3.4.1 Sensory pollution load of PCs

Sensory assessments of PCs have been carried out in three different experiments from the moment the new devices were brought from the dealers up to 2000 hours of being active for at least one type of computer. The results of the first experiment (section 3.1) revealed that the sensory emission rate of PCs depends on the brand and age of the devices. The reason for this may be the diversity of the electronic components that are used during manufacturing of such devices. Producers often change not only the technology of the manufacture but also the source of suppliers even within one brand, and may change it from batch to batch. This may influence the amount and content of chemical substances in the electronic components and subsequently affect the sensory and chemical emission rates. The decay of sensory emission rates of both PC types could be described using a first order decay model, which indicates similar trends with the decay of VOC emissions from PCs previously reported by Corsi and Grabbs (2000) and Wensing *et al.* (2002). In addition, it could be seen that the CRT monitors are the driving factors of the sensory pollutants originating from a PC unit. This observation derives from the fact that two distinct brands of PC monitors were connected to similar types of towers, made by the same IT company, but the measured sensory pollution loads and the decays of the two PC types were very different.

All of these findings were later verified in a subsequent study (Wargocki et al., 2003a) that was especially designed to generalize the current results for other types and brands of PCs. Figure 3.4.1 shows a fairly good agreement of the sensory pollution loads of PC obtained from these studies, although the sensory assessments were made by different people and other PC brands were also included. The mean sensory pollution of 4 popular brands of PCs with CRT monitors (Wargocki et al., 2003a) decay from 2.7±1.7 olf/unit to 1.4±1.2 olf/unit considering an operation time of 50 and 600 hours respectively. Although these values are lower than those obtained in the first experiment, the average sensory pollution load calculated over 2000 hours of operation, considering an exponential decay, is at the same level, i.e. a little above one olf/PC unit.

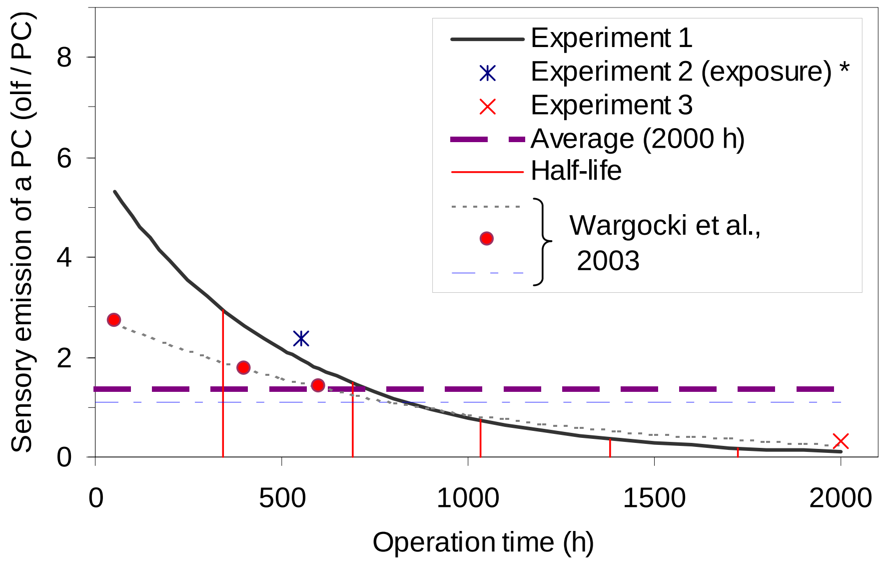


*Figure 3.4.1 Comparison of sensory pollution load of PCs measured in the three experiments and a subsequent study made on 4 popular brands of PCs with CRT monitors (Wargocki et al., 2003a); the average pollution load over 2000 h of operation time, i.e. 1 year of normal office use and the half-life of the decay is also indicated; * the sensory pollution loads are adjusted for a lower temperature of 22°C and relative humidity of 30% to match the conditions in the 1st experiment.*

The decay model of the PCs of type A given by the first experiment was a good approximation of the sensory pollution loads obtained from the air quality assessments of the exposure and supplementary studies (section 3.2 and 3.3), although different people made the sensory assessments. After 550 hours of operation the sensory emission rate on the decay curve corresponded to 2 olf/PC unit, which is somewhat lower than 2.6 olf/PC unit obtained from the exposure study after adjusting the sensory ratings of acceptability for the enthalpy difference between the experimental conditions (Fang et al., 1997). Similarly, after

2000 hours of operation, the measured level in the low-polluting office was 0.5 olf/PC unit, while the decay curve indicates 0.1 olf/PC unit.

The present results imply that the presence of PCs indoors may substantially degrade the perceived air quality over a long time-scale. Assuming that under a normal office-work condition a PC operates only for 8 hours daily, the sensory pollution loads from newly bought PCs may negatively affect the perceived air quality in real offices for up to one year. During this time the average extra pollution load from such devices may correspond to the load of a standard person, which should be considered when establishing ventilation requirements for spaces containing PCs. Presuming a typical life cycle of 24 – 36 months for desktop computers (PC Life Cycles, 2000) the people working with PCs would be exposed repetitively to elevated pollution from their PCs for one third of the life cycle. On the other hand after a long time of service, i.e. at the end of the life cycle, the sensory pollution of PCs may be less important. It should also be noted that in the case of 8 h daily operation the emissions may decay at a lower rate compared to a continuous operation mode as shown by the emission models developed by Corsi and Grabbs (2000). This would further extend the time period with higher emission rates. It was also seen in the supplementary study that the building surfaces in the office environment may act as a sink, adsorbing a substantial amount of pollutants. Although the same PCs with similar age were used to pollute the air in both stainless-steel chamber and test office, the sensory pollution load in the latter case was ca. twice as low compared to the levels obtained in the stainless-steel chamber. This implies that in a normal environment the initial pollution would be lower, as the pollutants are adsorbed on the surfaces. They will be released later to the environment by desorbtion, when the primary emissions may have decayed to presumably low levels (Sakr, 2004).

3.4.2 Chemical emissions from PCs

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 3.3.2). The measured TVOC and toluene emission rates fell in the range of those reported by Corsi and Grabbs (2000) and Wensing *et al.* (2002) although their results were obtained only during the first 250 hours of operation. Aromatic compounds accounted for almost 60% of the organic compounds identified in the PC emissions. This was also seen by Nakagawa et al. (2003). 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). Its concentration was, however ca. 100 times lower than its odour threshold even in the steel chamber, where the modelled concentrations were higher compared to the office. 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 product of hydrolysis 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. The calculated concentrations in the office air resulting from PC emissions were much smaller than its odour threshold (see Table 3.3.2). 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 modelled concentrations of chemicals in the office air fell well below any exposure and odour detection limits (Table 3.3.2), 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. It might be hypothesized 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 analysed) are not necessarily the chemicals responsible for the adverse effects (Wolkoff and Nielsen, 2001; Weschler and Shields, 1997; Wolkoff *et al.,* 1997;). The present study also shows that the human olfactory and chemical senses involved in the perception of air can be more sensitive than chemical analyses. This is also supported by the results of the subsequent study (Wargocki et al., 2003a; Nakagawa et al., 2003) where the sensory impact of PCs was much higher than expected from the results of the chemical analysis.

Finally, it should be noted that the present negative effects were seen in a well-ventilated office space where only 6 PCs polluted the air and the modelled concentrations were low. There are circumstances (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. According to a recent survey (NSF, 2004), 43% of school-aged children under 10 have a TV set in their bedroom, and 11% have a computer. They spend on average 1.6 hours watching TV and little over one hour to work or play on their computer. Considering that bedrooms with doors and windows closed may have a lower air change compared to a typical level of 0.5 h^{-1} accounted for homes, the concentration of pollutants originating either from TV or PCs may reach elevated levels. Consequently these children are at high risk of exposure to the pollutants originating from such devices even during sleep. Since the daily usage in this case is relatively short, the emission of pollutants will also decay over a long time-scale, perhaps over years.

Thermal images of an operating PC monitor (Figure 3.2.2) showed that several components on the cathode-ray tube and inside the CRT display reach high temperatures. 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).

Due to the heat load of PCs the air temperature inside the glass chamber increased up to 32°C. This elevated temperature in the surroundings of PCs might have strengthened the emission of pollutants, but this effect was not observed in the sensory evaluations made in the steel chamber. Comparing the sensory pollution load from PCs obtained in the condition when the pollutants from the glass chamber have been diluted into the air of the steel chamber with the condition when the PCs were directly placed in the steel chamber, no differences have been detected. This suggests that temperatures typically found indoors in the range between 22-32°C have little effect on the sensory pollution of PCs.

Turning the PCs on in the glass chamber, the I/O ratio of ozone was substantially decreased. This may indicate that ozone may be removed to some extent by oxidative reactions with the chemicals emitted in the glass chamber considering that thermal decomposition of ozone would occur at much higher temperatures (>200 °C). On the other hand, no such effect was observed in the office during the exposure study, where the results have shown that the presence of people was mostly the driving factor as regards the concentration of ozone in the space. The decline of the indoor ozone level after the subjects have walked in to the office reflects the greater total surface area introduced by people, which have consequently increased the surface removal rate inside the office (Weschler, 2000). Some ozone may also be scavenged during respiration or react with unsaturated bioeffluents.

3.4.3 Effects of 3-month-old PCs on PAQ, SBS symptoms and performance of office work

Introducing the 3-month-old PCs into an office, where the fresh air supply conformed to ventilation standards, significantly reduced the PAQ and increased odour intensity. Although the odour annoyance of PCs was clearly identified in the office, the irritation of mucous membrane remained at fairly low levels. This observation is similar to the findings of the previous experiment described in Chapter 2 and agrees well with the results of Wargocki (1998), suggesting that the air in the office was mainly judged in term of its odour rather than causing irritation in the mucous membrane. It was again seen, as in Chapter 2, that the sensory pollution originating from people did not alter significantly the PAQ in the office. The reasons may be similar as described earlier, i.e. cross-adaptation and bias of people to their own pollution may have occurred, but also some of the bioeffluents could be scavenged on the cooling unit or by reacting with ozone. The effects of PCs on the perceived air quality in the office are similar to the results described in the previous chapter of the present thesis, when the air was polluted by an assortment of building materials, and show that the percentage of dissatisfied in the office with sources was lower compared to the air quality levels measured in previous studies (Wargocki et al. 1999; 2000a; Lagercrantz, 2000) with similar settings. Consequently, the measurable effects can be expected to be lower. All these experiments demonstrate that reducing pollution sources indoors, as recommended by CEN (1998), is an effective means of improving the quality of air in buildings.

Although the subjects reported decreased satisfaction with air quality in the presence of PCs, there was a lack of strong effects on SBS symptoms. The exposure period may have been too short for the development of such symptoms, considering that the subjects have been exposed in the office with PCs present only on one occasion for a few hours, which is quite different compared to the conditions in real buildings where the occupants are exposed repetitively to their work environment for at least 8 hours each day. In the present experiment the subjects were students who were visiting classes during the time of one week between the two exposures with/without PCs in the office. It should be noted that during this time and all morning prior to the exposures in the office they spent time in various indoor conditions at home or at their workplace and were engaged in different activities. This could have an influence on their symptoms intensity on arrival, as significant differences in symptoms intensity were often detected in the waiting room between the two days of exposure, and consequently during exposures. Therefore the status of their symptoms on arrival before entering the office was always taken into consideration. Moreover, the changes in the severity of symptom during occupancy in the office with/without PCs present were also compared. While in the office the subjects maintained their thermal neutrality, and it may be assumed that factors related to the thermal environment did not influence their perceptions or activities during exposures.

Consistent with the sensory assessments, the subjects perceived the air to be significantly more stuffy during exposure in the office with PCs present, while no other significant changes in the perception of other environmental factors have been observed; the decrement in office cleanliness with PCs absent was probably caused by the difference imposed on arrival or simply by chance. Although the sensation of nose dryness was at some point slightly increased during exposure in the office with PCs present, it could not be seen for the whole exposure. The other differences in the intensities of skin dryness, nail brittleness, eye dryness and grittiness, and dizziness where absolute values were lower in the unpolluted office may be attributed to the initial differences observed on arrival for these symptoms. More people reported increased intensity of skin dryness in the presence of PCs during the exposure. This result complies with the indications of Knave *et al.* (1985) and Sundell *et al.* (1994) suggesting that the work with PCs may exacerbate the development of skin symptoms. Similar changes as for skin dryness were observed again in the intensity of sleepiness that could consequently affect the performance results of simulated office tasks.

The negative effects of air polluted by PCs on people perception and symptom intensity was more evident when the results were analysed for a subgroup of 10 subjects who experience dry air at home or at their workplace and report to have sensitive skin. These results indicate that this subgroup of the general population may experience more symptoms compared to the general population, which agrees with the finding reported earlier by Wargocki (1998). It should be noted that the classification of subjects presenting these symptoms was based on self-assessments rather than medical examination.

Although the intensity of SBS symptoms did not show substantial increment for the entire group in the office with PCs present, the performance of simulated office work was negatively affected compared to the results obtained in the office with PCs absent. This suggests that even before SBS symptoms that can be indicated by people are present, air pollution can negatively affect performance. When increments in the SBS symptoms are evident it is likely that performance will be affected. The negative effects of decreased PAQ effects were more prominent on the performance of text typing, although indications in the proof-reading task were also observed. No significant changes were seen in the performance of arithmetical tasks, perhaps due to a substantial learning effect observed between the experimental sessions and considering that the exposure condition could not be completely balanced for five groups of subjects, i.e. three groups were exposed to the polluted conditions in the second session of the experiment.

