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Human Perception, Productivity and Symptoms Related to Indoor Air Quality

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Pawel Wargocki

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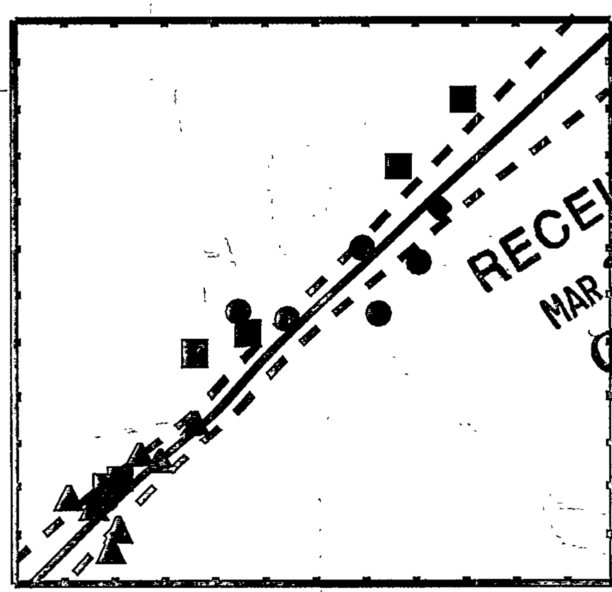

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by

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Centre for Indoor Environment and Energy
Department of Energy Engineering
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Centre for Indoor Environment and Energy
Department of Energy Engineering
Technical University of Denmark
Building 402, 2800 Lyngby
Denmark

Table of Contents

Preface

The research work presented in this Ph.D. thesis has been carried out at the Centre for Indoor Environment and Energy (previously Laboratory of Indoor Environment and Energy), Department of Energy Engineering, Technical University of Denmark in Lyngby from February 1995 to August 1998. Supervisors during my Ph.D. study have been Professor P. Ole Fanger, D.Sc. (principal supervisor) and Associate Professor Geo Clausen, Ph.D. from the Centre for Indoor Environment and Energy, Department of Energy Engineering, Technical University of Denmark.

I express my sincere gratitude to Professor P. Ole Fanger who invited me to stay in his laboratory in 1993 and extended my 4-month scholarship into a 5-year research adventure. This invitation has advanced into hundreds of hours of exciting experiments, data analysis, discussions, planning of new studies, etc. All these activities have ultimately brought about the submission of the present Ph.D. thesis. I want to thank Professor P. Ole Fanger for his valuable advice and suggestions, his inexhaustible store of "fresh" ideas, his enthusiasm and his pragmatic view of the results.

I thank most warmly Geo Clausen for valuable advice and for conveying to me the important aspects of becoming a good researcher, namely scrutiny and constructive criticism.

I appreciate very much the invaluable assistance of Fang Lei who, together with Arsen Melikov, invented and built the dilution system, a part of the VOC-generation system. Thanks to his technical skills and thorough investigation of the technical problems that arose, the instrumentation was ready on time, prior to the commencement of the experiments. Fang Lei also helped me during the preliminary stages of the literature review of measurements of VOCs.

I am most grateful to Dr. Lars Mølhave from the Institute of Environmental and Occupational Medicine at Aarhus University, who invented the principle of the VOC-generator and shared with me his expertise on VOC-mixtures and the ethics of experiments with human subjects.

Thanks are also due to Dr. David Wyon of Johnson Controls and of the Centre for Indoor Environment and Energy for devising the creative thinking task used in the study on the impact of emissions from a carpet on humans. I greatly appreciate the advice he gave on productivity issues and his review and detailed comments on Chapter 4.

I would like to thank Dr. Yong Kyu Baik, a visiting post-doctoral research fellow from the Department of Architecture, Seoil Junior College in Seoul, for assistance during the planning and performance of experiments on the effects of carpet emissions on humans and for transfer of data from questionnaires to computer.

Special thanks are due to Ms. Judith Ørting who has carefully edited the text of this thesis.

I address my further acknowledgements to the research staff, the staff in the workshops and students at the Centre for Indoor Environment and Energy, whose assistance and fruitful comments contributed to the final accomplishment of this research project. I thank: Till Blume for help during the field study on addition of sensory pollution sources; Jan Pejtersen and Claus Reichel for co-operation during the laboratory study on addition of sensory pollution sources; Mads Jørgensen, Marie Falk Nyboe and Liv Vestergaard for teamwork during experiments on the human sensory response to air polluted by single VOCs; Thomas Witterseh for help with all translations into Danish and who, together with Ole Alm and Wanja Andersen, retyped texts used by subjects during experiments of carpet emissions; Ole Alm also for help with the analysis of the creative thinking task; Jørn Toftum who was always eager to discuss statistical problems; Siroos Gholami for discussions on different matters; Arne Stegemann for skilful help with graphic designs of my presentations and posters, and for designing the cover of this thesis; Gunnar Langkilde for help with administrative issues; Benny Nielsen for technical advice; and Andreas Szekacs for solving unexpected problems with my PC. I thank Henrik Knudsen of the Danish Building Research Institute for many hours of discussions on modelling

Finally, I want to thank my dear parents and friends for their support and concern.

This work has been supported by the Danish Technical Research Council (STVF) both as part of the research programme "Healthy Buildings" in 1993-1997 and as part of the research programme of the Centre for Indoor Environment and Energy established at the Technical University of Denmark for the period 1998-2007. I acknowledge also support from the European Commission through the Joule II research programme (CEC-DGXII) "European Data Base on Indoor Air Pollution Sources in Buildings" (1994-1996) and from Rockwool International, Inc. A Ph.D. scholarship has been awarded by the Technical University of Denmark.

The present thesis reflects my research interests and I hope it can be useful for anyone trying to deal with complex indoor climate problems.

Lyngby, August 31, 1998

Pawel Wargocki

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Summary

The title of the present thesis is: "Human perception, productivity and symptoms related to indoor air quality".

In **Chapter 1**, entitled *"Introduction"*, three objectives of the present study are formulated: (1) to investigate whether total sensory pollution load on the air in spaces can be estimated by adding sensory pollution loads from the individual pollution sources; (2) to develop alternative reference exposures which can be used to calibrate sensory evaluations of the air quality indoors made by trained subjects; and (3) to investigate whether decreasing the pollution loads on the air indoors is an effective measure for improving the perceived air quality, reducing the prevalence of health symptoms and increasing people's productivity.

In **Chapter 2**, entitled *"Addition of sensory pollution sources for the calculation of required ventilation rates"*, four previous laboratory studies on the addition of sensory pollution sources are reviewed. The results revealed that limited data exist on the addition of families of sensory pollution sources, i.e., building materials, people and tobacco smoke (research was mainly performed on building materials), and that no field study on addition has been carried out previously. Consequently, laboratory and field experiments on the addition of families of sensory pollution sources were undertaken.

In the laboratory experiments, a panel of 43 untrained subjects assessed the quality of air sequentially in empty climate chambers, in chambers with three types of floor material placed one at a time inside the chambers, in chambers occupied by people, and in chambers that were occupied by people and in which at the same time three types of floor material were placed, one at a time, inside the chamber. A panel

assessed also outdoor air. The empty chambers were polluted by the HVAC system supplying the air. Floor materials comprised old carpet, new linoleum and new vinyl, each sample being 73 m^2 to provide a loading similar to a standard room (lxwxh=3.2x2.2x2.4 m) ventilated with 1 h^{-1}. People occupied the chambers in 4 groups of 5 persons each. The outdoor air was supplied to the chambers at a constant rate of 35 L/s by the HVAC system and conditioned to 23°C and 40% rh. Sensory evaluations were made on the air extracted from the chambers and from outdoors, using a continuous acceptability scale.

Field experiments were carried out in an existing office (lxwxh=6x4.3x3 m) which was ventilated with an air change rate of 0.4, 1 and 2 h^{-1} by a fan mounted in the window. At each ventilation rate, the air in the office was polluted sequentially by the building (building materials and furnishings in a space), by the building plus people, by the building plus tobacco smoke, and by the building plus people plus tobacco smoke. People occupied the office in groups comprising from 3 to 12 persons. Tobacco smoke was generated by lighting a cigarette at a predefined rate (from 0.3 to 1.1 cigarette per hour) and placing it in an ash-tray to produce side-stream smoke. A sensory panel of 43 untrained subjects assessed the air quality in the office under each of the above-mentioned conditions, as well as outdoors. Sensory evaluations, using a continuous acceptability scale, were made on the air extracted from the office and from outdoors and conditioned to 20°C. Carbon dioxide (CO_2) and carbon monoxide (CO) concentrations were measured and used to predict the sensory pollution loads caused by the occupants and tobacco smoking, respectively, adopting recent experimental data reported in the literature.

The measured total sensory pollution loads in the chambers and in the office were compared with the sensory pollution loads predicted by adding the loads of individual sources. Linear regression was used to model the experimental data. Results showed that the total sensory pollution load in a space can be reasonably well (r^2=0.91, $p<0.0001$) approximated by adding sensory pollution loads on the air caused by individual pollution sources such as the building, people and tobacco smoke. This implies that ventilation rates required to provide a certain prescribed air quality can therefore be found by adding the ventilation rates required to handle the building, the people and their tobacco smoking. Further full-scale studies on the addition of a wider range of sensory pollution sources are suggested at moderate pollution levels, causing less than 30% dissatisfied with the air quality. It is also proposed to continue studying the addition of sensory pollution loads caused by common building materials in the laboratory, but with better control of the sorption processes, comparing with investigations performed previously.

In **Chapter 3**, entitled *"Reference atmospheres for human sensory assessments of the perceived air quality"*, an account is given of a review of the measurements of volatile organic compounds (VOCs) in indoor non-industrial environments. The purpose of the review was to provide a basis for the selection of VOCs to be included in the reference atmospheres used as the perception reference exposures for humans during sensory evaluations of air quality in office buildings. A literature review was made by surveying international journals and proceedings of major international conferences since 1978 up to mid 1993, and was supplemented by a large investigation from 1995. Twenty-two studies reporting 742 measurements in 582 offices in 209 different buildings that were at least one year old were thoroughly reviewed. The results showed 133 VOCs with measured concentrations indoors, among which toluene was the most prevalent. Ethanol was the compound having the highest mean weighted (MW) concentration (the number of measurements was a weighting factor). Only three VOCs (n-decanal, n-octanal and ethylbenzene) had MW concentrations indoors exceeding their odour threshold. The bulk of VOCs had MW concentrations over 100 times lower than their odour thresholds. None of the VOCs were at MW concentrations higher than their known irritation thresholds.

Eight single VOCs were selected for the sensory tests: n-butanol, n-decane, ethylbenzene, n-hexane, 2-propanone, toluene, 1,2,4-trimethylbenzene and m-xylene. They all met the criteria for inclusion in the reference atmosphere: they occurred frequently indoors, they had the highest measured MW concentrations indoors, they had the highest sensory impact on humans at MW concentrations measured in indoor climates, and they were all ethically acceptable compounds, i.e., harmless to people and to the environment at the concentrations intended for human exposures. Three mixtures of VOCs were also selected for sensory evaluations: the mixture of 22 VOCs that was used previously as an exposure during experiments investigating the effects of indoor air pollutants on humans, and the mixtures of 8 and 19 VOCs being its daughters.

Untrained panels (total >200 subjects) and the panels of people trained to assess the air quality, comparing to a well defined reference of 2-propanone (total >50 subjects) assessed the quality of air polluted separately by the selected single VOCs and the mixtures of VOCs. The air pollution was generated by means of the specially built apparatus. Sensory assessments were used to develop the perception models, correlating the acceptability of air evaluated by untrained subjects with the logarithm of the VOC concentration (r^2=0.77-0.98), and the perceived air quality in decipol, assessed by trained panels with the VOC concentration using a power function (r^2=0.79-0.99). The perception models that were created using the assessments made by untrained subjects can be used to train people to assess the perceived air quality directly in decipol. Sensory ratings of the odour intensity revealed the possible combined effects of VOCs in a mixture. Further studies were suggested with mixtures of VOCs comprising single VOCs investigated in the present experiments.

Sensory evaluations of the air polluted with VOCs made by trained and untrained subjects were discrepant. This difference may be due to the incorrectly established relationship that is used at present to train sensory panels and/or to the psychophysical difference between the sensory sensation produced by the air containing 2-propanone and by the air containing other types of pollutant. The laboratory transfer model comparing the sensory assessments made by untrained and trained panels was created using the perception models developed for the air polluted with single VOCs and with the mixtures of VOCs. The model was validated during field experiments in the offices polluted by the building (building materials and furnishings) and by the building plus tobacco smoke. Acceptability of air in the offices predicted with the laboratory transfer model using the perceived air quality assessed by trained panels (a total of 22 subjects) differed ($p<0.01$) from the acceptability of air evaluated by untrained panels (a total of 77 subjects). The sensory evaluations made during face and whole-body exposures were also dissimilar. Field transfer models were developed accordingly. Further field validation of the laboratory transfer model is suggested.

In **Chapter 4**, entitled *"Impact of emissions from a carpet on perceived air quality, SBS-symptoms and productivity"*, it is investigated whether removing pollution sources indoors can improve the perceived air quality, can decrease the prevalence of SBS-symptoms and can improve the productivity of people.

The air pollution level in an existing office space (lxwxh=6x6x3 m) was modified by placing a sample of carpet inside the office or removing it from the space. The carpet was 20 years old and made of tufted bouclé polyamide fibres; it had a size corresponding to the floor area of the office and it was hung behind the screen so that it was invisible to occupants. The outdoor airflow rate at 10 L/s per person, the operative temperature at 24°C, the relative humidity at 50%, the air velocity <0.2 m/s and the noise level at 42 dB(A) remained unchanged in the office whether the carpet was present or not. The office was illuminated by daylight through the windows with a glazing surface of 6 m^2.

Thirty female subjects aged 20 to 31 years (average age 24±3) occupied the office with and without carpet, in groups of 6 persons at a time. They were all students and they were impartial to the building in which the office was selected for the investigation. The subjects performed simulated office work comprising typing text, adding numbers and carrying out creative thinking tasks; they were also given a diagnostic psychological battery test. These measures were used to estimate the subjects' productivity. Occupation lasted 4.4. hours in the afternoon. The subjects remained thermally neutral (PMV=0.7±0.8) by modifying their clothing. Their metabolism was on average 1.3 met (CO_2 concentration in the office was 560 ppm above outdoor level). The subjects could also adjust the lighting level (using a table lamp) if they felt it was too dark. The subjects assessed the perceived air quality, the indoor environment, thermal comfort and SBS-symptoms upon entering the office and again after 45, 125, 215 and 265 minutes. Following the occupation period, the subjects left the office and re-entered it after a short time to evaluate again the perceived air quality.

Perceived air quality upon entering the office without carpet caused 15% of persons to be dissatisfied while 22% were dissatisfied when the carpet was present. The perceived air quality evaluated upon entering the office with bioeffluents was

impaired further ($p<0.08$) independently of whether the carpet was present or not. Moderate adaptation to the air pollutants in the office was observed during the first hour of occupation. Visitors' and occupants' assessments of the air quality were significantly correlated. Chemical analysis revealed slightly higher concentrations of odorants and irritants in the office with carpet. Improved air quality in the office without carpet was a consequence of the removal of carpet and thus the reduced sensory pollution load on the air caused by the building, from 0.25 olf/m^2floor in the office with carpet to 0.14 olf/m^2floor in the office without carpet. Subjects reported that they more often suffered from headaches ($p<0.04$) in the office with carpet, especially when they were typing. Headache due to polluted air was thus more pronounced during tasks requiring concentration. They typed significantly less text (ca. 6% decrease in the number of characters typed) in the office with carpet ($p<0.003$). The results obtained from the psychological battery and the addition task also suggested a decreased performance in the office with carpet. The small difference between the office with and without carpet in the quality of air perceived by occupants (12% vs. 10% of persons dissatisfied), makes the comparison in terms of performance one that is almost a blind comparison. The effect of the reduced air quality due to carpet was to cause subjects to exert less effort ($p<0.02$). People regarding themselves as more sensitive to poor air quality were also more dissatisfied with the perceived air quality. Text typing proved to be a successful method for simulating office work that is sensitive to poor air quality, showing that simulated work for a long duration is more sensitive to environmental effects than diagnostic tests of short duration. The presence of carpet, a high workload and people reporting to be sensitive to poor air quality were found to be the possible risk factors for SBS.

Reducing the sensory pollution load on the air indoors proved to be an effective and energy-efficient measure to improve the perceived quality of air, to lower the prevalence of symptoms and to improve productivity. Suggestions for future experiments are made including, i.a., using other sub-populations of subjects stratified for age, sensitivity and type of work, other pollution sources, as well as the independent measures design and repeated exposures to the same environmental conditions.

Resumé

Titlen på nærværende afhandling er: "Menneskers perception, produktivitet og symptomer i relation til indendørs luftkvalitet"

I **kapitel 1**, *"Introduktion"*, er studiets tre formål formuleret: (1) at undersøge om den samlede sensoriske kildestyrke i et lokale kan estimeres ved at addere alle individuelle sensoriske kildestyrker; (2) at udvikle alternative reference-eksponeringer til brug ved kalibrering af sensoriske bedømmelser af indendørs luftkvalitet foretaget af trænede forsøgspersoner; og (3) at undersøge om en begrænsning af forureningsbelastningen på luften indendørs er en effektiv metode til at forbedre den oplevede luftkvalitet, reducere forekomsten af symptomer og forøge menneskers produktivitet.

I **kapitel 2**, *"Addition af sensoriske forureningskilder til beregning af nødvendige ventilationsrater"*, er fire tidligere laboratoriestudier af addition af sensoriske forureningskilder gennemgået. Resultaterne viste, at der kun eksisterer begrænset viden om addition af grupper af sensoriske forureningskilder, dvs. byggematerialer, mennesker og tobaksrøg, og at ingen feltstudier af addition har været foretaget hidtil. Der blev derfor udført laboratorie- og feltstudier af addition af grupper af sensoriske forureningskilder.

I laboratorieeksperimenterne bedømte et panel bestående af 43 utrænede forsøgspersoner kvaliteten af luften i tomme klimakamre, kamre med én af tre typer gulvmateriale, kamre med personer og kamre med én af tre typer gulvmateriale plus personer. Panelet bedømte også kvaliteten af udeluften. Luften i de tomme kamre var kun forurenet af selve kamrenes materialer og ventilationssystem. De tre typer gulvmateriale bestod af gammelt gulvtæppe, ny linoleum og ny vinyl, hvert med et areal på 73 m^2, svarende til belastningen i et standardrum (lxbxh=3.2x2.2x2.4 m)

ventileret med et luftskifte på 1 h^{-1}. Personerne opholdt sig i kamrene i 4 grupper á 5 personer. Udelufttilførslen til kamrene var konstant 35 L/s og konditioneret til 23°C og 40% RH. De sensoriske bedømmelser af luft trukket ud fra kamrene og udefra blev afgivet på en kontinuert acceptabilitetsskala.

Feltundersøgelserne blev foretaget i et eksisterende kontor (lxbxh=6x4.3x3 m) som blev ventileret med et luftskifte på hhv. 0.4, 1 og 2 h^{-1} ved hjælp af en ventilator monteret i vinduet. Ved hver ventilationsrate blev luften i kontoret forurenet af bygningen (byggematerialer og møbler i kontoret), bygning plus personer, bygning plus tobaksrøg, og bygning plus personer plus tobaksrøg. Personerne opholdt sig i kontoret i grupper fra 3 til 12 personer. Tobaksrøgen blev genereret ved at tænde mellem 0.3 og 1.1 cigaretter pr. time, placeret i et askebæger. Et sensorisk panel bestående af 43 utrænede forsøgspersoner bedømte luftkvaliteten i kontoret ved hver af ovennævnte konditioner, såvel som kvaliteten af udeluften. De sensoriske bedømmelser, afgivet på en kontinuert acceptabilitetsskala, blev foretaget på luft trukket ud fra kontoret og udefra, i begge tilfælde konditioneret til 20°C. Koncentrationen af carbondioxid (CO_2) og carbonmonooxid (CO) blev målt og anvendt til at forudsige den sensoriske forureningsbelastning stammende fra mennesker og tobaksrøg ved hjælp af de seneste eksperimentelle resultater fra litteraturen.

De målte samlede forureningsbelastninger i kamrene og i kontoret blev sammenlignet med de sensoriske forureningsbelastninger predikteret ved at addere belastningerne fra de enkelte kilder. Lineær regresssion blev anvendt til at modellere de eksperimentelle data. Resultaterne viste at den samlede sensoriske forureningsbelastning i et lokale med rimelighed ($r^2=0.91$, $p<0.0001$) kan approksimeres ved at addere den sensoriske forureningsbelastning på luften forårsaget af individuelle kilder, så som bygning, mennesker og tobaksrøg. Dette medfører at den nødvendige ventilationsrate for at opretholde en vis foreskrevet luftkvalitet kan findes ved at addere de nødvendige ventilationsrater for hhv. bygning, mennesker og deres tobaksrygning. Yderligere fuldskala studier af addition af et bredere udvalg af sensoriske forureningskilder er foreslået ved moderate forureningsniveauer, således at mindre end 30% af personerne er utilfredse med luftkvaliteten. Det er også foreslået at fortsætte laboratoriestudierne af addition af forureningsbelastninger stammende fra typiske byggematerialer, dog med bedre kontrol af sorptionsprocesserne end i de hidtidige studier.

I **kapitel 3**, "*Referenceatmosfærer for menneskers sensoriske bedømmelse af oplevet luftkvalitet*", er litteraturen beskrivende tidligere målinger af organiske gasser og dampe (VOC'er) i ikke-industrielle indendørs miljøer gennemgået. Formålet med gennemgangen var, at danne basis for udvælgelsen af VOC'er til en referenceatmosfære til brug som reference-eksponering i forbindelse med menneskers sensoriske bedømmelse af luftkvaliteten i kontorbygninger. Litteraturen blev udvalgt ved en gennemgang af internationale journaler og proceedings fra

større internationale konferencer i perioden fra 1978 og frem til midten af 1993, og blev suppleret med en stor undersøgelse fra 1995. 22 studier beskrivende 742 målinger i 582 kontorer i 209 forskellige bygninger, der var mindst et år gamle, blev grundigt gennemgået. Resultaterne viste koncentrationer af 133 VOC'er, hvor den hyppigst optrædende var toluen. Ethanol var den komponent, der havde den højeste vægtede gennemsnitlige (VG) koncentration (antallet af målinger hvor stoffet optrådte blev anvendt som vægt). Kun tre VOC'er: n-decanal, n-octanal og ethylbenzen havde indendørs VG-koncentrationer, der oversteg deres lugttærskel. Størstedelen af VOC'erne havde VG-koncentrationer der var mere end 100 gange under deres lugttærskel. Ingen af VOC'erne fandtes i VG-koncentrationer højere end deres kendte irritationstærskel.

Otte enkelte VOC'er blev udvalgt til sensorisk afprøvning: n-butanol, n-decan, ethylbenzen, n-hexan, 2-propanon, toluen, 1,2,4-trimethylbenzen og m-xylen. Alle otte opfyldte de opstillede krav til komponenterne i referenceatmosfæren: De var hyppigt forekommende indendørs, de havde de højeste målte indendørs VG-koncentrationer, de havde den største sensoriske indflydelse på mennesker ved de målte VG-koncentrationer i indemiljøet og de var alle etisk acceptable, dvs. harmløse for mennesker og miljø ved de koncentrationer, der var tænkt anvendt. Derudover blev tre blandinger af VOC'er udvalgt til sensorisk bedømmelse: Blandingen af 22 VOC'er, der tidligere har været benyttet i eksperimenter til undersøgelse af effekterne af indendørs luftforurening på mennesker, og blandinger af hhv. 8 og 19 VOC'er, udtaget fra førnævnte blanding.

Utrænede paneler (ialt >200 forsøgspersoner) og paneler af personer trænet til at bedømme luftkvalitet i forhold til en veldefineret 2-propanon reference (i alt >50 personer) bedømte kvaliteten af luft forurenet med enkelte VOC'er eller blandingerne af VOC'er. Luftforureningen blev genereret ved hjælp af et specialbygget apparat. De sensoriske bedømmelser blev anvendt til at udvikle modeller for perception. Utrænede personers acceptabilitet af luften blev korreleret med logaritmen til VOC-koncentrationen (r^2=0.77-0.98), og oplevet luftkvalitet bedømt i decipol af trænede paneler blev korreleret med en potensfunktion af VOC-koncentrationen (r^2=0.79-0.99). De perceptionsmodeller, der blev opstillet ved hjælp af bedømmelser foretaget af utrænede forsøgspersoner, kan anvendes til at træne personer til at bedømme luftkvalitet direkte i decipol. Sensorisk bedømmelse af lugtintensiteten afslørede muligheden for kombinationseffekter af VOC'er i en blanding. Yderligere studier af blandinger af VOC'er undersøgt enkeltvis i nærværende eksperiment er foreslået.

Sensoriske bedømmelser af luften forurenet med VOC'er foretaget af trænede og utrænede forsøgspersoner var forskellige. Det kan skyldes at sammenhængen, der i dag anvendes til at træne sensoriske paneler, er forkert, og/eller forskel i psykofysiske sammenhænge for 2-propanon og luften indeholdende andre typer forurening. En overføringsmodel til brug i laboratoriet ved sammenligning af

sensoriske bedømmelser foretaget af utrænede og trænede paneler blev opstillet ved hjælp af perceptionsmodellerne udviklet for luft forurenet med enkelte VOC'er og blandinger af VOC'er. Modellen blev testet gennem feltundersøgelser i kontorerne forurenet af bygningen (byggematerialer og møbler) og af bygning plus tobaksrøg. Acceptabiliteten af luften i kontorerne predikteret af laboratorie-overføringsmodellen, der er baseret på oplevet luftkvalitet bedømt af trænede paneler (i alt 22 forsøgspersoner), var forskellig ($p<0.01$) fra acceptabiliteten af luften bedømt af utrænede paneler (i alt 77 forsøgspersoner). De sensoriske bedømmelser foretaget ved fuld og delvis eksponering var også forskellige. Overføringsmodeller til brug i felten blev derfor udviklet. Det foreslås, at der foretages yderligere validering af laboratorie-overføringsmodellen.

I **kapitel 4**, *"Indflydelse af emissioner fra et tæppe på oplevet luftkvalitet, SBS-symptomer og produktivitet"*, er det undersøgt, om det at fjerne indendørs forureningskilder kan forbedre luftkvaliteten, mindske forekomsten af SBS-symptomer og forbedre menneskers produktivitet.

Luftforureningsniveauet i et eksisterende kontorlokale (lxbxh=6x6x3 m) blev ændret ved at placere en mængde tæppe i kontoret. Tæppet var et 20 år gammelt polyamid bouclé med en størrelse svarende til kontorets gulvareal. Tæppet var hængt skjult bag en skærm, sådan at personerne i kontoret ikke kunne se det. Mængden af tilført udeluft på 10 L/s, operativ temperatur på 24 °C, relativ luftfugtighed på 50%, lufthastighed på <0.2 m/s og støjniveau på 42 dB(A) forblev uændret i kontoret uanset om tæppet var i kontoret eller ej. Kontoret var oplyst af dagslys gennem vinduerne med et glasareal på 6 m^2.

Tredive kvindelige forsøgspersoner i alderen 20 til 31 år (gennemsnitlig alder 24±3) opholdt sig i grupper á 6 personer i kontoret med og uden tæppe. De var alle studerende og kendte ikke bygningen hvor kontoret udvalgt til undersøgelsen var beliggende. Forsøgspersonerne udførte simuleret kontorarbejde omfattende maskinskrivning, addition af tal og kreativ tænkning. Derudover udførte de opgaver til måling af præstation. Alle disse mål blev brugt til at estimere forsøgspersonernes produktivitet. Hver session, der blev gennemført om eftermidagen, varede 4.4 timer. Gennem sessionen forblev forsøgspersonerne termisk neutrale (PMV=0.7±0.8) ved løbende at ændre på deres beklædning. Deres metabolisme var i gennemsnit 1.3 met (CO_2 koncentrationen i kontoret var 560 ppm over udeluftniveauet). Forsøgspersonerne havde mulighed for at ændre på belysningen (ved at tænde en arkitektlampe) hvis de følte det var for mørkt. Forsøgspersonerne bedømte luftkvalitet, indendørsmiljø, termisk komfort og SBS-symptomer umiddelbart efter indtræden i kontoret og igen efter 45, 125, 215 og 265 minutter. Efter sessionen forlod forsøgspersonerne kontoret, men vendte tilbage kort efter for igen at bedømme den oplevede luftkvalitet.

Oplevet luftkvalitet umiddelbart efter indtræden i kontoret uden tæppe medførte at

15% af personerne var utilfredse, mens 22% var utilfredse når tæppet var til stede. Oplevet luftkvalitet bedømt ved indtræden i kontoret med bioeffluenter var yderligere forringet ($p<0.08$), uafhængigt af om gulvtæppet var til stede eller ej. Moderat tilvænning til luftforureningen i kontoret blev observeret i løbet af den første time af sessionen. Bedømmelsen af luftkvaliteten foretaget umiddelbart efter indtræden og efter længere tids ophold i kontoret var signifikant korreleret. Kemiske analyser viste en anelse højere koncentration af lugte og irritanter i kontoret med tæppe. Den forbedrede luftkvalitet i kontoret uden tæppe var en konsekvens af at tæppet blev fjernet, og dermed reducerede den sensoriske forureningsbelastning på luften stammende fra bygningen fra 0.25 olf/m^2 gulv i kontoret med tæppe til 0.14 olf/m^2 gulv i kontoret uden tæppe. Forsøgspersonerne rapporterede, at de oftere led af hovedpine ($p<0.04$) i kontoret med tæppe, specielt under maskinskrivning. Hovedpine på grund af forurenet luft var mere udtalt under arbejdsopgaver, der krævede koncentration. Forsøgspersonerne skrev signifikant mindre tekst (ca. 6% færre karakterer) i kontoret med tæppe ($p<0.003$). Resultaterne af additionsopgaverne og de andre præstationsopgaver viste også tegn på fald i præstationen i kontoret med tæppe. Personerne der opholdt sig i kontoret oplevede kun en lille forskel i luftkvalitet i kontoret med og uden tæppe (12% vs. 10% af personerne utilfredse), og dette medfører, at der næsten var tale om en blindtest. Effekten af den forringede luftkvalitet forårsaget af tæppet medførte, at forsøgspersonerne ydede en mindre arbejdsindsats ($p<0.02$). Personerne, der opfattede sig selv som mere sensitive overfor dårlig luftkvalitet, var også mere utilfredse med luftkvaliteten. Maskinskrivning viste sig at være velegnet til at simulere kontorarbejde, der er følsomt overfor dårlig luftkvalitet. Længerevarende aktiviteter er mere følsomme overfor miljømæssige effekter, end opgaver af kort varighed. Tilstedeværelsen af tæppe, høj arbejdsbelastning og personer, der anser sig selv for sensitive overfor dårlig luftkvalitet, blev vist at være mulige risikofaktorer for SBS.

Det blev vist, at en reduktion af den sensoriske forureningsbelastning på luften indendørs er en effektiv og energibesparende metode til at forbedre den oplevede luftkvalitet, mindske forekomsten af symptomer og forbedre produktiviteten. Forslag til fremtidige eksperimenter inkluderer blandt andre at anvende forsøgspersoner fra andre undergrupper af befolkningen, andre forureningskilder og gentagne eksponeringer til de samme klimamæssige konditioner.

CHAPTER 1

Introduction

1.1 Background

Indoor climates are multifactorial environments, in which physical and chemical factors can to a greater or lesser degree influence humans' sensory perception and well-being. Among these factors, there are sensory pollutants which, by stimulating olfactory and trigeminal (common chemical sense) nerve endings, have an impact on the perceived air quality. These pollutants may lead to decreased air quality and decreased comfort and well-being of people indoors. This in turn may lead to an increase in the prevalence of health symptoms, such as headaches, fatigue, etc., among people and eventually may result in impaired human performance.

Good air quality indoors can be provided by reducing the pollution level in indoor air, e.g., by dilution with clean outdoor air, so that only a small proportion of people occupying an indoor space is dissatisfied due to poor air quality. This is one of the main objectives of ventilation. A proportion of occupants dissatisfied with the air quality indoors is set in some standards at the level of 20% (ASHRAE, 1989). European guidelines for ventilation of buildings (ECA, 1992) specify three categories corresponding to 10%, 20% and 30% dissatisfied with the air quality, whereas a proposed European ventilation standard (prENV 1752, 1997) upgrades the first category to 15% dissatisfied, leaving the two remaining categories unchanged.

The important question is, however, not only how many people are dissatisfied with the air quality but also how much ventilation is required to provide comfort conditions for people in indoor environments so that the above-mentioned stringent requirements are met. Yaglou et al. (1936) studied this issue in relation to odorous pollutants emitted by people indoors (bioeffluents). He asked independent observers to judge the odour intensity of human bioeffluents immediately upon entering an experimental chamber. Based on these evaluations and assuming both that people are the exclusive pollutants indoors and that a moderate human odour is acceptable, recommendations were established concerning volumetric flow of outdoor air required for each person occupying an indoor space in order to provide acceptable indoor air quality for a visitor to a space. The results of Yaglou et al. (1936) were updated by similar recent investigations made by Cain et al. (1983), Berg-Munch et al. (1986) and Iwashita et al. (1990). Since Yaglou's experiments, it has been common practice to design outdoor air rates required predominantly to handle human bioeffluents (Fanger, 1996). Furthermore, outdoor air rates have been prescribed to satisfy unadapted visitors to spaces, and have thus been based on the "first impression" of the air quality expressed immediately upon exposure to the new environment. A total outdoor air rate for indoor spaces occupied by n people has been designed by adding outdoor air rates required for each of n occupants present. This has been accepted to be n-times the ventilation rate required for one person.

Yaglou's assumption that humans are the exclusive pollution source indoors may have been appropriate at his time but is no longer valid since other sources of pollution, including building materials, ventilation systems and human activities, have been found to contribute to the overall pollution of indoor spaces (Fanger et al., 1988a; Pejtersen et al., 1989; Thorstensen et al., 1990). Consequently, designing ventilation to handle only human bioeffluents and in some cases (CIBSE, 1978; ASHRAE, 1989) also moderate tobacco smoking taking place indoors, results in an insufficient air supply and consequently an absence of comfort criteria for the perceived air quality, as recommended in indoor climates by the above-mentioned ventilation guidelines and standards. Thus all sensory pollution sources present indoors should be taken into account when designing ventilation for acceptable indoor air quality, and this postulate formed the rationale for developing a comfort model for the perceived air quality (Fanger, 1988). According to the model [1.1], the total outdoor air rate in an indoor space (Q) is calculated depending on a designed level of air quality perceived by humans indoors (C_i), on a perceived quality of air supplied from outdoors (C_o), and on a total sensory pollution load on the air from all odorous sources in a space (G):

$$Q = 10 \cdot \frac{G}{C_i - C_o} \qquad [1.1]$$

To quantify the sensory pollution load from different sources in a space, the unit "olf" was introduced, which is the rate of air pollutants (bioeffluents) emitted by one standard person. To quantify perceived air quality, the unit "pol" was introduced, which is the pollution caused by one standard person (one olf) ventilated by 1 L/s of unpolluted air (Fanger, 1988).

An underlying assumption of the proposed model was that the sensory pollution load from any pollution source indoors can be quantified by the sensory pollution load from an equivalent number of standard persons (= olfs) in a space. When expressing the sensory pollution load from all pollution sources by the sensory pollution load from an equivalent number of standard persons, it was therefore assumed that at ventilation rates encountered indoors, pollution sources other than people behave similarly to human bioeffluents, i.e., basically, that their sensory strength depends neither on the concentration of sensory pollution in air nor on the ventilation rate. In other words, it was hypothesized that in the range of ventilation rates indoors, the exposure-response relationship associating the concentration of sensory pollution in air with the perceived air quality is for any source of pollution analogous to the exposure-response relationship for human bioeffluents (Fig. 1.1).

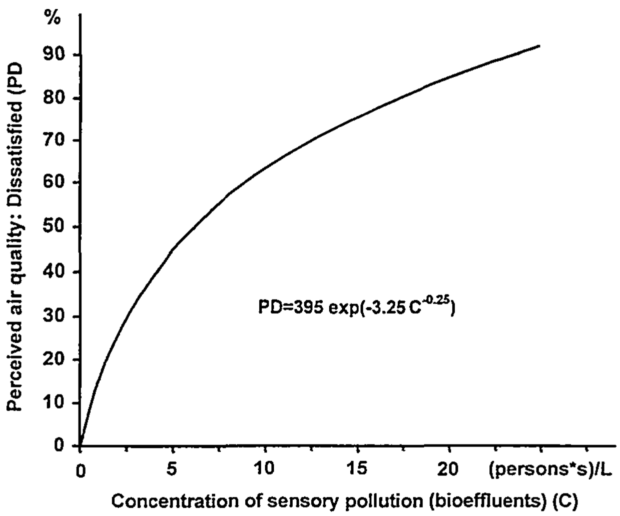


Figure 1.1 Exposure-response relationship for human bioeffluents relating the perceived air quality (expressed as the percentage of persons dissatisfied with the air quality) with the concentration of human bioeffluents in air (expressed as a reciprocal of ventilation rate per person (Fanger, 1988); when defining the comfort model it was assumed that within the range of ventilation rates encountered in indoor climates, the sensory impact on humans of pollution sources other than people can also be described using this relationship

It was furthermore surmised, that the total ventilation required for acceptable indoor air quality should be calculated by adding ventilation rates required to handle each standard person (olf) in a space, or in other words, to handle each individual pollution source present indoors. This is illustrated in Fig. 1.2 and is compared to currently accepted addition of ventilation rates required to handle each person in a space. Allowing for both the addition of ventilation rates required to handle the pollution sources indoors and the equivalence between the sensory pollution load from standard persons (olfs) and the load from other pollution sources, it was thus postulated that the total sensory pollution load in a space can be calculated by adding sensory pollution loads on the air from individual pollution sources.