The performance results of text typing indicated that the subjects made more misspelling errors and were less able to follow the text presented on the paper, which was shown by the higher number of words skipped while typing the texts, when PAQ was worse. This effect could be seen already in Chapter 2. Consequently, the higher error rate accounted for a significant increment in the estimated text processing time. In order to obtain the same quantity and quality of texts between the two conditions, the subjects should have worked ca. 17 minutes longer, that is a 9% increment in the time spent with text processing ($p<0.015$). In other words, in the office with PCs present, ca. 9 sec. delay for each minute of text typing may be accounted due to reduced typing performance compared to the office without PCs. For example, considering that office workers using computers ca. 65% of their work time, and 35% of the computer time is text-typing (Burr, 2000), on each day ca. 1.8 hours is spent with typing if they work 8 h a day. This is almost the same time (109 minutes) as the period used for text typing in the present experiment. Thus, the above result implies that ca. 17 minutes is lost in the daily work, i.e. 3.5% of the total work time due to the reduced typing performance when the air quality is reduced as in the present experiment in the presence of PCs. This would have a substantial economic impact as discussed earlier (see section 1.4).

Moreover, this time loss is accounted only for text processing; however, typical office work includes many other tasks, where performance would also be affected as a result of a distraction due to reduced air quality.

In the present study, removing the pollution sources (i.e. PCs) from the office increased the self-estimated performance by 4%, the overall performance of text typing by 1.2% and the CO_2 production of people by ca. 6%. All of these changes were in the expected direction, presenting a fairly good agreement with the results obtained in Chapter 2 on this issue, and may be attributed to the improved air quality environment in the office.

3.5 Conclusions

The results of the experiments carried out under realistic indoor environment conditions to evaluate the effects of air pollutants emitted by PCs on PAQ, human comfort and performance of office work are summarized in the following conclusions:

- PCs are strong indoor pollution sources, negatively affecting the perceived air quality over a long time-scale up to several hundred hours of operation that may be 1/3 of their life expectancy. The time-weighted average pollution of a PC unit with CRT display is approximately the sensory pollution of a standard person (1 olf) in the first year of PC use.
- The sensory emission rate of PCs depends on the brand and age of the devices; within a PC unit the CRT monitor represents a stronger pollution source than the tower containing the CPU, which may be caused by the elevated operating temperatures of electronic and other components of the monitor.
- The sensory pollution load of a PC unit, represented by one of the most popular brands, was ca. 3 olf/unit after ca. 550 hours and ca. 0.5 olf/unit after ca. 2000 hours of operation. The decay of sensory emission strength over the operation time of PCs with CRT monitors could be described using a first-order decay model. The half-life of the decay may reach more than 300 hours depending on the type/brand of PCs.
- Introducing 6 PCs with the above pollution load after ca. 550 hours of operation in a low-polluting office space, ventilated with 10 L/s per PC outdoor air supply rate, the acceptability of air significantly reduced, increasing the percentage of dissatisfied upon entering the room from 12% to 40% and the odour intensity from slight to moderate levels.
- 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 sensory effects.
- In the office with PCs present the air was perceived to be significantly more stuffy throughout the whole exposure period of 4.8 hours and the odds ratio for increased skin dryness and sleepiness significantly increased (OR=3.1; [1.1, 9.1]).

- The people who experience dry air at home or at their workplace and report to have sensitive skin experienced more sensory and neurobehavioural symptoms in the presence of PCs.
- The reduced air quality level in the office with PCs present negatively affected the performance of text typing, causing a 20% higher error rate at slightly reduced speed; the increased error rate has also accounted for a significantly longer text processing time by ca. 9%, estimated to be ca. 17 minutes delay accounted for a text-typing period of 110 minutes, i.e. ca. 9 seconds delay for each minute of text-typing.
- Significantly more subjects reported that the self-estimated ability to work significantly decreased during exposure with PCs present compared to the condition with PCs absent (OR=3.7; [1.1, 11.4] $p<0.027$). The absolute value of the self-estimated work ability after 243 minutes of exposure tended to be lower ($p<0.07$) in the office with PCs present.
- The decrement in the objective measures of performance was in a good agreement with the self-estimated work ability and with the reduced CO_2 emission of people occupying the office. In the office with PCs present the CO_2 production of people decreased by ca. 6% compared to the unpolluted condition.

Chapter 4

Discussion

In the present chapter the overall findings of the experiments are discussed, implementation of the results and suggestions for future investigations are given. The results of individual experiments are discussed in detail in the respective chapters.

The negative effects of a mediocre indoor climate on human comfort, health and productivity have been previously studied in a number of experiments (Wargocki *et al.* 1999, 2000a, Lagercrantz et al., 2000) with similar design, where the air quality level in an office was changed by either introducing a 20-year-old carpet or increasing the outdoor ventilation rate in the presence of the same pollution source. The experiments presented in the current thesis reaffirm the earlier findings on many aspects, and also the magnitude of the effects caused by changes in PAQ on SBS symptoms and performance is in agreement with the previous results. At this time, commonly used building materials and electronic equipment have been selected to pollute the air in an office where the outdoor air supply rate was selected to conform with the prescriptions of ventilation standards for different air quality requirements. The sensory assessments of both occupants and visitors of the space have demonstrated in each experiment that the presence of such pollution sources significantly degrades the perceived air quality and the office cannot be ventilated anymore for "acceptable indoor air quality" to comply with the current ventilation standards. In addition, it was shown that increasing the outdoor air supply rate in a polluted office may involve complex oxidation processes, if the nature of sources are not resistant to such reactions, and this may counteract the beneficial effect of increased ventilation.

4.1 Implementation of the current findings

Although the impact of pollution sources on PAQ was similar in both exposure studies the emission of contaminants were driven by different mechanisms. The building materials selected for the current research were seen to be more sensitive to remove ozone compared to PCs, and the ozone removal was presumably driven by secondary emission processes. Consequently, the pollution load from such sources may affect IAQ for the whole product lifetime. Contrary to this, the contaminants originating from PCs were driven mainly by primary emissions that were characterized by an exponential decay over time, whereas the ozone removal was little affected by such sources. Although the primary emissions of PCs were seen to decay within a few hundred hours, considering a relatively short lifecycle, the pollution load from such devices is regularly "renewed" when purchasing a new PC. On the other hand this type of pollution can be compensated by increased ventilation.

The findings of the current research imply that both source removal and increased ventilation rate in buildings may be simultaneously applied in order to obtain the highest improvements on PAQ and consequently on human comfort and performance. In addition, filtration of ozone in the supply air may result in additional benefits since it will lower the risk of oxidation processes occuring inside the buildings. As mentioned earlier (2.3.2), there is a strong incentive for the application of source control in any indoor environment as recommended by CEN (1998). This was also the main view of Pettenkofer more than a century ago, although people were believed to be the major pollution source indoors. Nowadays it seems that bioeffluents are of minor importance compared to the substantial emissions of materials and other electronic appliances that are commonly present in the indoor environment. An efficient source control is needed to reduce the exposure risks of people to such emissions. This may be obtained with the implementation of the existing labelling schemes for various building products (Wolkoff, 2003). Nevertheless, to achieve the benefits of a low-polluting indoor environment in both sensory and chemical terms the requirements in the current labelling protocols (see section 1.3) should be increased, to encourage the manufacture of low-polluting materials.

Several "Eco-Labels" and product certificates also exist in Europe and overseas with the aim of characterizing the environmental impact of computers, monitors and other peripherals (O'Brien & Company, 2001). However, a detailed chemical emission of the electronic devices may be given only in a voluntary declaration form (ECMA, 1999) of the European Computer Manufacturers Association (ECMA). The chemical evaluation should be made to conform to a standard measuring method (ECMA, 2001). Such declaration of emissions still does not guarantee that the product in question would not affect perceived air quality, since it was shown in the current investigations that the chemical characterization of the emissions from PCs was insufficient to evaluate the related sensory impacts. On the other hand, the information given in the present thesis on the negative effects of PCs on human health, comfort and productivity, may help computer producers to identify opportunities for improvements in the manufacture technology to reduce the potential adverse indoor environmental impact of their products.

CRT monitors currently dominate the global marketplace, as they provide rich, high-resolution image well suited to a range of applications. Flat panel monitors in the last few years have emerged on the electronics market as a replacement for CRTs primarily because they are lighter, smaller, and more portable, consuming less energy during operation. One type of flat panel monitor is liquid crystal display (LCD) based on thin-film transistor (TFT) technologies (Katayama, 1999) that are used primarily in portable computers, but are beginning to move into the desktop market. It was recently shown that TFT monitors are much less polluting than CRT monitors in both sensory and chemical terms (Wargocki et al., 2003a, Nakagawa, 2003). Thus substituting the traditionally used CRT monitors with TFT alternatives, the sensory pollution load of PCs would be significantly reduced already from the beginning of their use. In addition, the required cooling load would also be reduced, considering that TFT monitors consume typically half of the energy required for CRT monitors. Nevertheless, TFT technology is still relatively expensive, and hence it seems reasonable to expect that private users in homes will often use CRT monitors, whereas TFT monitors will become more prevalent in offices. It should be noted that CRT monitors are often used in high-end applications that require a superior image quality that TFT monitors with the current technology cannot provide. Although the unit shipment of CRT monitors is still dominating the market for the next few years, the annual revenue of TFT panels is already higher compared to CRTs (iSuppli/Stanford Resources, 2003).

The perceived air quality in the office polluted by either building materials or PCs was not unrealistically low, reflecting an air quality level that is commonly reported in field studies or even lower (Bluyssen et al., 1996, Pejtersen et al., 2001). Thus a similar improvement of the air quality levels in real buildings should result in significant improvements in symptom intensity and performance of employees. The results of the current laboratory investigations are in a good agreement with the findings of a recent intervention study established in a call centre (Wargocki et al., 2002a; 2003b) showing that increased ventilation improves PAQ, SBS and productivity when new filters are installed in the HVAC system. However, the same intervention had no beneficial effects when the system was running with dirty filters. The positive effect of increased ventilation on the performance of call-centre operators was also reported in another recent study that was carried out in the tropics (Tham et al., 2003). Thus it seems that the results obtained in the present experiments as regards both human comfort and productivity are applicable in real buildings as well, where occupants perform their daily work, which is not necessarily measured in terms of characters typed or number of units added.

4.2 Effects of emissions from building materials and PCs on PAQ and performance

The relation between PAQ and performance of office work was developed based on the results of three independent studies (Wargocki et al., 2000b, 2000c) involving 90 subjects exposed to the emissions from a 20-year-old carpet. The present results indicate a similar impact of PAQ on performance either in the case of a mixture of building materials (linoleum, sealant and shelves with books) (Chapter 2) or PCs with CRT monitors (section 3.2). Therefore it is worth combining the present and previous results in order to obtain a relationship that can be generally applied for various indoor air pollution sources. The relationship was developed using the results obtained for text-typing that was shown to be most sensitive to changes of air quality in all 5 studies. The noise and temperature/RH conditions in the office with/without subjects were kept constant in the present and previous exposures and varied in a narrow range of 22-24.5°C, 30-50% RH and ca. 40-45 db(A) between studies. A little impact of these factors on performance can thus be assumed considering also that in all experiments a within-subject analysis of results has been performed. The statistical significance (one-tiled p-values) of the effects obtained separately in each study were combined similarly to the method used by Wargocki et al. (2000c), regarding each experiment as an independent test of the same hypothesis that poor PAQ negatively affects performance.

To combine the p values from each experiment, a Chi-square statistic ($\chi^2=-2\cdot\Sigma\log_e p$) was used. Under the null hypothesis that the observed probabilities in each study are a random sample from a population of probabilities having a mean of 0.5, Chi-square statistic has a sampling distribution, which is approximated by the chi-square distribution having 10 degree of freedom (df=2x5). If the probability of obtaining the numerical value of Chi-square statistics is less than the required significance level set for 0.05, the null hypothesis may be rejected, meaning that the combined evidence from the 5 independent studies that poor PAQ negatively affects performance may be accepted (Winer, 1970). Normalization was also adopted as made by Wargocki et al. (2000c) to consider that performance was measured in different independent studies with different subjects. The normalization factor was calculated for each study as the ratio between the mean of performance at all air quality levels in all five studies and the mean of performance at all air quality levels in each individual study. The average number of characters typed per minute was used for analysis after each had been individually normalized.

The effects of exposure conditions on PAQ and the performance of text typing in each study are summarized in Table 4.2.1. The performance results from the study investigating the effects of decreased air quality in the presence of mixture of sources (Chapter 2) were taken only for the conditions with low ventilation rate and sources present/absent where most indications on performance measures were seen, i.e. the error rate of typing and absolute decrement in typing speed calculated as the difference between the first and second part of typing were significantly affected (see section 2.2.4); however, a significant difference in the absolute values could not be shown most likely due to the shortness of exposure (see discussion in section 2.3.6). It should be noted that in the earlier studies performance data were used without adjustments for learning and error rate because no significant learning occurred in either of them, and the typing errors were found not to influence typing. The performance data from the present experiments were taken after adjustments for learning and errors (Table 2.2.9 and Table 3.2.9).

Table 4.2.1Effects of exposure conditions in five independent studies on PAQ and performance of text typing

Study	Vent. rate (L/s.pers)	Pollution sources		PAQ upon re-entering (% dissatisfied)	Typing performance (char/min)		
					not normalized	normalized	Effect of intervention
Wargocki et al. (1999)	10	Carpet	present	68	136.1	145.4	p=0.002
			absent	25	145.5	155.4	
Lagercrantz et al. (2000)	10	Carpet	present	61	135.2	149.3	p=0.019
			absent	40	137.3	151.6	
Wargocki et al. (2000a)	3	Carpet present		58	149.5	147.7	p=0.077
	10			29	152.5	150.6	
	30			29	154.9	153.0	
Chapter 2	5	Mix. of build. mat	present	42	149.6 *	149.3	p=0.29
			absent	28	151.9 *	151.6	
Chapter 3	10	PCs	present	32	170.1 *	149.5	p=0.03
			absent	15	172.1 *	151.3	
Combined effect (all interventions): p=0.00013 (χ=34.9, df=10)							

* Adjusted for learning and errors

The combined effect of the interventions established in all five experiments show that the performance of text-typing is significantly increased (p<0.00013) when PAQ is significantly improved. Furthermore, positive correlation (Figure 4.2.1, left) was found between PAQ and performance (R^2=0.61, p<0.0045). These results imply that for every 10% decrease in the percentage dissatisfied with the PAQ, the performance of text typing can be improved by 0.8% (the data applies for the air quality level causing from 15% to 68% dissatisfied). This change is somewhat lower compared to the relation reported earlier (Wargocki et al., 2000b; 2000c). However, it is more general as it applies for a set of pollution sources including carpets, personal computers, linoleum, sealant and shelves with books and paper, which are typical indoor sources of pollution.

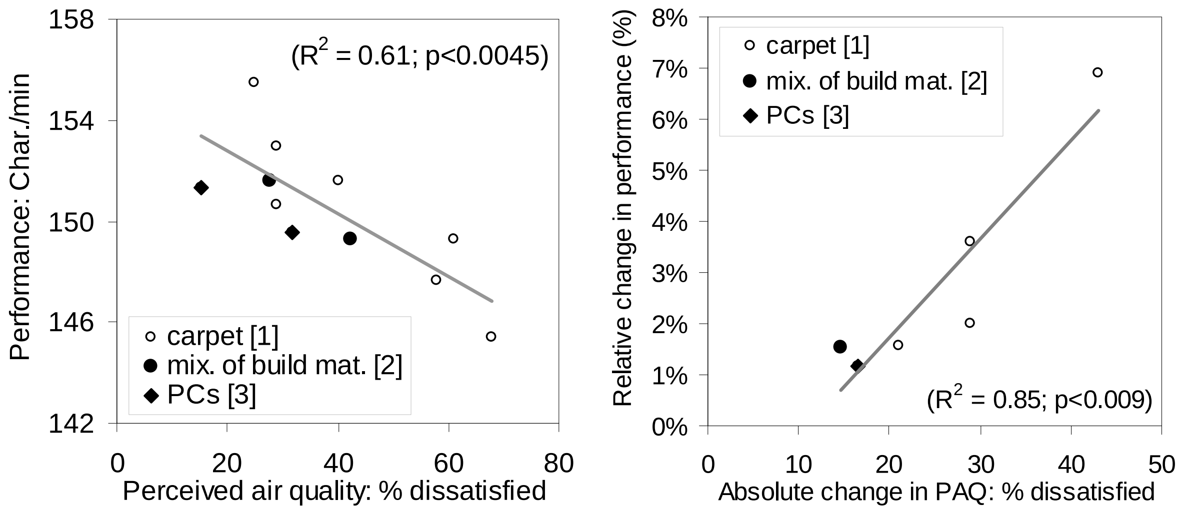


*Figure 4.2.1 **Left:** Performance of text-typing as function of PAQ expressed in % dissatisfied; **Right**: Relative change in the performance of text typing caused by an absolute change in PAQ; [1] Wargocki et al. (1999); Lagercrantz et al. (2000);. Wargocki et al. (2000a); [2] Chapter 2, Table 2.2.9; [3] Chapter 3, Table 3.2.9.*

Figure 4.2.1, right illustrates the relative change in performance caused by an absolute change in PAQ levels between two experimental conditions of the same study as a result of an intervention. It suggests that in laboratory experiments a difference of 10% in the absolute change of percentage dissatisfied would cause ca. 2% relative change in performance of text typing. Moreover, it is shown that more than 15% change in the absolute level of percentage dissatisfied is required between exposure conditions to be able to see ca. 1% change in performance that can be quantified at the level corresponding to statistical significance of $p<0.05$. Thus, the larger intervention to perceived air quality the higher chance that the effects on performance can reach formal statistical significance. This may explain the results of a number of laboratory experiments of similar procedure where no significant effects on the performance measures could be shown when exposing people to different indoor air quality environments. In the study of Fang et al. (1999b; 2002) increasing the ventilation rate from 3 L/s per person to 10 L/s per person, while the air temperature of 23°C, RH of 40% were unchanged, the percentage dissatisfied with PAQ decreased from 30% to 19%, i.e. only 11%, in the office with bioeffluents and polluted by carpet. No significant change in PAQ (PD generally decreased from 25% to 18%) were seen in the study of Alm (2001) when the sensory impact of emissions from an old or new filters were evaluated in the presence of bioeffluents and no other interventions were made on the temperature, RH and noise levels. Similarly, Witterseh (2001) could not show significant impact on performance when the PAQ (48-49% PD) was apparently unaffected by the pollutants originating from a carpet; the air temperature of 22°C, RH of 40% were unchanged and the background noise level was either 42db(A) or 45 db(A).

4.3 CO_2 emission and IAQ

Physical measurements during exposures in an office have indicated that the CO_2 concentrations were lower under conditions with pollution sources present compared to the same office with sources absent. This difference appears to be systematic regardless of the nature of pollution sources (i.e. building materials or PCs), outdoor air supply rates, and different groups of people exposed in the office for several hours. In these experiments a total of 60 people, divided into groups of 6 persons, were exposed in 30 sessions to the conditions in the office with different types of pollution source either present or absent when the outdoor air supply rate was respectively at 5, 10 and 15 L/s per person. On each exposure day the CO_2 concentration in the office and outdoors, and outdoor air supply rate were continuously measured; thus the CO_2 production of each group could be calculated using a mass-balance model. Dividing the emission rates by the number of people in the group resulted in an estimated average CO_2 production per person.

Figure 4.3.1 (left) shows that the CO_2 emission rate of subjects was lower in almost every group when the building materials or PCs polluted the office air compared to the conditions with pollution sources absent. Whenever a subject could not participate in the experiments the groups were supplemented by the inclusion of experimenters, to maintain the same occupation density in the office. However, their CO_2 emissions were presumably different from the group average considering that the experimenters did not perform any of the tasks simulating office work and had different body size compared to that of subjects' mean. This could have biased the results in either a positive or a negative direction depending on for which condition the experimenters were present in the office. Excluding these sessions and taking data for the complete groups, i.e. when the same subjects participated in each condition, it can be seen that the CO_2 emission rate was always lower in the polluted office. The summarized data for 30 subjects, including all completed and uncompleted groups (Figure 4.3.1 right) show that the average CO_2 emission rates in the polluted office were lower by 3-6% (on average ca. 5%) compared to the unpolluted conditions at each outdoor air supply rate. Excluding the supplemented groups did not change substantially the mean CO_2 emission rates and the average difference of 5% in the production rate between the polluted/unpolluted conditions was still maintained.

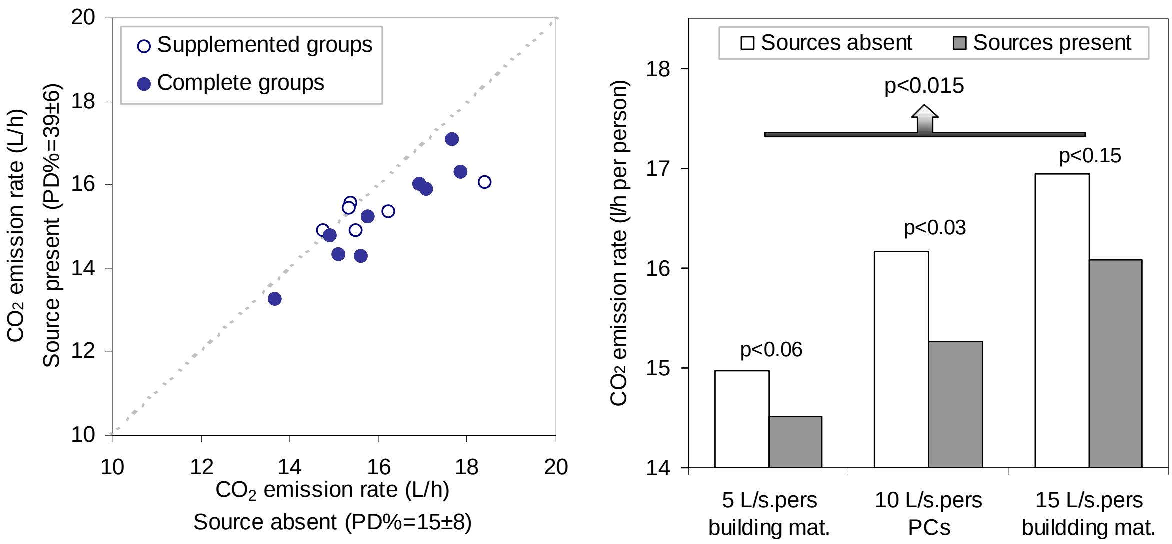


Figure 4.3.1 ***Left:*** *Carbon dioxide emission rate of people in different groups of 6 persons in the conditions with sources present/absent in the office ventilated with 5, 10 and 15 L/s per person respectively; whenever a subject dropped out from a session, the group was supplemented by another person among staff members;* ***Right:*** *CO_2 emission rate in the office as a function of presence/absence of pollution sources and outdoor air supply rates summarized for 30 people in each experimental condition.*

The observed decrements in the CO_2 production were not always statistically significant when testing the means for such differences with Wilcoxon test, because of the small number of groups and the variations introduced by completing the groups when necessary. However, the tests may be combined with respect to the overall hypothesis that CO_2

emission rates are lower in the presence of sources. Using the p values from each pair of conditions (sources present/absent), an over-all probability statement may be calculated using the chi-square statistic, under the null hypothesis that the observed probabilities are a random sample from a population of probabilities having a mean of 0.5 ($\Sigma \log_e p = -1/2\,\chi^2$). This analysis yields a probability of $p<0.015$, which shows the combined evidence of these experiments that the common hypothesis, i.e. CO_2 emission rates are lower in the presence of sources, may be accepted. To see whether it remains valid by excluding the supplemented sessions, the analysis above was repeated accounting only those groups where the same subjects were present in both polluted/unpolluted conditions; this resulted in a $p<0.03$ with respect to the common hypothesis that CO_2 emission rates are reduced in the presence of sources.

In Figure 4.3.2 (left) the average CO_2 emission rate of all subjects, having a mean body size of 1.7 m^2 (±0.1 SD) is plotted against the air quality acceptability ratings upon re-entering (i.e. office with bioeffluents) for each of the exposures studied. These results indicate that the subjects start to produce less carbon dioxide as the acceptability of air decreases, which is best approximated with a linear relationship ($R^2=0.6$; $p<0.07$). Assuming this connection, the changes in CO_2 emission rate of people may be expressed as a function of the perceived air quality in decipol, which is depicted in Figure 4.3.2 (right). It shows that the CO_2 production rate decreases by ca. 13% when the perceived air quality is changed from ca. 0.5 dp to ca. 4.5 dp, which implies that the percentage dissatisfied is increased from 8% to 40%.

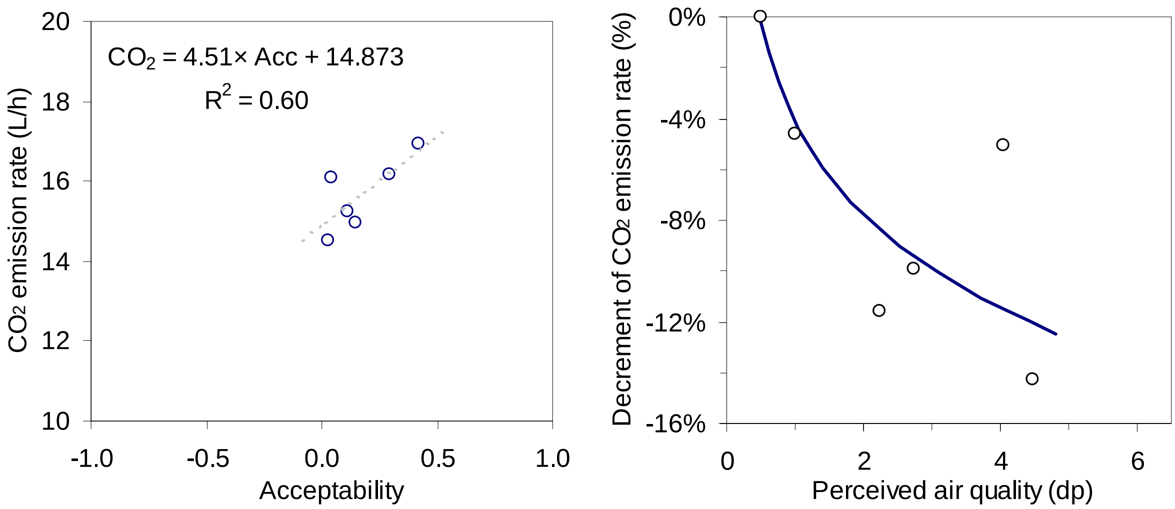


Figure 4.3.2 ***Left:*** *Carbon dioxide emission rate of people (A_{Du}=1.7±0.1 m^2) as a function of acceptability of air in the polluted/unpolluted office;* ***Right:*** *Decrement in CO_2 emission rate as function of perceived air quality expressed in decipol, considering a PAQ level of 8% dissatisfied as a reference.*

It is easy to calculate that a change of 13% in the CO_2 production of even 17 L/h per person due to a substantial change in the PAQ would result in ca. 60 ppm, a rather small difference in the absolute CO_2 levels in an office ventilated with a typical airflow rate of 10 L/s per person. This could explain that the effects of PAQ on the CO_2 production of people were overlooked earlier or attributed to measuring errors.