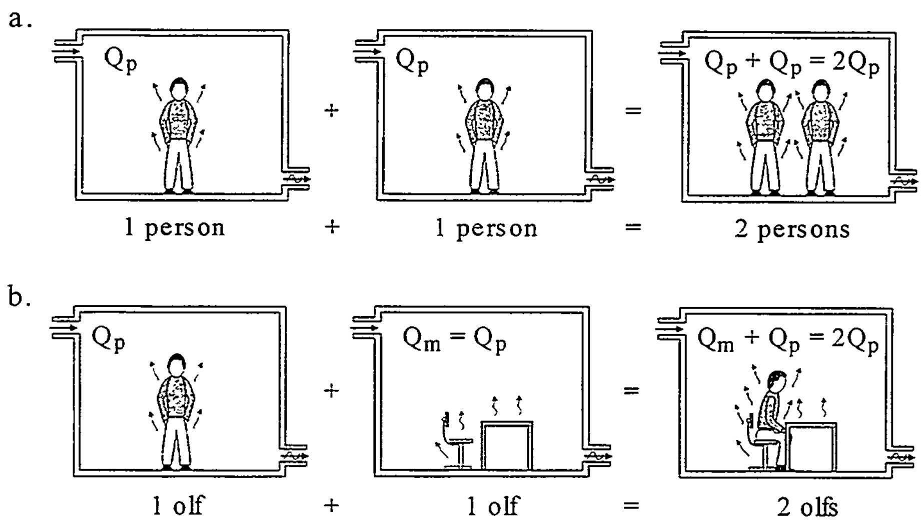


Figure 1.2 In a space occupied only by people, a total ventilation rate is calculated by adding ventilation rates required to handle each person in a space (Q_p), as shown in Fig. 1.2a. According to the comfort model (Fanger 1988), in a space with different pollution sources, the sensory pollution load on the air from each source should first be expressed by an equivalent number of standard persons (olfs). The ventilation rate required to handle each olf (standard person) can then be calculated. Finally, as if only people polluted a space, these ventilation rates can be added in order to find the total ventilation rate. This principle is illustrated in Fig 1.2b: in a room polluted by a person (= 1 olf) and a furnishing with the sensory strength equivalent to 1 olf, a total ventilation rate is calculated by adding the ventilation rate required to handle separately a person (Q_p) and a furnishing (Q_m)

At present, the perceived air quality can be evaluated only by humans, due to lack of instrumentation with which to measure the perceived air quality directly in decipol. It has been suggested that either untrained human subjects (Fanger, 1988; ASHRAE, 1989) or trained human subjects (Bluyssen et al., 1989) can be used. Untrained panels do not rate the perceived air quality directly in decipol, but assess the acceptability of air on a dichotomous (Fanger et al., 1988a) or a continuous scale (ASHRAE, 1989; Gunnarsen and Fanger, 1989), and these rating can be transformed into decipol (Gunnarsen and Fanger, 1992). On the other hand, sensory ratings of trained subjects are expressed directly in decipol. Subjects receive training during which their assessments are calibrated against reference exposures of 2-propanone. A relationship was established between 2-propanone concentration in air and the perceived air quality in decipol (Bluyssen et al., 1989). 2-propanone was selected as it is a major human bioeffluent. Other reference atmospheres can also be developed using, e.g., compounds emitted from building materials. In addition, it should be verified that air quality assessments made by trained panels are comparable to those made by untrained panels.

The proposed comfort model relates ventilation rates and sensory pollution loads with the immediate perceptions of air quality expressed upon entering a space. It was also suggested (Fanger, 1987) that a link exists between first impressions of air quality made by visitors and long-term symptoms of occupants. Up to now, however, no experimental evidence on such a link has been provided, although several studies have directly or indirectly tried to investigate this issue (Bluyssen et al., 1996; Parine and Oreszczyn, 1996).

The implication of the comfort model is that reducing the sensory pollution load by removing polluting sources indoors, should provide economical benefits by decreasing the ventilation rates required to provide acceptable air quality for people. Control of pollution sources is not a new measure for improving the air quality in buildings. Source control was recommended by Pettenkofer already in 1858 (Pettenkofer, 1858) and has been the philosophy behind legislation to decrease outdoor air pollution during several decades. But it is important to study how efficient this measure can be in relation to health symptoms and productivity. Would improved air quality reduce the occurrence of health symptoms among people and improve human's productivity? Still only rather limited experimental data can address this issue, although it has been suggested (Wyon, 1996) that poor air quality causing fatigue and headaches may negatively affect human performance.

1.2 Objectives

The objective of the present thesis is three-fold:

1. To investigate assumptions underlying the comfort model with special emphasis on whether total sensory pollution load on the air in spaces can be estimated by adding sensory pollution loads from individual pollution sources, implying further that ventilation rates required for acceptable indoor air quality can be calculated by adding ventilation rates required to handle separately each individual pollution source present indoors. This is investigated in Chapter 2.
2. To develop alternative reference exposures which can be used to calibrate sensory evaluations of the air quality indoors made by trained subjects and to investigate whether sensory ratings made by untrained and trained subjects are truly comparable. This is described in Chapter 3.
3. To investigate whether decreasing the pollution loads on the air indoors by substituting polluting material with low-polluting alternatives is an effective measure for improving the perceived air quality, reducing the prevalence of health symptoms and increasing people's productivity. This is investigated in Chapter 4.

CHAPTER 2

Addition of Sensory Pollution Sources for the Calculation of Required Ventilation Rates

2.1 Previous Studies on Addition of Sensory Pollution Sources

One of the assumptions of the comfort model is that the sensory pollution loads on the air from different individual pollution sources can be added to calculate the total sensory pollution load in a space. This assumption was examined in 4 laboratory experiments (Lauridsen et al., 1988; Iwashita et al., 1989; Bluyssen and Fanger, 1991; Bluyssen and Cornelissen, 1997) focusing mainly on the addition of sensory pollution loads from building materials. No field study on the addition of sensory pollution loads has yet been carried out. Nevertheless, the results of 3 field experiments (Fanger et al., 1988a; Thorstensen et al., 1990; Pejtersen et al., 1991) can be used to examine addition, for although performed for other reasons, the experimental procedures are applicable. The above-mentioned 4 laboratory and 3 field investigations are reviewed in the following.

2.1.1 Previous Laboratory Studies on Addition

The assumption of adding sensory pollution loads from different sources to calculate the total sensory pollution load in a space was examined in 4 laboratory experiments: Lauridsen et al. (1988), Iwashita et al. (1989), Bluyssen and Fanger (1991), and Bluyssen and Cornelissen (1997).

2.1.1.1 Description of Procedures Used in Previous Studies on Addition

Lauridsen et al. (1988) studied the addition of sensory pollution sources in binary and ternary mixtures of building materials, occupants and tobacco smoke (Table 2.1.1). The pollution sources were ventilated in twin climate chambers of 30 m^3 each

(Albrechtsen, 1988) at a temperature of 21.3±0.3°C and a relative humidity of 28±5%, with an average airflow corresponding to 10 air changes per hour; the airflow was selected to achieve perceived air quality in the chambers at approx. 30-40% dissatisfied. The air in the chambers was assessed by a panel of 88 untrained human subjects (45 women and 43 men, aged between 18 and 30 years, among whom 47 were smokers, but were not allowed to smoke during the experiments). They assessed the air immediately upon entering the chambers in groups of six persons, using a dichotomous acceptability scale (acceptable vs. not acceptable air quality, according to Fanger et al., 1988a and ASHRAE, 1989). All test conditions were evaluated twice during the two-week experimental period.

Iwashita et al. (1989) studied the addition of sensory pollution sources in binary mixtures of building materials, and mixtures of three building materials plus people and three building materials plus tobacco smoke (Table 2.1.1). Polluted air was generated in a 9 m^3 experimental chamber ventilated with 10 air changes per hour to achieve perceived air quality at approx. 30-40% dissatisfied. No information on temperature and relative humidity in the chamber was provided. A panel of 142 untrained human subjects (70 female and 72 male Japanese college-age students aged on average 21.7 years; 19 were smokers but were not allowed to smoke during the experiments) assessed the acceptability of air using a continuous acceptability scale (according to Gunnarsen and Fanger, 1989). The subjects assessed the air at a specially built "sniffing station" outside the chamber (they did not enter the chamber with pollution sources). Each test was run three times with a panel of approximately 12 judges (6 females and 6 males) among 142 subjects recruited.

Bluyssen and Fanger (1991) studied the addition of 11 different pollution sources in 13 binary mixtures and one quintuple mixture (Table 2.1.1). The polluted air was generated by ventilating a specific material loading in a 3 litre glass jar with an average airflow of 0.9 L/s at 22°C. The air was assessed by five judges trained to evaluate the annoyance of air directly in the decipol unit, comparing to a well-defined reference of 2-propanone (Bluyssen et al., 1989). The air for assessment was provided through the diffuser connected to the glass jar.

Bluyssen and Cornelissen (1997) studied the addition in 10 binary mixtures of different pollution sources (Table 2.1.1). The air for the assessments was generated in a 3 litre jar in which a sample of material was ventilated at 0.9 L/s at 22°C. A panel of 8-12 trained judges assessed the quality of air exhausted from the jars through a diffuser. The panel evaluated the annoyance of air directly in a decipol unit, comparing to a well-defined reference of 2-propanone (Bluyssen et al., 1989).

In the studies of Lauridsen et al. (1988) (sessions with mixtures of people plus building materials, and tobacco smoke plus building materials), Iwashita et al. (1989), and Bluyssen and Cornelissen (1997) the pollution sources were kept unchanged, regardless of whether the air was polluted by individual sources or by a mixture of sources. The sensory pollution loads from individual sources in mixtures were thus similar to sources that were tested individually, assuming that no changes occurred in the sensory emissions.

In studies of Lauridsen et al. (1988) (sessions with mixtures of building materials) and Bluyssen and Fanger (1991), during sensory evaluations of air polluted by mixtures of pollution sources the amount of pollution sources was 1/2 or 1/5 of the quantity that was used during sensory evaluations of air polluted by individual sources. Consequently, to predict the sensory pollution load from individual sources in the mixture, 1/2 or 1/5 of the estimated sensory pollution load from single sources was used, assuming the proportional relationship between sensory emission and the amount of material.

Table 2.1.1 Pollution sources used in the previous laboratory studies on addition

Study	Pollution sources	
Lauridsen et al. (1988)	Building materials	chipboard, synthetic carpet, painted gypsum board, sealant and lacquer
	People	5 and 9 sedentary occupants
	Tobacco smoke	generated by smokers; smoking rate was controlled to obtain carbon monoxide concentrations at levels of 0.3 ppm and 0.15 ppm above background
Iwashita et al. (1989)	Building materials	linoleum, vinyl carpet and varnished board
	People	3 sedentary people
	Tobacco smoke	generated by smokers; smoking rate was controlled to obtain a carbon monoxide concentration at the level of 3 ppm above outdoors
Bluyssen and Fanger (1991)	Building materials	carpet, rubber doormat, sealant, painted metal plate and linoleum
	HVAC materials	panel filter, rotating heat exchanger, humidifier paper and galvanised steel
	Other materials	newspapers and cigarette butts
Bluyssen and Cornelissen (1997)	Building materials	floor cloth, three types of carpet, multiplex, linoleum, hardboard and glass wool
	Other materials	newspapers

2.1.1.2 Results

In all the previous laboratory studies on addition described above, the measured sensory pollution load from a mixture of sources was compared with the sensory pollution load predicted by adding the sensory pollution loads of individual sources. The results of this comparison are summarized in Fig. 2.1.1.

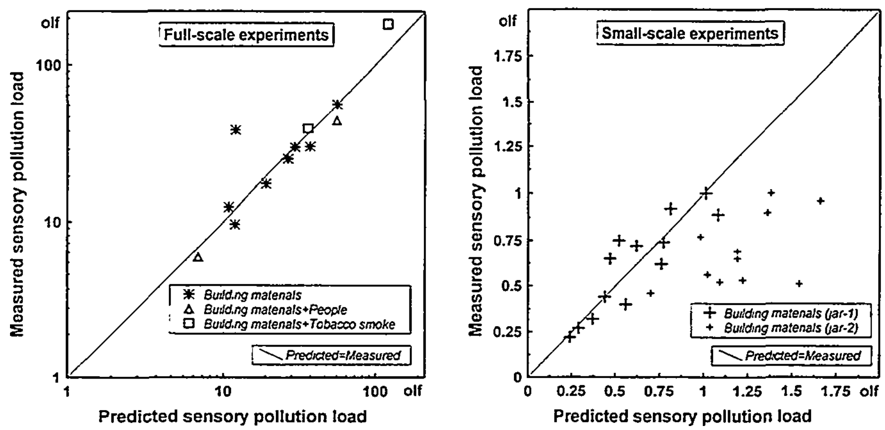


Figure 2.1.1 Results of laboratory studies of addition of sensory pollution sources. The results presented in the left chart were obtained for pollution sources (building materials, building materials plus people and building materials plus tobacco smoke) placed in a full-scale climate chamber and the air was assessed by untrained subjects (Lauridsen et al., 1988; Iwashita et al., 1989). The results presented in the right chart were obtained for building materials placed in 3 L glass jars (jar-1: Bluyssen and Fanger, 1991; jar-2: Bluyssen and Cornelissen, 1997) and the air was assessed by trained subjects

Three studies, Lauridsen et al., (1988), Iwashita et al. (1989) and Bluyssen and Fanger (1991), observed that adding sensory pollution loads from different sources is a fairly good approximation of the total sensory pollution load from all pollution sources in a multi-source mixture. A study of Bluyssen and Cornelissen (1997) concluded that the total sensory pollution load from a mixture is rather similar to the higher sensory pollution load of the two sources in a mixture.

No statistical analysis of the results reviewed above was carried out in the original investigations. A simple binomial test is nevertheless made here to examine whether the addition of sensory pollution loads applies under the hypothesis that the predicted total sensory pollution loads in the above reviewed studies would exceed measured total sensory pollution loads with a probability of 0.5, only if addition were true. This test rejects the hypothesis that the total sensory pollution load can be estimated by adding sensory pollution loads of individual sources ($N=40$, $z_o=2.37$, $p<0.009$). However, closer analysis indicates that this hypothesis is rejected only by 24 observations obtained in small-scale experiments when materials were ventilated in a 3 L jar and the air assessed by trained subjects ($N=24$, $z_o=2.25$, $p<0.01$). For 16 observations obtained in full-scale experiments by untrained subjects, the addition cannot be rejected ($N=16$, $z_o=0.75$, $p<0.23$). These findings are further discussed in the next section.

2.1.1.3 Discussion of the Results Obtained in Previous Studies on Addition

Impact of changing the concentration of sensory pollution in air. In studies of Lauridsen et al. (1988), Iwashita et al. (1989), and Bluyssen and Fanger (1991) the area-specific ventilation, i.e. the ratio of ventilation rate to the material loading, was not constant during sensory evaluations of single materials and mixtures of materials, due to changes in either the ventilation rate, the amount of material or both. Thereby, the individual materials and the mixtures of materials were exposed to different concentrations of sensory pollution in air. This could consequently cause a change of the sensory emission of pollution sources (Knudsen et al., 1997; Gunnarsen, 1997; Jørgensen et al., 1997), especially because air change rates in these studies were higher than 5 h^{-1} in a model office space (Nordtest, 1990), and were thus at levels where the effects become pronounced (Jørgensen and Vestergaard, 1998). The sensory pollution loads on the air from individual pollution sources in mixtures could thus differ from the sensory pollution loads on the air when sources were present alone. The latter loads were used for prediction of the total sensory load from the mixture. Accordingly, it may not be correct to assume the proportional relation between the sensory strength of a material and the material loading, as was done by Lauridsen et al. (1988) and Bluyssen and Fanger (1991).

Sorption processes. In all the studies reviewed above, the mixtures of materials investigated were produced by placing materials together in the chambers; in this way the sorption processes were allowed and they may have changed the sensory pollution load on the air from individual pollution sources when these sources were present in mixtures. In studies of Lauridsen et al. (1988) and Iwashita et al. (1989) the sensory assessments of air polluted by mixtures of materials were made shortly after the mixtures were produced (approx. 1/2 hour later), so it is not expected that sorption had a significant impact on the observed results. On the other hand, in studies of Bluyssen and Fanger (1991) and Bluyssen and Cornelissen (1997), sorption processes could substantially distort the final results, since materials were put together in a 3 L chamber and ventilated with 0.9 L/s; in such an environment equilibrium conditions concerning emission and sorption of pollutants are quickly obtained. In addition, in all ten binary mixtures studied by Bluyssen and Cornelissen (1997) at least one of the materials was fleecy (carpet, mineral wool, textile) with a strong ability for sorption. The sorption of fleecy materials may very well explain why Bluyssen and Cornelissen found a pollution load lower than addition of the two individual materials. A proper way of studying the combined effect for these materials would have been to place each material in separate jars and mix the two airflows for evaluation (see section 2.6.4). When sorption does take place, it should not be taken into account as a negative pollution load. Sorption is a completely different phenomenon that takes time and should be modelled in a different way than by combining emissions (sensory loads).

Use of trained and untrained subjects for sensory evaluations of indoor air quality. In studies by Bluyssen and Fanger (1991), and Bluyssen and Cornelissen (1997), trained subjects were used to assess the air quality in decipol, comparing to a well defined reference of 2-propanone, whereas in the studies of Lauridsen et al. (1988) and Iwashita et al. (1989) untrained subjects assessed the air quality using an acceptability scale. Since the comfort model was originally based on evaluations of perceived air quality made by untrained subjects, it can be debated whether the sensory pollution loads calculated using trained panel ratings can be used to investigate the addition. Furthermore, it should be noted, that trained panel ratings are different from untrained panel assessments. This aspect is discussed thoroughly in Chapter 3. Another issue requiring further investigations is the accuracy of transforming untrained subjects' ratings on acceptability into decipol levels.

Relevance of the results of previous studies on addition for indoor environments. In indoor climates, three families of pollutants generally exist: materials (building materials, furnishings as well as HVAC system materials), people and tobacco smoke. It is therefore most relevant to investigate whether these three families of pollutants can be added. This information is essential when designing ventilation requirements. Nevertheless, in the studies reviewed above, only 4 observations were made regarding the addition of sensory pollution loads from building materials, people and tobacco smoke. Some data on the addition of these families of pollution sources can be indirectly obtained from 4 previous field studies, which are described in the following section.

2.1.2 Field Studies Containing Data for Studying the Addition

No field study has previously been carried out with the purpose of investigating the addition of indoor air sensory pollution sources. Nevertheless, some information on the addition of sensory pollution sources in the field can be obtained by reanalysis of data obtained in previous field studies in offices and assembly halls (Fanger et al., 1988a), in schools (Thorstensen et al., 1990) and in kindergartens (Pejtersen et al., 1991). Due to the experimental procedures followed, the results of these investigations allow sensory pollution loads to be calculated exclusively for the building (i.e., building materials and furnishing in a space) plus HVAC system, people and tobacco smoke, as well as the total sensory pollution loads in spaces polluted by the mixtures of these sources.

2.1.2.1 Methods of Data Analysis

Experimental procedures used in the field studies. Table 2.1.2 gives a description of buildings investigated in selected field studies and of the sensory panels of human subjects making evaluations of indoor air quality in the buildings investigated.

In each study, the air quality in selected spaces in the buildings, as well as outdoor air quality, were assessed by a sensory panel of human subjects on three different days, as follows: when the building was unoccupied and the ventilation system was stopped, when the building was unoccupied and the ventilation system was operating as usual, and finally on a normal working day, i.e., when the building was occupied and the ventilation system was running. Sensory evaluations of the quality of indoor air were made by the subjects upon entering investigated spaces in the building. Sensory evaluations of outdoor air quality were made upon leaving the building, thus without pre-heating outdoor air presented for assessments. Air change measurements, the measurements of carbon dioxide (CO_2) and of carbon monoxide (CO) concentrations indoors and outdoors were carried out during sensory assessments.

Table 2.1.2 Description of the buildings investigated and the sensory panels used in the field studies

Study	Building	Spaces	Sensory panel
Fanger et al. (1988a)	18 office buildings	15 offices (2 without tobacco smoke)	54 untrained human subjects (27 females and 27 males), aged between 18 and 30 years, 17 smokers;
		5 assembly halls (3 without tobacco smoke)	quality of air assessed using dichotomous scale of acceptability
Thorstensen et al. (1990)	10 schools	10 non-smoking classrooms	15 trained human subjects assessing the air directly in decipol
Pejtersen et al. (1991)	10 kindergartens	21 non-smoking spaces	13 trained human subjects assessing the air directly in decipol

<u>Criteria for selection of the data for analysis.</u> The sensory evaluations selected for calculation of sensory pollution loads in spaces investigated in the field experiments were made: (1) in spaces on days when the ventilation system was operating and no occupants were present; and (2) on normal working days with occupants present and the ventilation system in operation. The assessments of air quality that were carried out on days when the ventilation system was switched off and no occupants were present in the buildings were not analysed since the outdoor air rate was generally below 0.5 h^{-1}, and was thus much lower compared to days on which the ventilation system was operating. On days when the ventilation system was turned off, the sensory pollution load of building materials and furnishings in spaces may therefore change due to a change of pollutant concentration in the air (Knudsen et al., 1997; Gunnarsen, 1997; Jørgensen et al., 1997).

Calculation of sensory pollution loads in the buildings. Sensory pollution loads were calculated on the basis of sensory evaluations and measured ventilation rates. The procedures used were similar to those described in detail in sections 2.3.1.6 and 2.4.1.6.

In short, the assessments of outdoor air were used to calculate the sensory pollution load on the supplied outdoor air. Sensory pollution loads from the building plus HVAC system were calculated using sensory assessments made on days when buildings were unoccupied and the ventilation system was in operation; they were adjusted, by subtraction, for sensory pollution load on the supplied outdoor air. Sensory pollution loads from the building plus HVAC system plus people, and the building plus HVAC system plus people plus tobacco smoke were calculated using sensory assessments of the quality of air in the investigated spaces made on a normal working day; they were adjusted, by subtraction, for the sensory load on the supplied outdoor air. Sensory pollution loads from people were calculated using measured CO_2 concentrations, assuming that an average rate of CO_2 production was 18 L/hour per person. Sensory pollution loads from tobacco smoke were calculated using measured CO, assuming that an average rate of CO production was 44 ml per cigarette.

Predicted total sensory pollution loads in the buildings were calculated by adding the sensory pollution loads from individual sources, i.e., the building plus HVAC system, people and tobacco smoke.

2.1.2.2 Results

Measured and predicted total sensory pollution loads in offices, assembly halls, classrooms and kindergartens polluted by the building plus HVAC system plus people and in offices and assembly halls polluted by the building plus HVAC system plus people plus tobacco smoke are shown in Figure 2.1.2. These data were collected at a fairly constant relative air humidity of 40%, and an air temperature of approx. 21-23°C (lower temperatures were measured on days without occupants in the buildings). The ventilation rates differed from 10% to 50% when measured on days with and without occupants in the building, and were generally higher in occupied buildings when smoking took place.

The results shown in Fig. 2.1.2 reveal that in spaces polluted by HVAC plus building plus people, adding sensory pollution loads from individual sources is a fair approximation. Conversely, in spaces in which tobacco smoking takes place, adding sensory pollution loads leads to significant overestimation of the total sensory pollution loads. These results are confirmed in a simple binomial analysis, similar to that carried out for the data obtained in the laboratory experiments reviewed (section 2.1.1.2). For all 41 observations obtained from field studies, binomial analysis rejects the hypothesis that the total sensory pollution load can be estimated by adding sensory pollution loads of individual sources ($N= 41$, $z_o=2.50$, $p<0.006$). A separate analysis made on 25 observations obtained in spaces polluted by HVAC plus building plus people does not reject that addition of sensory pollution loads is incorrect (N=25, z_o=0.8, p<0.21), whereas for 16 observations obtained in spaces polluted by HVAC plus building plus people plus tobacco smoke, addition of sensory pollution loads cannot be accepted (N=16, z_o=2.75, p<0.003).

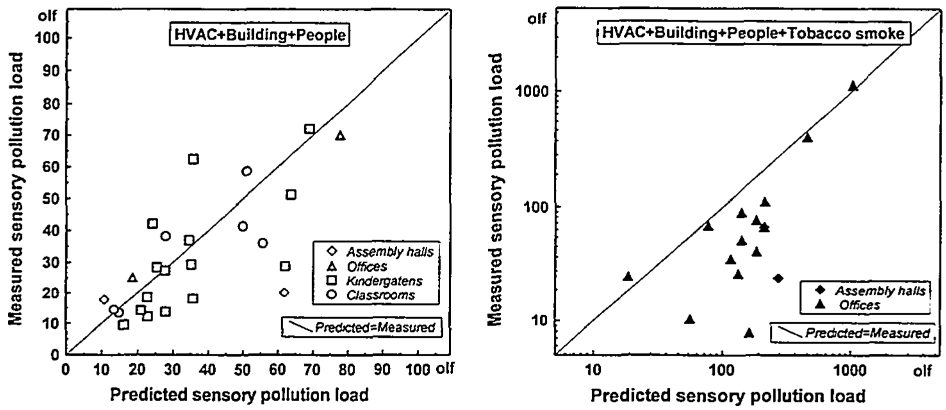


Figure 2.1.2 Measured and predicted total sensory pollution loads in offices, assembly halls, schools and kindergartens polluted by the building plus HVAC system plus people (left chart) and in offices and assembly halls polluted by the building plus HVAC system plus people plus tobacco smoke (right chart). Sensory pollution loads in the left chart were mainly calculated using sensory evaluations of trained subjects, whereas in the right chart, sensory ratings of only untrained subjects were used

Significant overestimation of the total sensory pollution loads in smoking-permitted spaces happened most likely due to three reasons: inaccurate spot measurements of CO concentrations in the field (on average below 0.3 ppm) later used to predict sensory pollution loads from tobacco smoke; sorption processes modifying sensory pollution loads on the air in smoking-permitted spaces; and varying ventilation rates on days with and without occupants in the offices and assembly halls, which could, by changing the concentration of sensory pollutants in the air, alter the sensory pollution strength of the building (Knudsen et al., 1997; Gunnarsen, 1997; Jørgensen et al., 1997).

2.1.3 Conclusion

In conclusion, the laboratory studies reviewed above provided incomplete information on whether the addition of sensory pollution loads is pertinent. Some methodological problems occurred in some of the studies and the main focus was on investigating the addition in mixtures of building materials; only in a few experimental sessions was the summation of sensory pollution loads investigated. Although some data on the addition of sensory pollution loads exist from previous field studies, they require further verification under controlled field investigation. As yet, this has never been carried out. Consequently, more research is needed before the addition of sensory pollution loads can be applied in practice. New research studies should be carried out in the field in particular with three families of sensory pollution sources such as building materials, people and tobacco smoke and at ventilation rates typically encountered in indoor environments.

2.2 Purpose

Taking into account the conclusions in section 2.1.3, new laboratory and field studies on the addition of sensory pollution loads were devised and they are described in the following sections. The purpose of these investigations was threefold:

1. To verify the data from previous laboratory experiments on the addition of sensory pollution sources, taking into account the effect of varying sensory strengths of materials with the pollution concentration in air.
2. To study the addition of sensory pollution loads in indoor air from common but widely different sources such as the building, the people and their tobacco smoking.
3. To provide missing field information on the addition of sensory pollution sources indoors.

2.3 Laboratory Study on the Addition of Sensory Pollution Sources

2.3.1 Methods

2.3.1.1 Experimental Plan

A panel of untrained human subjects assessed the quality of air sequentially in empty climate chambers, in chambers with three types of floor materials placed one at a time inside the chambers, in chambers occupied by people, and finally in chambers, that were occupied by people and in which at the same time three types of floor materials were placed, one at a time, inside the chamber. The outdoor air was supplied to the chambers at a constant rate by the HVAC system. A panel assessed also the quality of air outdoors. Sensory evaluations were made on the air extracted from the chambers and from outdoors.

2.3.1.2 Facilities

The experiments were carried out in two stainless steel climate chambers (chambers 1 and 2), each being 30 m^3 (including re-circulation ducts). The chambers were especially designed for indoor air quality studies (Albrechtsen, 1988). The ducts supplying the air to the chambers and the chambers themselves were made of stainless steel. Each chamber was served by a separate HVAC system.

The air from the chambers and from outdoors was extracted through glass tubes by means of a miniature fan. The air from the chambers was extracted from the exhaust ducts in the vicinity of the exhaust terminals in the chambers. The air from outdoors was extracted in the vicinity of the outdoor air intake for the chambers. The air samples were presented to the subjects through Teflon-coated diffusers at a flow of 1 L/s in the space immediately outside the chamber. The air for sensory assessments was not conditioned.

A large hall in the direct vicinity of the exposure systems supplying the air for the sensory assessments was used as the waiting room for the sensory panel. The hall was naturally ventilated. The air temperature and the relative humidity in the hall were not controlled, but they were similar to the temperature and relative humidity of air presented for sensory evaluations.

2.3.1.3 Pollution Sources

Air-conditioning units and the ducts supplying air to the empty chamber (i.e., without people or floor material inside) were a source of pollution from the HVAC system.

Specimens of old carpet, new linoleum and new vinyl were used as sources of pollution from flooring material. The sample of old carpet was obtained from an office building under renovation (Pejtersen et al., 1998); the carpet was approx. 20 years old. The samples of linoleum and vinyl were bought in a store a few months before the experiment. The sample of each material used during the experiment was 73 m^2, to provide a loading similar to a standard model room (3.2 x 2.2 x 2.4 m) ventilated with an air change of 1 h^{-1} (Nordtest, 1990).

Twenty students (3 females and 17 males; aged on average 22 years) were recruited to occupy the chambers and to serve as a source of bioeffluents. They were asked to abstain from eating spicy food or garlic on the experimental day and on the day prior to the experiment, and from using strong deodorants on the experimental day.

2.3.1.4 Sensory Panel

Forty-three healthy students were recruited to take part in the experiment as judges assessing indoor air quality. On average they were aged 23.5 years; 28% were females and 9% were smokers (not allowed to smoke during experiments). They were asked to abstain from eating spicy food or garlic on the experimental day and on the day prior to the experiment, and from using strong deodorants on the experimental day. They were instructed on how to use the questionnaire. Forty-one subjects completed all experimental sessions.

2.3.1.5 Procedure

The experiment took place on several days during two weeks. Before the experiment, the chambers were cleaned as well as the system extracting the air from the chambers and from outdoors, and the system presenting the air for sensory assessments; in addition, the chambers were baked-out at 40°C for 24 hours. During the entire experiment, the chambers were continuously ventilated with a total rate of approx. 420 L/s, corresponding to an air change of 50 h^{-1}. Of this total flow, 35 L/s was outdoor air and the remaining 385 L/s was re-circulated air. Outdoor air supplied to the chambers was first filtered and then conditioned to 23°C with a relative humidity of 40%. The ventilation rate was checked with the air change measurements. The temperature and the relative humidity of air in the chambers were continuously measured. The temperature and relative humidity of the air presented to subjects for sensory evaluations were measured before and after sensory evaluations.

A week before the experiments, the floor materials were unpacked, placed on an especially designed rack and stored at room temperature. The racks with the specimens of materials were then placed one at a time inside the chambers. Sensory assessments of the air quality in the chamber with floor material began three days after the material was placed inside the chamber.

Table 2.3.1 The assignment of pollution sources to the climate chambers

Climate chamber	Pollution sources
	Air-conditioning unit+supply ducts+ empty chamber 1=HVAC#1
Chamber 1	HVAC#1+people
	HVAC#1+vinyl
	HVAC#1+vinyl+people
	Air-conditioning unit + supply ducts+empty chamber 2= HVAC#2
Chamber 2	HVAC#2+linoleum
	HVAC#2+linoleum+people
	HVAC#2+carpet
	HVAC#2+carpet+people

People occupied the chambers in 4 groups of 5 persons each. During occupation they were allowed to read or to study; they were not allowed to smoke, however, or to carry overcoats, bags, food or beverages into the chambers. Sensory assessments of the quality of air in the chambers occupied by people began after reaching the pre-defined steady-state concentration of carbon dioxide (CO_2) inside the chambers (approx. 700 ppm above outdoor concentration). A matrix, according to which floor materials and people were placed inside the chambers, is outlined in Table 2.3.1.

Sensory evaluations of the air extracted from the chambers were carried out as follows. The subjects assessed the quality of air extracted: (1) from the empty chambers, thus in the chambers polluted only by chamber and HVAC system, (2) from the chambers in which floor materials were one by one placed inside, thus in chambers polluted by chamber and HVAC system plus a floor material, (3) from the chambers occupied by people, thus in chambers polluted by chamber and HVAC system plus people, and (4) from the occupied chambers in which floor materials were one by one placed inside, thus in the chambers polluted by the chamber and HVAC system plus people plus a floor material. Parallel to the assessments of the quality of air extracted from the chambers, sensory evaluations of the quality of air extracted from outdoors were made. The air quality was assessed using a continuous acceptability scale (Fig. 2.3.1). The panel did not see the chambers under study and was unaware of the type of exposure.

Imagine, that during your daily work you are exposed to this air.

How do you assess the air quality?

Answer by ticking on the scale. Pay attention to the dichotomy between acceptable and not acceptable

Clearly acceptable

Just acceptable
Just not acceptable

Clearly not acceptable

Figure 2.3.1 Continuous acceptability used by an untrained sensory panel to assess the perceived air quality

2.3.1.6 Calculations of Sensory Pollution Loads

Sensory assessments of the air acceptability were used to calculate sensory pollution loads. The continuous acceptability scale was coded as follows: clearly not acceptable=-1, just not acceptable/just acceptable=0, clearly acceptable=1. Then mean votes of acceptability were calculated for the whole sensory panel and they were transferred into perceived air quality (expressed in decipols) using formula [2.3.1] (Fanger, 1988; Gunnarsen and Fanger, 1992):

$$C = 112 \cdot \left[\ln\left(\frac{\exp(-0.18 - 5.28 \cdot ACC)}{1 + \exp(-0.18 - 5.28 \cdot ACC)} \cdot 100 \right) - 5.98 \right]^{-4} \qquad [2.3.1]$$

where:
C = perceived air quality, decipol;
ACC = mean vote on acceptability scale for a whole panel of subjects;
and the expression under the natural logarithm gives the number of dissatisfied people (%).

Then using the comfort equation [1.1] (Fanger, 1988) and measured ventilation rates, sensory pollution loads in the chamber and in the air supplied from outdoors were calculated and expressed in olfs:

$$G = 0.1 \cdot Q \cdot (C_i - C_o) \qquad [2.3.2]$$

where:
G = sensory pollution loads, olf;
Q = measured outdoor air supply to the chambers, L/s;
C_i = perceived air quality inside the chambers, decipol;
C_o = perceived quality of outdoor air, decipol.

Sensory evaluations of the air extracted from outdoors were used to calculate the sensory pollution load on the supplied outdoor air.

Sensory pollution loads from chambers and HVAC systems were obtained by subtracting the sensory pollution load on the air in the empty chambers and the sensory pollution load on the supplied outdoor air.

Sensory pollution loads from people and from a given floor material were obtained by subtracting sensory pollution loads in the empty chambers from the sensory pollution loads in the chambers in which, respectively, people were seated, or a given floor material was placed inside.

Sensory pollution loads from the mixtures of sources: chamber and HVAC system plus people, chamber and HVAC system plus a given floor material and chamber and HVAC system plus people plus a given floor material were obtained by subtracting the sensory pollution load on the supplied outdoor air from the sensory pollution loads in chambers in which, respectively, people were seated, or a given floor material was placed inside, or people were seated and at the same time a given floor material was placed inside.

Predicted total sensory pollution loads in the chambers were calculated by adding sensory pollution loads from individual sources: chamber and HVAC system, people and a given floor material. It was then compared with the measured total sensory pollution loads in the chambers polluted by chamber and HVAC system plus people plus a given floor material.

2.3.1.7 Statistical Analysis

Sensory assessments of the acceptability of air extracted from chambers were subjected to analysis of variance in repeated measures design. Mean assessments of the acceptability of air polluted by chamber and HVAC system, chamber and HVAC system plus people, chamber and HVAC system plus a given floor material and chamber and HVAC system plus people plus a given floor material were checked for parallelism using the multiple comparison Duncan test ($p<0.05$); the interaction of subject-by-pollution source in the chamber was used as the error term to remove the main effect of the subject.

2.3.2 Results

Mean temperatures and relative humidities of the air extracted from the chambers and from outdoors for sensory evaluations are shown in Table 2.3.2. Thermal conditions of the ambient air, i.e., in the room where the exposure systems extracting the air from the chambers and from outdoors and presenting it for sensory evaluations were located, were similar to those presented in Table 2.3.2 for the air extracted from the chambers. Measured outdoor air rates were 35 L/s for each chamber.

The sensory panel assessed the acceptability of air extracted from outdoors and from the chambers with an average standard error of ±0.07 (mean standard deviation of ±0.43) on the scale with endpoints coded -1=clearly not acceptable and +1=clearly acceptable, with the midpoint just not acceptable/just acceptable coded as 0. Mean acceptability of the air extracted from outdoors did not vary significantly when assessed on different experimental days ($F(8,320)=1.38$; $p<0.21$). Perceived acceptability of outdoor air was on average 0.284, which corresponds to 16% dissatisfied. This rather poor perceived quality of outdoor air may be due to its rather high temperature (Table 2.3.2) when presented for sensory evaluations (Fang et al., 1998a). The outdoor air was heated by the electric heater, which was, however, mounted on the outside surface of glass tubes. Therefore, the heater was not in direct contact with outdoor air and hence could not pollute the air presented for sensory evaluations.