The results of the present experiments demonstrated that people consistently emit less carbon dioxide when the perceived air quality is decreased. Similar indications may be derived from a number of previous studies where CO_2 levels and ventilation rates were registered at different air quality levels. In the study of Wargocki et al, (1999) the CO_2 levels increased when the pollution source was removed from an office while the outdoor air supply rate remained unchanged. In a later study (Wargocki et al., 2000a) it was reported that the metabolic rates estimated from the CO_2 measurements significantly increased with the ventilation rate, i.e. with the PAQ. The higher metabolic rate was attributed to an increased muscular tonus given by the higher work rate that was seen under the conditions with improved PAQ. It was also mentioned that breathing shallowly when air quality is poor might lower the metabolic rate. Although Witterseh (2001) investigated the combined effect of pollution and noise, the CO_2 levels measured in an unpolluted office were markedly higher compared to the condition when emissions from carpet polluted the air, while the ventilation rate and noise level was maintained at the same level. In the experiment carried out in Sweden (Lagercrantz et al, 2000) no such comparison can be made since the CO_2 measurement was incomplete between the conditions created. In field studies, unless it is well planed, the CO_2 emission rate is rather difficult to obtain due to a multitude of factors influencing the accuracy of ventilation and CO_2 measurements, and considering that the exact occupancy may vary as people move around in the buildings.

Assuming a constant body size, the lower CO_2 emission rates in the office with sources present may be caused by a decrement of RQ and/or the metabolic rate of subjects (Equation 2.4). Considering that in the polluted office the intensity of neurobehavioural symptoms increased, work ability decreased and people performed less well in the simulated office tasks, such changes may indicate that the metabolic rate was lower in the presence of pollution sources. On the other hand, it is unlikely that the subjects would have instantaneously reduced their metabolic rate from the very beginning of exposure in the office with sources present, as the CO_2 levels would suggest (see Figure 2.2.1 and Figure 3.2.4), since little effect on the speed of their work (i.e. on the exerted effort) and most of the SBS symptoms that could affect the activity level were seen when comparing the polluted/unpolluted conditions in the first part of the exposures. The RQ basically depends on the nutrition metabolized, body temperature and on the activity level of people. In a person at rest who has a normal diet (mixture of fats, carbohydrates, and proteins) it averages ca. 0.8. Although RQ can be as high as 1.5 after 1 minute severe exercising, it is little changed during moderate work (Consolazio et al., 1963). Body temperature was presumably maintained in both experimental conditions, since the air temperature was unchanged and the subjects remained thermally neutral. Consequently, if nutrition has also not changed from week-to-week, it may be assumed that RQ remains at the same level, i.e. 0.85 during sedentary work (ISO, 1990). Thus if neither RQ nor the metabolic rate was changed in the first part of exposures there is no apparent reason for the CO_2 emission to decrease in the office with sources present in comparison to the unpolluted condition. For a better understanding of this discrepancy, pulmonary physiology should also be considered (Martin, 1987; Paulev, 2000).

Body metabolism involves consumption of oxygen (O_2) and production of CO_2 that are both increased with muscular or mental effort. During respiration O_2 is transported from the atmosphere, via the alveolar ventilation and then carried by the pulmonary blood flow into the cells and their mitochondria for metabolic purposes. CO_2, the final end-product of metabolism, then enters the blood and is transported back to the lungs where it is expired into the atmosphere. In the blood CO_2 is present in three forms: as bicarbonate (the greatest amount), combined with haemoglobin and other proteins, and dissolved. These three forms of CO_2 are in equilibrium with one another, and it is the dissolved fraction in plasma that exerts the partial pressure measured as $PaCO_2$. In the case of oxygen, as it does not easily dissolve in water, very little is carried in the blood plasma (1.5%), the rest being transported by combining with haemoglobin in red blood cells. The exchange of O_2 and CO_2 between the alveolar air and blood takes place across a gas-permeable alveolar-capillary membrane and depends on the partial pressure gradient that exists on the two sides; it continues to take place until the partial pressure of gases evens out. During exercise the O_2 consumption and CO_2 production are greatly increased; as a result, ventilation of the lungs and lung blood flow both increase to meet the metabolic demand. The RQ mentioned up to now reflects the ratio of CO_2 produced to O_2 consumed at the cellular level, often called the metabolic RQ. In addition, a pulmonary respiratory quotient (R) is also defined as the ratio between the carbon dioxide output and the oxygen uptake by the lungs, which is measurable with gas exchange equipment at the mouth. Under steady-state conditions RQ equals R, reflecting that the amount of CO_2 produced from metabolism and that eliminated by the lungs is the same. However, this equilibrium may be disturbed if the breathing pattern in response to metabolic demands is changed for some reason. Shallow breathing, which may or may not be voluntary, or other dysfunctions in the respiratory system, due to obstructed airways or other pulmonary diseases, may all cause hypoventilation of the alveloli. Even a small decrement in the alveolar ventilation at a given metabolic rate will result in an excess of CO_2 that is retained in the arterial blood stream since there is no other way to eliminate it. This causes O_2 levels to fall and CO_2 levels to rise in both the alveolar and arterial regions. Consequently, CO_2 will build up in the arteries, and $PaCO_2$ will increase and change the acidity (pH) of the blood. At the same time R will fall because CO_2 is retained and the decrement in O_2 uptake is smaller than that of CO_2 in the exhaled air (Martin, 1987; Paulev, 2000).

The mechanism described above may have altered the CO_2 emission rate of people in the present experiments. The lower CO_2 levels measured in the office with sources present may indicate that poor air quality caused people to involuntarily breathe more slowly or more shallowly, as no changes in the metabolic rate or RQ would be expected. Breath holding would be a natural reaction of the body to minimize the amount of possibly harmful air taken in through the upper airways and into the lungs. It has already been shown that airway irritants resulting from terpene/ozone oxidation reactions cause a reduction of the respiratory rate (Larsen et al., 2000; Clausen et al., 2001; Rohr et al., 2002; Wilkins et al., 2003). Although these effects were seen in mouse bioassay studies at relatively high concentration of pollutants comparing to the typical levels occurring indoors, it may be hypothesized, based on the present results, that people react similarly, i.e. reducing their breathing rate or inhaling less air, when sensory pollutants in the air cause odour annoyance. Danuser (2001) reviews a number of studies reporting perceptual and breathing responses induced by exposure to environmental chemicals. She pointed out the work of Walker et al., (2001) who showed that tidal volume (amount of air inhaled per breath) decline may occur even with stimuli that are not detected by anosmics and elicit very low levels in normal individuals when exposed to propionic acid concentrations. Furthermore, Danuser concludes that breathing patterns appear to be useful in assessing vegetative components of annoyance.

Impairment of the breathing process implies a series of other mechanisms that may give rise to several neurobehavioural symptoms. In medical terms hypoventilation produces primarily hypercapnia (i.e. rise of $PaCO_2$ above normal levels in the arterial blood flow) although hypoxemia (i.e. insufficient oxygenation of the blood) also occurs. Hypercapnia and hypoxemia, which often develop in people who have respiratory disorders during nocturnal sleeping (Resta et al., 2000) were reported to cause daytime complaints such as fatigue, sleepiness, cognitive dysfunction and headache, although the nocturnal events were not always recognized by the patients (Kotterba et al., 2001). Hypoxemia also accounts for most of the symptoms of healthy humans who experience so-called “mountain sickness” at high altitudes, manifested as changes in intellectual and psychological function, headache, nausea, vomiting, loss of appetite, insomnia, and in more severe cases embolism (Vazquez, 2000; Domej and Schwaberger, 2002). The underlying mechanism of such symptoms, especially of headache, may be that increased $PaCO_2$ in the arteries during hypercapnia dilates cerebral vessels. Vasodilation of celebral vessels was linked to headache already decades ago (Graham and Wolff 1938) although the complete etiology is still a major subject for medical investigations.

Although acute or chronic hypercapnia is unlikely to develop as a result of shallow breathing in healthy people who are exposed to moderate levels of air pollution, the amount of CO_2 retained in the body will present a continuous strain that must be compensated (Walters, 1998). During a long exposure to polluted air, the symptoms characteristic of hypercapnia, but of the lower intensity seen in SBS symptoms, may be developed according to the mechanism described above. It should be noted that the risk of symptoms development could be much higher for atopic people (e.g. asthmatics) exposed to air pollution, since they are already at some risk of developing hypercapnia.

As a conclusion, it may be hypothesized that people exposed to poor IAQ may unconsciously breathe more slowly or more shallowly to reduce the amount of possibly harmful air inhaled. As the metabolic rate imposed by the type of work they perform is little affected initially, but hypoventilation occurs, CO_2 builds up in the circulatory system, leading to the development of neurobehavioural symptoms. Increased symptom intensity causes distraction from work resulting in reduced performance and activity level, lowering the metabolic rate and thus the CO_2 emission rate. This hypothesis would also be a feasible, tempting and a simple explanation for the high frequency of comfort complaints of people in so-called “sick buildings” that is commonly reported by most of the building investigation studies conducted earlier. Crucial experiments to investigate these hypothesized mechanisms are required that should include non-invasive measurement of end-tidal CO_2 in exhaled air, monitoring breathing rate and depth using non-invasive chest plethysmography, and possibly also cerebral blood flow and pCO_2 in the arterial blood. It is worth mentioning that voluntary decrement in metabolic rate due to a psychological effect of air pollution, i.e. people’s unwillingness to work when perceiving unpleasant odours, may also occur, in addition to the effects on breathing pattern (Danuser, 2001), that may explain reduced CO_2 emission rate.

4.4 Limitation of the methodology and recommendations for future experiments

One of the main goals in the design of the present work was to create realistic environmental and air quality conditions to which human subjects are exposed in their normal work. Among the shortcomings of this method was that although the negative effects of the pollution sources on PAQ could be clearly identified, the time of exposures might not be long enough to affect in a similar manner the intensity of most SBS symptoms and consequently the objective measures of performance at the air quality changes employed. A higher difference in the air quality levels, from 10% up to 60 % dissatisfied, would be favourable in order to obtain better responses on human comfort and performance when using similar investigations of the same duration.

In the present experiments the fresh air was taken directly from outdoors to avoid any pollution that could originate from a conventional the HVAC system. Although this approach was adequate to obtain a clean air delivery (without possible pollution from HVAC system) to the office, the cooling capacity of the supply air was not enough to maintain the required thermal conditions throughout the experimental period in May-June or June-July. Consequently, a SPLIT air-conditioner was used to maintain the office temperature. Using this unit has presumably removed some of the contaminants, which are known to cause sensory effects. These compounds include mostly hydrophilic aldehydes and acids originating from both the pollution sources and people that may be trapped in the condensed water leaving the AC unit. In this way the PAQ even in the presence of pollution sources in the office could be improved to some extent. The air scrubbing effect when a SPLIT type AC unit is applied should be avoided in future experiments or it should be compensated by increasing the strength of pollution accordingly.

Although personal factors will always influence to some extent the outcome of air quality investigations of this kind, the effects could be minimized with a proper protocol for selecting the sensory panel in order to obtain a more accurate "instrument" for PAQ evaluations, and to create a background for better comparison of results obtained from different independent studies. The sensory panel should not work as a bad wine tester that only differentiates the wine quality between the two extremities of good and bad. It should also tell us how good or how bad the wine is if the difference in the quality is more subtle. Choosing subjects with good olfactory sense and/or people considering them to be sensitive to poor IAQ may improve the sensitivity of the panel. Moreover, selecting subjects who were regularly involved in air quality investigations, even small changes in PAQ could be detected. Although these approaches may give less representative results for the general population there would be a way to reduce the remaining 10-15% dissatisfied people who are generally neglected even when applying the best air quality requirements given by the ventilation standards. The selection of sensitive people would also be beneficial to show the increased SBS symptoms intensity in relatively short exposures to poor IAQ.

Another drawback of the methods was that the experimental conditions could not be completely balanced for 5 groups of subjects making it difficult to show the negative effects of PAQ on peoples' performance especially when a substantial learning effect occurred. Therefore it is recommended to use an even number of groups for each experimental condition when a repeated design is applied. Moreover, the performance tasks should be selected to be simple and commonly used by the applicants to reduce the chance for learning effects to occur.