Table 2.3.2 Mean measured temperature and relative humidity (± standard deviation) of the air presented to the subjects for sensory evaluations

The air extracted from:	Temperature (°C)	Relative humidity (%)
Outdoors	23.7±0.4	34±7
Chamber 1	24.6±0.4	38±4
Chamber 2	24.7±0.4	39±3

Table 2.3.3 compares the assessments of perceived quality of air extracted from chamber 1 polluted by different sources. When the chambers was occupied successively by 4 different groups of people, the air quality in the chamber was similar ($F(3,120)=1.81$; $p<0.15$) as was the source strength of these four groups of subjects. This was probably a consequence of the instructions given to the subjects, namely that they should avoid spicy foods, garlic and strong deodorants prior to and on the experimental day. Therefore, the entry (HVAC#1+people) in Table 2.3.3 is the average acceptability of air in the chambers occupied by 4 different groups of people. Table 2.3.3 shows that the quality of air in chamber 1 worsened, i.e., the mean vote of acceptability decreased, both when people occupied the chamber, when vinyl was placed in the empty chamber, and when people occupied the chamber with vinyl placed inside. The Duncan test showed that only the mean acceptability of air

extracted from the empty chamber (HVAC#1) and the mean acceptability of air extracted from the chamber into which people and vinyl were introduced simultaneously (HVAC#1+people+vinyl), were significantly different.

Table 2.3.3 Perceived quality of air in chamber 1 polluted by chamber and HVAC system (HVAC#1) and mixtures of chamber and HVAC system, people and vinyl, including the sensory pollution load on the supplied outdoor air; F-test compares mean assessments of air acceptability in the chamber polluted by the specified sources

Source type	Perceived air quality		F-test
	acceptability	% dissatisfied	
HVAC#1*	0.005	44.9	
HVAC#1+people	-0.120	61.2	F(3,120)=1.69; p<0.17
HVAC#1+vinyl	-0.087	57.0	
HVAC#1+people+vinyl*	-0.160	66.0	

* significantly different from each other (p<0.05) using the Duncan test

Table 2.3.4 compares assessments of perceived quality of air extracted from chamber 2 polluted by different sources. Analogous to chamber 1, when additional pollution sources were introduced, perceived acceptability of air in chamber 2 decreased, except for one case in which people occupied the chamber with the carpet placed inside. The Duncan test showed that only the mean acceptability of air extracted from the empty chamber (HVAC#2) and the mean acceptability of air extracted from the chamber into which people and linoleum were introduced simultaneously (HVAC#2+people+linoleum), were significantly different.

Table 2.3.4 Perceived quality of air in chamber 2 polluted by chamber and HVAC system (HVAC#2) and mixtures of HVAC, people, carpet and linoleum, including the sensory pollution load on the supplied outdoor air; F-test compares mean assessments of air acceptability in the chamber polluted by the specified sources

Source type	Perceived air quality		F-test
	acceptability	% dissatisfied	
HVAC#2	-0.296	80.0	
HVAC#2+carpet	-0.377	85.9	F(2,80)=1.11; p<0.34
HVAC#2+people+carpet	-0.366	85.2	
HVAC#2*	-0.296	80.0	
HVAC#2+linoleum	-0.403	87.5	F(2,80)=3.91; p<0.02†
HVAC#2+people+linoleum*	-0.452	90.1	

† significant; * significantly different from each other (p<0.05) using the Duncan test

Tables 2.3.3 and 2.3.4 show additionally that the mean assessments of acceptability of air polluted exclusively by the HVAC system of chamber 1 (HVAC#1) and chamber 2

(HVAC#2) were different, and caused respectively 45% dissatisfied with the air quality in chamber 1 and 80% dissatisfied with the air in chamber 2. This difference was statistically significant ($F(1,40)=44.05$; $p<0.0001$).

Measured and predicted total sensory pollution loads in the chambers are shown in Figure 2.3.2 and Table 2.3.5. It can be seen that sensory pollution loads on the air polluted by the HVAC system in chamber 1, as well as on the air polluted by individual sources (people, carpet, linoleum and vinyl) were of similar magnitude. Sensory pollution loads on the air polluted by the HVAC system supplying the air to chamber 2 were, however, almost 4 times higher than the sensory pollution loads from people, carpet and linoleum. This may have been due to malfunctioning of the humidifier. Consequently, the data obtained in chamber 2 should be used with caution when discussing the addition issue. Sensory pollution load on the outdoor air supplied into the chambers was 3.6 olf, thus 4 times lower than the sensory pollution loads of individual pollution sources inside the chambers. The total predicted sensory pollution load for the mixture with carpet was much higher than the measured load, implying sorption of bioeffluents and pollutants from the HVAC system on carpet.

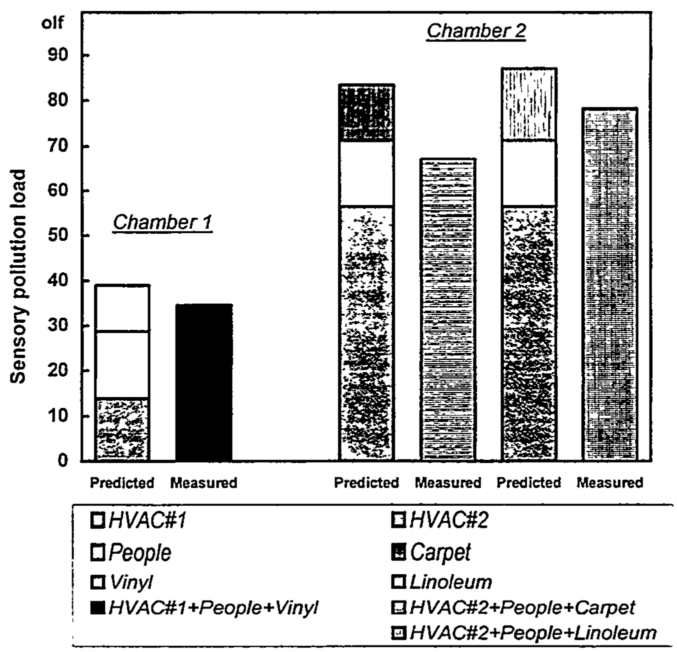


Figure 2.3.2 Measured and predicted total sensory pollution loads in the chambers polluted by three sources: HVAC system (including own emissions from the empty chamber), people and individual flooring material: vinyl, carpet or linoleum; predicted sensory pollution loads are broken into individual components of the total sensory pollution load

Table 2.3.5 Measured and predicted total sensory pollution loads in the chambers polluted by three triple mixtures of pollution sources: HVAC system supplying the air into the chambers (including own emissions from the empty chamber), people and a floor material

Floor	Sensory pollution load (olf)				
material	HVAC +	People +	Floor material =	Predicted	Measured
Vinyl	13.9	14.8	10.3	39.1	34.6
Carpet	56.4	14.8	12.2	83.4	67.1
Linoleum	56.4	14.8	15.8	87.1	78.3

2.4 Addition of Indoor Air Sensory Pollution Sources Studied in an Existing Office Space

2.4.1 Methods

2.4.1.1 Experimental Plan

The experiment was carried out in an existing office. A fan supplied outdoor air to the office at three different ventilation rates corresponding to an air change rate of 0.4, 1 and 2 h^{-1}. At each ventilation rate, the air in the office was polluted sequentially by the building (building materials and furnishings in a space), by the building plus people, by the building plus tobacco smoke and by the building plus people plus tobacco smoke. The number of people and the smoking rate in the office were controlled.

Under each of the above-mentioned conditions a sensory panel of untrained human subjects assessed the quality of air extracted from the office and from outdoors. Carbon dioxide (CO_2) concentration was measured and used as the indicator of the level of human bioeffluents in the office. Carbon monoxide (CO) was measured and used as the indicator of the concentration of tobacco smoke in the office.

2.4.1.2 Facilities

Outdoor air was supplied by a ventilation system consisting of an axial fan mounted in the window, and of a damper. The air from the office was exhausted through existing ventilation ducts. The ventilation air was neither filtered nor heated. Six small fans were installed in the office to ensure that the air was well mixed.

The air for sensory assessments was presented to the subjects through specially built exposure equipment located in the corridor adjacent to the office and hidden from view of the sensory panel. Miniature axial fans extracted the air from the central point of the office - 1.5 m above the floor, and from outdoors - in the vicinity of the axial fan intake. The air was extracted through glass tubes, and exhausted through Teflon-coated exposure diffusers at an airflow of 1 L/s. The temperature of the air for the assessment was controlled by electric heaters mounted on the outside surface of glass tubes.

An open-plan naturally ventilated office, situated in the vicinity of the exposure equipment, was used as a waiting room for the subjects resting in between sensory assessments. Neither temperature nor relative humidity of air were controlled in the waiting room.

Figure 2.4.1 shows an experimental set-up.

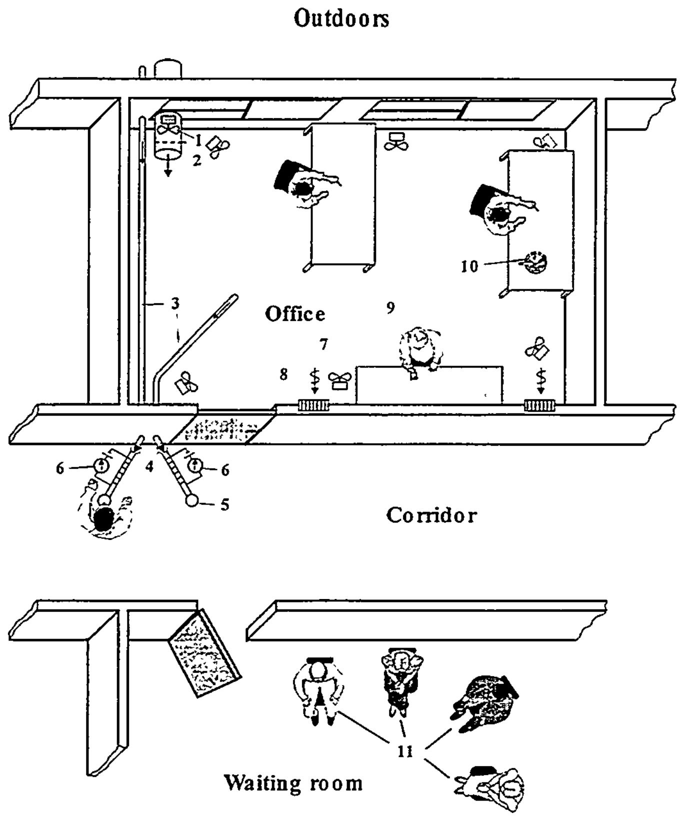


Figure 2.4.1 A view of the experimental set-up in the office; 1-axial fan; 2-damper; 3-glass tubes; 4-miniature axial fan; 5-diffuser; 6-electrical heater with power supply; 7-mixing fan; 8-exhaust ventilation grills; 9-occupants; 10-burning cigarette; 11-sensory panel

2.4.1.3 Pollution Sources

The experiments were carried out in a 25-year-old furnished office of 25.6 m^2 floor and a volume of 76.7 m^3 with two windows, cotton curtains, and a felt carpet. Substantial tobacco smoking had taken place in this office for many years in the past. The office had never been renovated since its completion in the early seventies. Building materials as well as furnishing in the office were used as the source of emissions from the building.

Fourteen paid volunteers (11 males and 3 females) aged on average 25.5±3 were used as the source of emissions from people. They were all students with the hygienic standard corresponding to 0.9 bath/day, changing underwear 0.8 times/day and 70% using deodorant every day.

Cigarettes with a tar content of 15 mg and a nicotine content of 1.3 mg were used as the source of tobacco smoke.

2.4.1.4 Sensory Panel

A pool of 43 healthy students (without previous history of asthma or allergy) participated as judges in the experiment. They were paid volunteers aged on average 22.6±4.1; 26% were females and 16% were smokers (not allowed to smoke during experiments). The only training they received was instruction on how to use the air quality questionnaire. They were also instructed not to use strong deodorants on the experimental day, and to abstain from eating spicy food, or garlic on the experimental day and the day prior to experiments. On average 33 subjects participated in each experimental session.

2.4.1.5 Procedure

The experiments took place over three months. Prior to assessments, the office was ventilated with a constant pre-defined ventilation rate corresponding to 0.4, 1 or 2 h^{-1} for a period of 72 hours and the exposure equipment was cleaned. Pre-defined ventilation rates were checked by air change measurements.

Table 2.4.1 Number of occupants and smoking rate at each designed air change rate in the office

Source type	Item	Designed air change rate (h^{-1})		
		0.4	1	2
Building+People	Number of people	3	10	12
Building+Tobacco smoke	Smoking rate (cigarette/hour)	0.3	1.4	1.1
Building+People+Tobacco smoke	Number of people	3	9	11
	Smoking rate (cigarette/hour)	0.3	0.7	1.0

The air in the office was polluted according to the matrix shown in Table 2.4.1. At first, the office was polluted by building plus people: people occupied the office in groups; during the occupation period they were clothed as they would normally be in the university; they read or studied but were not allowed to carry overcoats, bags, food or beverages into the office. Next the office was polluted by building plus tobacco smoke. Only side-stream tobacco smoke was produced: cigarettes were lit at a pre-defined rate and placed in ash-trays which were placed inside the office. Finally, the office was polluted by building plus occupants plus tobacco smoke: people occupied the office and concurrently side-stream tobacco smoke was produced by lighting cigarettes at the predefined rate and placing them in the ashtrays standing inside the office. Predefined levels of bioeffluents and tobacco smoke were checked by measurements of CO_2 and CO in the office and outdoors.

The panel assessed the air extracted from the office and from outdoors on two subsequent days. On the first day the air in the office was polluted exclusively by the building. On the second day the air in the office was polluted by either building plus people, or building plus tobacco smoke, or building plus people plus tobacco smoke; the sensory assessments on the second day began after the pre-defined steady-state concentration of CO_2 and CO were reached.

The air quality was assessed using a continuous acceptability scale (see Fig. 2.3.1). The location of the outdoor and indoor air in the exposure diffusers was randomized from day to day. The temperature and the relative humidity of the air presented for sensory assessments were measured. The sensory panel did not see the office under study and was unaware of the type of exposure. The air extracted from the office and from outdoors was assessed twice by each subject during one experimental session.

2.4.1.6 Calculations of Sensory Pollution Loads in the Office

Prediction of sensory pollution loads from people. Measurements of CO_2 concentration were used to calculate the sensory pollution loads from the people (Bluyssen et al., 1995). An average carbon dioxide production was estimated to be 18.6 L/h per occupant, for the assumed activity level (1.2 met), respiratory quotient (0.85) and the average body size of the occupants (1.9 m²) (ISO 8996, 1990; ISO 7730, 1993). The predicted sensory pollution load from people was calculated using the following relation:

$$G_P = \frac{3.6 \cdot 10^{-3} \cdot \Delta CO_2 \cdot Q}{18.6} \qquad [2.4.1]$$

where:
G_P = predicted sensory pollution load from people in the office, olf;
ΔCO_2 = measured CO_2 concentration over background, ppm;
Q = measured ventilation rate, L/s;
18.6 = average CO_2 production, L/h per occupant.

Prediction of sensory pollution loads from tobacco smoke. Measurements of CO concentration were used to calculate the sensory pollution loads from tobacco smoke. An average CO production was assumed to be 44 ml per cigarette (Clausen, 1988). The percentage of dissatisfied with the air polluted by tobacco smoke was predicted using the exposure-response relationship defined by Clausen (1986):

$$PD = f(Probit);\ Probit = 5.08 + 0.33 \cdot \ln(\Delta CO) \qquad [2.4.2]$$

where:
PD = percentage dissatisfied derived from probits (Finney, 1971);
Probit = probability unit of response (Finney, 1971);
ΔCO = measured CO concentration over background, ppm.
The predicted sensory pollution load from tobacco smoke was calculated according to:

$$G_{TS} = 11.2 \cdot Q \cdot \left[\ln(PD_{TS}) - 5.98\right]^{-4} \qquad [2.4.3]$$

where:
G_{TS} = predicted sensory pollution load from tobacco smoke in the office, olf;
Q = measured ventilation rate, L/s;
PD_{TS} = percentage of dissatisfied with the air polluted with tobacco smoke, according to [2.4.2].

<u>**Measured and predicted sensory pollution loads in the office.**</u> Sensory pollution loads in the office polluted by different sources and sensory loads on the supplied outdoor air were calculated using sensory evaluations made by untrained judges on the air extracted respectively from the office and from outdoors. Calculations were made similarly to the laboratory study on addition and are described in detail in section 2.3.1.6. In short, mean ratings of acceptability of air were transformed into decipol, and then, using measured ventilation rates and the comfort model, sensory pollution loads in olfs were derived. Two assessments of acceptability of air at each exposure were treated separately during the analysis.

Sensory pollution loads in the office polluted exclusively by the building, by the building plus people, by the building plus tobacco smoke and by the building plus people plus tobacco smoke were adjusted by subtracting the sensory pollution load on the supplied outdoor air.

Sensory pollution loads from individual sources - the building, people and tobacco smoke - were added to predict total sensory pollution loads in the space. Predicted total sensory pollution loads in the office were compared with the total sensory pollution loads measured in the office polluted by building plus people, building plus tobacco smoke and building plus people plus tobacco smoke. This comparison yielded altogether 18 experimental points: 2 assessments of each exposure x 3 mixtures of pollution sources in the office x 3 ventilation rates in the office.

2.4.1.7 Statistical Analysis

Assessments of the acceptability of air in the office were subjected to analysis of variance using a repeated measures design with the assessments of acceptability of outdoor air as co-variates.

2.4.2 Results

Measured air change rates, CO_2 and CO concentrations are shown in Table 2.4.2; measured CO concentration was in the range 0.48-0.75 ppm; it was thus higher than the estimated typical indoor CO exposure of 0.2 ppm (Walker et al., 1997). Measured concentrations of CO_2 in the office did not decrease with increasing air change rates since at different ventilation rates the number of people occupying the office varied from 3 at 0.4 h^{-1} to 11 or 12 at 2 h^{-1} (Table 2.4.1).

Table 2.4.2 Measured air change rate in the office and measured concentrations (above outdoors) of carbon dioxide (ΔCO_2) and carbon monoxide (ΔCO) in the office

Source type	Item	Designed air change rate (h^{-1})		
		0.4	1	2
Building+People	Measured air change rate (h^{-1})	0.42	1.1	2.1
	ΔCO_2 concentration (ppm)	1647	2335	1750
Building+Tobacco smoke	Measured air change rate (h^{-1})	0.41	1.1	2.0
	ΔCO concentration (ppm)	0.57	0.75	0.74
Building+People+Tobacco smoke	Measured air change rate (h^{-1})	0.35	1.1	2.1
	ΔCO_2 concentration (ppm)	1445	2144	1586
	ΔCO concentration (ppm)	0.48	0.55	0.48

Temperatures and relative humidities of the air which was extracted from the office and from outdoors and presented to the subjects for sensory assessments are shown in Table 2.4.3. Outdoor air presented for sensory evaluations had a mean temperature of 20.5±0.8°C and a mean relative humidity of 26±10%. The air extracted from the office and presented for sensory evaluations had thermal parameters similar to the outdoor air assessed by subjects, i.e., a mean temperature of 20.5±0.7°C and a mean relative humidity of 31±10%.

The sensory panel assessed the acceptability of air extracted from outdoors and from the office with an average standard error of ±0.07 (mean standard deviation of ±0.4) on the continuous acceptability scale, with endpoints coded -1=clearly not acceptable and +1=clearly acceptable, and the midpoint just not acceptable/ just acceptable coded as 0. Outdoor air quality caused on average less than 10% dissatisfied, and a mean vote of acceptability was above 0.382, which is in agreement with findings of Fang et al. (1998a), considering the thermal parameters of this air.

Table 2.4.3 Temperatures (T) and relative humidities (RH) of the air presented to subjects for sensory assessments

Pollution sources	Designed air change rate	Air presented for sensory assessments			
		Outdoor air		Office air	
		T	RH	T	RH
	h^{-1}	°C	%	°C	%
Building+People	0.4	19.6	35	19.6	41
	1	20.2	42	20.4	48
	2	20.4	21	20.3	26
Building+Tobacco smoke	0.4	21.5	14	21.3	19
	1	19.7	21	20.2	25
	2	20.2	31	20.4	33
Building+People+Tobacco smoke	0.4	21.6	27	21.6	33
	1	20.7	25	20.8	34
	2	20.9	19	20.2	21

Assessments of acceptability of air extracted from the office polluted by different sources and ventilated by various outdoor air rates are presented in Table 2.4.4. With the exception of three cases, the acceptability of air extracted from the office polluted by the building plus people, the building plus tobacco smoke and the building plus people plus tobacco smoke was perceived to be worse than the acceptability of air extracted from the office polluted only by the building. Worsening of the air acceptability was generally significant ($p<0.05$) when the office was polluted by the building plus tobacco smoke and by the building plus people plus tobacco smoke at 1 and 2 h^{-1}. Otherwise, it was only moderately significant ($p<0.10$). Unexpectedly, at ventilation rates of 0.4 and 1 h^{-1}, the acceptability of air extracted from the office polluted by the building plus people was assessed as being better than the air extracted from the office polluted only by the building; however, this effect was not significant ($p<0.46$).

Measured and predicted sensory pollution loads in the office are shown in Table 2.4.5 and also in Figure 2.4.2. The sensory pollution load from the building was quite high; it was a few times higher than sensory pollution loads from occupants and tobacco smoke, especially at the ventilation rate of 0.4 h^{-1}. The sensory pollution loads from people were similar to those of tobacco smoke. The sensory pollution load on the supplied outdoor air was generally below 1 olf, thus severalfold lower than the sensory loads caused by pollution sources inside the office.

Table 2.4.4 Perceived quality of air extracted from the office polluted: (a) by the building and the building plus people, (b) by the building and the building plus tobacco smoke, and (c) by the building and the building plus people plus tobacco smoke, and ventilated at 3 different outdoor air rates. Perceived air quality is expressed as acceptability of air (ACC),i.e., by the direct sensory ratings made by untrained subjects, and as the percentage of dissatisfied (PD), which was obtained from acceptability ratings using conversions of Gunnarsen and Fanger (1992) [2.3.1]. The two values at each air change rate are two replications of sensory evaluations of each exposure presented to subjects during experimental sessions

Designed air change rate (h^{-1})	Perceived air quality				F-test
	ACC	PD	ACC	PD	
(a)	Building		Building+People		(Building vs. Building+People)
0.4	-0.33	82.4	-0.31	81.2	F(1,75)=0.22; p<0.69
	-0.20	70.7	-0.36	85.0	F(1,75)=4.82; p<0.03**
1	-0.05	51.8	0.00	45.1	F(1,66)=0.11; p<0.74
	-0.02	48.8	0.08	35.0	F(1,66)=0.54; p<0.46
2	0.05	39.6	-0.04	50.7	F(1,63)=2.56; p<0.11*
	0.02	43.3	-0.03	48.9	F(1,63)=1.62; p<0.21
(b)	Building		Building+Tobacco smoke		(Building vs. Building+Tobacco smoke)
0.4	-0.45	90.0	-0.51	92.6	F(1,62)=0.48; p<0.49
	-0.35	84.4	-0.45	90.2	F(1,62)=1.01; p<0.32
1	-0.28	78.2	-0.44	89.5	F(1,66)=3.18; p<0.08*
	-0.18	68.0	-0.39	86.7	F(1,66)=5.37; p<0.02**
2	-0.20	70.4	-0.38	85.9	F(1,71)=2.60; p<0.11*
	-0.26	77.0	-0.46	90.6	F(1,71)=4.16; p<0.05**
(c)	Building		Building+People+ Tobacco smoke		(Building vs. Building+ People+Tobacco smoke)
0.4	-0.40	87.1	-0.45	90.0	F(1,52)=1.71; p<0.48
	-0.408	87.8	-0.412	88.0	F(1,52)=0.002; p<0.91
1	-0.26	76.6	-0.44	89.6	F(1,57)=2.91; p<0.09*
	-0.17	67.2	-0.46	90.6	F(1,57)=8.32; p<0.02**
2	-0.14	63.0	-0.20	70.6	F(1,60)=1.23; p<0.27
	-0.11	60.3	-0.27	77.6	F(1,63)=2.26; p<0.14

** significant (p<0.05); * moderately significant (0.05<p<0.11)

Table 2.4.5 Measured and predicted sensory pollution loads in the office polluted: (a) by the building plus people, (b) by the building plus tobacco smoke, and (c) by the building plus people plus tobacco smoke. Presented sensory pollution loads are adjusted for the sensory pollution load on the outdoor air supplied to the office. Two values of the sensory pollution loads at each air change rate are calculated using two repetitions of the sensory evaluations made by subjects at each exposure presented during experimental sessions (Table 2.4.4), separately for each replicate

Designed air change rate (h^{-1})	Sensory pollution loads (olf)				
	From individual sources			Total loads in the office	
	Building +	People +	Tobacco smoke =	Predicted	Measured
	(a) Office polluted by the building plus people				
0.4	16.1	2.7	-	18.8	15.6
	11.2	2.7	-	13.9	17.6
1	14.4	9.3	-	23.7	11.0
	12.9	9.3	-	22.2	7.0
2	13.7	14.3	-	28.0	27.3
	17.8	14.3	-	32.1	25.8
	(b) Office polluted by the building plus tobacco smoke				
0.4	19.5	-	4.5	24.0	21.7
	16.6	-	4.5	21.1	20.2
1	35.7	-	13.7	49.4	51.9
	25.2	-	13.7	38.9	47.8
2	53.7	-	25.7	79.4	87.5
	66.7	-	25.7	92.4	102.0
	(c) Office polluted by the building plus people plus tobacco smoke				
0.4	15.7	2.0	3.6	21.3	17.3
	16.1	2.0	3.6	21.7	16.3
1	35.9	9.2	12.2	57.3	54.7
	26.1	9.2	12.2	47.5	56.4
2	41.7	12.7	21.0	75.4	55.9
	38.5	12.7	21.0	72.2	70.1

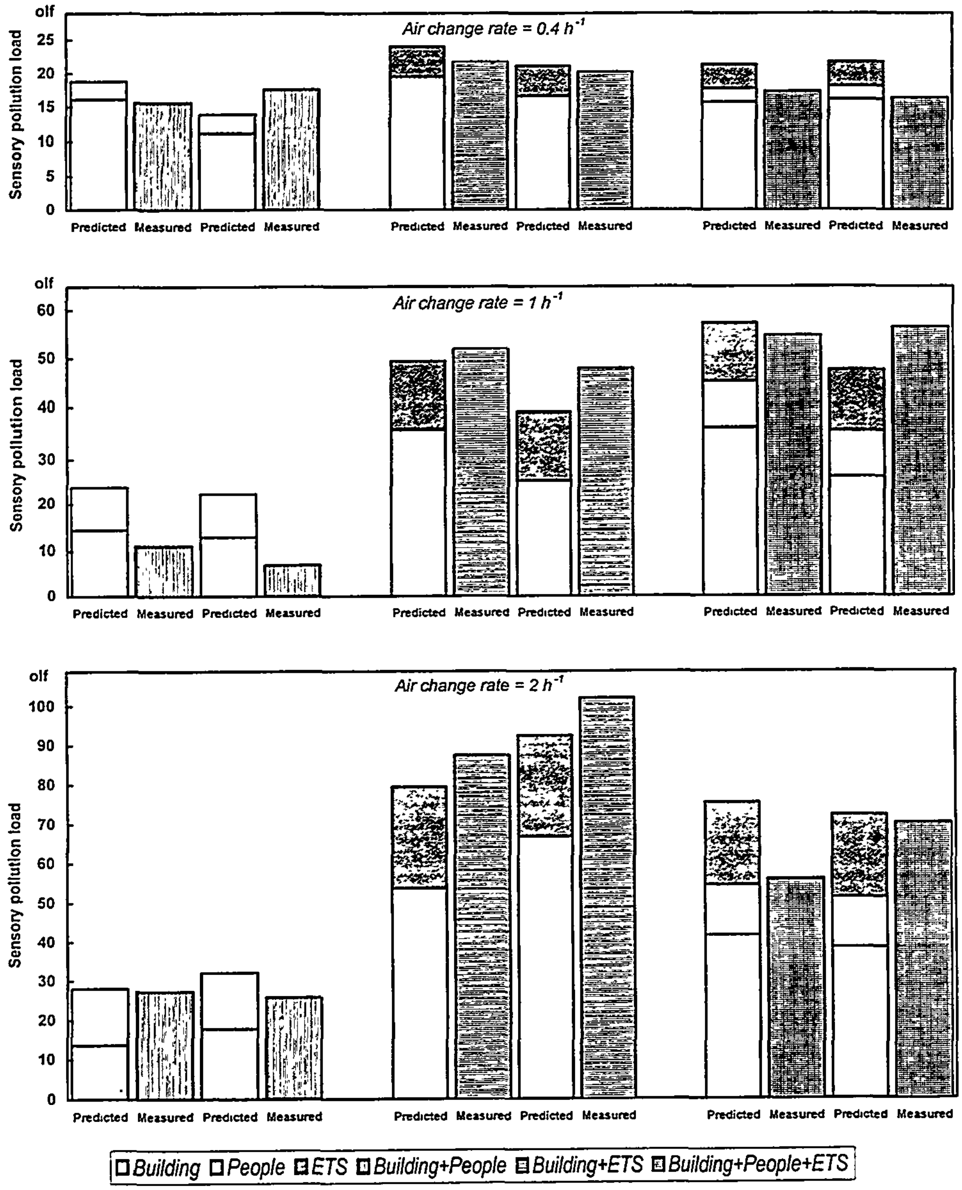


Figure 2.4.2 Measured and predicted total sensory pollution loads in the office. Predicted sensory pollution loads are split into their individual components

2.5 Modelling Data Collected in the Present Laboratory and Field Experiments on Addition

2.5.1 Method

Predicted and measured total sensory pollution loads in the climate chambers and in the existing office space were subjected to a linear regression analysis. Analysis was carried out first separately for each of the spaces, and then for the pooled data. In each case, the data were fitted with the following linear regression model:

$$G_M = a \cdot \sum G_i + b \qquad [2.5.1]$$

where:
G_M = total measured sensory pollution loads, olf;
G_i = sensory pollution loads from individual sources, olf;
ΣG_i = total predicted sensory pollution loads calculated by adding the sensory pollution loads from individual sources, olf;
a = slope of the fitted model;
b = interception of the fitted model.

If the total sensory pollution load in a space can be predicted by the summation of sensory pollution loads of individual sources, then the slope of the linear regression model should be equal to 1 (a=1) and its interception to 0 (b=0). The slope and the interception of the fitted linear regression model were thus tested, whether departing from 1 or 0, respectively (Montgomery, 1991).

2.5.2 Results

2.5.2.1 Laboratory Study in the Climate Chambers

Figure 2.5.1 (left chart) shows a linear regression model fitted to the predicted and measured total sensory pollution loads in the climate chambers. The model is described by the following:

$$G_M = 0.84 \cdot G_P + 1.64 \qquad [2.5.2]$$

where:
G_M = total measured sensory pollution loads in the climate chambers, olf;
G_P = total sensory pollution loads in the chambers predicted by adding the sensory pollution loads from chamber and HVAC system, people and the floor material, olf;
0.84, 1.64 = the slope and the interception of the fitted model, respectively.

Although the regression coefficient is high, $r^2=0.97$, the regression model is not statistically significant ($F(1,1)=29.67$, $p<0.12$). This is presumably due to the insufficient data - the model was created using only 3 experimental points. Testing the slope and the interception of the fitted model showed that the slope was not significantly different from 1 ($t=-1.07$, $df=1$, $p<0.48$), and that the interception was not significantly different from 0 ($t=0.15$, $df=1$, $p<0.91$).

Residuals, defined as the difference between the measured and predicted total sensory pollution loads, are plotted against the predicted total sensory pollution load in Fig. 2.5.1 (right chart). The plot reveals that in each of the cases studied, adding sensory pollution loads from individual sources led to overestimation of the total sensory pollution load in the chambers. Relative to the measured total sensory pollution load, the prediction of total sensory pollution load caused 13% overestimation for the mixture of chamber and HVAC system plus people plus vinyl, 11% for the mixture of chamber and HVAC system plus people plus linoleum and 24% for the mixture of chamber and HVAC system plus people plus carpet.

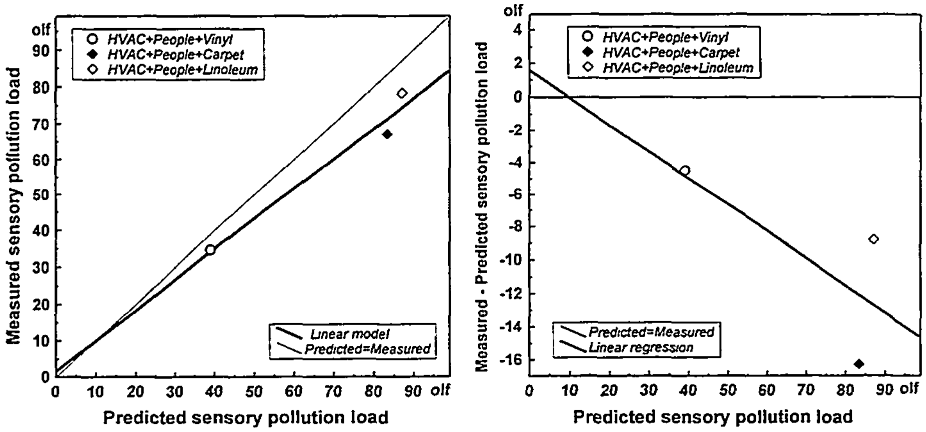


Figure 2.5.1 Left chart - measured and predicted total sensory pollution loads in the climate chambers polluted by triple mixtures of chamber and HVAC system, people and a flooring material. Right chart - residual difference between measured and predicted total sensory pollution loads in the climate chambers, plotted against total sensory pollution loads predicted by adding the sensory pollution loads caused by individual sources in the chambers

2.5.2.2 Field Study in the Office

Figure 2.5.2 (left chart) shows a linear regression model fitted to predicted and measured total sensory pollution loads in the office. The fitted model is as follows:

$$G_M = 1.09 \cdot G_P - 5.38 \qquad [2.5.3]$$

where:

G_M = measured total sensory pollution load in the office, olf;

G_P = total sensory pollution load in the office predicted by adding the sensory pollution loads from the building, people and tobacco smoke, olf;

1.09; -5.38 = the slope and the interception of the model, respectively.

The regression coefficient of the fitted linear model is high, r^2=0.92, and the model itself is statistically significant ($F(1,16)=178.4$, $p<0.0001$). Testing the slope and the interception of the model showed that the slope was not significantly different from 1 ($t=1.05$, $df=16$, $p<0.31$) and that the interception was not significantly different from 0 ($t=-1.39$, $df=16$, $p<0.18$).

Residuals, defined as the difference between the measured and the predicted sensory pollution loads, were calculated and are plotted against the predicted sensory pollution load in Fig. 2.5.2 (right chart). The figure shows the residuals quite evenly distributed along a line, depicting equal measured and predicted sensory pollution loads. Linear regression of the residuals versus predicted total sensory pollution loads indicates that the fitted linear regression model [2.5.3] overestimates total sensory pollution loads when the predicted sensory pollution loads are below ca. 60 olfs, and underestimates when the predicted sensory pollution loads are higher than ca. 60 olfs. These effects are nevertheless not statistically significant. Relative to the measured total sensory pollution loads, the prediction of the total sensory pollution load caused the highest discrepancy (i.e., either over- or underestimation of the total sensory pollution loads in the office) generally at ventilation rates of 0.4 h^{-1}; it was approx. ±25%. At ventilation rates of 1 and 2 h^{-1}, discrepancy was generally below ±15%. For the results presented in Fig. 2.5.2 (left chart) a binomial test showed that predicted total sensory pollution loads were not significantly different from the measured total loads ($N=18$, $z_o=1.18$, $p<0.12$).

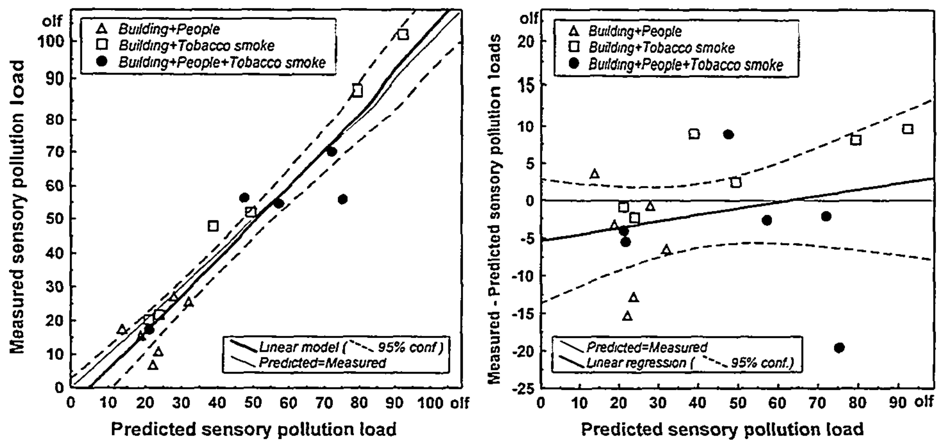


Figure 2.5.2 Left chart - measured and predicted total sensory pollution loads in the office polluted by mixtures of the building (i.e., building materials and furnishing), people and tobacco smoke. Right chart - residual difference between measured and predicted total sensory pollution loads in the office, plotted against total sensory pollution load predicted by adding the sensory pollution loads of individual sources in the office

2.5.2.3 Pooled Data from the Laboratory and Field Study

Predicted and measured total sensory pollution loads in the climate chambers and in the office are plotted against each other in Figure 2.5.3 (left chart). Experimental points fall closely to the diagonal identity line, depicting equal predicted and measured sensory pollution loads. For the pooled data from laboratory and field experiments, the following linear regression model was fitted:

$$G_M = 1.00 \cdot G_P - 3.17 \qquad [2.5.4]$$

where:

G_M = total measured sensory pollution load in the climate chambers and the office, olf;

G_P = total sensory pollution load in the climate chambers and in the office predicted by adding the sensory pollution loads from individual sources, olf;

1.00, -3.17 = the slope and the interception of the fitted model, respectively.

The regression coefficient of the fitted model is high, r^2=0.91, and the model itself is highly statistically significant ($F(1,19)$=189.52, p<0.0001). Testing the slope and the interception of the model showed that the slope was not significantly different from 1 (t=0.05, df=19, p<0.96) and that the interception was not significantly different from 0 (t=-0.84, df=19, p<0.41).

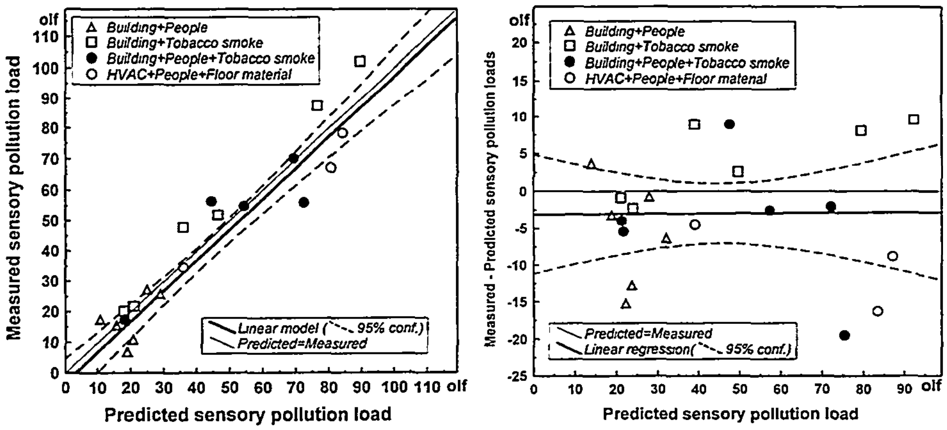


Figure 2.5.3 Left chart - measured and predicted total sensory pollution loads in the climate chambers and in the office polluted by different mixtures of sources. Right chart - residual difference between measured and predicted total sensory pollution loads in the climate chambers and in the office, plotted against total sensory pollution loads predicted by adding the sensory pollution loads from individual sources in the climate chambers and the office

Figure 2.5.3 (right chart) shows residuals for the fitted regression model. Residual distribution cannot be characterized by any particular pattern and does not depend on the predicted total sensory pollution loads. Linear regression of the residuals versus total predicted sensory pollution loads shows that the fitted model overestimates the total sensory pollution load in the space polluted by the HVAC system, the building or the flooring material, people and tobacco smoke by approx. 3 olfs. This overestimation can be disregarded since it is not significant; the interception of the regression line produced using residuals is not significantly different from 0 (p<0.41). For the results presented in Fig. 2.5.3 (left chart), a binomial test showed, however, that predicted total sensory pollution loads were significantly different from the measured total loads (N=21, z_o=1.75, p<0.04).

2.6 Discussion

2.6.1 Present Experiments on Addition of Sensory Pollution Sources

Present experiments showed that the addition of sensory pollution loads from building materials, people and tobacco smoke is a reasonable approximation of the total sensory pollution load on the air in indoor spaces. Nevertheless, the data from the present experiments cannot unequivocally be used for discussing the addition issue. This is due to the experimental procedures applied (prediction of sensory pollution loads from people and tobacco smoke, no control over adsorption and desorption of pollutants from materials) as well as to the highly polluted air in spaces (high pollution loads in the empty chambers and in the office polluted by building materials). These experimental pitfalls are thoroughly discussed later in this section. Moreover, no study was carried out during the present experiments to investigate the addition of sensory pollution loads from building materials. Neither was this problem conclusively elucidated by the previous studies, described in section 2.1.1, mainly due to a lack of control of sorption processes. Accordingly, recommendations for further studies investigating the principle of addition of sensory pollution sources are made in section 2.6.4, so that this important and controversial issue can be completely resolved in future.

2.6.1.1 Experimental Methods and Results

In the present study, the addition of indoor air sensory pollution sources was investigated in climate chambers in which the air was systematically polluted by the HVAC systems supplying the air into the chambers, by people and by three types of floor material (new vinyl, new linoleum and old carpet), as well as in an existing regularly furnished office which was ventilated with the air change rates of 0.4, 1 and 2 h^{-1} (typical as regards indoor non-industrial environments (ECA, 1997)) and was polluted systematically by three typical sources of indoor air pollution: the building (building materials and furnishings inside the office), people and tobacco smoke. A sensory panel of untrained human subjects assessed "blindly" the quality of air extracted from the chambers and from the office, without entering these spaces. In this way, assessments of air quality in the investigated spaces were not influenced by visual factors - subjects could not see that, e.g., the office was occupied or tobacco smoke was generated - or by their liking for the investigated spaces.

The addition of sensory pollution loads was studied using the comfort equation of Fanger (1988). The sensory pollution loads of individual sources were calculated by solving the comfort equation for the sensory loads, using air quality ratings in the spaces investigated and the measured outdoor air rates. Thus, an underlying assumption of the comfort model was examined by applying the comfort model. It can consequently be debated whether such methodology is correct. It should be emphasised, however, that at present sensory pollution loads cannot be measured objectively, e.g., by using instruments with direct reading or chemical measurements.

Until such objective methods become available, sensory evaluations made by humans together with the comfort equation need to be used when deriving sensory pollution loads of different sources.

Predicted sensory pollution loads were calculated by adding the sensory pollution loads on the air caused by individual sources. They were then compared with measured total sensory pollution loads in the spaces investigated. Comparisons of the measured and predicted sensory pollution loads were always made at the constant area-specific ventilation rate, i.e., within one ventilation rate, which in the laboratory study was constant throughout the entire experiment and in the office study corresponded to either 0.4, 1 or 2 h^{-1}, and without changing the amount of pollution source when present alone or in a mixture. This was done in order to avoid a possible change of the sensory emission from the pollution sources due to alteration of the concentration of sensory pollution in air (Knudsen et al., 1997; Gunnarsen, 1997; Jørgensen et al., 1997).

Linear regression models were fitted to the data collected in the present laboratory and office studies. The models compared measured total sensory pollution loads with the total sensory pollution load predicted by adding sensory pollution loads from individual sources. The analysis performed on all results obtained in the present study in climate chambers and in the office showed that measured and predicted sensory pollution loads are highly correlated, and that the total sensory pollution loads in spaces can be approximated reasonably well by adding sensory pollution loads on the air caused by individual sources. These results corroborate findings of previous investigations on addition of sensory pollution sources carried out mainly with mixtures of building materials (Lauridsen et al., 1988; Iwashita et al., 1989; Bluyssen and Fanger 1991) and also with mixtures of building materials, humans and tobacco smoke (Lauridsen et al., 1988; Iwashita et al., 1989).

For indoor climates, it is particularly relevant whether sensory pollution loads from three large groups or "families" of pollutants - human bioeffluents, environmental tobacco smoke and building pollutants (including HVAC system pollutants) - when present at the same time in a space, can be added to predict the total sensory pollution load. As mentioned above and as shown in the left chart of Fig. 2.6.1, the present chamber and field study, as well as two previous full-scale experiments (Lauridsen et al., 1988; Iwashita et al., 1989) with untrained subjects (as prescribed in Appendix C of ASHRAE Standard 62 (1989)) performed under controlled conditions, verify that for these three "families" of pollutants, addition of sources is a reasonable approximation for estimating the total sensory pollution load on the air. In a binomial test, predicted total sensory pollution loads were not significantly different from the measured total loads ($N=25$, $z_o=1.2$, $p< 0.12$).

Further corroboration of the above findings for three "families" of pollutants in a wider range of indoor spaces is shown in the right chart of Fig. 2.6.1. In this chart, total sensory pollution loads in offices and assembly halls, schools and kindergartens, which were predicted by the addition, are plotted against measured total sensory pollution loads in these spaces. These loads were calculated by reanalysing the data obtained in published field investigations (Fanger et al., 1988a; Thorstensen et al., 1990; Pejtersen et al., 1991). This was possible because of the experimental procedures applied (see section 2.1.2.1). The data were obtained using sensory evaluations made by both untrained and trained subjects. Only sensory pollution loads in spaces polluted by people and building are presented in the right chart of Fig. 2.6.1, since in rooms where smoking took place, the prediction of sensory pollution loads was probably incorrect due to inaccurate spot measurements of CO concentration and varying ventilation rates in these spaces (see section 2.1.2.2), which in consequence could alter the sensory pollution loads caused by the building (see Fig. 2.6.2). For these results, a binomial test showed that predicted total sensory pollution loads were not significantly different from the measured total loads (N=25, $z_o=0.8$, $p< 0.21$).

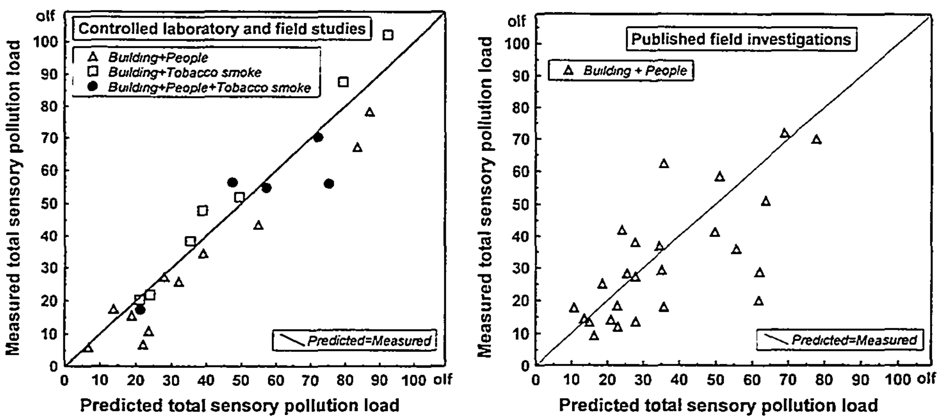


Figure 2.6.1 Total sensory pollution loads predicted by adding sensory loads on the air caused by the building (building materials, furnishings, HVAC system), people and tobacco smoke, compared with the measured total sensory pollution loads. Left chart - data from controlled laboratory and field studies using untrained subjects to assess the perceived air quality (Lauridsen et al., 1988; Iwashita et al., 1989; present field and chamber studies). Right chart - data from previously published field investigations in offices, assembly halls, kindergartens and schools using mainly trained subjects to evaluate the perceived air quality (Fanger et al., 1988a; Thorstensen et al., 1990; Pejtersen et al., 1991)

In the present experiments examining addition of sensory pollution sources, inaccuracies were introduced by the prediction of sensory pollution loads of tobacco smoke and by the non-constant sensory pollution loads of the building in the office study during sessions with tobacco smoke generation. It was also a concern that air quality in the office and climate chambers in general was rather poor during most of the experiments. These topics are discussed in the following sections.

2.6.1.2 Prediction of Sensory Pollution Loads Caused by People and Tobacco Smoke

In the field study, it was attempted to make objective measurements of sensory pollution loads from humans and tobacco smoke using markers, i.e., carbon dioxide and carbon monoxide, respectively. Measured concentrations of CO_2 and CO, along with the recent experimental data reported in the literature (Berg-Munch et al., 1986; Clausen, 1986; Clausen, 1988), were used to predict sensory pollution loads caused by people and tobacco smoke. This prediction was also made, since it was not possible in the present experimental set-up to study exclusively air polluted by people or tobacco smoke.

Data of Berg-Munch et al. (1986) (for bioeffluents emitted by European subjects) were chosen to predict the sensory pollution load from people. These data proved to be consistently similar for North Americans (Cain et al., 1983) and Japanese (Iwashita et al., 1990) at levels below 40% dissatisfied. Considering also that an average occupant in the present study (section 2.4.1.3) met the definition of one standard person (Fanger, 1988), it is expected that the prediction of sensory pollution loads from occupants was fairly accurate in the present field study. In the laboratory study, people were present alone in the empty climate chamber; thus sensory pollution loads caused by occupants could be estimated using sensory assessments made by untrained subjects and were not predicted using measured concentrations of CO_2.

Data of Clausen (1986, 1988) were chosen for the prediction of the sensory pollution loads from tobacco smoke, in view of two similarities between his study and the present field experiment: (1) the same brand of cigarettes was used and (2) the sensory panel of untrained subjects consisted of young Danish students. Despite these similarities, the data of Clausen were obtained using sensory evaluations of tobacco smoke produced actively by people smoking cigarettes, whereas in the present study tobacco smoke was produced passively in the office by lighting a cigarette and placing it in an ashtray to produce side-stream smoke. This difference can be a source of experimental error, especially considering results of Gunnarsen and Fanger (1992), which showed that at ventilation rates per cigarette lower than 100 m^3/cig., passively produced tobacco smoke is perceived as more annoying than actively produced tobacco smoke, and conversely at ventilation rates above 100 m^3/cig. This applies for the results in the office experiment. When the ventilation rate per cigarette was ca. 50 m^3/cig. (office polluted by building plus tobacco smoke at 1 h^{-1}), predicted total sensory pollution loads were lower than the measured total loads, whereas at a ventilation rate per cigarette of ca. 150 m^3/cig. (office polluted by building plus people plus tobacco smoke at 2 h^{-1}), predicted total sensory pollution loads were higher than the measured total loads.

It has recently been shown by Fang et al. (1998a, 1998b) and Toftum et al. (1998) that the perceived air quality depends significantly on the temperature and relative humidity (enthalpy) of air. Accordingly, another source of experimental error when predicting sensory pollution loads caused by people and tobacco smoke could be the difference in enthalpy of air in the present field experiments and in the investigations on which the prediction was based. In the present experiments, the air assessed by subjects had a temperature in the range 19.6 - 21.6°C and a relative humidity between 21% and 48%. In the experiments of Berg-Munch et al. (1986), on which the prediction of the sensory pollution load from people was based, the air presented for sensory assessments had a temperature between 17 and 26°C and a relative humidity between 25% and 45%. In the experiments of Clausen (1986, 1988), which were the basis for the prediction of sensory pollution loads from tobacco smoke, the air presented for sensory evaluations had a temperature of 21°C and a relative humidity of 30%. The differences in enthalpy of air were thus minor and it is expected that they did not contribute to any unilateral error of the predicted sensory pollution loads caused by people and tobacco smoke.

It can be debated whether the method of presentation of polluted air for sensory assessments (in this case facial exposure through diffusers) may have an impact on the results observed in the present experiment. A recent investigation of Jørgensen and Vestergaard (1998) showed that subjects assess the air quality to be less acceptable (poorer) when only the face is exposed, as compared to sensory evaluations of the same air during whole-body exposures. Consequently, the predicted sensory pollution loads from people and tobacco smoke in the office investigated in the present experiments may be underestimated considering that in the studies of Berg-Munch et al. (1986) and Clausen (1986), subjects entered the spaces polluted respectively by people and tobacco smoke, and thus exposed their whole body during sensory evaluations. On the other hand, in the experiments of Cain et al. (1983) and Iwashita et al. (1990), bioeffluents were assessed by subjects exposing only their face outside the chamber; nevertheless their results agreed well with the data of Berg-Much et al. (1986).

2.6.1.3 Sensory Pollution Loads in Climate Chambers and in the Office

It was intended that all pollution sources used in the present study should have a sensory pollution load of a similar magnitude. This criterion was defined to avoid mixtures comprising one very strong pollution source and other sources of pollution being relatively weak. It was expected that in highly unbalanced mixtures the total sensory pollution strength would be rather similar to the strength of the dominant source (which was the case in the present study during sessions in the office ventilated at 0.4 h^{-1}) and in this way the power of the experimental results would be decreased. The foregoing criterion was actually met only in chamber 1 polluted with the HVAC system, people and vinyl, and in the office polluted by the building and people at the air change rate of 2 h^{-1}. In both cases sensory pollution loads of all sources in these spaces were equivalent in magnitude, and adding loads of individual sources proved to be a true estimation of the total sensory pollution load. The reason for obtaining only few mixtures with individual sources causing similar sensory pollution loads on the air in the chambers and the office was a heavy pollution in chamber 2 and a rather highly polluted office.

Sensory pollution loads on the air passing the HVAC systems supplying the air to the chambers were quite high: 1.5 olf/m^2floor for chamber 1 and 6.3 olf/m^2floor for chamber 2, even though the climate chambers in which the experiments were carried out and their HVAC systems were designed for air quality studies: they were made of stainless steel or were Teflon-coated (Albrechtsen, 1988). The high sensory pollution load on the air extracted from the empty chambers may have been due partly to the high temperature of the air (Table 2.3.2). According to the results of Fang et al. (1998a), this high air temperature could elevate the sensory pollution loads by ca. 0.6 olf/m^2floor. Some pollution may have been introduced by the system used to extract the air from the chambers and present it for sensory evaluations. However, the pollution contributed by these systems is anticipated to be low since they were made of glass only and the heaters were not in direct contact with the air. Heavy sensory pollution of the HVAC system, particularly in chamber 2, may have been due to malfunctioning humidifiers. Due to high pollution loads on the air extracted from the empty chambers, it was decided to treat the HVAC system plus the system extracting the air from the chambers as another pollution source in addition to people and floor materials introduced into the chamber. In this way, the data collected could still be used to investigate the addition of sensory pollution sources.

The sensory pollution load on the air in the office caused by the building in sessions when tobacco smoke was not generated equalled 0.6 olf/m^2floor. This high load was probably due to heavy smoking having taking place in the office for many years in the past, as well as to pollution from the felt carpet (Wargocki and Fanger, 1997). Generation of tobacco smoke (ETS) aggravated even more the already poorly perceived air quality in the office and thus elevated by three times the sensory pollution load caused by the building (plus ETS from previous smoking) to 1.6 olf/m^2floor at a high ventilation rate (Fig. 2.6.2 - left chart). An explanation for such a significant elevation of sensory pollution loads could be that some people are very sensitive to the presence of ETS in the air, immediately voting that the air is unacceptable if only sensing ETS, independently of whether pollutants are present in the air due to active or passive smoking, or due to ETS deposits desorbing from the surfaces.

The present study confirmed that tobacco smoke (both during smoking and post-smoking periods) as well as poorly maintained ventilation systems can be serious pollution sources in the buildings.

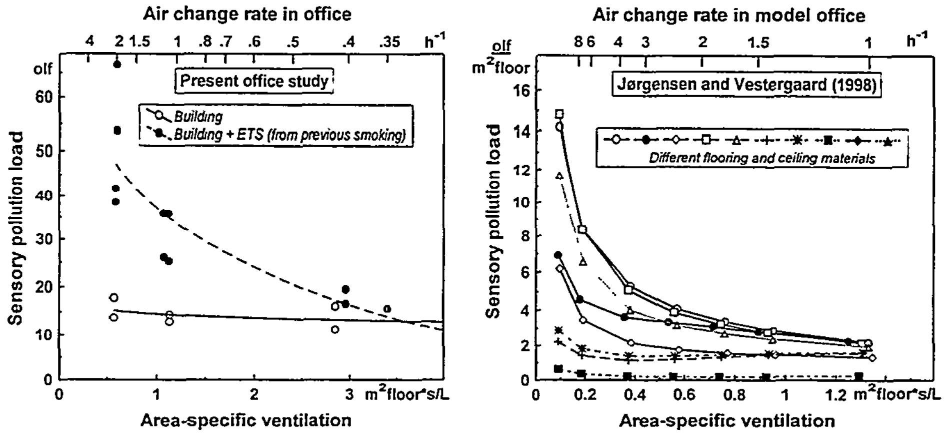


Figure 2.6.2 Impact of changing ventilation rate on the sensory pollution load of materials. Left chart- the relationship between the area-specific ventilation rate and the sensory pollution loads on the air caused by the building (building materials and furnishing) and building plus tobacco smoke (from previous smoking) in the present field experiment. Right chart - results from the previous laboratory studies for the range of flooring and ceiling materials (Jørgensen and Vestergaard, 1998)

The office investigated in the present study was ventilated at three ventilation rates. Hence it was studied whether the sensory pollution load on the air caused by the building (building materials and furnishing in the office) changed when ventilation rates were altered. The results are plotted in Fig. 2.6.2 (left chart) and show that in sessions before tobacco smoke was generated in the office (carried out at the beginning of experiments), the sensory pollution load on the air caused by the building was constant and did not change when altering the air change rate from 0.4 h^{-1} to 2 h^{-1}. Similar results were obtained by Jørgensen and Vestergaard (1998) (see right chart of Fig. 2.6.2), who showed that for the air change rates below 3 h^{-1} in the model test office (Nordtest, 1990), sensory emissions from a range of building materials do not depend on the concentration of sensory pollution in air. After tobacco smoke had been produced in the office, the sensory pollution load on the air caused by the building plus tobacco smoke from previous smoking became unstable and changed correspondingly with an increasing ventilation rate (Fig. 2.6.2 - left chart). Considerable variation in sensory pollution loads on the air caused by the building plus tobacco smoke from previous smoking was most likely due to tobacco smoke deposits which adsorbed on fleecy surfaces in the office (e.g., felt carpet, cotton curtains) when cigarettes were lit, and desorbed when the production of tobacco smoke ceased.

Also, during a laboratory study in the chambers, sorption could occur, especially when the mixture of pollution sources studied contained carpet with a large sorbing capacity. Adsorption of bioeffluents and pollutants emitted by the HVAC system on the carpet surface may have decreased the sensory pollution load on the air in the chamber.

The dynamic sorption processes described above could modify the sensory pollution load on the air in the chamber and the office, and thereby inflate experimental error. However, due to meagre sensory data on sorption, accurate estimation of its impact on the present results is difficult.

2.6.1.4 Perceived Air Quality in Climate Chambers and the Office

High sensory pollution loads from the HVAC system in climate chambers and from the building in the offices caused in turn rather poor perceived air quality in these spaces. Air pollution in the empty chambers caused 45% and 80% dissatisfied, and in the office polluted by the building from 40% up to 90% dissatisfied. Introducing an additional source of pollution, i.e., people, flooring materials or tobacco smoke, into already highly polluted spaces caused an aggravation of the perceived air quality in most of the cases investigated. This aggravation was at the same time in many cases not statistically significant. This happened probably due to: (1) an insufficiently large untrained panel, considering that standard deviations around mean ratings of acceptability for untrained subjects are large, and (2) olfactory suppression of the perceived intensity increasing together with concentration of stimuli (Cain, 1988) and resulting in rather small changes of the perceived levels of air quality when the air is poor (i.e., percentage of dissatisfied is high). In the present study, 40 subjects were used. A panel of this size can distinguish two levels of air acceptability at 5% significance when they differ by minimum 0.2 on the acceptability scale shown in Fig. 2.3.1. As mentioned above, the air quality in the chambers and in the office investigated in the present study caused above 50% dissatisfied. Consequently, the differences between perceived levels at this poor air quality were probably diminished by the olfactory suppression when the air polluted by various sources in the spaces was assessed by untrained subjects.

In Fig. 2.6.3 (left chart), the percentage of persons dissatisfied with the quality of the air in the climate chambers and in the office measured by a sensory panel of untrained subjects is plotted against the percentage of dissatisfied predicted using measured ventilation rates and total sensory pollution load on the air in these spaces, predicted by adding sensory pollution loads from all individual sources. It can be seen that the air quality in the climate chambers and in the office was rather poor and did not meet the requirements of the ventilation guidelines (ECA, 1992) and proposed ventilation standards (ASHRAE, 1996; prENV 1752, 1997). For comparison, a similar plot was made in Fig. 2.6.3 (right chart) for the data obtained in previous laboratory studies on addition and discussed in earlier published field investigations (only data from non-smoking spaces is presented). Also in this case, laboratory experiments were carried out at rather poor air quality, in most cases causing more than 40% dissatisfied. In published field investigations, better levels of air quality were observed. This difference is systematic and can probably occur due to the way the air was presented for sensory evaluations. In the present experiments and in previous laboratory studies, subjects exposed only their face to polluted air during sensory evaluations, whereas in published field investigations subjects assessed the air upon entering a space. Sensory evaluations during facial exposures were also found to be more critical than sensory ratings during whole-body exposures in the earlier mentioned study of Jørgensen and Vestergaard (1998).

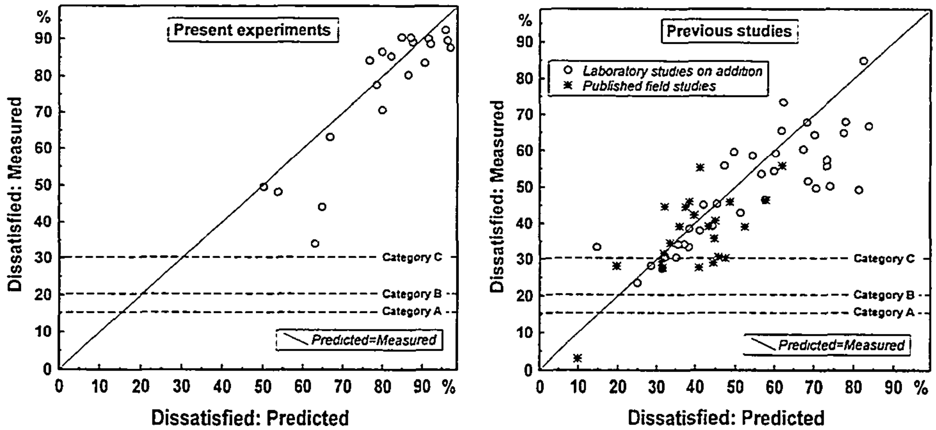


Figure 2.6.3 Percentage of dissatisfied predicted using measured ventilation rates and total sensory pollution load on the air, predicted by adding sensory pollution loads from all individual sources, plotted against the percentage of persons dissatisfied with the quality of air measured by a sensory panel of untrained subjects. Left chart - data from present experiments in climate chambers and the office. Right chart - data from previous laboratory studies on addition (Lauridsen et al., 1988; Iwashita et al., 1989, Bluyssen and Fanger, 1991; Bluyssen and Cornelissen, 1997) and published field studies (Fanger et al., 1988a; Thorstensen et al., 1990; Pejtersen et al., 1991). Data from non-smoking spaces only are presented in the figure. Three categories of perceived air quality in buildings suggested in the proposed European pre-standard (prENV 1752, 1997) are indicated on both charts

2.6.2 Addition of Sensory Sources vs. Addition of Sensory Effects

To find total perceived intensity of an odour mixture, intensities of individual odours are used (Cain and Moskowitz, 1974). At supra-threshold concentrations, perceived intensity of the mixture of odours is lower than the sum of the perceived odour intensities of its unmixed components and it thus exhibits hypo-addition (incomplete-addition) of perceived odour intensities (Zwaardemaker, 1900; Jones and Woskow, 1964; Berglund et al., 1973; Laffort and Dravnieks, 1982; Cometto-Muñiz and Hernández, 1990; Cometto-Muñiz et al., 1997). This is in agreement with the psychophysical power law of Stevens (1975), which shows that the olfactory system attenuates input so that perceived intensity grows more slowly than increasing stimulus concentration. At supra-threshold concentrations, it is also reasonable to expect that the perceived odour intensity of the mixture of odours will be close to the perceived intensity of the strongest odorant in the mixture when it is present alone (Cain and Drexler, 1974; Cain et al., 1995). Only at sub-threshold concentrations can complete addition of perceived odour intensity in mixtures (Patterson et al., 1993;

Hau and Connell, 1998) or hyper-addition (synergism) of perceived odour intensity (Baker, 1964; Laska and Hudson, 1991) be expected, although they are quite rare phenomena.

Addition of sensory pollution sources follows the so-called stimulus addition principle and not the addition of perceived levels (see Rifkin and Bartoshuk (1980) for comparison of the two principles). Stimulus addition occurs when substances providing effectively the same stimulus are mixed and consequently form a mixture that acts as a higher concentration of mixed substances. Consequently, in a space with n people, the total sensory pollution load is n-times sensory pollution from one person, similar to a space with m identical smokers, where the total sensory pollution load is m-times sensory pollution from each smoker, or to a space with n people (n olfs) and m smokers (k olfs), where the total sensory pollution load is $n+k$ olfs. Therefore, adding sensory pollution (olfs) from different sources in a space results in a higher concentration of the sensory pollution (olfs) in a space, and not proportionally higher perceived levels. This occurs because the percentage of dissatisfied with the air quality, and also perceived odour intensity, is not proportional to the strength of the pollution sources and is not additive. Although two decipols is twice the air pollution caused by one olf ventilated at the constant airflow of 10 L/s, two decipols are not perceived as twice as strong as one decipol, since the perceived air quality expressed in decipol is non-linearly related to the percentage of dissatisfied. This is illustrated in Table 2.6.1, where doubling, tripling and quadrupling the number of persons (and accordingly the sensory pollution strength of bioeffluents) in a non-polluting space ventilated with a constant outdoor air rate of 7 L/s, does not proportionally increase the percentage of dissatisfied among persons assessing the quality of air polluted by bioeffluents.

Table 2.6.1 Perceived air quality, expressed as percentage of dissatisfied, in a non-polluting space occupied by different numbers of people; a space is ventilated with a constant rate of 7 L/s

Number of persons	Equivalent sensory pollution strength (olf)	Perceived air quality (% dissatisfied)
1 person	1	20
2 persons	2	32
3 persons	3	41
4 persons	4	48

Another example illustrating that a proportional increase of the sensory pollution strength does not cause a proportional increase of the percentage of dissatisfied can be taken from the results of air quality measurements in climate chamber 1 in the present laboratory study; this chamber was polluted by three sources that were equivalent as regards sensory pollution strength. As shown in Table 2.6.2, doubling the total sensory pollution load in the chamber by introducing people, and tripling it by introducing people and vinyl did not respectively double or triple the percentage of dissatisfied in an evaluation of the quality of air in the chamber.

Table 2.6.2 Perceived air quality, expressed as percentage of dissatisfied, in the climate chamber polluted by chamber and HVAC system, people and new vinyl, each of these three pollution sources having an approximately similar sensory pollution strength equivalent to ca. 12 standard persons (olfs); the chamber was ventilated at a constant outdoor air rate of 35 L/s (data taken from the present laboratory study)

Pollution source in the chamber	Equivalent sensory pollution strength (olf)	Air quality perceived by sensory panel (% dissatisfied)
Chamber and HVAC	13	40
Chamber and HVAC+people	24	54
Chamber and HVAC+people+vinyl	35	63

Hence, addition of sensory pollution sources does not contradict psychophysical laws as discussed by some authors (Parine, 1994; Aizlewood et al., 1996). It is similar to the well-known additive rules for the strength of light, noise and heat sources. For these cases, their source strength expressed in lumens and watts are additive, while the perceived levels are not additive.

2.6.3 Addition of Pollution Sources as a Basis for Calculating Ventilation Rates for Acceptable Indoor Air Quality

Modelling the results of the present experiments carried out in climate chambers and in the office showed that in indoor environments, the addition of individual sensory pollution sources, such as people, tobacco smoke and the building is a reasonable approximation when calculating the total sensory pollution load in a space. This implies that the total ventilation rates required for a prescribed level of perceived air quality in a space can be found approximately by summation of ventilation rates required to handle the building, persons and their tobacco smoking (if permitted), i.e. to handle each individual pollution sources when occurring alone. This principle is recommended as an approximation in the European "Guidelines for Ventilation Requirements in Buildings" (ECA, 1992), in the proposal of the European draft prestandard prENV 1752 "Ventilation for buildings: Design criteria for the indoor environment" (prENV 1752, 1997) and in the proposed revised version of ASHRAE Standard 62-1989R "Ventilation for Acceptable Indoor Air Quality". The results of the present experiments reject the recommendation given in the document "Indoor Climate - Air Quality" prepared by the Nordic Committee on Building Regulations (NKB, 1991), in which total ventilation rates are calculated by summation of the half rate required to handle the occupants and the total rates required to handle other pollution sources.

An obvious implication of ventilating for all sensory pollution sources in indoor spaces is an increased total required ventilation rate and this higher ventilation demand can be seen as increased energy consumption in buildings. On the other hand, a need for higher ventilation rates involves a strong incentive to decrease sensory pollution loads in buildings in order to reduce the ventilation required for acceptable indoor air quality as well as the use of energy. A decrease in sensory pollution loads indoors can be achieved by, e.g., proper selection of building materials or the avoidance of superfluous pollution sources (see Chapter 4 of the present thesis for further discussion). Existing ventilation guidelines (ECA, 1992) and proposed ventilation standards (ASHRAE, 1996; prENV 1752, 1997) thus recommend designing for buildings having sensory pollution strengths lower than 0.1 olf/m^{2}floor.

Recently, Rosenbaum and Sterling (1998) proposed a new principle, the so-called "maximum pollution source" principle. According to this, it is exclusively the strongest sensory compound among ca. 6000 pollutants in indoor air (ca. 500 human bioeffluents, ca. 500 pollutants emitted by building materials and ca. 5000 pollutants in tobacco smoke) that determines the perceived air quality and the ventilation required to make the air acceptable for people, thereby signifying that the perceived air quality, the acceptance of air and the required ventilation rate would be the same whether the other 5999 pollutants were present or not.

To support the "maximum pollution source" principle, Rosenbaum and Sterling quoted data of Bluyssen and Cornelissen (1997), which show that the total sensory pollution load can be predicted fairly well by the sensory pollution strength of the strongest source in the mixture. These findings (shown in the left chart of Fig. 2.6.4) were obtained only for a few binary mixtures consisting mainly of fleecy materials ventilated in small 3 L glass chambers; under these conditions, sorption could distort the final outcome of their experiment (as thoroughly discussed in section 2.1.1.3). Even though no sorption had occurred in the study of Bluyssen and Cornelissen, their data cannot be used to support the principle of Rosenbaum and Sterling. This principle is not based on dimensioning the ventilation based on the strongest sensory source, but on the strongest sensory compound. Logically then, only the strongest sensory compound in a mixture of compounds emitted by the strongest sensory source should be used to derive the ventilation rates. This seems to be quite unrealistic.

The results mentioned above of Bluyssen and Cornelissen (1997) cannot be confirmed by the data collected in the present experiments for a wide range of pollution sources investigated in full-scale experiments by untrained subjects. This is indicated in Fig. 2.6.4 (right chart), where the results of the present experiments on addition are plotted in a different way, so that comparison with the results of Bluyssen and Cornelissen can be made. The total sensory pollution loads in the climate chambers and in the office are predicted by the highest sensory pollution load of the sources present and plotted against the total measured sensory pollution loads. This plot reveals that total sensory pollution loads predicted by the highest load underestimate the total sensory pollution load in a space. A linear regression model on these data is significant ($F(1,19)=152.2$; $p<0.0001$) with $r^2=0.88$; it has a slope of 1.5, significantly different from 1 ($p<0.0006$) and interception of -1.15, not significantly different from 0 ($p<0.78$). These results, together with the outcome of binomial test ($N=21$, $x=3$, $p<0.001$) point to a need to account for all sensory pollution loads when estimating total load on the air in a space.

That a "maximum source principle" is fundamentally wrong is further illustrated in Table 2.6.3. In this table, ventilation rates were calculated for three of the strongest sensory compounds selected from human bioeffluents, pollutants from building materials and tobacco smoke, which according to the principle suggested by Rosenbaum and Sterling (1998) should govern the ventilation requirements in buildings. The ventilation rates required to handle the maximum compounds are several orders of magnitude lower than the rates in the present standards and guidelines. This discrepancy is probably due to the fact that the "maximum source principle" does not take into account that individual air pollutants occur indoors at extremely low, subthreshold concentrations which cannot be perceived by humans when present alone, but which become perceptible in a mixture comprising many compounds at subthreshold concentrations (Patterson et al., 1993; Cometto-Muñiz et al., 1997; Hau and Connell, 1998).

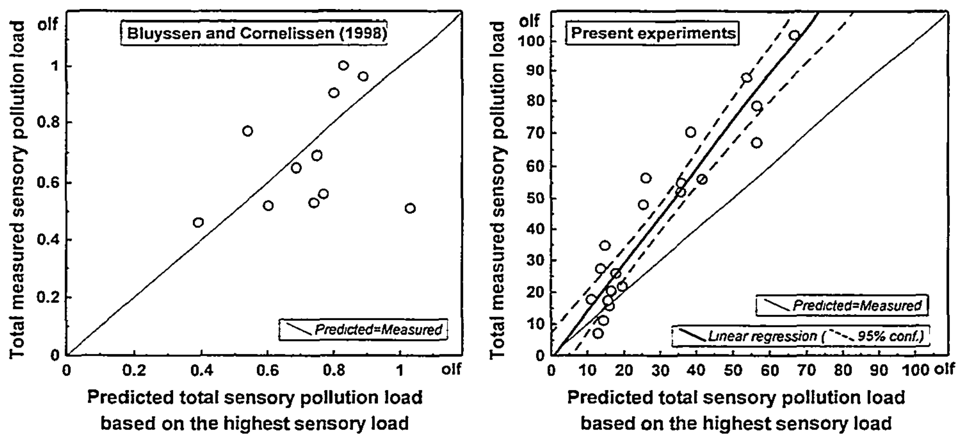


Figure 2.6.4 Total sensory pollution loads predicted as the highest available sensory pollution load among all sources present in the mixture, compared with the measured total sensory pollution load. Left chart - data from experiments of Bluyssen and Cornelissen (1997) for binary mixtures of building materials ventilated in small glass chambers. Right chart - data from the present experiments carried out in climate chambers and in an office with mixtures of pollutants from building, people and tobacco smoke

Table 2.6.3 Ventilation rates calculated for the strongest sensory pollutants selected from human bioeffluents, building materials and tobacco smoke, according to the "maximum source principle" suggested by Rosenbaum and Sterling (1998), as compared to currently recommended ventilation requirements in buildings for these three families of pollutants

Pollution sources	The strongest compound	Emission rate (ER)	Sensory endpoint (SE)	Ventilation rate	
				"maximum source principle" (ER/SE)	currently used
Human bioeffluents	2-propanone	0.66 µg/h*person (Wang, 1975)	6.05† µg/L (Bluyssen et al., 1989)	0.11 L/s*person	7 L/s*person (Fanger and Berg-Munch, 1983)
Building materials	toluene	0.043¶ mg/m³*h (Chapter 3 of present thesis)	5.89‡ mg/m³ (Devos et al., 1990)	0.007 h^{-1}	1 h^{-1} (Nordtest, 1990)
Tobacco smoke	hydrogen sulphide	78 µg/cigarette (Guerin, 1980)	26‡ µg/m³ (Devos et al., 1990)	3 m³/cigarette	120 m³/cigarette (Cain et al., 1983)

† concentration of 2-propanone in air causing 20% dissatisfied with the air quality
¶ in the model room of 17m³ at the air change rate of 1 h^{-1} (Nordtest, 1990)
‡ odour threshold concentration

2.6.4 Recommendations for Future Research

Taking into account the poor air quality in the spaces investigated (Fig. 2.6.3), the high sensory pollution loads and the experimental errors introduced mainly by prediction of the sensory pollution strength of tobacco smoke and sorption processes, it is recommended that supplementary full-scale studies be performed on the addition of sensory pollution loads of building materials (including HVAC system), people and tobacco smoke. These studies should be carried out at a perceived air quality below 30% dissatisfied. Experiments with people and tobacco smoke should include separate studies on the human perception of bioeffluents and tobacco smoke. A wider range of building materials than that investigated in the present experiment should be included; in particular, recommended low-polluting building materials, i.e., those having a sensory pollution strength below 0.1 olf/m²floor, should be used. In all studies, particular attention should be paid to the likely change of sensory pollution strength at air change rates above 3 h^{-1}.