The length of exposures described in Chapter 2 was shorter compared to the previous studies of this kind (Wargocki et al, 1999, 2000a; Lagercrantz, 2000). Using shorter exposures would reduce experimental expenses. However, if no or little effect is found it is difficult to say whether there is no effect at all or that it is due to short exposure conditions. Consequently, the study should be designed to minimize any possible interaction with factors that may lead to erroneous conclusions. Longer exposures of 4-6 hours are also recommended if the objectives of future studies justify such investment.

Due to the lack of proper instrumentation, the ozone concentrations indoors and outdoors could not be followed continuously. On some experimental days the outdoor ozone levels were quickly altered by the weather conditions, whereas indoor concentrations were affected by the presence of people. Consequently, the I/O ratio of ozone was difficult to obtain especially when low indoor levels occurred. Therefore a proper evaluation of the I/O ratio requires parallel measurements both indoors and outdoors. Application of a charcoal filter in the fresh air supply is also recommended in the future investigations to avoid any unwanted effect of ozone on the sensory/chemical emission rates of materials that was seen to initiate oxidation processes indoors if the material surfaces are sensitive to such reactions. However, such filters might also act as source of pollution in case of improper maintenance.

Finally, it should be mentioned that the coarse and ultrafine particle level was not monitored in the present design. The level of particles in the office was probably influenced by the outdoor conditions considering that there was no filtration applied on the supply air. Future investigations should include the monitoring of particles, especially in the sub-micron range, since it may provide additional information on the chemistry occurring indoors.

4.5 Conclusions

The findings of the present work are summarized in the following:

- The presence of typical indoor pollution sources such as building materials and electronic equipment reduced the perceived air quality in a low-polluting office where the outdoor air supply rate was selected to meet the requirements of ventilation standards in a range of 5–15 L/s per person. The percentage dissatisfied with the perceived air quality was changed from 8-17% (office without sources) to 40-45% when either common building materials or 3-month-old PCs were placed in the office.
- The time-weighted average pollution of a PC unit with CRT display was found to be approximately the sensory pollution of a standard person (1 olf) in the first year of PC use.
- Increasing the outdoor air supply rate in the presence of building materials that are sensitive to oxidation processes increased both the sensory and chemical emission rate in the office and was probably the reason why the increased ventilation was less beneficial when sources were present in the office.
- Reduced perceived air quality in the office increased the intensity of some SBS symptoms and negatively affected the performance of office work. The magnitude of the effects was similar to those obtained in the previous investigations where a 20-year-old carpet was used to alter the perceived air quality. A new relation between PAQ and performance of text-typing was developed by including data of several independent experiments. It shows that for every 10% decrease in the percentage dissatisfied with the PAQ, the performance of text typing can be improved by 0.8% (the data applies for the air quality level causing from 15% to 68% dissatisfied). Moreover, it was indicated that more than 15% change in the absolute level of percentage dissatisfied is required between exposure conditions to be able to see ca. 1% change in typing performance.
- In the presence of pollution sources in the office the CO_2 produced by people significantly decreased by ca. 5% compared to the unpolluted condition. This effect can be caused by involuntary change in breathing pattern (shallow breathing) or voluntary reduction of working pace in polluted air. Both changes cause reduction in metabolic rate and may be a cause for the reduced performance observed. An empirical relation between PAQ and CO_2 emission rate of people was developed.

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Appendices

Appendix 1

List of prevalent VOCs in buildings and related sources

List of chemical compounds provided by Wargocki (1998) based on a literature survey of 22 investigations carried out in 209 office buildings and related pollution sources; four categories are defined according to the reported occurrence and the odour index of each compound: 1) Prevalent compounds that are likely to affect PAQ (detected in >10% of the buildings at OI>0.01); 2) Prevalent compounds with low odour index (detected in >10% of the buildings with OI<0.01 or unknown); 3) Compounds less prevalent but may affect PAQ (detected in <10% of the buildings, OI>0.01); 4) Compounds less prevalent with low odour index (detected in <10% of the buildings, OI<0.01 or unknown).

Catg.	Compound	Odour threshold[1] (mg/m^3)	No. of buildings	Odour index (OI)	Indoor sources				
					Floor and wall coverings	Building materials	Paints, adesives, waxes, etc.	Wooden products	Other products
1	styrene	0 .63	94	0 .101	nylon carpet, latex-backed carpet, rubber floor covering, german cushion vinyl, PVC of dif. sort, carpet, undercarpet	mineral wool, expanded polistyrene, polystyrene foam, building materials	solvent-free latex, solvent based adhesives, floor tile adesive		laser printer, photocopiers
1	butanol, (n-)	1 .51	78	0 .045	wallpapers of dif. sort, nylon carpet, carpet glued to plywood, cushion vinyl, Cl-free tiles, PVC of dif. sort	mineral wool, cellulose wool, silicone caulk	solvent-free latex	plywood	laser printer
1	xylene, (m-)	1 .41	61	0 .013	nylon carpet, PVC, linoleum, vinyl flooring			plywood	laser printer, photocopiers, computers
1	benzaldehyde	0 .19	52	0 .014	linoleum, carpet glued to plywood, cushion vinyl	glass wool, expanded polistyrene	alcyd paint	particleboar d	photocopiers, laser printer
1	ethylbenzene	0 .01	51	1 .630	nylon carpet, latex-backed carpet, rubber floor covering, cushion vinyl, PVC of diff. sort, vinyl flooring, carpet, undercarpet	mineral wool, cellulose wool, expanded polistyrene, polystyrene foam	solvent-free latex, solvent-free acrylate latex old composition, floor wax, floor tile adesive, paint water based, polyurethane lacquer	furniture polish	laser printer, photocopiers, computers
1	limonene	2 .45	48	0 .014	nylon carpet, latex-backed carpet, german cushion vinyl		alcyd paint, paint water based	furniture polish	surface cleaners/disinf ectants, air fresheners
1	trimethylbenzene, (1,2,4-)	0 .78	42	0 .022	wallpapers of dif. sort, cushion vinyl, Cl-free tiles, PVC of dif. sort, carpet, undercarpet	glass wool, cellulose wool, expanded polistyrene, building materials	alcyd paint, solvent-free acrylate latex old composition		photocopier
1	acetic acid	0 .36	21	0 .048	linoleum, carpet glued to plywood				

Catg.	Compound	Odour threshold[1] (mg/m³)	No. of buildings	Odour index (OI)	Indoor sources				
					Floor and wall coverings	Building materials	Paints, adesives, waxes, etc.	Wooden products	Other products
2	toluene	5 .89	177	7 .3E-03	wallpapers of dif. sort, nylon carpet, carpet glued to plywood, latex-backed carpet, linoleum, rubber floor covering, cushion vinyl, Cl-free tiles, PVC of dif. sort, vinyl flooring, carpet, undercarpet	mineral wool, glass wool, cellulose wool, expanded polistyrene	alcyd paint, solvent-free acrylate latex old and new composition, water-resistant latex system, water based adhesives, solvent based adhesives, floor tile adesive, paint water based, solvent based paints	plywood,	computers, laser printer
2	trichloroethane, (1,1,1-)	125 .89	89	3 .1E-04	rubber flooring				Cleaning agents/aerosol spot removers, computers
2	xylene		75	n/a	nylon carpet, latex-backed carpet, linoleum, vinyl flooring		water based adhesives, polyurethane lacquer	plywood,	laser printer, photocopiers, computers
2	hexane, (n-)	79 .43	72	2 .1E-04	nylon carpet, latex-backed carpet, rubber floor covering, , finnish cushion vinyl, Cl-free tiles, PVC of dif. sort	glass wool, cellulose wool, sealant	solvent-free latex		photocopiers
2	phenol	0 .43	66	2 .0E-03	PVC of dif. sort, german cushion vinyl				computers
2	acetone	34 .67	65	4 .6E-04	linoleum, nylon carpet, carpet glued to plywood, rubber floor covering	sealant	paint water based	particleboar d	laser printer, photocopiers
2	decane, (n-)	4 .37	64	3 .2E-03	wallpapers of dif. sort, latex-backed carpet, PVC, rubber floor covering, cushion vinyl, Cl-free tiles, vinyl flooring	mineral wool, glass wool	alcyd paint, floor wax, water based adhesives, solvent based adhesives, wood stain, polyurethane lacquer		surface cleaners/disinf ectants, air freshener
2	xylene, (o-)	3 .8	62	3 .3E-03	nylon carpet, latex-backed carpet, PVC of dif. sort, linoleum, cushion vinyl, Cl-free tiles, vinyl flooring	mineral wool, cellulose wool, expanded polistyrene	alcyd paint, solvent-free latex, solvent-free acrylate latex old composition	plywood	laser printer, photocopiers, computers
2	tetrachloroethene	42 .66	62	8 .0E-05	german cushion vinyl				
2	heptane, (n-)	40 .74	61	1 .3E-04	nylon carpet, PVC	mineral wool, glass wool, cellulose wool	alcyd paint, solvent-free latex, solvent-free acrylate latex new composition	furniture polish	surface cleaners/disinf ectants

Catg.	Compound	Odour threshold[1] (mg/m³)	No. of buildings	Odour index (OI)	Indoor sources: Floor and wall coverings	Building materials	Paints, adesives, waxes, etc.	Wooden products	Other products
2	undecane, (n-)	7 .76	61	1 .0E-03	wallpapers of dif. sort, nylon carpet, latex-backed carpet, german cushion vinyl, PVC of dif. sort, Cl-free tiles, carpet, undercarpet	mineral wool, glass wool, cellulose wool, building materials	alcyd paint, solvent-free acrylate latex new composition, floor wax, water based adhesives, solvent based adhesives, wood stain, paint water based, polyurethane lacquer, latex paint	plywood	surface cleaners/disinf ectants, air freshener
2	trichloroethene	26 .92	60	5 .6E-04					
2	benzene	12 .02	57	4 .6E-04	nylon carpet, latex-backed carpet, rubber floor covering, finnish cushion vinyl, PVC of dif. sort	cellulose wool, expanded polistyrene, silicone caulk	floor tile adesive	particleboard	photocopier
2	methylcyclohexane		50	n/a	PVC, rubber floor covering		water based adhesives	furniture polish	
2	dodecane, (n-)	14 .45	48	1 .2E-03	latex-backed carpet, PVC, german cushion vinyl, Cl-free tiles, vinyl flooring, vinyl wallpapers	mineral wool, cellulose wool, gypsum boards	alcyd paint		
2	ethanol	54 .95	47	2 .0E-03					
2	nonane, (n-)	6 .76	41	2 .0E-03	wallpapers of dif. sort, latex-backed carpet, rubber floor covering, german cushion vinyl, Cl-free tiles, vinyl flooring	glass wool	alcyd paint, water-resistant latex system, floor wax, water based adhesives, wood stain, polyurethane lacquer		surface cleaners/disinf ectants, air freshener
2	pinene, (alpha-)	3 .89	38	1 .0E-03	carpet glued to plywood, latex-backed carpet, linoleum, cushion vinyl	gypsum board			surface cleaners/disinf ectants, deodorants
2	octane, (n-)	27 .54	38	6 .2E-04	nylon carpet, german cushion vinyl, PVC of dif. sort, vinyl flooring	cellulose wool		furniture polish	
2	methylpentane, (2-)		37	n/a					
2	ethylacetate	9 .77	35	3 .3E-04	wallpapers of dif. sort, carpet glued to plywood, german cushion vinyl	silicone caulk	floor tile adesive, solvent, adhesives		
2	xylene, (m- & p-)		33	n/a	latex-backed carpet, cushion vinyl, PVC of dif. sort, Cl-free tiles, wallpaper, textile wallpaper	mineral wool, glass wool, cellulose wool, expanded polistyrene	alcyd paint, solvent-free latex, solvent-free acrylate latex old and new composition, solvent based paints		photocopier

Catg.	Compound	Odour threshold[1] (mg/m³)	No. of buildings	Odour index (OI)	Indoor sources				
					Floor and wall coverings	Building materials	Paints, adesives, waxes, etc.	Wooden products	Other products
2	dichlorobenzene, (m- & p-)		29	n/a	vinyl wallpapers	gypsum boards		plywood	moth crystals, toilet deodorizers
2	carbon tetrachloride	120 .23	28	7 .5E-06	nylon carpet				
2	propanol, (2-)	25 .7	27	7 .3E-04	PVC		paint water based	particleboard	
2	cyclohexane	77 .62	25	4 .3E-04	linoleum, rubber floor covering		water based adhesives, solvent based adhesives		
2	methylcyclopentane		23	n/a			solvent based adhesives		
2	isoprene		22	n/a					
2	butylacetate, (n-)	0 .93	22	1 .0E-03	wallpapers of dif. sort		alcyd paint, solvent, solvent based paints, spray paints, adhesives		
2	chlorobenzene	3 .55	22	2 .8E-05					
2	butoxyethanol, (2-)	1 .66	21	4 .0E-03	linoleum, PVC of dif. sort	silicone caulk	paint water based		
2	trimethylbenzene, (1,3,5-)	1 .15	21	4 .0E-03	PVC of dif. sort	glass wool	alcyd paint, floor wax		
2	dichloropropane, (1,2-)	3 .98	21	3 .3E-04					
3	hexanal, (n-)	0 .06	20	0 .092	linoleum, nylon carpet, carpet glued to plywood, PVC, linoleum, wallpaper	gypsum board, cellulose wool	alcyd paint, solvent-free latex, solvent-free acrylate latex old composition, paint water based	particleboard	laser printer
3	nonanal, (n-)	0 .01	19	0 .253	linoleum, wallpaper, PVC of dif. sort		alcyd paint	plywood	photocopiers, laser printer
3	pentanal	0 .02	17	0 .012	linoleum, carpet glued to plywood, finnish PVC tile			particleboard	
3	acetaldehyde	0 .34	10	0 .027	wallpapers of dif. sort, carpet glued to plywood			particleboard	photocopiers
3	decanal, (n-)	0 .01	8	1 .500	linoleum				
3	ethoxyethylacetate, (2-)	1	5	0 .010					
3	octanal, (n-)	0 .01	4	1 .380	linoleum, carpet glued to plywood	mineral wool	alcyd paint		photocopiers
3	hexanol	0 .19	3	0 .135	german cushion vinyl	glass wool			
3	heptanal, (n-)	0 .02	3	0 .044	linoleum, carpet glued to plywood				
3	dichlorobenzene,	0 .3	2	0 .017					deodorants, air

Catg.	Compound	Odour threshold[1] (mg/m³)	No. of buildings	Odour index (OI)	Indoor sources: Floor and wall coverings	Building materials	Paints, adesives, waxes, etc.	Wooden products	Other products
	(1,4-)								fresheners
3	cymene, (p-)	0 .01	1	0 .187					surface cleaners/disinfectants
3	octanol, (1-)	0 .03	1	0 .056			alcyd paint		
4	trichloromethane	58 .88	20	0					
4	dichloromethane	100	20	0					
4	dichloroethene, (1,2-)	77 .62	20	0					
4	trimethylbenzene, (1,2,3-)		20	n/a	finnish cushion vinyl		alcyd paint		
4	bromo-dichloromethane		20	n/a					
4	ethyltoluene		19	n/a					
4	pentane, (n-)	95 .5	18	0	nylon carpet				
4	xylene, (p-)	2 .14	17	0 .005	PVC				
4	methylpentane, (3-)		15	n/a	linoleum				
4	octane, (iso-)		15	n/a	PVC				
4	carene, (3-)		15	n/a	linoleum	gypsum board, expanded polistyrene	alcyd paint		
4	butanone, (2-)	23 .44	14	0 .002	wallpapers of dif. sort, latex-backed carpet		solvent, solvent based paints, spray paints		
4	methylbutane, (2-)		14	n/a	nylon carpet				
4	trichloro-fluoromethane		13	n/a					
4	methylhexane, (3-)		13	n/a	nylon carpet, rubber floor covering, PVC of dif. sort				
4	ethyltoluene, (2-)		13	n/a	rubber floor covering				
4	tetradecane, (n-)		12	n/a	nylon carpet, carpet: 60% polyester 30% nylon 4% polyolefin fibers, cushion vinyl, finnish calendered PVC, Cl-free tiles, vinyl wallpapers	cellulose wool, gypsum boards	plywood		
4	trimethylhexane, (2,2,5-)		12	n/a	PVC of dif. sort			furniture polish	
4	tridecane, (n-)	16 .6	10	0	PVC, german cushion vinyl	cellulose wool	alcyd paint		

Catg.	Compound	Odour threshold[1] (mg/m³)	No. of buildings	Odour index (OI)	Indoor sources: Floor and wall coverings	Building materials	Paints, adesives, waxes, etc.	Wooden products	Other products
4	propylbenzene, (n-)		8	n/a	german cushion vinyl, PVC of dif. sort	expanded polistyrene	alcyd paint, paint water based		photocopier
4	trimethylbenzene		7	n/a	latex-backed carpet, linoleum			wood stain	
4	propylbenzene, (i- & n-)		7	n/a					
4	pentadecane, (n-)		6	n/a	nylon carpet, carpet 60% polyester 30% nylon 4% polyolefin fibers, vinyl flooring, finnish cushion vinyl, Cl-free tiles	cellulose wool			
4	methylmethacrylate	1 .48	6	n/a					
4	butylbenzene, (n-)		6	n/a	german cushion vinyl, PVC of dif. sort		alcyd paint, floor wax		photocopier
4	nitrobenzene	0 .22	5	0 .003					
4	ethylhexanol, (2,1-)	1 .32	5	0 .002	wallpapers of dif. sort, vinyl flooring, cushion vinyl, PVC of dif. sort, vinyl flooring, carpet	glass wool	alcyd paint		computers
4	amylalcohol, (i-)	1 .7	5	0 .001					
4	benzylalcohol		5	n/a					
4	ethyltoluene, (m-)		5	n/a	PVC				
4	hexadecane, (n-)		5	n/a	german cushion vinyl, finnish cushion vinyl, Cl-free tiles	mineral wool, cellulose wool			
4	furfuryl alcohol		5	n/a					
4	heptadecane		3	n/a	carpet 60% polyester 30% nylon 4% polyolefin fibers, vinyl flooring				
4	pentanal, (n- & i-)		3	n/a					
4	pinene, (beta-)		3	n/a			alcyd paint		
4	dioxane, (1,4-)	20 .42	2	0 .001					
4	methyl, (4-)- Pentanone, (2-)	2 .29	2	0 .001			solvent based paints		
4	texanol di-iso-butyrate		2	n/a					
4	octadecane		2	n/a	carpet 60% polyester 30% nylon 4% polyolefin fibers, vinyl flooring, PVC of dif. sort				
4	texanol		2	n/a					

Catg.	Compound	Odour threshold[1] (mg/m³)	No. of buildings	Odour index (OI)	Indoor sources				
					Floor and wall coverings	Building materials	Paints, adesives, waxes, etc.	Wooden products	Other products
4	cyclohexanone	2 .88	2	n/a	wallpapers of dif. sort, PVC of dif. sort, vinyl wallpapers	gypsum boards			
4	dibuthylphtalate, (n-)		2	n/a					
4	diethylbenzene, (m-)		2	n/a			floor wax		
4	dimethylphtalate		2	n/a					
4	nonene, (n-)		2	n/a			floor wax		
4	tetramethylbenzene, (1,2,4,5-)	0 .15	1	0 .01	wallpapers of dif. sort		alcyd paint		
4	decene, (n-)	5 .01	1	0 .008					
4	ethoxyethanol, (2-)	4 .57	1	0 .005	PVC				
4	cumene	0 .12	1	0 .004					
4	cyclohexene	1 .23	1	0 .002					
4	methylstyrene, (alpha-)	0 .76	1	0 .001	rubber floor covering, german cushion vinyl		alcyd paint		photocopier
4	dimethylpentane, (2,4-)	363 .08	1	0	PVC of dif. sort				
4	methyl, (4-)-pentanone, (1-)		1	n/a					
4	epoxy, (2,3-), methylpentane, (4-)		1	n/a					
4	trimethyloctane, (2,5,6-)		1	n/a	PVC				
4	diethylcyclohexane		1	n/a					
4	phenoxy-2-ethanol		1	n/a					
4	trimethyl, (2,4,4-)-pentene, (2-)		1	n/a					
4	methyldecane, (5-)		1	n/a					
4	methylethylbenzene, (o-)		1	n/a	vinyl flooring				
4	pentamethylheptane, (2,2,4,6,6-)		1	n/a	latex-backed carpet, PVC				laser printer
4	ethyltoluene, (4-)		1	n/a					
4	trimethyldecane, (3,3,4-)		1	n/a					

Catg.	Compound	Odour threshold[1] (mg/m³)	No. of buildings	Odour index (OI)	Indoor sources: Floor and wall coverings	Building materials	Paints, adesives, waxes, etc.	Wooden products	Other products
4	dimethylethylbenzene, (2,5-)		1	n/a	PVC of dif. sort				
4	heptene, (1-)		1	n/a	rubber floor covering				surface cleaners/disinfectants
4	methyl-propylbenzene, (o-)		1	n/a	rubber floor covering				
4	methylnonane, (2-)		1	n/a			water based adhesives	wood stain	
4	butoxyethoxyethyl-acetate		1	n/a					
4	dimethyl (2,4-) ethylpentane, (3-)		1	n/a					
4	dimethyl-cyclohexane		1	n/a					
4	phenyl-cyclohexene, (4-)		1	n/a	nylon carpet, latex-backed carpet, carpet rubber backed nylon				
4	methylalkyl-cyclohexane		1	n/a					
4	tetramethyl-benzene, (1,2,3,5-)		1	n/a					
4	diethylphtalate		1	n/a					
4	camphene		1	n/a					
4	terpinene, (alpha-)		1	n/a					
4	undecene, (n-)		1	n/a					
4	terpinene, (gamma-)		1	n/a					
4	ethylmethyl-benzene, (1,2-)		1	n/a	wallpapers of dif. sort, latex-backed carpet		floor wax		
4	methyl, (4-), pentanol, (1-)		1	n/a					

[1] From Devos et al. (1990)

Appendix 2

VOC concentrations and emissions related to building materials measured in the office

Table A-2.1 Concentration of VOCs (µg/m³) according to Tenax TA in the office polluted by building materials plus bioeffluents and in the supplied outdoor air as function of experimental conditions; the values are geometric means ± geometric standard deviation; dl. indicates that the concentration was below detection limits

Name	Low outdoor air supply rate				High outdoor air supply rate			
	Sources present		Sources absent		Sources present		Sources absent	
	Office	Outdoor	Office	Outdoor	Office	Outdoor	Office	Outdoor
1,2-Propanediol	1.33±1.35	dl	1.37±1.13	dl	dl	dl	dl	dl
1-Butanol	4.09±1.04	dl	4.65±1.16	dl	1.65±1.08	dl	1.50±1.20	dl
2-Ethyl-1-hexanol	1.07±1.05	dl	1.02±1.12	dl	0.51±1.24	dl	dl	dl
2-Methyl-1-propanol	2.80±1.11	dl	dl	dl	1.06±1.06	dl	dl	dl
Ethanol	1.31±1.09	dl	dl	dl	dl	dl	dl	dl
2-(2-butoxyethoxy)-ethanol	1.49±1.32	dl	dl	dl	dl	dl	dl	dl
2-(2-butoxyethoxy)-ethanol acetate	0.65±1.04	dl	0.67±1.00	dl	0.44±1.03	dl	dl	dl
2-(2-ethoxyethoxy)-ethanol	dl	dl	dl	dl	0.37±1.02	dl	dl	dl
Phenol	1.61±1.24	0.62±1.26	1.43±1.09	0.59±1.07	1.42±1.22	0.52±1.14	dl	0.85±1.21
2-Butanone	0.75±1.19	dl	dl	dl	dl	dl	dl	dl
2-Propanone (acetone)	4.55±1.13	dl	dl	dl	2.57±1.10	dl	dl	dl
1-Phenyl ethanone	dl	0.86±1.28	0.78±1.29	0.83±1.09	0.58±1.08	0.73±1.18	dl	1.27±1.43
Acetaldehyde	dl	dl	2.31±1.11	dl	dl	dl	dl	dl
Benzaldehyde	1.22±1.12	1.29±1.21	1.39±1.22	1.31±1.09	1.11±1.05	1.04±1.17	1.18±1.13	1.68±1.25
Decanal	2.23±1.35	0.56±1.23	2.49±1.21	0.55±1.17	1.86±1.24	0.53±1.30	2.22±1.11	0.50±1.10
Heptanal	0.76±1.20	dl	dl	dl	dl	dl	dl	dl
Hexanal	1.62±1.43	dl	1.03±1.17	dl	1.03±1.14	dl	dl	dl
Nonanal	3.37±1.32	0.51±1.22	2.94±1.13	0.50±1.14	2.25±1.23	0.52±1.13	2.45±1.22	0.52±1.10
Octanal	1.66±1.42	dl	0.99±1.15	dl	0.77±1.19	dl	dl	dl
Pentanal	1.39±1.06	dl	dl	dl	dl	dl	dl	dl
Benzoic acid	1.34±1.16	0.82±1.36	1.39±1.15	1.11±1.09	1.45±1.30	1.10±1.40	1.55±1.22	1.29±1.35
Butanoic acid	0.57±1.15	dl	dl	dl	dl	dl	dl	dl
Heptanoic acid	0.55±1.07	dl	dl	dl	dl	dl	dl	dl
Hexanoic acid	1.73±1.09	dl	dl	dl	dl	dl	dl	dl
Propanoic acid	0.81±1.24	dl	dl	dl	dl	dl	dl	dl
1-Ethyl-2-methyl benzene	0.52±1.25	dl	dl	0.43±1.12	dl	dl	dl	dl
Ethyl benzene	0.66±1.11	dl	0.87±1.22	dl	dl	dl	dl	0.63±1.23
Methyl benzene (toluene)	1.94±1.14	1.48±1.19	2.74±1.12	2.03±1.21	1.46±1.11	1.52±1.21	1.84±1.25	1.81±1.28
Octamethyl cyclotetrasiloxane	1.05±1.13	dl	dl	dl	dl	dl	dl	dl
Hexamethyl cyclotrisiloxane,	1.14±1.11	dl	dl	dl	dl	dl	dl	dl
Xylene	1.66±1.26	dl	1.74±1.09	dl	dl	dl	dl	dl
Decane	dl	dl	1.17±1.38	dl	dl	dl	dl	dl
Dodecane	0.42±1.06	dl	dl	dl	dl	dl	dl	dl
Heptadecane	0.64±1.05	dl	dl	dl	0.64±1.14	dl	dl	dl
Heptane	0.79±1.07	0.40±1.10	dl	0.47±1.14	1.03±2.05	dl	dl	dl
Hexadecane	0.69±1.03	dl	0.60±1.22	dl	0.47±1.06	dl	dl	dl
Nonane	0.99±1.26	dl	1.41±1.12	dl	1.00±1.13	0.44±1.17	1.16±1.42	dl
Octane	1.59±1.10	dl	1.33±1.14	dl	1.21±1.19	0.70±1.32	0.90±1.35	dl
Pentadecane	0.60±1.02	dl	0.70±1.43	dl	dl	dl	dl	dl
Tetradecane	0.48±1.02	dl	0.87±1.56	dl	dl	dl	dl	dl
Undecane	dl	dl	0.62±1.35	dl	dl	dl	dl	dl
1,2-Pentadiene	1.84±1.50	dl	dl	dl	dl	dl	dl	dl
Diethyl phthalate	0.41±1.14	dl	dl	dl	dl	dl	dl	dl
α-Pinene	1.16±1.14	dl	dl	dl	dl	dl	dl	dl