The pragmatic approach of studying the addition of sensory pollution loads caused by the families of sources, i.e., building materials, people and tobacco smoke, in full-scale experiments should be supplemented with laboratory studies investigating the way in which sensory pollution loads caused by individual building materials should be combined. This information exists from previous studies (see section 2.1.1); nevertheless, additional experiments are suggested. In these studies, common building materials should be used and the sorption should be better controlled than previously. For this purpose, the experimental set-up presented in Fig. 2.6.5 can be used. The principle of this set-up is that each of the materials studied is ventilated separately and the air polluted by materials (not the materials themselves) is mixed. Sensory assessments are carried out on the air polluted by individual sources (ACC_{i1}, ACC_{i2}, ..., ACC_{in}), as well as on the air with a mixture of pollutants emitted from the sources studied (ACC_m). Only relevant mixtures should be studied, e.g., a mixture of flooring, wall and ceiling materials. Mixtures including, e.g., two flooring materials, or two ceiling materials should not be examined as such mixtures would not normally be present in an indoor environment.

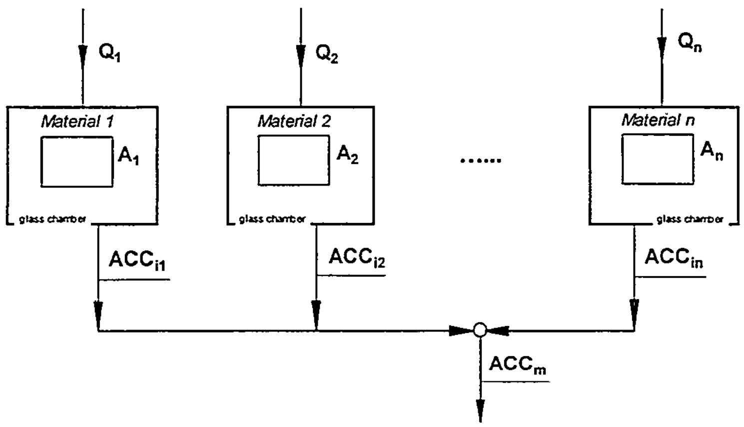


Figure 2.6.5 Experimental set-up recommended for use in future studies investigating the addition of sensory pollution loads caused by building materials

To be able to adapt results for building materials obtained in laboratory experiments using facial exposures for full-scale modelling with whole-body exposures, transfer functions should be developed. An attempt to create a transfer function between facial and whole-body assessments of air polluted by two floor materials and a mixture of flooring, wall and ceiling materials has recently be made by Jørgensen and Vestergaard (1998). In future, a wider range of sources should be used in order to produce such a transfer function.

At present, it is assumed in the comfort model (Fanger, 1988) that sensory pollution loads from sources other than people behave similarly to human bioeffluents, implying that the exposure-response relationships between the concentration of air pollutants and the perceived air quality is uniform (Fig. 1.1). Consequently, the sensory strength of pollution sources other than people is expressed by an equivalent strength of bioeffluents in air. This assumption can be modified in future, depending on whether sensory pollution loads are constant or are a function of ventilation rates. The experimental set-up presented in Fig. 2.6.5 can also be used to investigate this issue.

Sorption is a phenomenon which should also be addressed in future studies. As shown in the present experiment, it can significantly change the total sensory load on the air caused by many pollution sources.

The addition of sensory pollution loads caused by the components of the HVAC system should also be studied in future. In the HVAC system, each component can act as a sink or a source of pollution, and this may have to be considered when calculating the total sensory pollution load on the air caused by a HVAC system.

Future studies may also provide an update on existing data for human bioeffluents and tobacco smoke. Further information on sensory pollution from building materials and HVAC components can be collected simultaneously. This information is at present quite limited, although it is currently being expanded and collected in two new research projects: AIRLESS and MATHIS, a continuation of the European Data Base project on Indoor Air Pollution Sources (Clausen et al., 1996). Data on sensory emissions from different pollution sources and on addition of sensory pollution sources are essential for designers, architects and engineers for the design of comfortable indoor environments for human beings.

2.7 Conclusions

- The underlying assumption of the comfort model for perceived air quality regarding the addition of sensory pollution sources was investigated in a climate chamber and in an office. The results show that the total sensory pollution load in a space can be approximated fairly well by adding the sensory pollution loads of individual sources such as the building (building materials, furnishing, HVAC system), people and tobacco smoke. In most of the previous independent studies on addition, similar results were obtained.

- The sensory pollution strength of the building (building materials and furnishing) in the non-smoking office was constant and did not vary when the air change rate in the office was altered from 0.4 to 2 h^{-1}, indicating that in the range of typical ventilation rates encountered indoors, sensory emission from the building is not influenced by the concentration of sensory pollution in air. Similar results were obtained in recent independent laboratory investigations with a range of building materials.

- The sensory pollution strength of the building in a smoking-permitted office increased due to deposits of tobacco smoke adsorbing on surfaces during smoking periods. These deposits caused the sensory pollution strength of the building to vary when ventilation rates were changed.

- The addition of sensory pollution sources is similar to the addition of sources of light, noise and heat. It should not be confused with the combination of different perceived levels of light or odour intensities which usually exhibit hypo-addition.

- All individual pollution sources present in indoor spaces should be accounted for when estimating the ventilation requirement. Ventilation rates required to provide a certain prescribed air quality can with reasonable approximation be found by adding the ventilation rates required to handle the building, the occupants and their tobacco smoking.

- Further full-scale studies on the addition of a wider range of sensory pollution sources are suggested. These studies should be carried out at moderate pollution levels, causing less than 30% dissatisfied with the air quality. Laboratory experiments are also recommended to investigate the addition of sensory pollution loads caused by individual building materials. In future studies, sorption effects should be carefully controlled. Exposure-response relationships for the pollution sources investigated should also be created and compared with the exposure-response relationship for bioeffluents.

CHAPTER 3

Reference Atmospheres for Human Sensory Assessments of Perceived Air Quality

3.1 Introduction

At present, human olfactory and chemical senses are superior to chemical analysis as regards prediction of the sensory effects of complex mixtures of air pollutants on humans. Despite considerable progress made in analytical chemistry over the past decade, a complex compound-by-compound approach employing detailed chemical analysis does not usually provide an adequate basis on which to model air quality as it is perceived by humans. This is due to complicated indoor air chemistry, measuring problems, interactions between compounds, and insufficient sensory and toxicological information regarding mixtures.

People are usually asked directly to rate whether the air quality is acceptable or not, whether the air pollution causes irritation of the eyes, nose or throat, whether they experience headaches, or increased tiredness, etc. To study such effects on humans in simulated conditions in the laboratory, the air pollution to which people are exposed in indoor climates in practice should be well defined and carefully reproduced in the laboratory. This can be achieved by ventilating typical indoor air pollution sources such as building materials, furnishing, carpets, etc. (Pejtersen et al., 1998; Knudsen et al., 1998) or by controlled addition of mixtures of pollutants to the air during laboratory exposures (Mølhave et al., 1986). The advantage of the latter method is that the composition and concentration of the air pollution can be reproduced with a high level of accuracy. The former method may guarantee a wider range of pollutants from real materials, but the pollution may be more difficult to control over time.

Controlled addition of pollutants to the air can be used to create reference exposures used in sensory evaluations of indoor air quality. Bluyssen et al. (1989) selected 2-propanone for that purpose and established a relationship between 2-propanone concentration and the decipol unit used to quantify perceived air quality (Fanger, 1988). Several studies concerning indoor air quality (Pejtersen et al., 1991; Bluyssen et al., 1996) have been carried out in which human subjects were trained to assess the perceived air quality directly in the decipol unit, using 2-propanone as a reference exposure.

The choice of 2-propanone was based mainly on two considerations: first, that it is a major human bioeffluent (Bluyssen, 1990), and second that the decipol unit was defined using a well-described human perception of bioeffluents (Fanger, 1988). Other reference exposures should also be considered in sensory evaluations of indoor air quality, especially, when one takes into account that the air indoors is not only polluted by human bioeffluents but also by hundreds of other organic chemical compounds emitted by a wide range of pollution sources present in the indoor environment (Brown et al., 1994).

It is essential to verify that sensory evaluations of perceived air quality using 2-propanone as a reference exposure can be used to model human response to any type of indoor air pollutant. Such validation was not performed by Bluyssen et al. (1989). Several studies (e.g., Groes, 1995) have shown that human subjects can assess well the quality of air polluted with 2-propanone, using 2-propanone as a reference exposure; however, it is rather difficult for human subjects to assess the quality of air polluted by emissions from building materials, furnishing, flooring materials, etc. using this reference exposure. It was hypothesized that these results could be due to a difference in odour character of 2-propanone and of pollutants emitted by indoor sources, as well as to the fact that some people assess the odour of 2-propanone to be pleasant, causing almost no irritation of the mucous membranes. It is consequently suggested that alternatives be considered to 2-propanone that are more representative as regards the sensory character of the atmospheres encountered in indoor climates. Such reference exposures have not yet been developed.

3.2 Objectives

The purpose of the present study was:

- to develop reference atmospheres for use in sensory evaluations of indoor air quality as alternatives to the currently used reference atmosphere of 2-propanone;
- to verify the method of using 2-propanone as a sensory reference exposure when evaluating perceived air quality.

3.3 Selection of Organic Chemical Compounds to be used in Reference Atmospheres

3.3.1 Background

3.3.1.1 Volatile Organic Compounds in Indoor Air

Organic chemical compounds are the major sensory pollutants in indoor air. They originate from outdoor sources, e.g., urban traffic, and from indoor sources, i.e., people and their activities, tobacco smoking, emissions from buildings materials, floor coverings and furnishings, etc. (Wolkoff, 1995). The entire range of organic chemicals polluting indoor air, based on the boiling point range (volatility), is categorized by a World Health Organization working group (WHO, 1989) and is presented in Table 3.3.1. The most prevalent indoor pollutants are the volatile organic compounds (VOCs).

A large number of investigations have been carried out (section 3.3.1.2) aimed at defining the levels of exposures to VOCs in indoor environments, the prevailing VOCs, and the main sources of VOCs. These studies indicate that indoor air is polluted typically by mixtures of hundreds of VOCs, which differ to a large extent as regards the composition and the measured concentrations of single VOCs; observed differences in the composition and the exposure levels depend, *inter alia*, on the application of spaces and their age. Moreover, these studies reveal that VOCs originate mainly indoors (Ekberg, 1993) and occur at very low concentrations, much below threshold limit values established for industrial environments (ACGIH, 1995). For example Jarke et al. (1981) identified 249 organic compounds in the indoor air of 36 dwellings, and none of the compounds measured had a concentration above 100 ppb, a value well below any published occupational exposure limits.

Table 3.3.1 Classification of organic pollutants present in indoor air; boiling points in brackets refer to polar compounds (WHO, 1989)

Description	Boiling point range (°C)
Very volatile (gaseous) organic compounds (VVOC)	< 0 ÷ 50 (100)
Volatile organic compounds (VOC)	50 (100) ÷ 240 (260)
Semivolatile organic compounds (SVOC)	240 (260) ÷ 380 (400)
Organic compounds associated with particulate matter or particulate organic matter (POM)	> 380

Despite the low concentrations, VOCs occurring in the indoor air can reduce comfort conditions for people by causing unpleasant odours, irritation of nose, eyes and throat, headaches, inflammatory reactions, etc. (Mølhave, 1991; Berglund et al., 1992b; Leinster and Mitchell, 1992; Sundell, 1994). Various hypotheses have been put forward to explain why VOCs cause complaints among occupants of indoor climates at these low concentrations; they include possible reactions in complex VOC mixtures resulting in chemically and sensorily active compounds (Weschler and Schields, 1997; Wolkoff et al., 1997), the addition or synergism of effects caused by VOCs at concentrations below thresholds (Cain and Cometto-Muñiz, 1995) and multifactorial effects (Berglund et al., 1986) such as the impact of temperature (Mølhave et al., 1993).

3.3.1.2 Published Reviews of the Measurements of VOCs Indoors

In order to provide information on indoor exposures to VOCs, and at the same time a rational basis for developing occupational standards for VOCs occurring indoors, the results of investigations of the chemical composition of indoor air have been summarized in several review publications or databases. These compilations have been made notwithstanding difficulties in direct comparison of the chemical measurements of VOCs performed by different experimental teams; these differences are due to varying sampling strategies, sampling techniques, and applied analyses (Brown et al., 1994; Wolkoff, 1995). The reviews revealed in general that existing information on the effects of VOCs on humans is rather limited; it is therefore difficult to interpret collected data on measured VOCs (Brown et al., 1994).

One of the first reviews of VOCs measured indoors was prepared by Berglund et al. (1986); the objective of this review was to show that complex patterns of sensory stimuli typically occur in indoor air. They collected results from eight studies carried out in Scandinavia, Italy and the USA. They reported as many as 307 VOCs being broadly present in the indoor environment and, among them, 68 VOCs being frequently detected.

A VOC national ambient database published by the U.S. Environmental Protection Agency (Shah and Singh, 1988) included a total of 320 VOCs; 261 VOCs were measured in the outdoor air and 66 were measured indoors. Approx. 75% of VOCs occurring indoors were at median concentrations below 1 ppb (i.e., approx. 0.4 $\mu g/m^3$, assuming a molecular weight of 100).

A working group of World Health Organization (WHO, 1989; see also Stolwijk, 1990) compiled measurements of VOCs from more than 1000 residential environments in the USA, Germany, the Netherlands and Italy. Their goal was to describe the effects of indoor air organic pollutants on humans. Seventy-three compounds were listed and their median concentrations rarely exceeded 10 $\mu g/m^3$.

An extensive review of Dutch studies, comprising more than 400 houses, was prepared by Kliest and Bloemen (1990). They re-analysed the old data of Lebret et al. (1986) and reported as many as 274 VOCs occurring in concentrations above 1 $\mu g/m^3$ in more than 10% of the houses investigated.

Hoskins et al. (1993) carried a literature survey of studies made after 1982. The objective was to build up a database on indoor air pollutants occurring in European environments including public places, homes, means of transportation, etc. They found the average concentration of total volatile organic compounds (TVOC) in public non-smoking places to be approx. 270 $\mu g/m^3$ and in places where smoking was permitted it was approx. 470 $\mu g/m^3$.

A comprehensive review of 47 studies measuring VOCs was made by Brown et al. (1994); studies performed before 1991 were included. The review summarized information on the types of VOCs measured indoors, the levels of exposures to VOCs, the types of sources of VOCs, and the health effects of exposures to VOCs indoors. The authors reported the detection of several hundred VOCs but only 111 with measured concentrations. In dwellings, which neither were new nor newly renovated, the highest weighted average concentration was above 50 $\mu g/m^3$, and it was measured for ethanol. Eighteen compounds were considered to be major VOCs in indoor air as their concentrations exceeded 5 $\mu g/m^3$; these VOCs are shown in Table 3.3.2. Derived weighted concentrations of TVOC in complaint offices were 490 $\mu g/m^3$, whereas in new offices they were as much as eight times higher.

Table 3.3.2 VOCs with the highest mean concentration measured in dwellings (Brown et al., 1994) and VOCs occurring frequently in offices (Bernhard et al., 1995)

Building type	Major VOCs
Dwellings (Brown et al., 1994)	benzene; n-decane; p-dichlorobenzene; ethylacetate; ethylbenzene; nonanal; tetrachloroethylene; 1,2,4-trimethylbenzene; o-xylene; camphene; 1,2-dichloroethylene; dichloromethane; m,p-xylene; (o,m,p-xylene); 2-propanone; limonene; toluene; 1,1,1-trichloroethane; ethanol
Offices (Bernhard et al., 1995)	2-propanone; isoprene; 2-methylpentane; n-hexane; 2-methylhexane/benzene; n-heptane; toluene; m-xylene; o-xylene; decane; trimethylbenzene; L-limonene

The results of the European audit project (Bernhard et al., 1995) provided a database on VOCs identified in 56 office buildings in nine European countries. The VOCs were measured using identical methods, but in each building investigated only one air sample was taken for detailed chemical analysis. Seventy-six compounds were identified and 12 compounds were considered to be ubiquitous (Table 3.3.2), since they were measured in more than 50% of the buildings investigated; the ubiquitous VOCs had mean concentrations of between 8 $\mu g/m^3$, measured for isoprene, and 52 $\mu g/m^3$, measured for n-hexane. The median TVOC concentration measured in the offices was 200 $\mu g/m^3$. For most of the compounds the ratio between the odour threshold and the measured concentration was above 50.

Wolkoff (1995) listed 12 major national field studies measuring VOCs in over 3000 buildings and several epidemiological studies in which VOCs were measured. He concluded that generally field studies failed to find associations between measured TVOC concentration and increased prevalence of the Sick Building Syndrome (SBS) among occupants in non-industrial buildings. Similar conclusions were drawn by Sundell (1994), Andersson et al. (1997) and Mølhave et al. (1997).

3.3.2 Literature Review of the Measurements of VOCs in Offices

3.3.2.1 Purpose

The purpose of the present survey was to build up a database on exposures to VOCs occurring in office buildings and to identify VOCs having a significant sensory impact on the occupants. Such a database could be used for the selection of VOCs when creating reference atmospheres for investigating human sensory response to controlled exposures containing air polluted with VOCs, or when creating a perception reference exposure for humans in connection with sensory evaluations of indoor air quality in offices.

Information on exposures to VOCs in indoor climates can be retrieved from the reviews and databases described in section 3.3.1.2; nevertheless, the present review was made primarily to update data collected previously on exposures to VOCs in indoor non-industrial environments.

3.3.2.2 Methods

The following two preliminary criteria were defined for inclusion of studies in the review process:

(1) a study should have reported measurements of VOCs in non-industrial indoor environments, i.e., in offices, dwellings, schools, etc.; all studies fulfilling this criterion were accepted notwithstanding the differences in building age, i.e., old vs. new or newly renovated buildings, and the prevalence of complaints of poor air quality or SBS symptoms among occupants, i.e., non-complaint vs. complaint buildings;

(2) a study should have reported qualitative and quantitative chemical analysis of air sampled indoors; all studies fulfilling this criterion were accepted notwithstanding the differences regarding sampling strategy, sampling methods and analysis applied.

A literature survey was then carried out through international journals and proceedings of major conferences covering indoor air quality topics and published in the period 1978-1993, the investigations being selected according to the above defined criteria. Next, among the selected studies, only the investigations carried out in office buildings and those measuring VOCs at least one year after completion or renovation of building were chosen. These investigations were subsequently supplemented with the audit project from 1995 (Bernhard et al., 1995) and subjected to a thorough review.

During the review process, the following information was retrieved from selected studies: (1) the type and concentration of VOCs measured; (2) the number of buildings investigated; (3) the number of spaces in which the measurements were performed; and (4) the total number of measurements made, i.e., total number of air samples taken indoors. This information was broadened by the data on olfactory properties of VOCs such as the description of odour (Arctander, 1969), the odour threshold (Devos et al., 1990), and the irritation threshold (Ruth, 1986; Cometto-Muñiz and Cain, 1990).

Finally, all data collected were organized in tabular form. The table provided twofold information. First, information on the frequency of VOC occurrence was given, including the number of studies reporting the measurement of a given VOC, the number of buildings in which a VOC was measured, plus the number of indoor spaces and the number of measurements carried out. Secondly, information on the distribution of measured VOC concentrations was provided comprising the minimum, 50-percentile, 90-percentile and maximum concentration measured plus the mean weighted concentration calculated using the number of measurements as a weighting factor. Additionally, the sensory impact of VOCs on humans was described by providing an odour index for those compounds for which the odour threshold could be retrieved from the literature; the odour index was defined as the ratio of mean weighted concentration to the odour threshold.

3.3.2.3 Results and Discussion

Forty-four studies reporting chemical measurements in all types of indoor non-industrial environments were found through the literature survey; they comprised 6208 measurements taken in 5336 offices and dwellings in 5482 old and new, complaint and non-complaint buildings. The complete list of these studies is given in Appendix 1. Twenty-two investigations carried out chemical measurements in office buildings completed or renovated one year prior to the measurements. These studies are listed in Table 3.3.3 and they were a source of data regarding concentrations and types of VOCs occurring in offices; complete data on VOCs is presented in Appendix 2.

The 22 studies reviewed were carried out in 582 offices in 209 buildings. Altogether 133 different VOCs or groups of VOCs were measured, although only eight compounds were widespread, being measured in more than half of the investigations surveyed. These compounds were: toluene measured in 18 studies; 1,1,1-trichloroethane and benzene measured in 14 studies; ethylbenzene measured in 13 studies; n-decane, n-nonane and n-undecane measured in 12 studies; and n-dodecane measured in 11 studies.

The results of the present review are fairly similar to the data summarized in the previous reviews (see section 3.3.1.2). This is mainly due to the inclusion of similar investigations in the review process. It should be stressed, however, that the present review refers only to the measurements of VOCs in office buildings that were completed or renovated at least one year prior to the chemical measurements; differences can thus be expected when comparing with previous reviews reporting data on VOCs from all types of indoor non-industrial environments.

Table 3.3.3 The list of 22 studies measuring VOCs in offices and selected for the review

Study	No. of buildings	No. of spaces	No. of measurements	No. of VOCs
Bernhard et al. (1995)	56	56	56	44
Cottica et al. (1993)	1	14	28	37
Daisey et al. (1993)	12	32	32	38
Nieslochowski (1993)	66	66	66	7
Saarela et al. (1993)	5	61	73	35
Singhvi and Haseman (1993)	1	7	7	32
Schields and Weschler (1992)	1	2	8	17
de Bortoli et al. (1990)	10	83	83	8
Gebefuegi and Korte (1990)	1	132	132	36
Weschler et al. (1990)	2	5	5	28
Weschler and Schields (1989)	1	4	8	19
Black and Bayer (1988)	1	10	10	21
Jungers and Sheldon (1987)	4	5	5	9
Seifert and Ulrich (1987)	1	2	2	13
van der Val et al. (1987)	3	7	7	8
Vallance et al. (1987)	7	21	137	16
de Bortoli et al. (1984)	1	1	1	9
Hartwell et al. (1984)	20	58	58	10
Turiel et al. (1983)	1	1	2	11
Mølhave et al. (1982)	14	14	14	23
Johansson (1978)	1	1	8	7
Total 22 studies	*209*	*582*	*742*	*133 (different VOCs)*

Figure 3.3.1 shows how frequently the individual VOCs were measured in the office buildings. It can be seen that almost 70% of VOCs measured in office buildings were identified in less than 20 buildings and a substantial number of VOCs (37) was measured only in one office building; the compounds measured in one building cannot be considered as being representative of office environments. These results imply that the bulk of VOCs occur rarely indoors. The reason for so many

sporadically measured compounds could be the limited measuring protocol used in the investigations reviewed, according to which only the most prevalent VOCs and the VOCs with the highest concentrations, i.e., so-called target compounds, were quantified in a detailed chemical analysis. Another possible explanation could be that VOCs were measured in specially selected offices in which unusual sources of pollution may have been present. These sources, e.g., uncommon building materials, floor materials, furniture, office equipment, etc., could emit specific compounds infrequently occurring in offices. However, no analysis has been carried out to substantiate such associations; they are therefore purely speculative.

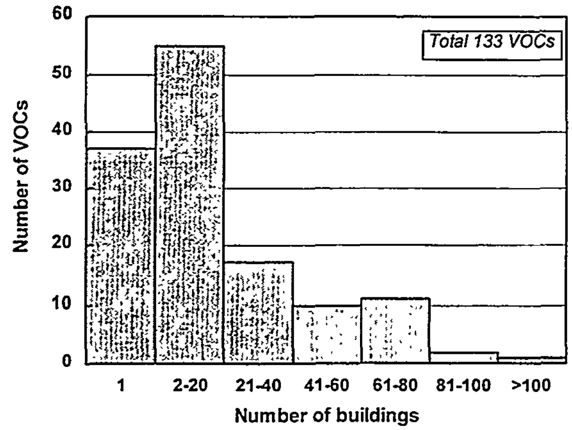


Figure 3.3.1 Frequency of measuring individual VOCs in the office buildings by the 22 studies reviewed

Table 3.3.4 lists the compounds measured in more than 20 office buildings; the most frequently occurring compound was toluene, measured in 177 office buildings.

Table 3.3.4 A list of VOCs measured in more than 20 office buildings by the 22 studies reviewed

No. of buildings	Volatile organic compounds
>100	toluene
81 - 100	styrene; 1,1,1-trichloroethane
61 - 80	1-butanol; n-hexane; phenol; 2-propanone; n-decane; tetrachloroethene; o-xylene; n-heptane; n-undecane; m-xylene
41 - 60	trichloroethene; benzene; benzaldehyde; ethylbenzene; methylcyclohexane; n-dodecane; limonene; ethanol; 1,2,4-trimethylbenzene; n-nonane
21 - 40	n-octane; α-pinene; 2-methylpentane; ethylacetate; m-p-xylene; m-p-dichlorobenzene; carbon tetrachloride; 2-propanol; cyclohexane; methylcyclopentane; n-butylacetate; chlorobenzene; isoprene; acetic acid; 2-butoxyethanol; 1,2-dichloropropane; 1,3,5-trimethylbenzene

As seen in Figure 3.3.2, nearly all VOCs found in the present review were at mean weighted concentrations below 40 µg/m³, which is similar to the results of a review made by Brown et al. (1994). Mean weighted concentrations were calculated as the average concentrations of VOCs measured in the office buildings, weighted by a number of chemical measurements, i.e., the number of air samples taken indoors. No adjustments were made regarding the differences in the chemical analyses applied by various investigations in order to quantify the VOCs. Mean weighted concentrations should thus be seen as rough estimates of an average level of the likely exposure to VOCs occurring in offices. As shown in Appendix 2, the actual concentrations of VOCs measured in different office buildings can deviate quite substantially from the mean weighted concentrations. For example, the maximum concentration measured for ethanol was 680 µg/m³, whereas the mean weighted concentration for this compound was 112.4 µg/m³.

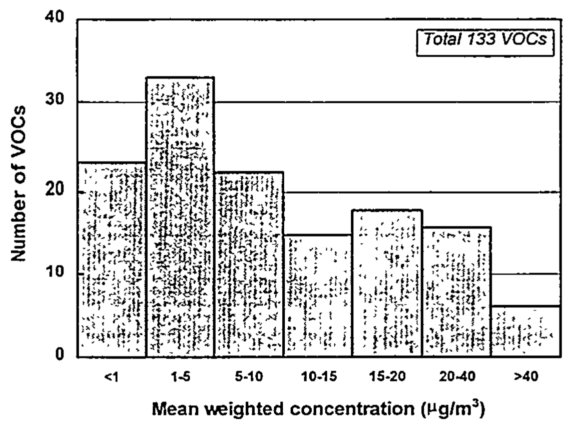


Figure 3.3.2 Distribution of the mean weighted concentrations of individual VOCs measured in the office buildings by the 22 studies reviewed

The list of VOCs with mean weighted concentrations above 10 µg/m³ is shown in Table 3.3.5.

The odour detection threshold is the lowest concentration of an individually occurring compound that can be detected by 50% of human judges (Cain, 1988; WHO, 1987). Taking into account that odour detection thresholds reported by different studies can vary up to five orders of magnitude, mainly due to the application of various measuring techniques (WHO, 1989), it was decided in the present review to use odour detection thresholds provided by the compilation of Devos et al. (1990). This compilation was believed to provide the most up-to-date and the most homogeneous set of standardized human olfactory thresholds, since a scatter of data on human olfactory thresholds was considerably decreased by assigning a specific weighting coefficient to the thresholds reported by different laboratories. From the compilation of Devos et al. (1990), the odour threshold was obtained for only 63 compounds out of 133 found in the present review; it was nevertheless obtained for VOCs occurring most frequently and those having the highest mean weighted concentrations.

Table 3.3.5 A list of VOCs measured by the 22 studies reviewed, having mean weighted concentrations above 10 $\mu g/m^3$

Mean weighted concentration ($\mu g/m^3$)	Volatile organic compounds
>40	ethanol; 2,3-epoxy-4-methylpentane; 1-butanol; styrene; 2-butanone; toluene
20 - <40	1,1,1-trichloroethane; n-decene; limonene; cyclohexane; texanol di-iso-butyrate; 2,5,6-trimethyloctane; heptadecane; 3-methylpentane; diethylcyclohexane; hexanol; octadecane; 1,4-dioxane; 2-ethoxyethanol; phenoxy-2-ethanol; texanol
15 - <20	1,2,3-trimethylbenzene; 2-propanol; m-xylene; m-ethyltoluene; n-dodecane; 1,2,4-trimethylbenzene; acetic acid; methylcyclohexane; iso-octane; n-octane; 2,4,4-trimethyl-2-pentene; n-hexane; ethylbenzene; 2-propanone; 5-methyldecane; 2-methylpentane; n-pentadecane; trichloroethene; cyclohexanone
10 - <15	2,4-dimethylpentane; o-methylethylbenzene; n-pentane; n-decane; n-nonane; 2,2,4,6,6-pentamethylheptane; o-xylene; 4-ethyltoluene; 3,3,4-trimethyldecane; methylmethacrylate; n-i-pentanal; methylcyclopentane; 2-methylbutane; p-xylene; n-octanal

Figure 3.3.3 shows a distribution of odour indices of individual VOCs measured by the studies reviewed. Only three VOCs had odour indices higher than 1 and almost 70% of VOCs for which the odour thresholds were obtained had mean weighted concentrations 100 times lower than their odour threshold.

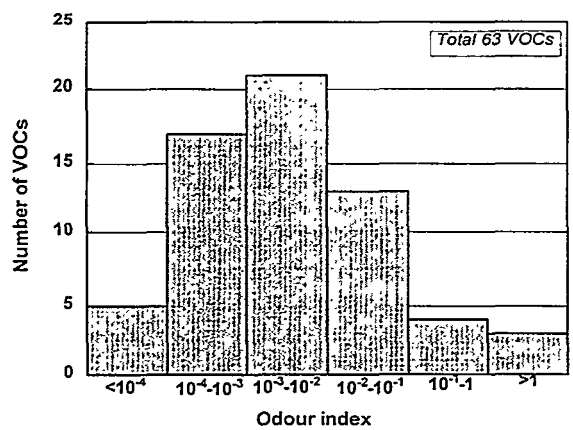


Figure 3.3.3 Distribution of odour indices of individual VOCs measured in the office buildings by the 22 studies reviewed

Due to individual differences in sensitivity to odorants, odour thresholds can differ between persons by a factor of 1000 or higher (Stevens et al., 1988). These variations should be taken into account when discussing the results of the present review as regards olfactory properties of measured VOCs. To account for variations in individual sensitivity, as well as the occurrence of VOCs in mixtures, Wolkoff et al. (1997) suggested using a factor of 0.1 when estimating odour effects; this factor is apparently similar to the results of recent studies with human exposures to rigorously generated and carefully presented propionic acid (Kendal-Reed et al., 1998), indicating that the variations in human sensitivity to odour can be decreased to a 10-fold difference between individuals in the group. Applying a factor of 0.1 to the results of the present review, only eight VOCs would have a mean weighted concentration higher than 10% of their odour threshold.

Table 3.3.6 A list of VOCs measured by the 22 studies reviewed, having odour indices above 0.001

Odour index	Volatile organic compounds
>1	n-decanal; n-octanal; ethylbenzene
1 - <0.1	n-nonanal; p-cymene; hexanol; styrene
0.01 - <0.1	n-hexanal; 1-octanol; acetic acid; n-butanol; n-heptanal; acetalaldehyde; 1,2,4-trimethylbenzene; 1,4-dichlorobenzene; limonene; benzaldehyde; m-xylene; pentanal; 1,2,4,5-tetramethylbenzene
0.001 - <0.01	2-ethoxyethylacetate; n-decene; toluene; p-xylene; 2-ethoxyethanol; 1,3,5-trimethylbenzene; cumene; 2-butoxyethanol; o-xylene; n-decane; nitrobenzene; phenol; 2,1-ethylhexanol; 2-butanone; ethanol; n-nonane; cyclohexene; α-pinene; n-dodecane; 4-methyl-2-pentanone; 1,4-dioxane

The results of the present review showed, that practically all VOCs had a mean weighted concentration below the odour detection threshold, thus implying that they would not be perceivable or detected indoors. This is an apparently conflicting statement as regards an obvious omnipresence of odours in indoor air, although not surprising since similar results were found in the audit project carried out in the European office buildings (Bernhard et al., 1995). Odour detection thresholds should, however, be used carefully for such reasoning, since they do not take into account the sensory effects of mixtures of odorants. They refer only to the detection of odorants occurring individually, a condition rather unlikely to be encountered indoors. The detection of individual compounds in a mixture can generally follow two principles, depending on the concentration of a compound as compared to its odour threshold: hypo-addition in a mixture of VOCs that are above threshold concentrations or a complete addition in a mixture of VOCs that are below threshold concentrations (section 2.6.2). In the present review, the mean weighted concentrations were sub-threshold concentrations for nearly all VOCs. Assuming therefore that the effects were additive in a mixture of all 133 VOCs found in this review, each compound would then be detected at a concentration approximately

100 times lower than the concentration at which it would be detected if present alone. Under these assumptions, nearly 20 VOCs would have a mean weighted concentration higher than the detection threshold and thus not merely three infrequent VOCs would be at concentrations detectable by humans indoors. If the above-mentioned factor of 0.1 (taking into account variations in human sensitivity to odours) is also considered, then nearly 40 VOCs shown in Table 3.3.6 would be detectable by humans, if these VOCs were present in mixtures. This table reveals that VOCs with the highest odour indices are mainly aldehydes and acids.

None of the VOCs found in the present review was at a mean weighted concentration higher than the irritation threshold or the threshold limit value (TLV) (ACGIH, 1995); TLV can be used to indicate the presumable sensory irritants (Alarie et al., 1996). Even if the additive effects of irritants on humans were accepted (see, e.g., Cometto-Muñiz and Hernándes, 1990; Cometto-Muñiz and Cain, 1995), all VOCs found in this review would still have mean weighted concentrations far below the estimates of their potency to evoke sensory irritation.

3.3.3 Selection of VOCs

Using the results of the literature review of VOC measurements in offices, described in section 3.3.2, VOCs and their exposure levels were selected for potential use in reference atmospheres. No guidelines exist, however, in which criteria for inclusion of VOCs in reference atmospheres for perception tests with humans are defined. These criteria should in general deal with selection of the relevant and ethically accepted compounds and exposures. This is discussed by Mølhave (1992a, 1998).

3.3.3.1 General Criteria for Selection of Relevant Compounds and Exposures

<u>Relevant compounds.</u> The relevant compounds can be defined as VOCs frequently occurring in normal indoor air; VOCs with high concentrations measured indoors; VOCs that when present indoors can evoke sensory effects in humans, including both odour and irritation of mucous membranes; and finally VOCs meeting ethical requirements concerning health and environmental hazards.

A number of buildings in which the compounds were measured can be used in establishing a criterion for the frequency of occurrence of VOCs indoors. Using this criterion, a broader profile of VOCs occurring in offices can be obtained pertaining to a wide range of office buildings rather than to individual buildings in which a large number of measurements were performed, or in which a large number of offices were selected for chemical measurements.

An odour index and an irritation index can be used as a criterion for selecting the compounds having a sensory impact on humans. They are defined respectively as a ratio of the mean weighted concentration of a compound to the odour threshold and to the irritation threshold. Odour detection thresholds are generally lower than irritation thresholds. For potent compounds, with thresholds around 0.04 $\mu g/m^3$, they are four orders of magnitude lower, and for less potent compounds they progressively incline towards irritation thresholds (Cain and Cometto-Muñiz, 1995). Perception of odour precedes sensory irritation. Thus an odour index can be used to select VOCs for the investigation of short-term (acute) effects, and an irritation index for studies of long-term (gradual) effects of exposures to VOCs.