Table A-2.2 Concentration of VOCs (µg/m³) according to Tenax GR in the office polluted by building materials plus bioeffluents and in the supplied outdoor air as function of experimental conditions; the values are geometric means ± geometric standard deviation; dl. indicates that the concentration was below detection limits

Name	Low outdoor air supply rate				High outdoor air supply rate			
	Sources present		Sources absent		Sources present		Sources absent	
	Office	Outdoor	Office	Outdoor	Office	Outdoor	Office	Outdoor
Ethanol	1.43±1.07	dl	dl	dl	dl	dl	dl	dl
1,2-Propanediol	0.95±1.57	dl	dl	dl	dl	dl	dl	dl
1-Propanol, 2-methyl-	2.74±1.11	dl	dl	dl	0.91±1.06	dl	dl	dl
1-Butanol	3.87±1.17	dl	3.45±1.06	dl	1.23±1.31	dl	1.68±1.05	dl
1-Hexanol, 2-ethyl-	1.10±1.08	dl	dl	dl	0.62±1.48	dl	dl	dl
2-Propanone (acetone)	4.81±1.12	dl	1.98±1.22	dl	dl	dl	1.82±1.22	dl
2-Butanone	0.43±1.28	dl	dl	dl	dl	dl	dl	dl
Acetaldehyde	dl	dl	dl	1.18±1.73	1.83±1.63	0.59±1.17	1.44±1.23	4.37±4.07
Butanal	0.54±1.26	dl	dl	dl	dl	dl	dl	dl
Pentanal	1.35±1.06	dl	0.72±1.14	dl	dl	dl	dl	dl
Hexanal	2.87±1.10	dl	1.27±1.18	dl	1.35±1.13	dl	dl	dl
Heptanal	0.79±1.29	dl	dl	dl	0.53±1.36	dl	dl	dl
Octanal	1.24±1.48	dl	0.69±1.35	dl	0.85±1.10	dl	1.01±1.20	dl
Nonanal	4.04±1.23	dl	2.76±1.15	0.88±1.60	1.97±1.16	1.10±1.35	1.86±1.07	dl
Decanal	2.60±1.31	dl	1.61±1.37	0.71±1.17	1.42±1.20	0.65±1.05	1.50±1.02	dl
Acetic acid	1.92±1.57	dl	0.63±1.22	dl	1.39±1.84	dl	dl	dl
Propanoic acid	1.07±1.37	dl	dl	dl	dl	dl	dl	dl
Ethanol, 2-butoxy	dl	dl	0.54±1.05	dl	0.39±1.07	dl	dl	dl
Ethanol, 2-phenoxy-	0.65±1.94	dl	dl	dl	dl	dl	dl	dl
Ethanol, 2-(2-butoxyethoxy)-	1.27±1.45	dl	dl	dl	dl	dl	dl	dl
Ethanol, 2-(2-butoxyethoxy)-, acetate	0.70±1.07	dl	0.47±1.15	dl	0.40±1.02	dl	dl	dl
Acetic acid, butyl ester	0.46±1.20	dl	dl	dl	dl	dl	dl	dl
6-Methyl-5-heptene-2-one	1.03±1.31	dl	1.05±1.13	dl	dl	dl	dl	dl
1-Phenyl ethanone (acetylbenzene)	dl	0.45±1.13	dl	0.32±1.09	0.64±1.36	0.39±1.18	dl	dl
Phenol	1.66±1.21	dl	dl	0.57±1.39	0.90±1.29	0.50±1.17	0.88±1.11	dl
Benzaldehyde	1.25±1.16	0.52±1.20	0.88±1.25	0.80±1.35	1.20±1.40	0.86±1.24	0.99±1.21	0.72±1.17
Benzoic acid	1.55±1.16	0.68±1.32	1.33±1.30	0.94±1.48	3.12±1.68	1.54±1.34	1.33±1.26	1.02±1.13
Heptane	0.75±1.04	0.36±1.15	dl	dl	dl	dl	dl	dl
Octane	dl	dl	dl	dl	0.73±1.55	dl	dl	dl
Undecane	0.51±1.05	dl	0.41±1.06	dl	0.28±1.03	dl	dl	dl
Dodecane	0.45±1.05	dl	dl	dl	dl	dl	dl	dl
Tridecane	0.36±1.03	dl	dl	dl	dl	dl	dl	dl
Tetradecane	0.51±1.01	dl	dl	dl	0.36±1.15	dl	dl	dl
Pentadecane	0.65±1.02	dl	dl	dl	0.36±1.09	dl	dl	dl
Hexadecane	dl	dl	dl	dl	0.53±1.10	dl	dl	dl
Heptadecane	dl	dl	0.33±1.14	dl	0.54±1.11	dl	dl	dl
1,2-Pentadiene	dl	dl	0.86±1.43	dl	dl	dl	dl	dl
Benzene	dl	0.64±1.09	dl	0.79±1.22	dl	0.72±1.28	2.17±1.18	0.64±1.17
Methyl benzene (toluene)	2.59±1.21	1.41±1.25	2.63±1.12	1.71±1.22	1.62±1.09	1.16±1.07	1.65±1.05	1.32±1.21
Ethyl benzene	0.67±1.25	0.38±1.24	0.59±1.07	0.37±1.28	0.37±1.08	0.32±1.15	0.78±1.45	dl
Benzene, 1,4-dimethyl-	1.23±1.22	dl	dl	dl	dl	dl	dl	dl
Benzene, 1,3,5-trimethyl-	0.88±1.52	dl	dl	dl	dl	dl	dl	dl
Benzene, 1-ethyl-2-methyl-	0.76±1.33	dl	dl	dl	dl	0.36±1.19	dl	dl
Benzene, 1-methyl-4-(1-methylethyl)-	0.42±1.06	dl	dl	dl	dl	dl	dl	dl
Xylenes	dl	dl	1.53±1.25	0.90±1.07	1.18±1.07	dl	dl	0.71±1.04

Name	Low outdoor air supply rate				High outdoor air supply rate			
	Sources present		Sources absent		Sources present		Sources absent	
	Office	Outdoor	Office	Outdoor	Office	Outdoor	Office	Outdoor
dl-Limonene	0.61±1.08	dl	dl	dl	dl	dl	dl	dl
δ 3-carene	0.59±1.33	dl	dl	dl	dl	dl	dl	dl
Cyclotrisiloxane, hexamethyl-	dl	dl	dl	dl	0.66±1.61	4.19±1.46	dl	dl
Octamethylcyclotetrasiloxane	1.03±1.31	dl	dl	dl	0.61±1.29	dl	dl	dl

Table A-2.2 Odour indices of VOCs in the office polluted by building materials plus bioeffluents as function of the experimental conditions created, and according to the type of sampling tube (Tenax TA/Tenax GR); the odour threshold of compounds are obtained from compilation of Devos et al. (1990);

Name	Odour threshold (μg/m³)	Low outdoor air supply rate				High outdoor air supply rate			
		Sources present		Sources absent		Sources present		Sources absent	
		Tenax TA	Tenax GR	Tenax TA	Tenax GR	Tenax TA	Tenax GR	Tenax TA	Tenax GR
Ethanol	54954	2.38E-05	2.59E-05						
1,2-Propanediol	n/a								
1-Propanol, 2-methyl-	2570	1.09E-03	1.07E-03			4.13E-04	3.54E-04		
1-Butanol	1514	2.70E-03	2.56E-03	3.07E-03	2.28E-03	1.09E-03	8.15E-04	9.89E-04	1.11E-03
1-Hexanol, 2-ethyl-	1318	8.11E-04	8.32E-04	7.77E-04		3.88E-04	4.67E-04		
2-Propanone (acetone)	34674	1.31E-04	1.39E-04		5.71E-05	7.41E-05			5.26E-05
2-Butanone	23442	3.22E-05	1.85E-05						
Acetaldehyde	339			6.82E-03			5.41E-03		4.26E-03
Butanal	28		1.96E-02						
Pentanal	22	6.37E-02	6.17E-02		3.29E-02				
Hexanal	58	2.81E-02	4.99E-02	1.78E-02	2.20E-02	1.79E-02	2.35E-02		
Heptanal	23	3.32E-02	3.44E-02				2.31E-02		
Octanal	7	2.29E-01	1.72E-01	1.37E-01	9.53E-02	1.06E-01	1.17E-01		1.40E-01
Nonanal	13	2.50E-01	3.00E-01	2.18E-01	2.05E-01	1.66E-01	1.46E-01	1.82E-01	1.38E-01
Decanal	6	3.79E-01	4.42E-01	4.23E-01	2.74E-01	3.16E-01	2.42E-01	3.76E-01	2.55E-01
Acetic acid	363		5.30E-03		1.74E-03		3.84E-03		
Propanoic acid	110	7.43E-03	9.72E-03						
Butanoicacid	14	3.94E-02							
Hexanoicacid	60	2.87E-02							
Heptanoicacid	148	3.72E-03							
Ethanol, 2-butoxy	1660				3.25E-04		2.34E-04		
Ethanol, 2-phenoxy-	n/a								
Ethanol, 2-(2-ethoxyethoxy)-	3981					9.37E-05			
Ethanol, 2-(2-butoxyethoxy)-	9	1.62E-01	1.38E-01						
Ethanol, 2-(2-butoxyethoxy)-, acetate	n/a								
Acetic acid, butyl ester	933		4.90E-04						
6-Methyl-5-heptene-2-one	204		5.05E-03		5.15E-03				
1-Phenyl ethanone (acetylbenzene)	1820			4.29E-04		3.20E-04	3.50E-04		
Phenol	427	3.78E-03	3.90E-03	3.36E-03		3.34E-03	2.11E-03		2.06E-03
Benzaldehyde	186	6.54E-03	6.71E-03	7.48E-03	4.72E-03	5.95E-03	6.43E-03	6.34E-03	5.34E-03
Benzoic acid	n/a								
Diethyl phthalate	n/a								
Heptane	40738	1.94E-05	1.84E-05			2.52E-05			
Octane	27542	5.79E-05		4.83E-05		4.40E-05	2.65E-05	3.26E-05	
Nonane	6761	1.46E-04		2.09E-04		1.47E-04		1.72E-04	
Decane	4365			2.68E-04					
Undecane	7762		6.52E-05	8.03E-05	5.31E-05		3.55E-05		
Dodecane	14454	2.89E-05	3.13E-05						
Tridecane	16596		2.19E-05						
Tetradecane	n/a								
Pentadecane	n/a								
Hexadecane	n/a								
Heptadecane	n/a								
1,2-Pentadiene	n/a								
Benzene	12023								1.81E-04
Methyl benzene (toluene)	5888	3.29E-04	4.40E-04	4.65E-04	4.47E-04	2.47E-04	2.76E-04	3.12E-04	2.80E-04

Name	Odour threshold (µg/m³)	Low outdoor air supply rate				High outdoor air supply rate			
		Sources present		Sources absent		Sources present		Sources absent	
		Tenax TA	Tenax GR	Tenax TA	Tenax GR	Tenax TA	Tenax GR	Tenax TA	Tenax GR
Ethyl benzene	13	5.12E-02	5.20E-02	6.79E-02	4.57E-02		2.90E-02		6.02E-02
Benzene, 1,4-dimethyl-	2138		5.74E-04						
Benzene, 1,3,5-trimethyl-	1148		7.70E-04						
Benzene, 1-ethyl-2-methyl-	n/a								
Benzene, 1-methyl-4-(1-methylethyl)-	12		3.46E-02						
Xylenes	1413	1.18E-03		1.23E-03	1.08E-03		8.38E-04		
a-Pinene	3890	2.99E-04							
dl-Limonene	2455		2.47E-04						
δ 3-carene	n/a								
Cyclotrisiloxane, hexamethyl-	n/a								
Octamethylcyclotetrasiloxane	n/a								

Table A-2.3 Emission rates of VOCs ($\mu g/h$) in the office polluted by building materials plus bioeffluents as function of experimental conditions and type of sampling media (Tenax TA/Tenax GR)