Odour thresholds are the principal indicators of sensory effects on humans. For example, the ASHRAE 62-89 ventilation standard (ASHRAE, 1989) defines outdoor air rates for acceptable indoor air quality based on the evaluations of air quality made within 15 seconds after entering the office; it is thus based on short-term assessments (visitors' evaluations) of air quality. Accordingly, if a reference atmosphere was created for sensory evaluations of indoor air quality made by visitors, then an odour index, rather than an irritation index would be a more appropriate criterion for the selection of VOCs included in such an atmosphere. An odour index can easily be derived, since the data on odour thresholds is quite comprehensive (see, e.g., Devos et al., 1990). When using odour thresholds it should be remembered, however, that odour detection thresholds refer to detection of the compounds when they are present separately, and other rules can govern the detection of odours in mixtures (Cometto-Muñiz et al., 1997). Little information is available on irritation thresholds; however, threshold limit values can be used to estimate the irritative potency of VOCs (Alarie et al., 1996).

Ethically acceptable VOCs are those that do not pose a risk of adverse health effects on humans. Consequently, compounds shown in human or animal tests to be allergenic, mutagenic or carcinogenic, as well as compounds with unknown toxicity, should be ruled out. Furthermore, only VOCs harmless to the environment can be included in a reference atmosphere.

Relevant exposures. Relevant exposures are the concentrations of particular compounds that reflect the mean reported concentrations indoors and the power of their potency to evoke sensory effects. These exposures should be within the normal range for indoor climates, and no individual compound should occur in a concentration exceeding 1/10 of its TLV (ASHRAE, 1989). It has also been suggested (Nielsen et al., 1995) that a preliminary indoor air guideline for health effects should be equal to 1/40 of the occupational exposure limits. In exposures containing multicomponent mixtures of VOCs, the summation of ratios of concentrations over known or estimated TLVs should not exceed a total of one (Mølhave, 1992b; ACGIH, 1995).

3.3.3.2 Selection of Single VOCs

Table 3.3.7 reveals a discrepancy between the compounds having high odour indices and those occurring frequently; this demonstrates that the selection of VOCs meeting all criteria for selection of relevant compounds is quite difficult.

Table 3.3.7 VOCs occurring most frequently in office buildings, and those having the highest mean weighted concentration and the highest odour index; each list shows successively 10 VOCs starting with a compound having the highest frequency, concentration and odour index among 133 VOCs found through the literature survey in section 3.3.2

Most frequent VOCs	VOCs with the highest mean weighted concentration	VOCs with the highest odour index
toluene	ethanol	n-decanal
styrene	2,3-epoxy-4-methylpentane	n-octanal
1,1,1-trichloroethane	1-butanol	ethylbenzene
1-butanol	styrene	n-nonanal
n-hexane	2-butanone	p-cymene
phenol	toluene	hexanol
2-propanone	1,1,1-trichloroethane	styrene
n-decane	n-decene	n-hexanal
tetrachloroethene	limonene	1-octanol
o-xylene	cyclohexane	acetic acid

In selecting relevant compounds, the following procedure was applied. First, the most frequent VOCs and concurrently those having the highest concentrations were selected. The most frequent VOCs were defined as those occurring in at least 20 buildings, i.e., in approx. 10% of the total number of buildings in which measurements were carried out in the studies reviewed. The VOCs having the highest mean weighted concentration were defined as those at concentrations above 10 $\mu g/m^3$, i.e., above approx. 10% of the highest mean weighted concentration (which was found for ethanol). This selection yielded 25 VOCs that can be called ubiquitous compounds, and are shown in Figure 3.3.4. Next, 25 selected VOCs were assigned a separate increasing rank according to the descending number of buildings in which they occurred, descending mean weighted concentration and descending odour thresholds. Finally, the ranks were added and the 10 VOCs with the lowest sum of ranks were selected for experiments with human subjects. Among the selected compounds, two VOCs were ruled out: styrene as being carcinogenic and 1,1,1-trichloroethane as being harmful for the environment; they were substituted with the two VOCs with the next lowest sum of ranks. Due to some technical problems while generating ethanol and limonene, the atmospheres with these two VOCs were not assessed by human subjects. Table 3.3.8 lists the selected VOCs together with their mean weighted concentrations found through the literature review.

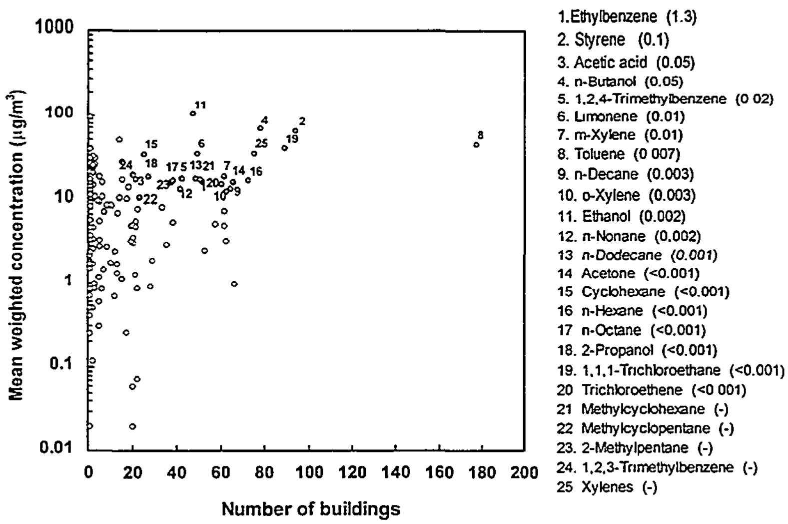


Figure 3.3.4 A plot of the mean weighted concentrations of 133 individual VOCs measured in the office buildings in the 22 studies reviewed, against the frequency of occurrence of VOCs defined as the number of buildings in which individual VOCs were measured; each circle represents one specific VOC; the 25 compounds listed are ubiquitous VOCs, i.e., the most prevalent compounds and those having the highest mean weighted concentrations (values in brackets show odour indices)

Table 3.3.8 A list of 10 VOCs selected for experiments with human subjects; numbers in the first column correspond to the numbering shown in Figure 3.3.4

No.	VOCs	No. of buildings	Mean weighted concentration (µg/m³)	Odour index
1	ethylbenzene	51	16.3	1.3
2	*styrene*†	*94*	*63.5*	*0.1*
4	n-butanol	78	68.1	0.05
5	1,2,4-trimethylbenzene	42	17.5	0.02
6	*limonene*¶	*49*	*33.9*	*0.01*
7	m-xylene	61	18.5	0.01
8	toluene	177	43.7	0.007
9	n-decane	64	13.5	0.003
11	*ethanol*¶	*47*	*107.2*	*0.002*
14	2-propanone	65	16	<0.001
16	n-hexane	72	16.6	<0.001
19	*1,1,1-trichloroethane*‡	*89*	*39.1*	*<0.001*

† ruled out - carcinogenic; ‡ ruled out - harmful to environment; ¶ not used - technical problems while generating atmospheres polluted with these VOCs

Table 3.3.9 Comparison of the VOCs constituting a reference exposure of 22 compounds (Mølhave et al., 1986) with the results of the present review

Reference exposure	VOCs found through the literature review			
with 22 VOCs	Widespread[1]	Table 3.3.7[2]	Figure 3.3.4[3]	Not found
n-butanol		+	+	
2-butanone		+		
n-butylacetate				
cyclohexane		+	+	
n-decane	+	+	+	
1-decene		+		
1,2-dicholoroethane				+
ethoxyethylacetate				
ethylbenzene	+	+	+	
n-hexanal		+		
n-hexane			+	
3-methyl-2-butanone				+
4-methyl-2-pentanone				
n-nonane	+		+	
1-octene				+
n-pentanal				
α-pinene				
2-propanol			+	
n-propylbenzene				
1,2,4-trimethylbenzene			+	
n-undecane	+			
m-xylene			+	

[1] reported by more than 11 studies surveyed
[2] a list of 10 VOCs being the most frequent, 10 VOCs with the highest mean weighted concentration, and 10 VOCs with the highest odour index
[3] a list of 25 VOCs with both the mean weighted concentration >10 μg/m^3, and occurring in > 10 office buildings

3.3.3.3 Selection of Multicomponent Mixtures of VOCs

The results of the literature review can also be used to select VOCs for creating exposures containing multicomponent air pollution. As a first step, however, it was decided to compare the results of the literature review with the composition of a previously developed and widely used atmosphere for studying the effects of indoor air pollution on humans (Mølhave et al., 1986; Mølhave et al., 1991; Hudnell et al., 1992). This multicomponent atmosphere contains a mixture of 22 VOCs and is called m22-mixture. It was created using results of chemical measurements in Danish dwellings and offices of various ages (Mølhave and Møller, 1978) and measurements of the chemical emissions from building materials (Mølhave, 1982) by selecting the most frequently occurring VOCs, the VOCs with the highest concentrations and known or suspected mucous irritants (Mølhave et al., 1986). The relative concentrations of compounds in the atmosphere reflect the average measured concentrations of VOCs in the Danish building stock (rounded for simplicity to the nearest factor of 10). Comparison with the results of the literature review (Table 3.3.9) revealed that 19 compounds among 22 VOCs in the m22-mixture were found in the literature survey, and that as many as 9 of the ubiquitous VOCs shown in Figure 3.3.4 were included in the m22-mixture. Taking into account that the m22-mixture was quite well documented in the literature, it was decided to use this mixture as a multicomponent exposure for investigations with human subjects.

Table 3.3.10 Composition and mass mixing ratio (summation of 31.81) of the atmospheres polluted by mixtures of VOCs that were selected for studies with human subjects; mass mixing ratio, defining the relative concentrations of the compounds in the atmospheres, reflects the average measured concentrations of VOCs in the Danish building stock (rounded for simplicity to the nearest factor of 10) for m22-mixture, the mean weighted concentrations measured in the offices surveyed in the literature review for m19-mixture, and the odour threshold concentrations for m8-mixture

Chemical compound	Mass mixing ratio		
	m22-mixture	m19-mixture	m8-mixture
n-butanol	1	5.23	0.54
2-butanone	0.1	4.63	-
n-butylacetate	10	0.15	-
cyclohexane	0.1	2.39	-
n-decane	1	1.34	3.02
1-decene	1	3.58	-
1,2-dicholoroethane	1	-	-
ethoxyethylacetate	1	0.9	-
ethylbenzene	1	1.49	-
n-hexanal	1	0.45	-
n-hexane	1	1.94	4.71
3-methyl-2-butanone	0.1	-	-
4-methyl-2-pentanone	0.1	0.45	-
n-nonane	1	2.24	21.53
1-octene	0.01	-	1.81
n-pentanal	0.1	0.15	0.01
α-pinene	1	0.9	0.01
2-propanol	1	1.79	-
n-propylbenzene	0.1	0.3	-
1,2,4-trimethylbenzene	0.1	1.49	0.18
n-undecane	0.1	0.75	-
m-xylene	10	1.64	-

Two other atmospheres containing multicomponent pollution of VOCs were also selected for experiments with human subjects. They are both daughters of the atmosphere containing m22-mixture since the VOCs were selected among those constituting the m22-mixture. The first one is an atmosphere polluted by a mixture of 8 VOCs, termed m8-mixture. This atmosphere was used while developing instrumentation for evaporating multicomponent VOC mixtures into air (see section 3.4.3). VOCs were chosen according to their thermodynamic properties, i.e., the boiling points and vapour pressures, and were mixed, preserving the odour threshold concentrations. The second one is an atmosphere polluted by 19 VOCs, termed m19-mixture. The compounds were selected according to the results of the literature review (Table 3.3.9) and their relative concentrations preserve the mean weighted concentrations found through the literature survey.

Table 3.3.10 shows the composition of atmospheres polluted with the three mixtures of VOCs that were used in the experiments with human subjects.

3.4 Human Sensory Response to Air Pollution Containing Single VOCs and Mixtures of VOCs Selected for Use in a Reference Atmosphere

3.4.1 Background

A number of studies have been carried out with single volatile organic compounds (VOCs) and their mixtures; a few relevant experiments are summarized in the following sections. The aim of these experiments was to establish the sensory endpoints for odour and irritation of the pollutants present in indoor air, and the psychophysical relations between the concentrations of these pollutants and the human sensory response. Toxicological endpoints for indoor air pollutants were also established (Nielsen et al., 1982; Indoor Air - Supplement 5, 1998). These endpoints can be used in setting standards for indoor air pollution as regards comfort and health.

From the comfort point of view, it would be interesting to know at which concentrations of air pollutants the perceived air quality is at levels acceptable for humans; acceptable air quality has been a requirement used for many years when setting ventilation standards (ASHRAE, 1989). Existing information on the sensory endpoints or the psychophysical relations between the odour intensity and the concentration cannot, however, be used directly to evaluate whether the air is acceptable for humans or not. Nevertheless, Yaglou et al. (1936) decided *a priori* that the moderate or higher intensity of odour would not be acceptable for humans when recommending ventilation rates required to control body odour. Such attempts as Yaglou et al. may not always be appropriate, and transfer functions between the intensity of odour and its acceptance are thus required. However, they have not yet been developed.

It would be an enormous task to produce the relationships between concentration of the air pollutants and the acceptable air quality, considering the hundreds of VOCs occurring indoors, the indefinite number of mixtures, the possible reactions in mixtures, the transfer of the chemical compounds into the new compounds, etc. Nevertheless, few compounds or mixtures can be selected and used as markers for a prediction of the sensory effects on humans in the presence of specific pollution sources. Carbon dioxide can be quoted here as an example of such a marker that is used as an indicator of bioeffluents in a space at the time of ventilation measurements. An added advantage of devising markers can be their application as reference exposures for sensory evaluations of indoor air quality or for calibration of measuring instrumentation.

3.4.1.1 Human Sensory Response to Air Polluted by Single VOCs

Sensory endpoints. Patte et al. (1975) presented psychophysical relations between suprathreshold odour intensities and the concentrations for 110 substances. These relations described detection thresholds, slopes of intensity and ceiling limits. All the slopes were below unity and were thus in agreement with psychophysical law, indicating that the perceived intensity grows more slowly than the strength of the stimulus (Stevens, 1975).

Cometto-Muñiz and Cain (1990, 1994) studied homologous series of alcohols, acetates and ketones and found that all sensory thresholds decreased systematically with carbon chain length. The difference between odour and irritation thresholds was approximately four orders of magnitude for highly odorous compounds but it decreased with increasing carbon chain length and for weak odours the difference was only one order of magnitude (Cain and Cometto-Muñiz, 1995). They found also that nose irritation thresholds are the function of saturated vapour concentration, implying that nasal irritation depends on a physicochemical interaction between the stimulus and the receptor. In addition, their results showed (Cometto-Muñiz and Cain, 1995) that eye irritation thresholds are remarkably close to nasal irritation, implying a similar mechanism for both sensations. A power of air pollutant potency to produce sensory irritation can be obtained from studies with humans and animals, as discussed by Nielsen and Alarie (1992).

Reference exposures. As a standard reference for expressing perceived odour intensity, the results obtained by scaling n-butanol were suggested (Engen, 1982), and the psychophysical function obtained for this compound using magnitude estimation is shown below (Moskowitz et al., 1974):

$$\Psi = 0.261 \cdot \Phi^{0.66} \qquad [3.4.1]$$

where: Ψ = subjective odour intensity;
Φ =concentration of n-butanol, ppm.

As a reference for sensory evaluations of perceived air quality in the decipol unit (Fanger, 1988), 2-propanone was selected, this being one of the major human bioeffluents (Bluyssen et al., 1989). A relationship between 2-propanone concentration and perceived air quality [3.4.2] is illustrated in Fig. 3.4.1 and has been widely used to train panels used for sensory evaluations of indoor air quality (Bluyssen et al., 1996).

$$C = 0.84 + 0.22 \cdot \Delta C \qquad [3.4.2]$$

where: C = perceived air quality, decipol;
ΔC =concentration of 2-propanone over background, ppm.

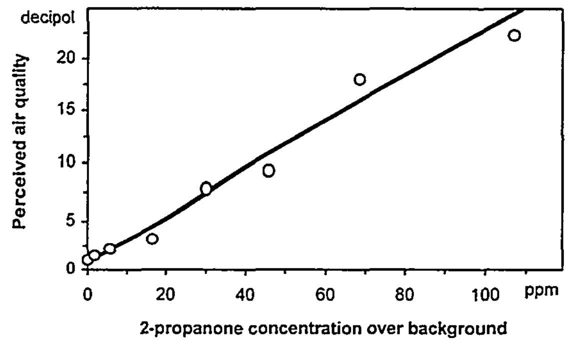


Figure 3.4.1 Exposure-response relationship for 2-propanone, a reference gas used in sensory evaluations of perceived air quality (Bluyssen et al., 1989)

An exposure-response relationship for subjectively rated irritation of mucous membranes, odour intensity and air quality has been established by Kjærgaard et al. (1989) for n-decane, which is a relatively inert but common indoor air pollutant emitted by building materials. Even at low concentration of n-decane, below 10 ppm, decrease of film tear stability was observed, implying that irritation of eyes was evoked.

3.4.1.2 Human Sensory Response to Air Polluted by Mixtures of VOCs

Sensory endpoints. Perception of a mixture of odorants depends on whether the concentrations of the constituents of the mixture are above or below odour threshold, and it can exhibit hypo-addition, complete addition or hyper-addition (see section 2.6.2). Sensory irritation in mixtures can, with good approximation, be estimated by adding the effects of mixture components (Cometto-Muñiz and Hernández, 1990; Cometto-Muñiz et al., 1997).

Reference exposures. A tentative dose-response relationship was developed (Mølhave, 1991) for a mixture containing 22 VOCs (m22-mixture (section 3.3.3.3)), based on several laboratory human experiments with that type of air pollution (e.g., Mølhave et al., 1986; Mølhave et al., 1991). This dose-response relationship can be used as a guideline when estimating total concentration of VOCs at which effects on humans are to be expected, and it is presented in Table 3.4.1. The levels presented in the table should be used with care, as they refer mainly to the effects expected during exposures to this type of air pollution. For other VOC mixtures, the effects can occur even at lower concentrations, especially when sensorily potent oxidizing products are present in indoor air (Wolkoff et al., 1997).

Table 3.4.1 Tentative dose-response relationship for discomfort due to air pollution containing 22 VOCs (the m22-mixture) (Mølhave, 1991)

Exposure range	Total concentration mg/m³	Effect
Comfort range	<0.20	no irritation or discomfort
Multifactorial exposures	0.20-3.0	irritation or discomfort possible if other exposures interact
Discomfort	3.0-25	exposure effect and probable headache possible if other exposures interact
Toxic exposure	>25	headache; additional neurotoxic effects other than headache may occur

3.4.2 Objective

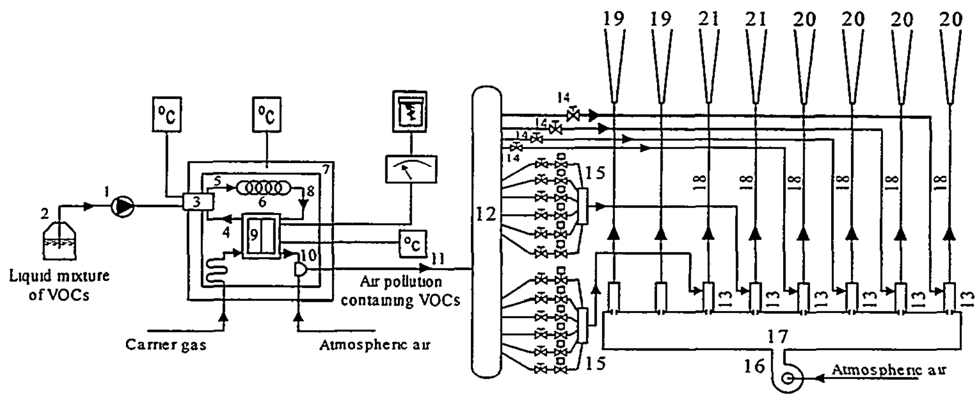
The purpose of the present study was to develop exposure-response relationships describing how humans perceive quality and odour intensity of the air polluted by single VOCs and mixtures of VOCs, which were selected in section 3.3.3 using the results of the literature survey presented in section 3.3.2.

3.4.3 Generation of Atmospheres Containing VOCs

Atmospheres with controlled addition of single VOCs (Table 3.3.8), except for 2-propanone, and mixtures of VOCs (Table 3.3.10) were produced using a specially built apparatus. The apparatus is called the VOC-generation system and consists of the VOC-generator and the dilution system. A detailed description of the system instrumentation, calibration and the performance tests is provided elsewhere (Fang and Melikov, 1994; Wargocki et al. 1996b); the basic information is given in the following section. 2-propanone was passively evaporated into air in 3-L jars according to Bluyssen and Cornelissen (1995).

3.4.3.1 The VOC-Generator

At the VOC-generator an atmosphere containing a well controlled level of single VOCs and mixtures of VOCs in a high concentration is produced by dynamic evaporation of liquid pollutants into a carrier gas and subsequent dilution of the mixture of vaporized liquids and carrier gas into clean atmospheric air. This is indicated in Fig. 3.4.2. A metering pump (#1) injects the liquid pollutants (#2) into an injection block (#3), where it is evaporated and mixed with a hot carrier gas, nitrogen (#4). Due to the low injection rate of the metering pump, the pressure produced by the pump is lower than the surface tension of the liquid at the injection block and drops of liquid are created and injected, one at a time. This can create an unacceptable pulsation of the concentration of the resulting mixture of vapours and carrier gas (#5). To avoid this pulsation, the vaporized liquids pass a packed gas chromatographic (GC) column (#6) with a non-polar coating, which is placed in the oven (#7). The GC-column acts as a buffer: at a properly selected flow of the carrier gas and appropriate choice of column temperature and dimensions (which depend on the flow rate of the injected liquid), the fluctuations in the injection rate caused by drop-formation are levelled out at the outlet of the column (#8). The concentration of pollutants in the carrier gas from the column is continuously monitored at the thermal conductivity detector (#9). The mixture of vaporized liquids and carrier gas is subsequently diluted (#10) and cooled by clean air to achieve the desired temperature and pollutant concentration in the exhaust air from the generator (#11).



The VOC-generator   The dilution system

Figure 3.4.2 The principle of the VOC-generation system (description of captions in text)

The generator ensures the reproduction of the relative concentrations of liquid pollutants in the mixture injected in the air from the generator containing their vapours, constant concentration of the total amount of VOCs (TVOC) in the air leaving the generator with limited variation in time, and a constant relative concentration of the components in the vaporized mixtures. Under properly selected operational conditions, the concentration of organic pollutants leaving the generator is supposed to be proportional to the flow rate of the injected liquid and inversely proportional to the flow of atmospheric air and a carrier gas. Thus, by documenting flow rates of the liquid, the carrier gas and the atmospheric air, the concentration at the generator outlet can be calculated according to the following formula:

$$C_{gen} = \frac{\rho \cdot I}{Q_a + Q_{cg}} \cdot \frac{10^6}{60} \qquad [3.4.3]$$

where:
C_{gen} = concentration of organic pollutants at the generator outlet, mg/m^3;
ρ = density of the liquid injected, kg/L;
I = flow rate of the injected liquid; ml/h;
Q_a = flow rate of diluting air, L/min;
Q_{cg} = flow rate of the carrier gas, nitrogen, L/min;

$10^6/60$ = conversion factor for units.

The above-mentioned principles of operation of the VOC-generator were tested by producing an atmosphere containing 22 VOCs (the m22-mixture) and by performing gas chromatography/mass spectroscopy (GC/MS) analysis of the injected liquid and of the polluted air at the generator outlet. In general, the analysis showed that the measured concentration was approx. 10% lower than the calculated concentration, and thus led to some validation of the instrument (Wargocki et al., 1996b).

3.4.3.2 The Dilution System

In the dilution system (Fang and Melikov, 1994) the atmosphere containing organic pollutants from the generator is simultaneously diluted to six well controlled exposure levels. Afterwards, it is presented to human subjects for sensory assessments through diffusers; the shape of the diffusers ensures that the air presented to subjects is not mixed with the surrounding air. This principle is indicated in Fig. 3.4.2. The VOC-polluted air from the VOC-generator is supplied to the VOC-gas cylinder (#12) and then to mixing chambers (#13). The flow of polluted air to the mixing chambers is determined by four fixed-flow controllers (#14) and two step-flow controllers (#15). Fixed-flow controllers consist of metering valves which supply the polluted air to the mixing chambers in a constant flow proportion of 1:5:10:20. Step-flow controllers consist of six solenoid valves and six metering valves which supply the polluted air to a cylinder in a constant flow proportion of 0.5:1:2:4:8:16. The variable flow of gas from the cylinder to the mixing chamber is obtained by opening a certain combination of solenoid valves. This procedure is controlled by a microprocessor together with manual code switches. Atmospheric air for the dilution is impelled by a fan (#16) to the air reservoir (#17) and then to the mixing chambers (#13). Constant flow of the dilution air is determined by a constant air pressure in the air reservoir and by an orifice. Dilution takes place in the mixing chambers. The VOC-polluted air is then supplied through mixing tubes (#18) to six diffusers: four diffusers (#20) supply fixed exposure levels in the proportion 1:5:10:20, and two diffusers (#21) supply variable exposure levels in a proportion within the range 0.5 to 31.5, with steps of 0.5. Two additional diffusers (#19) supply air used for the dilution, i.e., the background exposure levels.

The dilution system ensures dilution of highly concentrated pollution in the air from the VOC-generator to well controlled levels required for assessments by human subjects. The minimum flow rate of the air polluted by VOCs (at a flow proportion of n=0.5) is 0.019 L/min. The flow rate of the air used for dilution is for each diffuser 40 L/min. Thus, the concentration of organic pollutants in the air presented at the dilution system to human subjects through diffusers can be calculated by documenting the flow proportion of polluted air and the concentration of pollution in the air from the VOC-generator:

$$C_{dif\text{-}n} = \frac{n \cdot C_{gen}}{n + 1026} \qquad [3.4.4]$$

or by evaluating the concentration at one flow proportion of the polluted air in the diffuser; the concentration at any other flow proportion can then be simply calculated according to:

$$C_{dif-n^*} = C_{dif-n} \cdot \frac{n^*}{n} \cdot \frac{n+1026}{n^*+1026} \qquad [3.4.5]$$

where:
$C_{dif\text{-}n}$ = concentration of organic pollutants in the diffuser with a flow proportion of polluted air corresponding to n, mg/m³;
C_{gen} = concentration of organic pollutants at the generator outlet [3.4.3], mg/m³;
$C_{dif\text{-}n^*}$ = concentration of organic pollutants in the diffuser with a flow proportion of polluted air corresponding to n*, mg/m³;
n, n* = flow proportions of polluted air in the diffuser.

3.4.3.3 The VOC-Generation System

Stability of the TVOC concentration during operation of the VOC-generation system, as well as the repeatability of the created exposure to VOCs, were tested by producing atmospheres containing 8 VOCs (m8-mixture) and 22 VOCs (m22-mixture) (see Table 3.3.10), in the VOC-generator and continuously monitoring total concentration of VOCs (TVOC) in the outlets of diffusers in the dilution system, using photo-acoustic spectroscopy (PAS). These tests are reported in detail elsewhere (Wargocki et al., 1996b). They showed stability of the maximal exposure level produced in the dilution system (i.e., in the diffuser with the highest proportion of polluted air, n=31.5) to be ±5% during 5-hours' continuous operation, and day-to-day repeatability of this exposure level to be ±3%.

3.4.4 Documentation of the Exposures to Air Polluted with Single VOCs and Mixture of VOCs

Documentation of the exposure levels of the VOC-polluted air produced in the VOC-generation system during sensory assessments made by human subjects included the following:

- registration of the flow rates of liquid pollutants, the carrier gas and dilution air, and temperatures of the injection block and the oven (in the VOC-generator), as well as flow proportions of polluted air supplied to diffusers (in the dilution system);
- GC/MS analysis of the air from the dilution system in the diffuser with the highest flow proportion of polluted air (n=31.5);
- PAS measurements of the air from the dilution system in the diffusers with different flow proportions of polluted air.

3.4.4.1 Registration of the Operating Parameters of the VOC-Generation System

The flow rates were registered in order to calculate the concentration of pollutants in the atmospheres presented through diffusers in the dilution system according to equations [3.4.3] and [3.4.4]. The flow rates were registered using a calibrated metering pump (pollutant liquids) and calibrated flow meters (carrier gas and atmospheric air). The flow proportion of the polluted gas was registered by manually controlled code switches opening or closing calibrated metering valves. Temperatures were registered using calibrated Pt-100 sensors. All parameters of the VOC-generator documented during sensory evaluations are shown in Appendix 3.

3.4.4.2 GC/MS Analysis of the Air Polluted by VOCs

GC/MS analysis was performed in order to check whether concentrations of organic pollutants in the air calculated (formulae [3.4.3] and [3.4.4]) by registering the flows of pollutant liquids and the air used for dilution correspond to the measured concentrations. The analysis was carried out only for the air polluted with seven single VOCs: n-butanol, n-decane, ethylbenzene, n-hexane, toluene, 1,2,4-trimethylbenzene and m-xylene. The air from the diffuser in the dilution system with the highest flow proportion of the air polluted by VOCs (n=31.5) was adsorbed on the activated charcoal tubes; two samples were taken for each compound. The samples from the tubes were then desorbed (DMF-desorption) and analysed using the specific quantitative gas chromatography analysis with flame ionization detection. The error of the analysis was estimated to be 10%, and it includes analytical accuracy and sampling errors. GC/MS analysis was carried out by an external chemical laboratory (Miljø-Kemi A/S, Galten, Denmark).

The results of the analysis (Table 3.4.2) show that the concentration of single VOCs in the polluted air calculated according to formulae [3.4.3] and [3.4.4] was in each case lower than the measured concentration; similar results were obtained during performance tests with the m22-mixture (see section 3.4.3.1). These data indicate a systematic error in the calculated concentration. The components of this error include: measuring error of the flow rates of the liquid, the carrier gas and the diluting air in the VOC-generator; measuring error of the flow rates of the polluted air and the diluting air in the dilution system; as well as measuring errors of the GC/MS analysis. When comparing calculated and measured concentrations it was assumed that the air used for dilution was clean and contained VOCs at such low concentrations that they could be disregarded. The concentration of VOCs in the air used for dilution may nevertheless have had an impact on the resultant exposure levels presented for sensory assessments and thus on the measured concentrations which were compared with the calculated concentrations.

Table 3.4.2 Measured (using GC/MS) maximum concentrations of VOCs in air presented for sensory assessments to humans as compared to calculated concentrations

Exposure	Maximum concentration presented for sensory evaluations (mg/m^3)	
	Measured GC/MS, error:±10%	Calculated formulae [3.4.3] & [3.4.4]
n-butanol	2.142	2.760
n-decane	42.400	50.651
ethylbenzene	2.636	2.977
n-hexane	50.267	56.728
2-propanone	-	-
toluene	11.900	14.741
1,2,4-trimethylbenzene	2.710	3.009
m-xylene	9.960	11.756
m8-mixture	-	9.474
m19-mixture	-	4.489
m22-mixture	-	4.532

During sensory assessments with the air polluted with three mixtures of VOCs, GC/MS analysis was not carried out. In this case, the results of GC/MS analysis carried out during performance tests of the VOC-generator while generating the air polluted with m22-mixture (see section 3.4.3.1) were recognized as being sufficient to accept functioning of the instrumentation according to the design criteria when multicomponent pollution of air is produced.

3.4.4.3 PAS Measurements of the Air Polluted with VOCs

PAS measurements were carried out in order to check stability and repeatability of the TVOC concentration of the air polluted by both single organic compounds and mixtures of compounds. By monitoring several exposure levels in the diffusers in the dilution system, the flow proportions of polluted air were investigated as well.

The TVOC concentrations of organic pollutants in the air were measured with a Brüel & Kjær Multi-Gas Monitor, Type 1302. For 2-propanone, an optical filter calibrated with 2-propanone concentrations was used, the concentration of 2-propanone in air thus being directly measured with the instrument. For all other single VOCs and mixtures of VOCs presented for sensory evaluations, an optical filter calibrated against toluene concentrations was used. Their concentrations in air measured using the Multi-Gas Monitor are therefore toluene-equivalent total concentrations of volatile organic compounds in air (TVOC-toluene equivalent). PAS measurements were performed in the dilution system in the diffusers presenting the air polluted with VOCs to human subjects for sensory evaluations. Measurements were also made in diffusers presenting the air used for dilution (TVOC-toluene equivalent concentration in background air). During analysis, this concentration was subtracted from the TVOC-toluene equivalent concentration measured in diffusers presenting the air polluted by VOCs for sensory evaluations.

Table 3.4.3 Stability and repeatability of PAS measurements of the maximum exposures of single VOCs and mixtures of VOCs presented to human subjects for sensory evaluations

Exposure	TVOC-toluene equivalent (over bgr.†) of VOCs in air (mg/m^3)	Stability (%)	Repeatability (%)
n-butanol	11.06	± 3.5	-
n-decane	268.90	± 10.5	-
ethylbenzene	5.82	± 5.8	-
n-hexane	318.85	± 2.0	-
2-propanone	194.61*	± 2.5	± 1
toluene	12.00**	± 2.8	-
1,2,4-trimethylbenzene	7.18	± 10.8	-
m-xylene	18.38	± 1.6	-
m8-mixture	52.03	± 3.7	± 4.0
m19-mixture	16.80	± 6.8	± 6.0
m22-mixture	11.70	± 3.2	± 2.5

† background concentration subtracted
* 2-propanone concentration in air
** toluene concentration in air

Stability and repeatability of the TVOC-toluene equivalent concentration of the maximal exposures produced for the sensory assessments are presented in Table 3.4.3. The results are in general similar to the results obtained during performance tests of the VOC-generation system (Wargocki et al., 1996b) and show the stability of the TVOC-toluene equivalent concentration at the highest exposure to the air polluted with VOCs to be below ±10% and repeatability below ±5%. The results of PAS measurements of the air polluted with single VOCs and the mixtures containing 22 and 8 VOCs are shown in Appendix 4; such measurements were continuously made during sensory assessments for each of the pollutants studied.

3.4.5 Sensory Assessments

3.4.5.1 Experimental Plan

Panels of untrained (ASHRAE, 1989) and trained human subjects (Bluyssen et al., 1989) assessed the quality of air polluted by single VOCs and mixtures of VOCs.

These VOCs are candidates for reference exposures used during sensory evaluations of indoor air quality and were selected through a literature survey (section 3.3). The atmospheres polluted by VOCs were produced in the VOC-generator and after dilution with clean air, they were presented to subjects for sensory assessments through diffusers in the dilution system. The concentrations of pollutants in air were varied in order to obtain a wide range of exposures.

Air quality and odour intensity of each exposure level for each generated air pollution containing VOCs were evaluated once by each subject. For each generated air pollution, subjects assessed also (one evaluation) quality and odour intensity of air used for dilution.

To minimize the concentration of pollutants in background air, the experiments were carried out in climate chambers (Albrechtsen, 1988) ventilated with high rates, or in a well ventilated hall. The air for dilution was supplied to the dilution system directly from outdoors; it was pre-heated before being presented to subjects for assessments.

3.4.5.2 Sensory Panels

Subjects for sensory panels were selected without restriction to gender and smoking habits. Generally, subjects below 35 years of age participated in the experiments and they were mainly students from the Technical University of Denmark. The subjects were paid volunteers selected via advertisements distributed on the university campus.

Untrained panel. An untrained panel of over 200 subjects was used during experiments and on average a panel of 41 subjects was used in different experimental sessions; Table 3.4.4 summarizes data on subjects in untrained panels used during experiments. Untrained human subjects assessed the quality and odour of air polluted by VOCs using respectively the continuous acceptability scale (Gunnarsen and Fanger, 1989) and Yaglou's scale of odour intensity (Yaglou et al., 1936); both scales are shown in Fig. 3.4.3. Subjects did not receive any training except for instruction on how to use the scales.

Trained panel. A trained panel of over 50 subjects was used during the experiments, and on average a panel of 13 subjects was used in different experimental sessions; Table 3.4.4 summarizes data on the trained panels used in the experiments. The subjects were trained to assess the quality of air polluted with VOCs directly in the sensory unit decipol (Fanger, 1988), comparing to five known references of 1, 3, 5, 10 and 20 decipol created using 2-propanone as a reference gas (Bluyssen et al., 1989). The references were produced by passive evaporation of 2-propanone in 3-L jars ventilated with approx. 1 L/s of unpolluted air. During the training procedure, subjects assessed several different exposure levels of 2-propanone, as well as emissions from different building materials; the samples of materials were placed in 3-L jars and ventilated with approx. 1 L/s of unpolluted air. The training and selection procedure of trained subjects is described in detail elsewhere (Bluyssen et al., 1989; Pejtersen and Mayer, 1993; Bluyssen at el., 1995). Before each experimental session with exposures to VOCs, trained panels were re-trained for a period of 1 hour, using 2 to 4 different concentrations of 2-propanone.

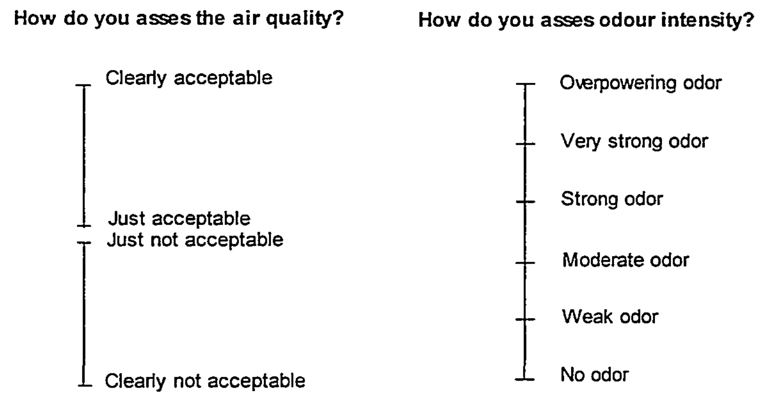


Figure 3.4.3 Left: Continuous scale of acceptability (slightly modified from the original introduced by Gunnarsen and Fanger, 1989) used by untrained panels to evaluate the quality of air polluted with VOCs. Right: Intensity scale (Yaglou et al., 1936) used by untrained panels to assess the odour of air polluted with VOCs. Both scales were placed on one voting sheet and were preceded by the following introductory sentence: "Imagine that during your daily work you are exposed to this air."

Table 3.4.4 Data on sensory panels assessing the quality and odour intensity of air polluted by 8 single VOCs and 3 mixtures of VOCs

Exposure		Number of subjects (% females; % smokers)	
		Untrained panel	Trained panel
Single VOCs	n-butanol n-decane ethylbenzene n-hexane toluene 1,2,4-trimethylbenzene m-xylene	41 (32%; 17%)	15 (33%; 7%)
	2-propanone	43 (26%; 19%)	8 (25%; -)
Mixtures of VOCs	m8-mixture	33	14 (38%; -)
	m19-mixture	59 (12%; -)	11 (38%, -)
	m22-mixture	33 36 43 (26%; 19%)	14 (29%; 0%) 14 (38%; -) 8 (25%; -)

3.4.6 Modelling Human Response to Air Polluted with VOCs

To model human sensory response, the results of sensory assessments of air polluted with single VOCs and mixtures of VOCs were plotted against the derived concentration of exposures presented for sensory evaluations. Then, using all single assessments of subjects, non-linear least square regression models were created (Bates and Watts, 1988) separately for the assessments made by untrained subjects and for those made by trained subjects (excluding sensory evaluations of the air used for dilution). For developed models, residual plots were inspected to investigate whether residuals form any particular patterns; these plots are not presented here.

3.4.6.1 Derivation of VOC Exposures Presented for Sensory Evaluations and Used for Modelling of Human Sensory Response

Air polluted with single VOCs. Concentrations of air polluted with n-butanol, n-decane, ethylbenzene, n-hexane, toluene, 1,2,4-trimethylbenzene and m-xylene were obtained using GC/MS measurements, and for 2-propanone using PAS measurements. The highest exposure levels presented for sensory evaluations were obtained using GC/MS measurements, except for 2-propanone for which the highest exposure level was obtained using PAS measurements. Other exposure levels were calculated (formula [3.4.5]) using the flow proportion of the polluted air registered in the dilution system (see Appendix 3).

Air polluted with mixtures of VOCs. Exposures presented for sensory evaluations were derived using PAS measurements of TVOC-toluene equivalent concentrations of the air polluted by m8-mixture, m19-mixture and m22-mixture, subtracting the measured TVOC-toluene equivalent concentration in the air used for dilution. In this way, sensory evaluations refer only to VOC pollution which in a controlled manner was added to the air by the VOC-generation system. If PAS measurements of TVOC-toluene equivalent concentration were missing for particular exposure levels, they were calculated (formula [3.4.5]) using the flow proportion of the polluted air which was registered in the dilution system (see Appendix 3).

3.4.6.2 Modelling Sensory Evaluations of an Untrained Panel

Assessments of the air quality. The continuous scale used by untrained subjects for evaluating the acceptability of air is a categorical (interval) scale (Cain and Moskowitz, 1974). A model of the following form was hence proposed to fit sensory evaluations of the air quality using the acceptability scale:

$$ACC = k_1 \cdot \log C_{VOC} + k_2 \qquad [3.4.6]$$

where:

ACC = acceptability of air evaluated by human subjects using the continuous scale (Fig. 3.4.3) coded as follows: clearly not acceptable = -1; just not acceptable/just acceptable = 0; and clearly acceptable = 1;

C_{VOC} = real concentration of single VOCs or TVOC-toluene equivalent concentration

above a background of mixtures of VOCs in the air presented for sensory assessments; mg/m^3;
k_1, k_2 = constant coefficients.

Using transformation between acceptability and percentage of dissatisfied (data of Gunnarsen and Fanger (1989) modelled with logistic regression) and the transformation between percentage of dissatisfied and decipol (Fanger, 1988), the above models (formula [3.4.6]) describing assessments of the air acceptability were further transformed to express the perceived air quality in the sensory unit decipol by applying the following conversion:

$$PAQ = 112 \cdot \left[5.98 - \ln\left(\frac{\exp(-0.18 - 5.28 \cdot ACC)}{1 + \exp(-0.18 - 5.28 \cdot ACC)} \cdot 100 \right) \right]^{-4} \qquad [3.4.7]$$

where:
ACC = acceptability of air as in formula [3.4.6];
PAQ = perceived air quality expressed in the decipol unit.

Assessments of odour intensity. The continuous scale used by untrained subjects for assessing odour intensity of air is a categorical (interval) scale (Cain and Moskowitz, 1974). To fit sensory ratings of odour intensity, a model in the following form was suggested:

$$OI = k_3 \cdot \log C_{VOC} + k_4 \qquad [3.4.8]$$

where:
OI = odour intensity of air evaluated by human subjects on the scale (Fig. 3.4.3) coded as follows: no odour = 0; slight odour = 1; moderate odour = 2; strong odour = 3; very strong odour = 4; and overpowering odour = 5;
C_{VOC} = real concentration of single VOCs or TVOC-toluene equivalent concentration above a background of mixtures of VOCs in the air presented for sensory assessments; mg/m^3;
k_3, k_4 = constant coefficients.

To obtain the odour threshold concentration for single VOCs and mixtures of VOCs, the above model (formula [3.4.8]) was equalled to 0, i.e., to odour intensity = 0 (no odour), and was solved for the concentration:

$$OT = 10^{-\frac{k_4}{k_3}} \qquad [3.4.9]$$

where:
OT = odour threshold concentration - the real concentration of single VOCs or TVOC-toluene equivalent concentrations above a background of mixtures of VOCs in the air presented for sensory assessments at which odour intensity equals 0 (no odour); mg/m^3;
k_3, k_4 = constant coefficients from formula [3.4.8].

3.4.6.3 Modelling Sensory Evaluations of a Trained Panel

Perceived air quality was assessed by a trained panel in decipol by matching the annoyance of air polluted by VOCs with the annoyance of air polluted with 2-propanone producing reference exposures of known decipol levels. Sensory responses of trained subjects were modelled using the following model (Cain and Moskowitz, 1974):

$$PAQ = k_5 \cdot C_{VOC}{}^{k_6} + k_7 \qquad [3.4.10]$$

where:

PAQ = perceived air quality, decipol;

C_{VOC} = real concentration of single VOCs or TVOC-toluene equivalent concentrations above a background of mixtures of VOCs in the air presented for sensory assessments; mg/m^3;

k_5, k_6, k_7 = constant coefficients.

3.4.7 Results

Figures 3.4.4 to 3.4.14 present results of the modelling of untrained panels' ratings of acceptability and odour intensity of air polluted with 8 single VOCs and 3 mixtures of VOCs. Each figure shows mean assessments of VOC-polluted air and air used for dilution made on either the continuous acceptability scale or the odour intensity scale, together with a fitted non-linear regression model. The mathematical form for the fitted models, together with coefficients of correlation (R^2), are presented in Table 3.4.5. The models shown in Figs. 3.4.4 to 3.4.14 and Table 3.4.5 can be applied to produce well controlled levels of VOC-polluted atmospheres used as reference exposures during sensory evaluations of indoor air quality.

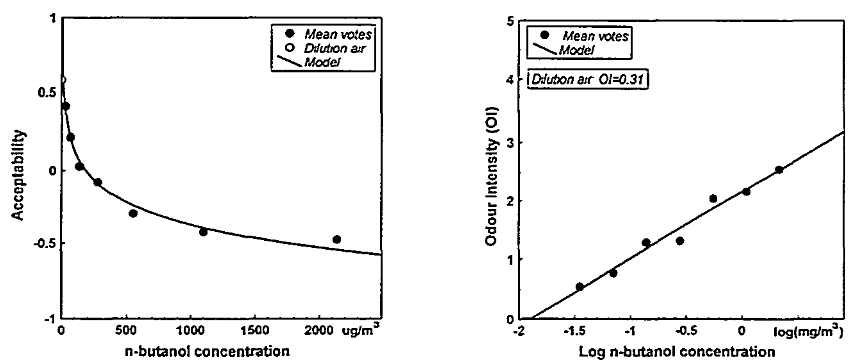


*Figure 3.4.4 Mean ratings of acceptability (left) and odour intensity (right) made by untrained panels of human subjects on the air polluted by **n-butanol** with the fitted non-linear regression models*

Table 3.4.5 Perception models describing relationships between assessments of acceptability and odour intensity of air polluted by single VOCs and mixtures of VOCs and the concentrations of VOCs in air; the strength of each relationship is assessed by providing a correlation coefficient (R^2). For each VOC-exposure presented for sensory evaluation, odour thresholds are shown; odour thresholds were derived both from the literature (Devos et al., 1990) and by using assessments of odour intensity (formula [3.4.8])

Exposure type	Least square non-linear regression models for perceived acceptability (ACC) and odour intensity (OI)	R^2	Range of C_{VOC}‡ (mg/m³)	Odour threshold (mg/m³)	
				Devos et al. (1990)	derived from intensity scale
n-butanol	$ACC=-0.51 \cdot logC_{VOC}-0.37$ $OI=1.14 \cdot logC_{VOC}+2.16$	0.98 0.97	0.035-2.14	1.51	0.02
n-decane	$ACC=-0.30 \cdot logC_{VOC}+0.55$ $OI=0.54 \cdot logC_{VOC}+0.26$	0.87 0.83	0.693-42.40	4.37	0.77
ethylbenzene	$ACC=-0.56 \cdot logC_{VOC}-0.23$ $OI=1.16 \cdot logC_{VOC}+1.78$	0.97 0.96	0.043-2.64	0.01	0.05
n-hexane	$ACC=-0.25 \cdot logC_{VOC}+0.56$ $OI=0.48 \cdot logC_{VOC}+0.17$	0.77 0.85	0.822-50.27	79.43	1.69
2-propanone†	$ACC=-0.92 \cdot logC_{VOC}+1.35$ $OI=1.76 \cdot logC_{VOC}-0.80$	0.83 0.82	2.42-82.37	14.56	4.00
toluene	$ACC=-0.67 \cdot logC_{VOC}+0.25$ $OI=1.18 \cdot logC_{VOC}+0.76$	0.92 0.89	0.195-11.90	5.89	0.36
1,2,4-trime-thylbenzene	$ACC=-0.62 \cdot logC_{VOC}-0.19$ $OI=1.02 \cdot logC_{VOC}+1.42$	0.96 0.91	0.044-2.710	0.78	0.09
m-xylene	$ACC=-0.54 \cdot logC_{VOC}+0.07$ $OI=1.27 \cdot logC_{VOC}+1.16$	0.98 0.97	0.163-9.960	1.41	0.20
m8-mixture	$ACC=-0.57 logC_{VOC}+0.60$ OI= (*no data*)	0.96 –	2.130-52.03	–	–
m19-mixture	$ACC=-0.54 logC_{VOC}+0.03$ OI=(*no data*)	0.92 –	0.34-16.80	–	–
m22-mixture	$ACC=-0.51 \cdot logC_{VOC}-0.02$ $OI=0.83 \cdot logC_{VOC}+1.99$	0.79 0.76	0.11-11.71 0.11-6.53	–	0.01

‡ concentration in air for single VOCs; TVOC-toluene equivalent concentration over background for mixtures of VOCs; † for 2-propanone, concentration range and odour thresholds are given in ppm;

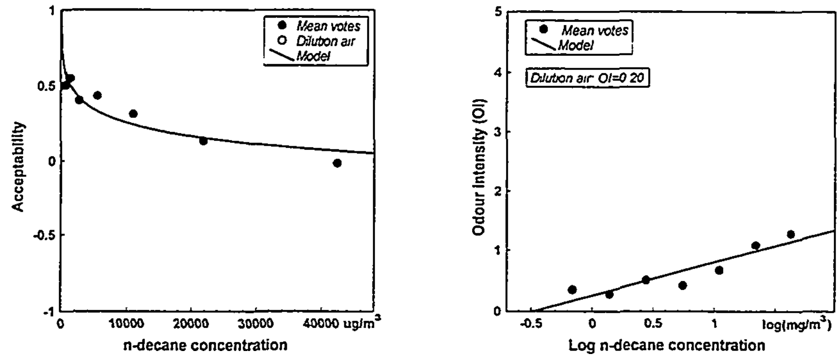


Figure 3.4.5 Mean ratings of acceptability (left) and odour intensity (right) made by untrained panels of human subjects on the air polluted by ***n-decane*** *with the fitted non-linear regression models*

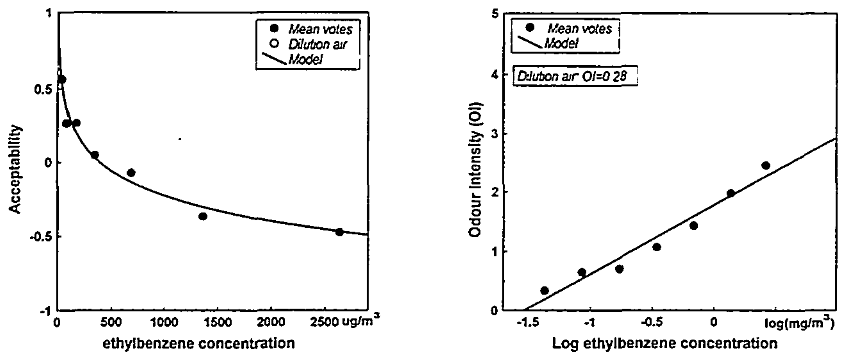


Figure 3.4.6 Mean ratings of acceptability (left) and odour intensity (right) made by untrained panels of human subjects on the air polluted by ***ethylbenzene*** *with the fitted non-linear regression models*

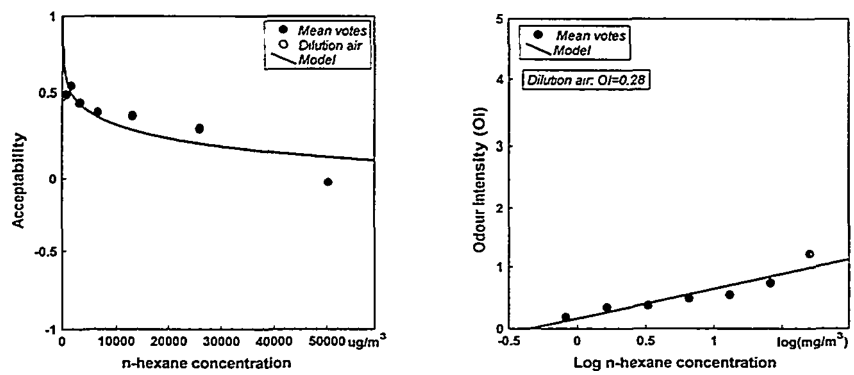


Figure 3.4.7 Mean ratings of acceptability (left) and odour intensity (right) made by untrained panels of human subjects on the air polluted by ***n-hexane*** *with the fitted non-linear regression models*

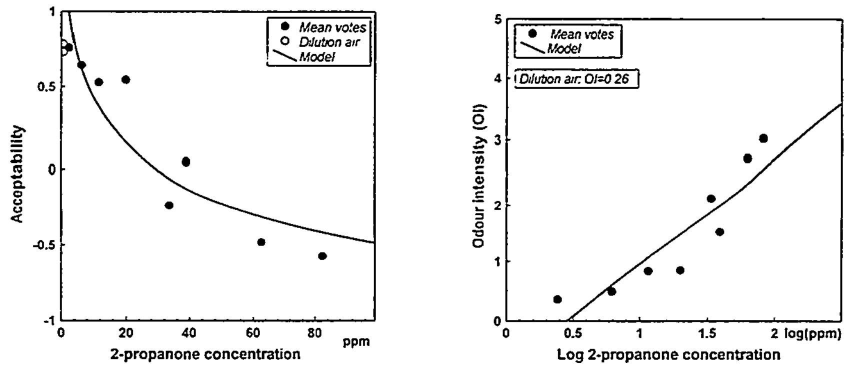


Figure 3.4.8 Mean ratings of acceptability (left) and odour intensity (right) made by untrained panels of human subjects on the air polluted by ***2-propanone*** *with the fitted non-linear regression models*

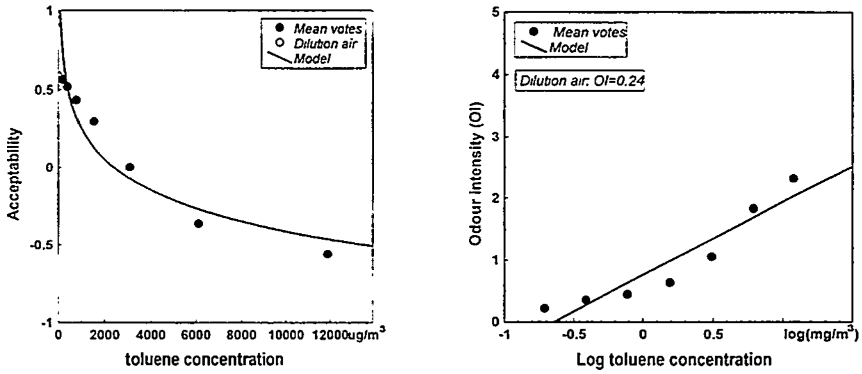


Figure 3.4.9 Mean ratings of acceptability (left) and odour intensity (right) made by untrained panels of human subjects on the air polluted by ***toluene*** *with the fitted non-linear regression models*

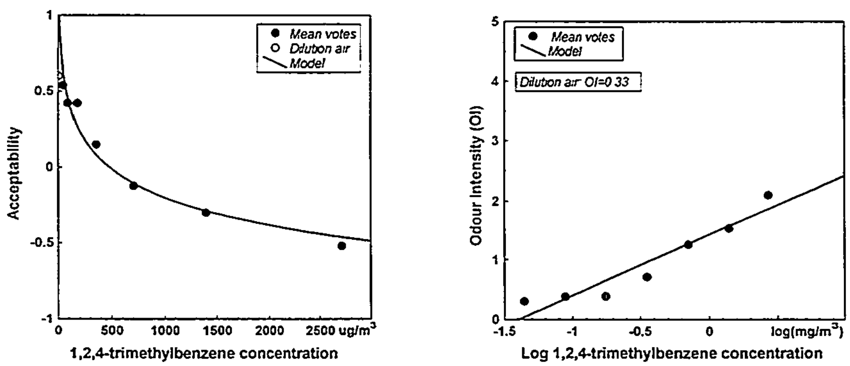


Figure 3.4.10 Mean ratings of acceptability (left) and odour intensity (right) made by untrained panels of human subjects on the air polluted by ***1,2,4-trimethylbenzene*** *with the fitted non-linear regression models*

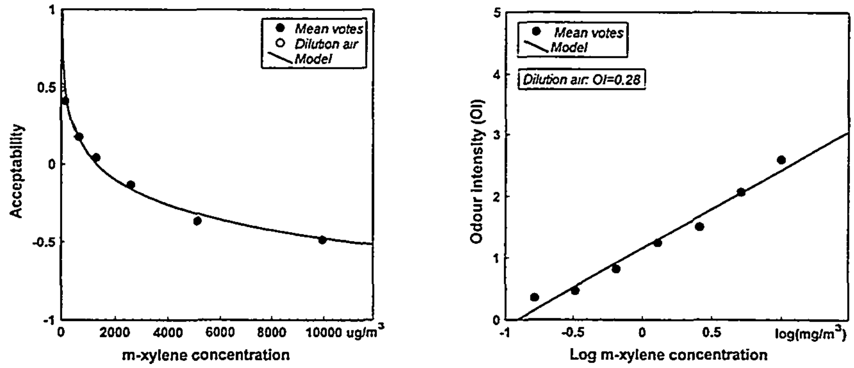


Figure 3.4.11 Mean ratings of acceptability (left) and odour intensity (right) made by untrained panels of human subjects on the air polluted by ***m-xylene*** *with the fitted non-linear regression models*

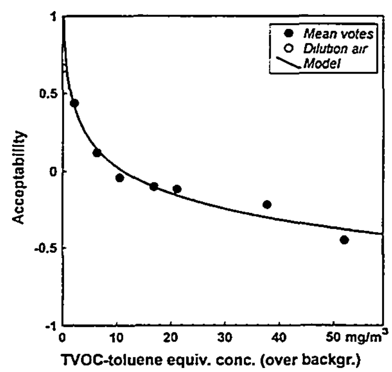


Figure 3.4.12 Mean ratings of acceptability made by untrained panels of human subjects on the air polluted by ***m8-mixture*** *with the fitted non-linear regression model; data for odour intensity are missing*

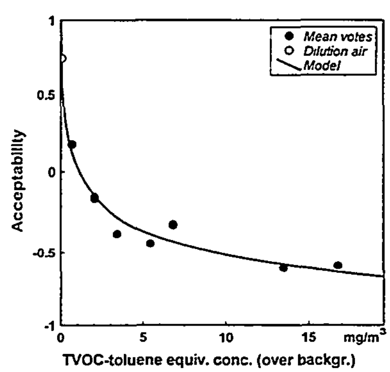


Figure 3.4.13 Mean ratings of acceptability (left) made by untrained panels of human subjects on the air polluted by ***m19-mixture*** *with the fitted non-linear regression model; data for odour intensity are missing*

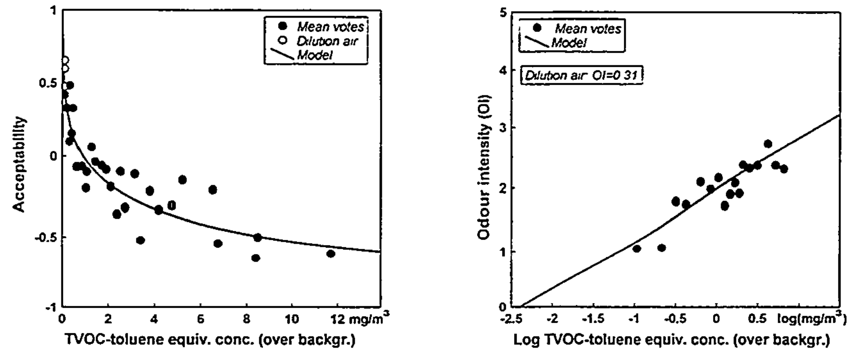


Figure 3.4.14 Mean ratings of acceptability (left) and odour intensity (right) made by untrained panels of human subjects on the air polluted by m22-mixture with the fitted non-linear regression models

To evaluate the extent to which the potency of single VOCs and mixtures of VOCs can evoke sensory effects in humans, Fig. 3.4.15 was created by plotting iso-lines of constant perception of air acceptability separately for each air pollutant. The top chart of Fig. 3.4.15 shows that n-butanol was the most potent compound among 8 single VOCs studied, i.e., it caused the greatest number of persons dissatisfied with the air quality at the lowest concentration; the least potent were n-decane, n-hexane and 2-propanone. These results agree in general with the odorous properties of these compounds (Table 3.4.5). Two mixtures of VOCs, m19-mixture and m22-mixture, produced the same perceived quality of air at the same TVOC-toluene equivalent concentration (bottom chart of Fig. 3.4.15). However, the calculated concentration of VOCs in air (formulae [3.4.3] and [3.4.4]), were not identical at the same TVOC-toluene concentration - the calculated concentration for the m22-mixture was lower, indicating that it was more potent. The least potent mixture was the m8-mixture. Since the m8- and m19-mixtures are daughters of the m22-mixture, these results may suggest that at the same concentration of VOCs in air, the percentage of dissatisfied persons assessing the quality of air polluted by a mixture of non-reactive VOCs may rise with an increasing number of mixture constituents.

In Fig. 3.4.16, the odour intensity is plotted against the acceptability of air containing single VOCs and mixtures of VOCs. The results show that the odour intensity is strongly negatively correlated with the air acceptability and that, except for m22-mixture and 2-propanone this correlation does not depend to any great extent on the type of exposure. These results imply that odour intensity and acceptability of air can be used alternately as measures of the perceived quality of air polluted by the VOCs investigated.

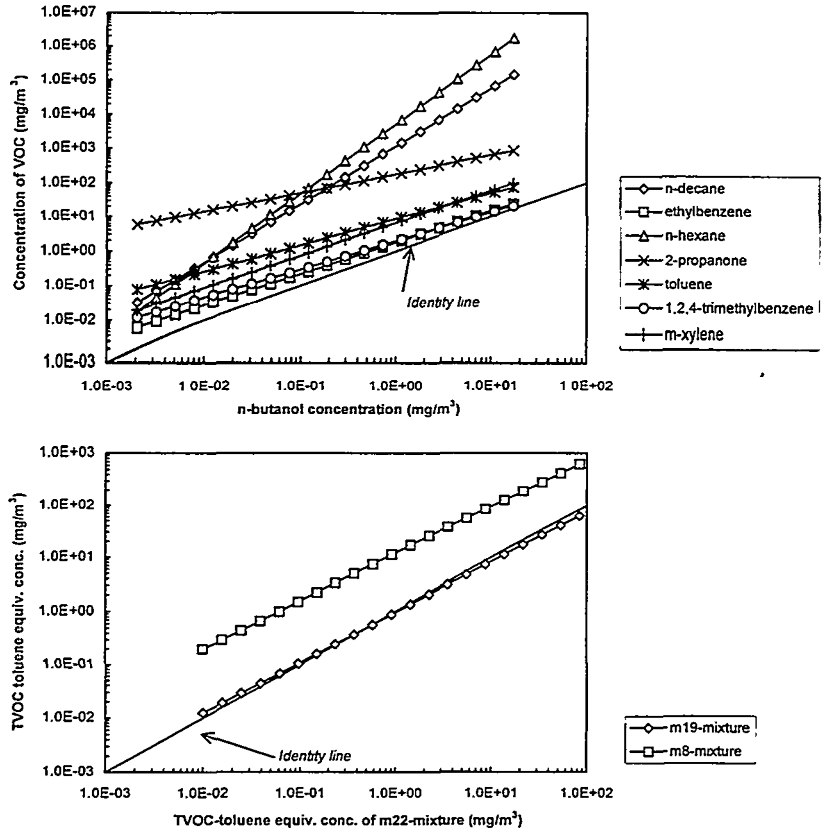


Figure 3.4.15 Iso-lines of constant air acceptability. Top: concentration of single VOCs plotted against the concentration of n-butanol. Bottom: TVOC-toluene equivalent concentration (over background) of mixtures of VOCs plotted against the TVOC-toluene equivalent concentration (over background) of the m22-mixture

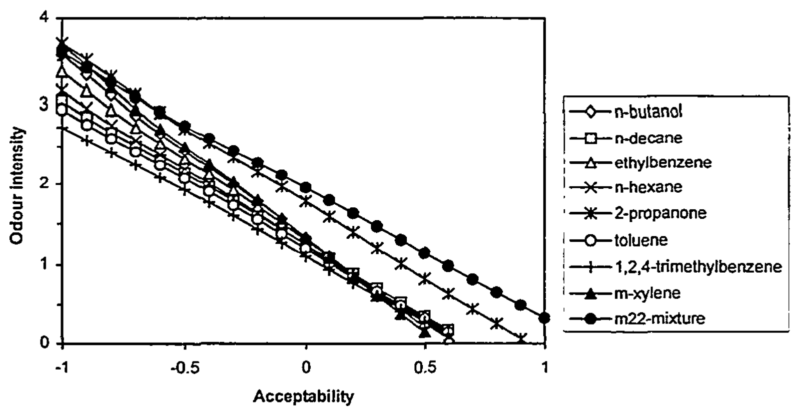


Figure 3.4.16 Odour intensity as a function of air acceptability for 8 single VOCs studied and the mixture of 22 VOCs

Figures 3.4.17 and 3.4.18 present results of the modelling of trained panels' ratings of the perceived quality of air polluted with 8 single VOCs and with 3 mixtures of VOCs. Each figure shows mean assessments (made directly in decipol) of the quality of VOC-polluted air and of the air used for dilution. The mathematical form for the fitted models, together with the coefficients of correlation (R^2), are presented in Table 3.4.6. For comparison, models created using assessments made by untrained subjects are shown on each chart after the perceived acceptability of air was transformed into decipol using formula [3.4.7].

Table 3.4.6 Perception models of air polluted by single VOCs and mixtures of VOCs assessed by a trained panel directly in decipol

Exposure type	Least-square non-linear regression model	Range of C_{VOC} mg/m³	R^2
n-butanol	$PAQ = -50.04+62.15 \cdot C_{VOC}^{0.048}$	0.035-2.14	0.954
n-decane	$PAQ = 1.61+0.095 \cdot C_{VOC}^{1.14}$	0.693-42.40	0.957
ethylbenzene	$PAQ = -0.27+9.52 \cdot C_{VOC}^{0.51}$	0.043-2.64	0.981
n-hexane	$PAQ = 1.28+0.09 \cdot C_{VOC}^{0.90}$	0.822-50.27	0.904
2-propanone	$PAQ = 0.72+0.34 \cdot C_{VOC}^{0.86}$	1.51-98.38†	0.924
toluene	$PAQ = -2.20+5.05 \cdot C_{VOC}^{0.40}$	0.195-11.90	0.974
1,2,4-trimethylbenzene	$PAQ = -1.80+10.08 \cdot C_{VOC}^{0.49}$	0.044-2.710	0.964
m-xylene	$PAQ = -9.49+16.42 \cdot C_{VOC}^{0.19}$	0.163-9.960	0.992
m8-mixture	$PAQ = 3.50+1.93 \cdot C_{VOC}^{0.46}$	0.67-32.58††	0.839
m19-mixture	$PAQ = -26.42+35.19 \cdot C_{VOC}^{0.10}$	0.34-6.71††	0.929
m22-mixture	$PAQ = -28.12+36.68 \cdot C_{VOC}^{0.07}$	0.11-8.68††	0.785

† ppm; †† TVOC-toluene equivalent concentration over background (mg/m³)

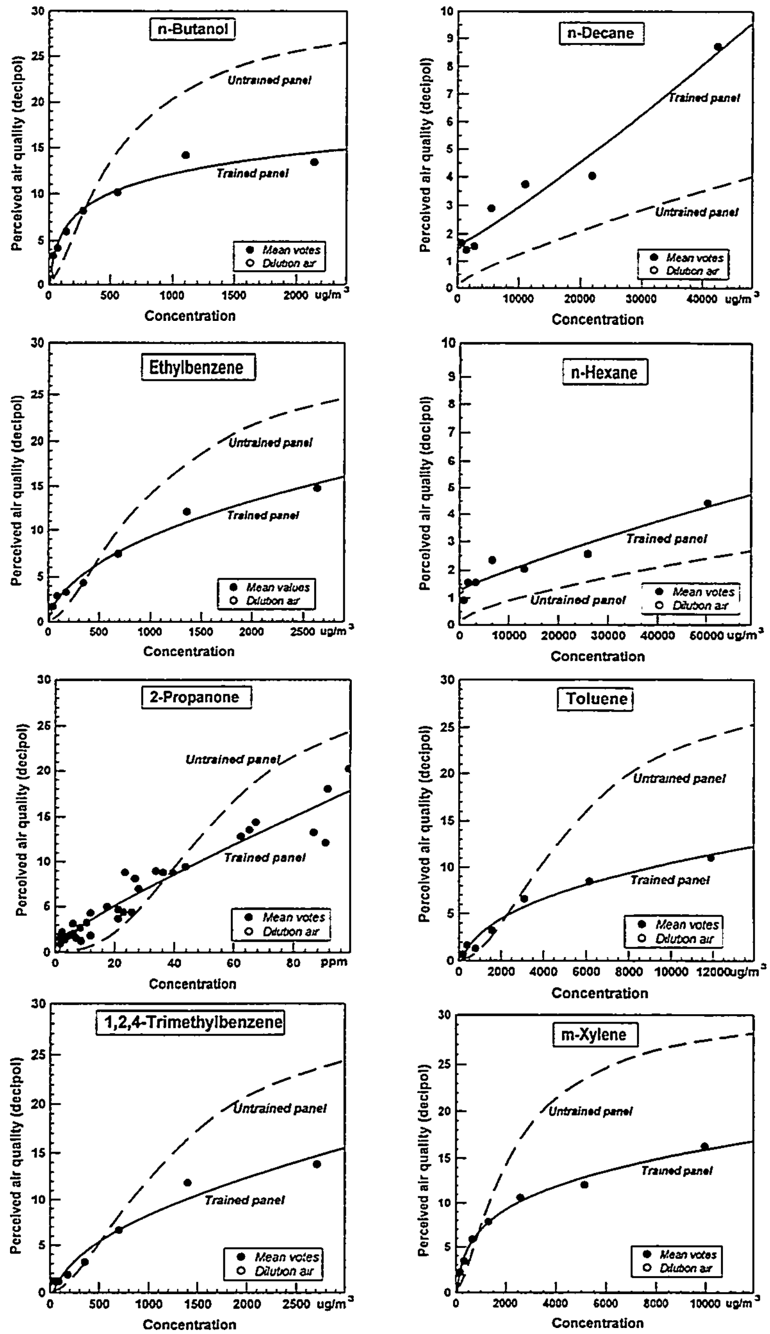


Figure 3.4.17 Mean ratings of perceived air quality in decipol made by trained panels of human subjects on the air polluted by single VOCs with the fitted non-linear regression models; models created using assessments made by untrained panels are also shown on the charts

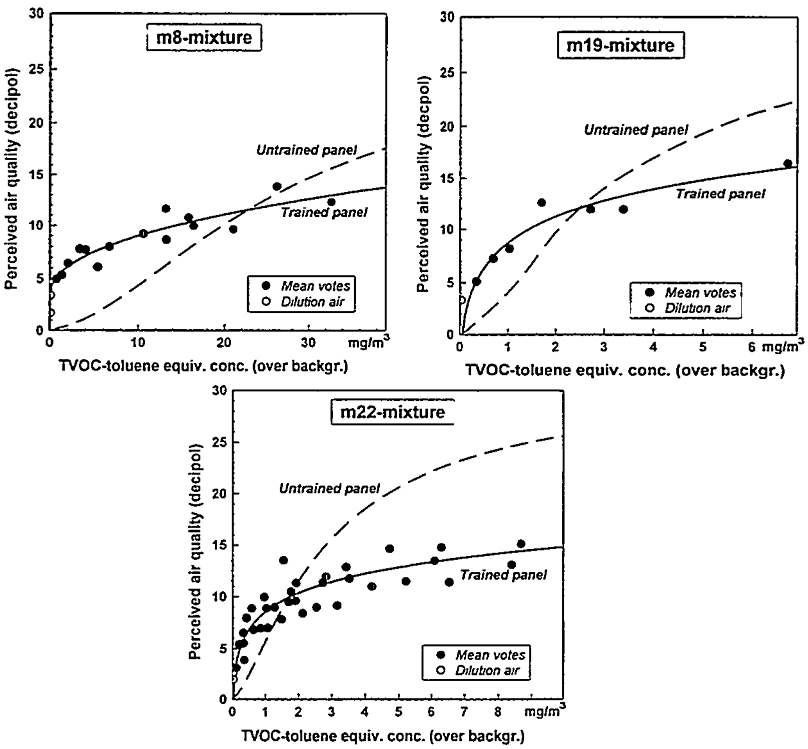


Figure 3.4.18 Mean ratings of perceived air quality in decipol made by trained panels of human subjects on the air polluted by mixtures of VOCs with the fitted non-linear regression models; models created using assessments made by untrained subjects are also shown on the charts

3.4.8 Discussion

At present, 2-propanone is used as a reference exposure to train people to assess the perceived air quality in decipol (Bluyssen et al., 1989). In this study, the exposure-response relationships were developed for the other 7 VOCs and 3 mixtures of VOCs using the sensory evaluations of untrained subjects, and they can also be used to train people to assess the perceived air quality. 2-propanone was selected to create a reference exposure as it is one of the most prevalent bioeffluents. Other criteria were used for selecting the VOCs in the present experiments. The single VOCs were selected as they are representative of indoor air in offices that are at least one year old, taking into account the frequency of occurrence, the measured concentrations and the potential to evoke odour perception in humans at the concentrations measured indoors. The constituents of three of the mixtures studied are VOCs that are typically emitted by building materials (Mølhave, 1982; Mølhave et al., 1986). The single VOCs and mixtures of VOCs investigated, together with 2-propanone, create a family of reference atmospheres which can be used alternately when training people for sensory evaluations of perceived air quality or in connection with the calibration of measuring instruments. It is worth mentioning here that the relationships developed are valid only in the range of concentrations indicated in Table 3.4.5. Moreover, the relationships for n-decane and n-hexane should be used with caution, as too low concentrations of these VOCs were generated and only the lower end of the exposure-response relationship was created.

One decipol is defined as the air pollution caused by one standard person (one olf) ventilated by 10 L/s of unpolluted air, whereas one olf is the emission rate of air pollutants (bioeffluents) from a standard person (Fanger, 1988). Using the results of the present study, one decipol and one olf can be defined by respectively the concentration and the emission rate of the 8 single VOCs and 3 mixtures of VOCs investigated (Table 3.4.7).

Table 3.4.7 *Concentrations of the single VOCs and mixtures of VOCs investigated corresponding to one decipol, as compared to their mean weighted concentrations measured in offices (see section 3.3.2), and the strengths of the pollution sources emitting VOCs that are equivalent to the sensory source strength of one olf*

Exposure type	Mean weighted concentration in offices (section 3.3.2) (µg/m3)	Concentration equivalent to one decipol (µg/m3)	Source strength equivalent to one olf (µg/s)
n-butanol	68.1	51	0.51
n-decane	13.9	7300	73
ethylbenzene	16.3	118	1.18
n-hexane	16.6	12000	120
2-propanone	0.006†	14†	333
toluene	42.8	872	8.72
1,2,4-trimethylbenzene	17.5	168	1.68
m-xylene	18.5	391	3.91
m8-mixture	-	3500 ††	35
m19-mixture	-	168††	1.68
m22-mixture	-	391††	3.91

† ppm; †† TVOC-toluene equivalent concentration over background

Figures 3.4.17 and 3.4.18 show the perceived quality of air polluted singly by 8 VOCs and 3 mixtures of VOCs being assessed differently by untrained subjects and the subjects trained to assess the air quality directly in decipol, using 2-propanone as a reference exposure according to the method proposed by Bluyssen et al. (1989). A possible rationale for this discrepancy is given in section 3.5.