Name	Low outdoor air supply rate				High outdoor air supply rate			
	Sources present		Sources absent		Sources present		Sources absent	
	Tenax TA	Tenax GR	Tenax TA	Tenax GR	Tenax TA	Tenax GR	Tenax TA	Tenax GR
Ethanol	101	115						
1,2-Propanediol	103	66	107					
1-Propanol, 2-methyl-	254	249			240	194		
1-Butanol	386	366	439	318	433	299	351	406
1-Hexanol, 2-ethyl-	76	81	72		61	98		
2-Propanone (acetone)	434	461		169	732			451
2-Butanone	44	13						
Acetaldehyde			202			407		
Butanal		24						
Pentanal	110	107		41				
Hexanal	133	263	72	97	230	338		
Heptanal	45	49				70		
Octanal	137	96	68	39	145	174		189
Nonanal	293	383	248	191	562	283	623	462
Decanal	172	235	197	92	436	251	553	348
Acetic acid		166		33		351		
Propanoic acid	50	78						
Butanoicacid	25							
Hexanoicacid	144							
Heptanoicacid	23							
Ethanol, 2-butoxy				23		23		
Ethanol, 2-phenoxy-		35						
Ethanol, 2-(2-ethoxyethoxy)-					16			
Ethanol, 2-(2-butoxyethoxy)-	120	99						
Ethanol, 2-(2-butoxyethoxy)-, acetate	33	40	35	16	36	27		
Acetic acid, butyl ester		15						
6-Methyl-5-heptene-2-one		74		75				
1-Phenyl ethanone (acetylbenzene)						80		
Phenol	101	139	86		294	130		146
Benzaldehyde		75	8	8	23	108		90
Benzoic acid	53	89	28	40	114	514	83	101
Diethyl phthalate	9							
Heptane	40	40			229			
Octane	130		103		166	135	158	
Nonane	68		111		182		243	
Decane			86					
Undecane		20	31	10				
Dodecane	10	15						
Tridecane		6						
Tetradecane	16	21	55			14		
Pentadecane	28	35	38			15		
Hexadecane	37		29		47	69		
Heptadecane	32			2	104	73		
1,2-Pentadiene	155			56				
Benzene								496
Methyl benzene (toluene)	47	121	72	93		151	9	107

Name	Low outdoor air supply rate				High outdoor air supply rate			
	Sources present		Sources absent		Sources present		Sources absent	
	Tenax TA	Tenax GR	Tenax TA	Tenax GR	Tenax TA	Tenax GR	Tenax TA	Tenax GR
Ethyl benzene	34	29	56	23		18		113
Benzene, 1,4-dimethyl-		94						
Benzene, 1,3,5-trimethyl-		59						
Benzene, 1-ethyl-2-methyl-	20	46						
Benzene, 1-methyl-4-(1-methylethyl)-		11						
Xylenes	137		144	64		283		
a-Pinene	86							
dl-Limonene		31						
δ 3-carene		29						
Cyclotrisiloxane, hexamethyl-	83							
Octamethylcyclotetrasiloxane	74	75				96		

Appendix 3

Randomisation of the exposure conditions in the office and presentation of the performance tasks

Table A-3.1 Randomisation of the exposures with/without pollution sources, consisting of common building materials, in the offices for order of presentation among 5 groups including 6 subjects each.

Groups (6 people)	Day of a week	Week 1	Week 2	Week 3	Week 4
Group 1	Monday	II	I	IV	III
Group 2	Tuesday	III	IV	I	II
Group 3	Wednesday	IV	I	II	III
Group 4	Thursday	I	II	III	IV
Group 5	Friday	II	III	IV	I

Conditions:

I. office without pollution sources (pollution load low), low ventilation rate (1 h^{-1})

II. office with pollution sources (pollution load low), low ventilation rate (1 h^{-1})

III. office without pollution sources (pollution load low), high ventilation rate (3 h^{-1})

IV. office with pollution sources (pollution load low), high ventilation rate (3 h^{-1})

Table A-3.2 Randomisation of different versions of the performance tasks (multiplication, addition and text-typing) for order of presentation; each version (V1-V4) had similar difficulty level and length that was impossible to finish within one exposure condition

Subjects					Conditions			
Gr. 1	Gr. 2	Gr. 3	Gr. 4	Gr. 5	I	II	III	IV
1	7	13	19	25	V 1	V 2	V 3	V 4
2	8	14	20	26	V 2	V 3	V 4	V 1
3	9	15	21	27	V 3	V 4	V 1	V 2
4	10	16	22	28	V 4	V 1	V 2	V 3
5	11	17	23	29	V 1	V 4	V 3	V 2
6	12	18	24	30	V 3	V 2	V 1	V 4

Table A-3.3 Randomisation of the exposure conditions with/without PCs in the office for order of presentation among 5 groups including 6 subjects each.

Groups (6 people)	Day of a week	Week 1	Week 2
Group 1	Monday	without PCs	with PCs
Group 2	Tuesday	with PCs	without PCs
Group 3	Wednesday	without PCs	with PCs
Group 4	Thursday	with PCs	without PCs
Group 5	Friday	without PCs	with PCs

Table A-3.4 Randomisation of different versions (V1-V4) of performance tasks for order of presentation to the subjects during occupation in the office with PCs present or absent.

Group	Subject	Multiplication		Addition		Proof reading				Text typing			
		without PCs	with PCs	without PCs	with PCs	without PCs		with PCs		without PCs		with PCs	
						Part I.	Part II	Part I.	Part II	Part I.	Part II	Part I.	Part II
1	1	V1	V2	V2	V1	V1	V2	V3	V4	V4	V3	V2	V1
	2	V2	V1	V1	V2	V2	V3	V4	V1	V3	V2	V1	V4
	3	V1	V2	V2	V1	V3	V4	V1	V2	V2	V1	V4	V3
	4	V2	V1	V1	V2	V4	V1	V2	V3	V1	V4	V3	V2
	5	V1	V2	V2	V1	V1	V2	V3	V4	V4	V3	V2	V1
	6	V2	V1	V1	V2	V2	V3	V4	V1	V3	V2	V1	V4
2	7	V1	V2	V2	V1	V3	V4	V1	V2	V2	V1	V4	V3
	8	V2	V1	V1	V2	V4	V1	V2	V3	V1	V4	V3	V2
	9	V1	V2	V2	V1	V1	V2	V3	V4	V4	V3	V2	V1
	10	V2	V1	V1	V2	V2	V3	V4	V1	V3	V2	V1	V4
	11	V1	V2	V2	V1	V3	V4	V1	V2	V2	V1	V4	V3
	12	V2	V1	V1	V2	V4	V1	V2	V3	V1	V4	V3	V2
3	13	V1	V2	V2	V1	V1	V2	V3	V4	V4	V3	V2	V1
	14	V2	V1	V1	V2	V2	V3	V4	V1	V3	V2	V1	V4
	15	V1	V2	V2	V1	V3	V4	V1	V2	V2	V1	V4	V3
	16	V2	V1	V1	V2	V4	V1	V2	V3	V1	V4	V3	V2
	17	V1	V2	V2	V1	V1	V2	V3	V4	V4	V3	V2	V1
	18	V2	V1	V1	V2	V2	V3	V4	V1	V3	V2	V1	V4
4	19	V1	V2	V2	V1	V3	V4	V1	V2	V2	V1	V4	V3
	20	V2	V1	V1	V2	V4	V1	V2	V3	V1	V4	V3	V2
	21	V1	V2	V2	V1	V1	V2	V3	V4	V4	V3	V2	V1
	22	V2	V1	V1	V2	V2	V3	V4	V1	V3	V2	V1	V4
	23	V1	V2	V2	V1	V3	V4	V1	V2	V2	V1	V4	V3
	24	V2	V1	V1	V2	V4	V1	V2	V3	V1	V4	V3	V2
5	25	V1	V2	V2	V1	V1	V2	V3	V4	V4	V3	V2	V1
	26	V2	V1	V1	V2	V2	V3	V4	V1	V3	V2	V1	V4
	27	V1	V2	V2	V1	V3	V4	V1	V2	V2	V1	V4	V3
	28	V2	V1	V1	V2	V4	V1	V2	V3	V1	V4	V3	V2
	29	V1	V2	V2	V1	V1	V2	V3	V4	V4	V3	V2	V1
	30	V2	V1	V1	V2	V2	V3	V4	V1	V3	V2	V1	V4

Appendix 4

Abstracts of papers published by the author about the effects of pollution from building materials and PCs on PAQ, SBS symptoms and productivity

Bakó-Biró, Zs., Wargocki, P., Clausen, G., and Fanger, P.O. (2001) "The use of low-polluting materials on indoor air quality and ventilation requirements", Magyar Épületgépészet (Hungarian Building Services), **L**(12), 3-7.

Abstract:

Air quality and annual energy consumption were studied in an office space classified as low-polluting and ventilated with 1 h^{-1}, the pollution load in the office being increased by introducing common pollution sources and the ventilation rate being altered to 3 h. The concentration of volatile organic compounds, the percentage of persons dissatisfied with the air quality, and the annual energy use were lower in an office classified as low-polluting. Present results confirm that pollution source control is an effective means of improving air quality and reducing energy use in offices.

Wargocki, P., Bakó-Biró, Z., Clausen, G., Fanger, P.O. (2001) "The effect of using low-polluting materials on air quality and energy consumption in an office", In: *Proceedings of Clima 2000,* The 7th REHVA World Congress, Napoli, on CD-ROM.

Abstract:

Air quality and annual energy consumption were studied in an office space classified as low-polluting and ventilated with outdoor air at a rate of 1 h^{-1}. The pollution load in the space was changed by introducing or removing common pollution sources so that the space could no longer be classified as low-polluting. The ventilation rate in the office was altered from 1 to 3 h^{-1} when sources were both present and absent. An air temperature of 23°C, a relative humidity of 50% and noise level of 35dB(A) remained unchanged. Chemical measurements showed that removing the sources or increasing the ventilation decreased the total concentration of volatile organic compounds (TVOC). Perceived air quality assessed by a panel of 30 female subjects improved when the sources were removed or when ventilation increased in the office. Simulations showed that the impact of increased ventilation on the annual energy use would be less than 20%. Present results confirm that pollution source control is an effective means of improving air quality and reducing energy use in offices.

Wargocki, P., Bakó-Biró, Zs., Clausen, G. and Fanger, P.O. (2002) "Air quality in a simulated office environment as a result of reducing pollution sources and increasing ventilation", Energy and Buildings, **34**(8), 775-783.

Abstract:

Air quality was studied in an office space classified as low-polluting and ventilated with outdoor air at a rate of 1 h^{-1}. The pollution load in the space was changed by introducing or removing common building-related indoor pollution sources (linoleum, sealant and wooden shelves with books and paper documents) so that the space could no longer be classified as low-polluting. The outdoor air supply rate in the office was altered from 1 to 3 h^{-1} (0.83 and 2.5 L/s per m^2 floor, respectively) when sources were present and absent. Air temperature of 23°C, relative humidity of 50% and noise level of 35dB(A) remained unchanged. Under each of the four conditions of air quality in the office, concentrations of volatile organic compounds (VOCs) were measured and perceived air quality was assessed by a panel of 30 female subjects. Removing the sources reduced the chemical and sensory pollution load in the office, and increasing the outdoor air supply rate decreased concentrations of many

VOCs, including those emitted by building materials and furnishing, and human bioeffluents. The perceived air quality in the office was consequently improved. The improvement in air quality obtained by removing the sources was similar to that obtained by increasing the outdoor air supply rate. The study, thus, confirmed that the systematic use of low-polluting building materials will lead to improved air quality.

Bakó-Biró, Zs., Wargocki, P., Weschler, C.J. and Fanger, P.O. (2002) "Personal computers pollute indoor air: effects on perceived air quality, SBS symptoms and productivity in offices", In: *Proceedings of Indoor Air 2002*, Monterey, The 9th International Conference on Indoor Air Quality and Climate, Vol. **2**, pp 249-254.

<u>Abstract:</u>

Perceived air quality and Sick Building Syndrome (SBS) symptoms were studied in a low-polluting office space ventilated at an air change rate of $2h^{-1}$ (10 L/s per person with 6 people present) with and without personal computers (PCs). Other environmental parameters were kept constant. Thirty female subjects were exposed for 4.8 h to each of the two conditions in the office and performed simulated office work. They remained thermally neutral by adjusting their clothing and were blind to the interventions. In the absence of PCs in the office the perceived air quality improved, odour intensity was reduced and air freshness increased; all effects were significant. In the presence of PCs the performance of text typing significantly decreased. The sensory pollution load of the PCs was found to be 3 olf per PC, i.e. three times the load of the occupants. Present results indicate negative effects of PCs on human comfort and performance.

Bakó-Biró, Z., Wargocki, P., Weschler, C.J. and Fanger, P.O. (2004) "Effects of pollution from personal computers on perceived air quality, SBS symptoms and productivity in offices", Indoor Air, **14**(3), 178-187.

<u>Abstract:</u>

In groups of six, thirty female subjects were exposed for 4.8 h in a low-polluting office to each of two conditions -- the presence or absence of three-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 SBS symptoms. The PCs were found to be strong indoor pollution sources, even after they had been in service for three 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.