3.4.8.1 Methodological Considerations

On average, 41 untrained subjects assessed the quality of air polluted by VOCs. This is much less than in the experiment of Bluyssen et al. (1989) where 265 subjects were used when the relationship between 2-propanone concentration and decipol was established. This can be seen as the weakness of the present experiment, especially if one considers the large variation in subjects' votes on the acceptability scale (on average 0.45 units on a scale with endpoints coded -1 and +1). Non-linear regression models developed using the sensory assessments of untrained subjects (relating the concentration of VOCs with the perceived acceptability of air) are nevertheless characterized by the high correlation coefficients ($r^2>0.77$), indicating that they are established with reasonably good accuracy. As confirmed by chemical measurements, the concentrations of VOCs in the exposures presented to human subjects for assessment, which were independent variables in the non-linear models, were well controlled and thereby are not expected to inflate the experimental error.

The form of the non-linear regression model that was used to fit the sensory ratings of untrained subjects was previously adopted by Katz and Talbert (quoted by Cain and Moskowitz, 1974) to model the ratings of odour intensity made on the categorical scale with equal intervals. It was selected because the continuous acceptability scale (Gunnarsen and Fanger, 1989) has the properties of the interval scale. Other models, such as the exponential, probit or logit models, for which a rationale is discussed in detail by Groes (1995), were also considered. They were not adopted, however, as the high correlation coefficients for the non-linear regression model selected suggested that the choice was right. Similar models to those adopted in the present experiment can be suggested for use in future experiments when exposure-response relationships are established between the acceptability of air (being a primary psychophysical judgement of the air quality) and the area-specific airflow rate (used to characterize the loading of building materials) (Knudsen et al., 1998).

In this study, VOC exposures were generated using a specially built system which enables the mass ratios between pollutants in the liquid mixture injected into hot nitrogen and diluted with air to remain unchanged after evaporation; the mass ratios reflect the ratios between the concentrations of pollutants in the air containing mixture of pollutants, presented for sensory evaluations (Wargocki et al., 1996b). Such instrumentation may be costly and difficult to operate. Therefore, for future experiments, the simpler method of generating reference exposures is suggested. Different concentrations of reference exposures containing single VOCs can, for example, be generated by controlling the rate of passive evaporation of the pollutant liquid into the air at the constant flow rate of clean air used for dilution; this principle is at present used to produce the reference exposure containing 2-propanone (Bluyssen and Cornelissen, 1995). Different concentrations of reference exposures containing mixtures of VOCs can be generated in a similar way. However, in order to obtain specific ratios between concentrations of the mixture constituents, the evaporation rate should be determined based on the vapour pressure of the pollutants and kept constant, whereas the flow rate of the dilution air should be changed.

In the present study, the subjects were only asked to rate acceptability and odour intensity of the air polluted by different single VOCs and mixtures of VOCs. No attempt was made to characterise the qualitative nature of the perceived odour, e.g., whether the odour was pleasant/unpleasant, healthy/unhealthy, fresh/foul, sweet/sour, dry/damp, sound/rotten, etc. This multi-dimensional and qualitative odour characterization is recommended for future experiments when selecting mixtures of VOCs simulating the office air, as well as reference air in experiments on acceptable air quality.

3.4.8.2 Enhancing Effect of the Mixture of Air Pollutants

In Table 3.4.8, the odour thresholds for six single VOCs obtained using sensory assessments of the odour intensity (section 3.4.6.2) are compared with the concentrations of these compounds in m22-mixture when the mixture is at the odour threshold concentration. It can be seen that the concentrations of six single VOCs in the mixture are several orders of magnitude lower than their odour threshold concentrations measured when the VOCs were present alone. These results show that otherwise imperceptible VOCs become perceptible in a mixture; this is in agreement with other studies showing that an enhancement of odour properties of VOCs occurs in the mixture with constituents below their odour thresholds (Patterson et al., 1993; Hau and Connell, 1998). These results can provide an explanation as to why the air quality is poor and the objectionable odours occur in indoor environments polluted by hundreds of single VOCs, even though the single VOCs are at concentrations below their sensory endpoints (see section 3.3.2.3).

Table 3.4.8 Concentrations of 6 single VOCs in the m22-mixture, when the mixture is at the odour threshold concentration, as compared to the odour threshold concentrations of these compounds measured when they were present alone

Compound	Odour threshold when the compound is present alone (see Table 3.4.5) (mg/m^3) OT	Concentration in m22-mixture when the mixture is at the odour threshold (mg/m^3) PC	Ratio PC/OT
n-butanol	0.02	0.00012	$6.0 \cdot 10^{-3}$
n-decane	0.77	0.00012	$0.2 \cdot 10^{-3}$
ethylbenzene	0.05	0.00012	$2.4 \cdot 10^{-3}$
n-hexane	1.69	0.00012	$0.1 \cdot 10^{-3}$
1,2,4-trimethylbenzene	0.07	0.000012	$0.2 \cdot 10^{-3}$
m-xylene	0.20	0.0012	$6.0 \cdot 10^{-3}$

It is suggested that the experiments with mixtures of single VOCs investigated in the present experiments be continued. These mixtures can be constituted of 2 to 8 compounds, and the compounds can be mixed according to different criteria, e.g., according to their odour thresholds, according to the concentrations causing 20% to be dissatisfied, etc. For such mixtures, the exposure-response relationships should be created and compared with the models developed in the present study. These comparisons may provide additional information required for understanding the combined effects in mixtures of VOCs.

3.4.8.3 Variability of the Sensory Pollution Load

The present results were used to examine whether the sensory pollution loads on the air caused by 8 single VOCs and 3 mixtures of VOCs are constant. Acceptability ratings in the non-linear regression models for the air pollutants investigated (Table 3.4.5) were transferred to decipol [3.4.7] and the relationships obtained, relating the perceived air quality in decipol with the concentration of pollutants in air, were differentiated against the concentration. The first derivatives were then plotted against the VOC concentration (Fig. 3.4.19). If the sensory pollution loads were constant, the first derivative should not have changed with the concentration.

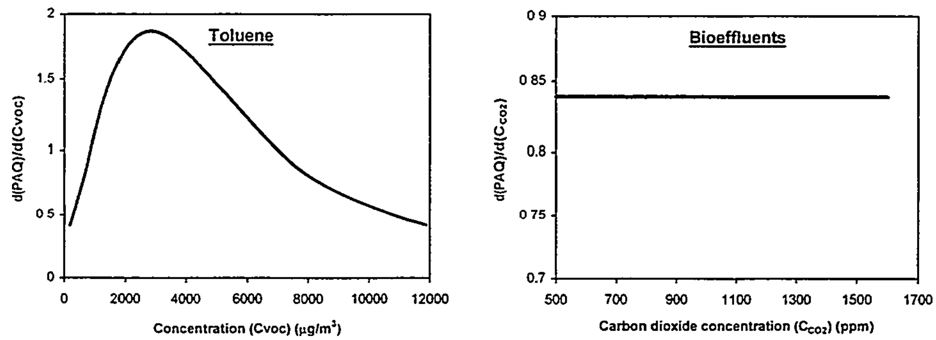


Figure 3.4.19 Left: A change of the first derivative (dPAQ/dCVOC) of the perceived quality of air (PAQ, in decipol) [3.4.7] polluted with toluene with increasing concentration of toluene in air (CVOC). Right: First derivative (dPAQ/dCCO2) of the perceived quality of air (PAQ, in decipol) polluted by bioeffluents (Fanger, 1988) as a function of the carbon dioxide concentration (CCO2)

In the left chart of Fig. 3.4.19, the first derivative of the perceived quality of air polluted by toluene is shown as a function of concentration; for other single VOCs and mixtures of VOCs investigated in the present experiment, similar relations were obtained but they are not presented here. It can be seen that the first derivative and thereby the sensory pollution load caused by toluene is not constant: at low concentrations it rises with increasing concentration and the inverse effect is observed for high concentrations. Similar results were obtained for sensory pollution loads for the pollutants emitted from building materials (Knudsen et al., 1997). For comparison, in the right-hand chart of Fig. 3.4.19, the first derivative of the perceived quality of air polluted by bioeffluents is plotted against the concentration of carbon dioxide (CO_2) - a marker of bioeffluents; the relationship between the perceived air quality in decipol and CO_2 from human bioeffluents was obtained from Fanger (1988). It can be seen that the first derivative is constant and does not depend on the CO_2 concentration in air. This agrees with the underlying assumption of the comfort model (Fanger, 1988; Chapter 1 of the present thesis), that the sensory strength of human bioeffluents does not depend on the ventilation rate.

The above-mentioned results indicate that the sensory pollution loads caused by sources other than people are not constant and may change with varying concentration. This is probably caused by a non-uniform human olfactory response to various odorous pollutants (Patte et al., 1975) and to pollutants emitted from building materials (Knudsen et al., 1997; 1998). The way in which the variation occurs depends probably on the position of the exposure-response relationships for the air pollutants towards the corresponding exposure-response relationship for bioeffluents (Knudsen et al., 1997). Further studies are recommended investigating the form of the function describing the relationship between the sensory pollution load and the concentration of pollutants, or the area-specific ventilation rate (used to characterize the loading of building materials). This information is essential for modelling the perceived air quality.

3.5 Comparison of the Perceived Air Quality Assessed by Untrained and Trained Panels

3.5.1 Objective

It was observed in section 3.4.7, that the perceived quality of air polluted singly by 8 VOCs and 3 mixtures of VOCs is different when assessed by untrained subjects and by the subjects trained to assess the air quality using 2-propanone as a reference exposure. The purpose of the present experiment was to develop the transfer model comparing the sensory evaluations made by untrained and trained subjects.

3.5.2 Laboratory Transfer Model Comparing Sensory Evaluations of Trained and Untrained Subjects

3.5.2.1 Method

Perception models for single VOCs and mixtures of VOCs developed using the sensory assessments of untrained and trained panels (Table 3.4.5 and 3.4.6) were solved for the concentration of pollutants in air (C_{VOC}). For each type of air pollution studied, transformed models were then equalled. This procedure yielded relations comparing directly sensory assessments made by untrained panels using the continuous acceptability scale (ACC) and sensory ratings of trained subjects in decipol (PAQ). To find the general relation, comparing the sensory assessments of untrained and trained panels, discretization of these relations was made every 0.01

decipol in the domain in which the perception models apply, i.e., for the range of concentrations (C_{VOC}) for which the perception models were developed. Discretization yielded a cloud of points for which a model in the following form was fitted:

$$ACC = k_8 + k_9 \cdot \log(PAQ + k_{10}) \qquad [3.5.1]$$

where:
ACC = perceived air quality assessed by a panel of untrained subjects using the continuous acceptability scale;
PAQ = perceived air quality assessed by a panel of trained subjects directly in the decipol unit, using 2-propanone as a reference exposure, decipol;
k_8, k_9, k_{10}=coefficients.

To check the goodness of fit for the model [3.5.1], the following procedure was adopted. For each type of air pollution, i.e., single VOCs and mixtures of VOCs, presented to subjects for sensory evaluations, the exposures were specified that had similar concentrations of air pollutants (C_{VOC}), during the assessments made by both untrained and trained subjects. At these concentrations, the mean assessments of the air quality made by the trained panel directly in decipol were transferred into equivalent acceptability of air using the developed model [3.5.1] (predicted acceptability of air), and were compared with the corresponding mean assessments of the air acceptability made by the untrained panel (measured air acceptability). Predicted and measured mean votes of the air acceptability were eventually subjected to linear regression analysis.

3.5.2.2 Results

Figure 3.5.1 shows the linear models comparing assessments of trained and untrained subjects; mathematical formulae for these models are given in Table 3.5.1. For many pollutants, there is remarkable agreement between the relations, indicating that sensory evaluations made by both panels do not depend much on the type of air pollutant. Only the perception models for toluene, 1,2,4-trimethylbenzene and ethylbenzene differ slightly from the models for the other pollutants investigated. The largest difference between air quality assessments for various sources at constant acceptability reached on average ca. 5 decipol and at a constant decipol ca. 0.3 units on the acceptability scale. As regards the perceived air quality in decipol, the difference between the perception of various sources is not constant and increases with decreasing acceptability. This variation can be caused by an increasing standard deviation of the mean vote of the perceived air quality in decipol made by the trained panel with increasing decipol levels (Gunnarsen and Bluyssen, 1994).

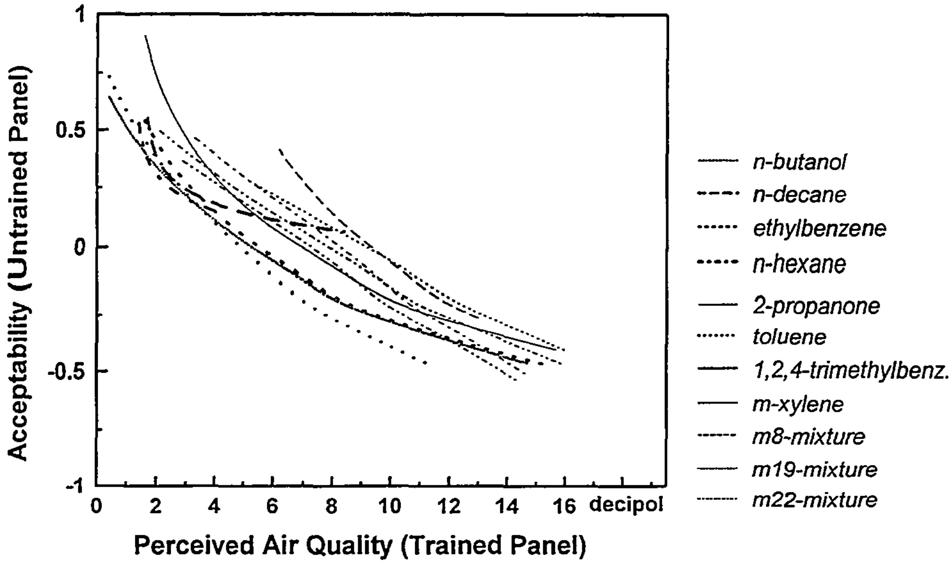


Figure 3.5.1 Acceptability of air assessed by untrained subjects as a function of the perceived air quality assessed by trained subjects for the air polluted singly by 8 VOCs and 3 mixtures of VOCs

Table 3.5.1 Perception models comparing sensory assessments of untrained subjects with the perceived air quality evaluated by trained subjects for the air polluted by single VOCs and mixtures of VOCs

Exposure type	Perception model	Range of PAQ
n-butanol	ACC=18.7-10.6·log(PAQ+50)	2.9-14.4
n-decane	ACC=0.3-0.3·log(PAQ-1.6)	1.7-8.4
ethylbenzene	ACC=0.8-1.1·log(PAQ+0.3)	1.6-15.3
n-hexane	ACC=0.3-0.3·log(PAQ-1.3)	1.4-4.3
2-propanone	ACC=0.9-1.1·log(PAQ-0.7)	1.6-15.7
toluene	ACC=1.4-1.7·log(PAQ+2.2)	0.4-11.4
1,2,4-trimethylbenzene	ACC=1.1-1.3·log(PAQ+1.8)	0.4-14.7
m-xylene	ACC=3.5-2.8·log(PAQ+9.5)	2.1-15.9
m8-mixture	ACC=1-1.3·log(PAQ-3.5)	6.2-13.1
m19-mixture	ACC=8.4-5.4·log(PAQ+26.5)	5.2-16.1
m22-mixture	ACC=11.4-7.3·log(PAQ+28.1)	3.3-14.6

The left chart of Fig. 3.5.2 shows the perception models of Fig. 3.5.1 after discretization. To these discrete models, a model in the following form was fitted (r^2 = 0.86):

$$ACC = 2.7 - 2.3 \cdot \log(PAQ + 7.4) \qquad [3.5.2]$$

where:
ACC = mean assessment of air quality made by a panel of untrained subjects using the continuous acceptability scale;
PAQ = mean perceived quality of air assessed by a panel of trained subjects directly in decipol, using 2-propanone as a reference exposure, decipol.
The model given by equation [3.5.2] is hereafter called the laboratory transfer model, comparing sensory evaluations of trained and untrained subjects, and can be used for the perceived air quality (PAQ) assessed by trained panels in the range from 0.4 to 16.1 decipol.

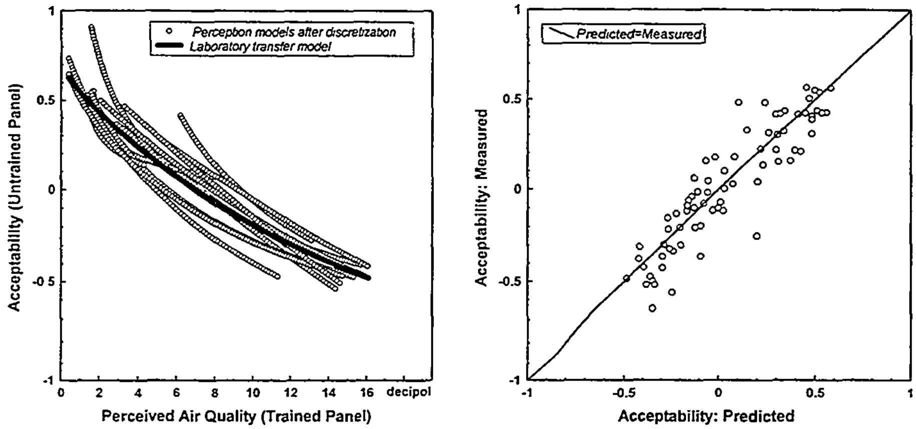


Figure 3.5.2 Left: Perception models after discretization; the laboratory transfer model comparing sensory evaluations of trained and untrained subjects is superimposed on the discrete models. Right: Check of the model adequacy - the prediction is made using laboratory model [3.5.2] applied to mean perceived air quality evaluated by a trained panel; the predicted values are compared with the mean acceptability of air measured by an untrained panel. The points in the right chart represent sensory assessments made by panels on the air polluted by different VOCs at different concentrations, whereas each point represents the sensory rating of one type of VOC exposure which was at the same concentration in air when assessed by trained and untrained subjects

In the right chart of Fig. 3.5.2, the model adequacy is checked by plotting the predicted assessments of air acceptability against the measured assessments of acceptability at various concentrations of air polluted by 8 different VOCs and 3 mixtures of VOCs. Predicted and measured votes fall close to the diagonal line depicting perfect agreement between measurement and prediction. Linear regression analysis carried out for the measured and predicted values yielded the following relation:

$$\text{Measured Acceptability} = -0.02 + 1.0 \cdot \text{Predicted Acceptability} \qquad [3.5.3]$$

The measured and predicted votes were highly correlated, r^2=0.83, and the regression was significant: $F(1,77)$=389.5; $p<0.0001$. These results validate the model developed to some extent, as regards the adequacy of fitting the data collected in the present experiments.

Formula [3.5.4] shows the laboratory transfer model, comparing sensory evaluations of untrained and trained panels in which the assessments of acceptability were transferred into decipol using formula [3.4.7]. This relation is illustrated in Fig. 3.5.3:

$$PAQ_{ACC} = 112 \cdot \left[5.98 - \ln \frac{100}{1 + \frac{1}{EXP(-14.2 + 12.1 \cdot \log(PAQ + 7.4))}} \right]^{-4} \qquad [3.5.4]$$

where:
PAQ_{ACC} = perceived air quality of air calculated, using equation [3.4.7], from the assessments of air acceptability made by an untrained panel, decipol;
PAQ = perceived quality of air assessed by a panel of trained subjects directly in decipol, using 2-propanone as a reference exposure, decipol.

The apparent difference between sensory evaluations made by trained and untrained panels can be seen in Fig. 3.5.3. At low levels of perceived air quality (< 8 decipol), mean assessments made by a trained panel are higher than the mean levels of air quality perceived by an untrained panel, and inversely at high perceived air quality (> 8 decipol). At ca. 8 decipol, the perceived air quality evaluated by a trained panel is similar to the air quality assessed by an untrained panel.

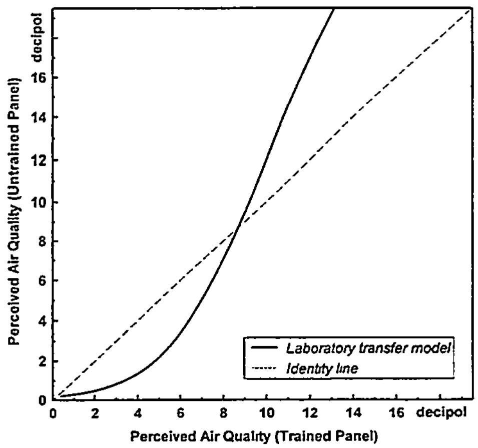


Figure 3.5.3 Perceived air quality assessed by an untrained panel as a function of the perceived air quality assessed by a trained panel. If the assessments made by both panels were equal, the continuous line describing the laboratory transfer model comparing sensory evaluations made by untrained and trained panels would follow the dashed diagonal line

3.5.3 Field Validation of the Laboratory Transfer Model

The laboratory transfer model, comparing sensory evaluations of the air quality made by untrained and trained subjects, was validated in the field using simultaneous assessments of the air quality in offices polluted by building materials, and building materials plus tobacco smoke, made by both sensory panels.

3.5.3.1 Method

Experimental plan. Sensory panels of untrained and trained subjects assessed simultaneously the air quality in three naturally ventilated offices polluted by building materials, and building materials plus tobacco smoke, as well as in the office polluted by building materials and ventilated at three different ventilation rates. Both panels assessed also outdoor air quality. Offices having different levels of perceived air quality were selected. Sensory evaluations were made during whole-body exposures, i.e., immediately upon entering the offices or upon leaving the building for outdoor air evaluations, as well as during face-exposure outside the office on the air extracted from the office and from outdoors.

Facilities. The experiments were carried out in three naturally ventilated offices and one mechanically ventilated office. Naturally ventilated offices had a volume of 220 m^3 (two offices) and 160 m^3 (one office). They had three different types of floor material: a felt carpet, floor tiles made of polyolefine and linoleum, respectively. Moreover, these offices differed as regards other pollution sources such as furnishing and amount of paper. A normally furnished mechanically ventilated office with felt carpet had a volume of 77 m^3. The mechanical ventilation system supplying outdoor air into this office consisted of an axial fan and a damper mounted in the window. The air was naturally exhausted through the existing exhaust ventilation system. Supplied outdoor air was neither filtered nor heated.

The air from the mechanically ventilated office and from outdoors was extracted through glass tubes by a miniature axial fan and then presented through Teflon-coated diffusers to subjects for sensory assessment at an airflow of 1 L/s; diffusers were placed outside the office but in direct vicinity. Extracted air was heated by electric heaters mounted on the outside surface of glass tubes.

To ascertain whether the air in the offices was well mixed, small fans were installed in the offices. The fans were in operation during sensory evaluations.

Sensory assessments. Subjects for sensory panels were selected without restriction to gender or smoking habits. The subjects were generally students from the Technical University of Denmark; they were paid volunteers selected via advertisements distributed on the university campus. An untrained panel of 77 subjects and a trained panel of 22 subjects participated. Sensory evaluations were carried out according to procedures described in section 3.4.5.2; in addition, the subjects in a trained panel were trained to assess the air quality immediately upon entering different indoor spaces. No assessments of the intensity of odour were made. A detailed description of the sensory panels participating in the experiment is given in Table 3.5.2.

Table 3.5.2 Description of untrained and trained panels participating in field experiments validating the laboratory transfer model

Exposure	Panel	Number of subjects		Age±sd	%	%
		Total	Average*		females	smokers
Whole-body (upon entering)	Untrained**	36	36	24±5	33	17
	Trained	14	14	23.8	33	7
Face (on the extracted air)	Untrained	41	37	22.8±4.1	24	17
	Trained	8	7	-	25	-

* Average number of subjects taking part in the experiments.

** The subjects were selected from a group of 68 people who took part in a selection test comprising a ranking test with n-butanol at 4 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 8587 (1988) and ISO 8586-1 (1993). Only people who had 100% correct ranking and 80% correct matching were selected as members of a sensory panel.

Procedure. *Face exposure.* The office was ventilated at three ventilation rates, corresponding to 0.4, 1 or 2 h^{-1}; outdoor air change rates were measured in the office prior to experiments. At each ventilation rate, the subjects assessed the air quality extracted from the offices and the air extracted from outdoors. The air presented for sensory assessments was pre-heated to 20°C and had a relative humidity of ca. 25% rh. Sensory evaluations were first carried out by the panel of trained subjects. Sensory evaluations made by the panel of untrained subjects began within 1 hour thereafter. Between sensory evaluations, panels rested in the open-plan office in the direct vicinity of the exposure equipment. Both panels were unaware of the type of exposure that they were assessing.

Whole-body exposure: The subjects assessed the air quality outdoors and in naturally ventilated offices (measured air change rates in the offices were ca. 0.2 h^{-1}) in three groups, each consisting of 13 untrained subjects and 5 (or 4) trained subjects. The assessments were made immediately upon leaving the building, for sensory evaluations of outdoor air, and upon entering the offices. For sensory evaluations of air quality in offices, the subjects were asked to move about within the office just after entering and then to instantly assess the air quality. Tobacco smoke was passively produced in each type of three naturally ventilated offices by lighting 2 cigarettes, placing them in an ash-tray and letting them burn for 5 minutes. As soon as the cigarettes were extinguished and ash-trays with cigarette butts removed from the offices, sensory evaluations began; sensory evaluations were completed within 20 minutes from the moment cigarettes were extinguished. The doors to offices were kept closed during the entire experiment, except for periods when the subjects entered or left the offices.

The subjects first assessed outdoor air quality; they then assessed the air quality in the offices polluted by building materials, then again the air quality outdoors, and finally in the offices polluted by building materials plus tobacco smoke. Between assessments of offices the subjects took a 2-3 minute rest in a well ventilated hall. During sensory evaluations, temperatures and relative humidities of the air in the offices were 23.5°C and 35% rh; outdoor air had the temperature of 4°C and the relative humidity of 95% rh.

Data treatment. Mean assessments of perceived air quality made by a panel of trained subjects were transformed into corresponding assessments of an untrained panel, using the laboratory transfer model comparing sensory evaluations made by trained and untrained subjects [3.5.1]. When predicted in this way, the acceptability of air was compared with the mean acceptability of air measured in the field by an untrained panel. Comparison was made by subjecting measured and predicted acceptability to linear regression analysis and observing whether the interception and slope of the fitted regression line were different respectively from 0 and 1 (Montgomery, 1991); a separate analysis was made for the mean assessments obtained during face exposure and whole-body exposure experiments.

3.5.3.2 Results

Mean levels of the perceived air quality assessed by a trained panel in decipol are plotted in the left chart of Fig. 3.5.4 against corresponding mean assessments of the acceptability of air evaluated by untrained panels. The laboratory transfer model comparing sensory evaluations made by untrained and trained subjects is shown as well. It can be seen that the field assessments of air quality differ from the assessments made in the laboratory; the discrepancy can be observed especially as regards the assessments of air quality made upon entering the offices (whole-body assessments). This could be expected, as the laboratory transfer model was developed using sensory evaluations taken during face exposures. The difference between field evaluations and the laboratory transfer model is further studied in the right chart of Fig. 3.5.4, by regressing assessments of perceived air quality made by trained panels, after they were transferred, using the laboratory transfer model, into acceptability of air (predicted acceptability), against the acceptability of air measured by untrained panels (measured acceptability). The analysis yielded the following regression lines:

- Sensory evaluations made on extracted air - face exposure ($r^2 = 0.98$):

$$\text{Predicted Acceptability} = -0.02 + 1.47 \cdot \text{Measured Acceptability} \qquad [3.5.5]$$

- Sensory evaluations made upon entering the offices and upon leaving the building - whole-body exposure ($r^2 = 0.97$):

$$\text{Predicted Acceptability} = -0.17 + 1.62 \cdot \text{Measured Acceptability} \qquad [3.5.6]$$

The slopes of the fitted regression lines ([3.5.5] & [3.5.6]) are significantly different from 1 ($p<0.01$ and $p<0.001$ respectively) and the interception of the regression line [3.5.6] is significantly different from 0 ($p<0.002$). These results confirm that the field evaluations differ significantly from the transfer model developed in the laboratory.

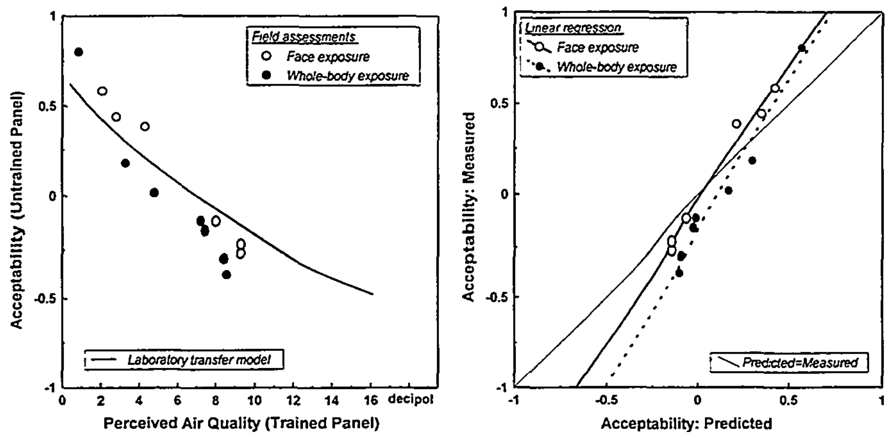


Figure 3.5.4 Left: Field assessments of the air quality in offices and outdoors made by untrained and trained panels during whole-body and face exposures compared to the laboratory transfer model. Right: Test of the model adequacy - field assessments of perceived air quality in decipol made by trained panels are transformed, using the laboratory transfer model, into mean assessments of air acceptability (predicted acceptability) and are regressed against mean assessments of air acceptability in the field measured by untrained panels (measured acceptability)

Since sensory evaluations in the field differed significantly from the laboratory transfer model, separate transfer functions between sensory assessments made by trained and untrained panels during field experiments were established. These models are similar to the laboratory transfer model [3.5.1] and their mathematical form and the domain in which they can be used is as follows:

- Sensory evaluations made on extracted air - face exposure - for PAQ_f =[2.8÷9.3] (r^2 = 0.96):

$$ACC_f = 1.1 - 1.3 \cdot \log PAQ_f \qquad [3.5.7]$$

- Sensory evaluations made upon entering the offices and upon leaving the building - whole-body exposure - for PAQ_{Wh} =[0.7÷8.6] (r^2 = 0.99):

$$ACC_{Wh} = 0.7 - 1.1 \cdot \log PAQ_{Wh} \qquad [3.5.8]$$

where:
ACC = mean assessment of air quality made by a panel of untrained subjects using the continuous acceptability scale;
PAQ = mean perceived quality of air assessed by a panel of trained subjects directly in decipol, using 2-propanone as a reference exposure, decipol;
f, Wh = face and whole-body exposures, respectively.

Formulae [3.5.9] and [3.5.10] show the field transfer models comparing sensory evaluations of untrained and trained panels during face and whole-body exposures, in which the assessments of acceptability were transferred into decipol using formula [3.4.10]. These relations are illustrated in Fig. 3.5.5:

- Sensory evaluations made on extracted air - face exposure for $PAQ_f = [2.8 \div 9.3]$:

$$PAQ_{ACC_f} = 112 \cdot \left[5.98 - \ln \frac{100}{1 + \frac{1}{EXP(-5.8 + 6.9 \cdot \log(PAQ_f))}} \right]^{-4} \quad [3.5.9]$$

- Sensory evaluations made upon entering the offices and upon leaving the building - whole-body exposure for $ACC_{Wh} = [0.7 \div 8.6]$:

$$PAQ_{ACC_{Wh}} = 112 \cdot \left[5.98 - \ln \frac{100}{1 + \frac{1}{EXP(-3.9 + 5.5 \cdot \log PAQ_{Wh})}} \right]^{-4} \quad [3.5.10]$$

where:

PAQ_{ACC} = perceived air quality calculated, using equation [3.4.7], from the assessments of air acceptability made by an untrained panel, decipol;

PAQ = perceived quality of air assessed by a panel of trained subjects directly in decipol, using 2-propanone as a reference exposure, decipol.

f, Wh = face and whole-body exposures, respectively.

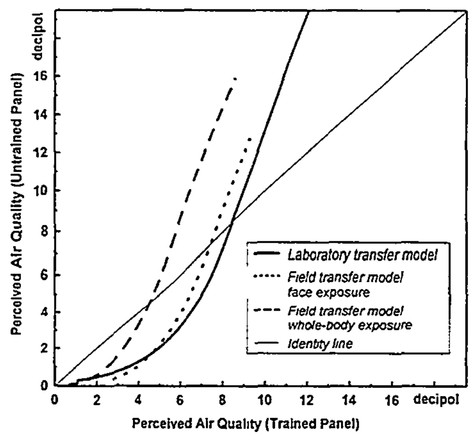


Figure 3.5.5 Comparison of the laboratory and field transfer models comparing assessments of the air quality made by untrained and trained panels. If the assessments made by both panels were equal, the lines describing laboratory and field transfer models would follow the continuous diagonal line

Fig. 3.5.5 highlights the difference between assessments made by trained and untrained panels. At good perceived air quality, i.e., at low decipol levels, mean assessments of trained panels are higher than the corresponding assessments of untrained panels and inversely at poor perceived air quality. In addition, Fig. 3.5.5 shows that the field transfer model developed using sensory evaluations during face exposures gives quite similar results to the laboratory transfer model, unlike the field transfer model based on whole-body exposures. It can thus be recommended that for face exposures, the laboratory transfer model developed be used, independent of whether the assessments are made in the laboratory or in the field.

3.5.4 Discussion

The present study can be seen as a validation experiment for the method of using panels trained to assess the perceived air quality in reference to the exposure of 2-propanone (Bluyssen et al., 1989); no such validation was carried out when the method was introduced. The results clearly indicate that the trained panel cannot simply replace the untrained panel for the sake of a reduced number of subjects. This has been emphasised earlier as an advantage of the method (Pejtersen and Mayer, 1993; Bluyssen and Elkhuizen, 1996). Sensory assessments of trained panels are different from the corresponding sensory evaluations of untrained subjects, and correction of their votes is necessary. This has been shown during laboratory experiments when subjects assessed the quality of air polluted by common VOCs, as well as in the field when the air was polluted by the emissions from building materials and tobacco smoke. Correction of the trained panel votes can be made using the transfer models developed, comparing sensory evaluations of both panels.

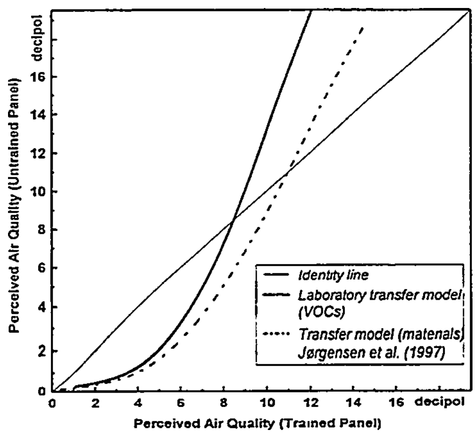


Figure 3.5.6 Comparison of the transfer models comparing assessments of air quality made by untrained and trained panels. The laboratory transfer model was developed in the present study using the sensory assessments of air polluted by single VOCs and mixtures of VOCs, whereas the transfer model of Jørgensen et al. (1997) was developed using the sensory assessments of air polluted by common building materials. If the assessments made by both panels were equal, the lines describing transfer models would follow the continuous diagonal line

Similar results to these observed in the present experiments were obtained by Jørgensen et al. (1997). In their experiments, sensory panels of trained and untrained subjects assessed the air polluted by 10 common building materials. The samples of materials were placed in 200-L glass chambers and ventilated with approx. 1 L/s of unpolluted air; seven different concentrations of pollutants from each material were prepared by changing the material loading; they were then presented to subjects for sensory evaluations. The transfer model developed by Jørgensen et al. is slightly different from the laboratory transfer model developed in the present experiment (Fig. 3.5.6), especially at higher levels of perceived air quality in decipol; however, below 6 decipols, as assessed by a trained panel, the two models are quite similar. This discrepancy may be due to different ways of modelling the data. Jørgensen et al. regressed untrained panel votes against trained panel assessments, whereas the laboratory transfer model was developed by comparing non-linear perception models (see additional comments on this issue in section 3.5.4.3). This discrepancy may also be due to a difference in sensation produced by the pollutants emitted from the building materials studied by Jørgensen et al. and by the VOCs investigated in the present experiment. Further studies should investigate whether this discrepancy is pertinent.

3.5.4.1 Plausible Rationale for the Difference between Assessments of the Air Quality made by Untrained and Trained Panels

The difference observed between the assessments of trained and untrained panels can stem from the incorrect establishment of the relationship between the perceived air quality and 2-propanone concentration or it could be due to the psychophysical phenomenon. Both effects are discussed in the following.

<u>Incorrectly established relationship between decipol and 2-propanone concentration.</u> Two types of error may have occurred while developing the relationship between the perceived air quality and 2-propanone in the original study (Bluyssen et al., 1989; Bluyssen, 1990). An error may have occurred due to inaccurate measurements of the 2-propanone concentration or an error may have been introduced during transformation of mean assessments of acceptability of air polluted by 2-propanone into decipol.

To aid discussion on the significance of both errors, it should be remembered that in the original studies of Bluyssen, 8 different concentrations of 2-propanone were measured using a Brüel & Kjær Toxic Gas Monitor Type 1306 and assessed by a panel of 265 untrained subjects; sensory evaluations were made using the continuous acceptability scale (Gunnarsen and Fanger, 1989). Furthermore, that to find the mathematical form of the relationship between 2-propanone concentration and decipol [3.4.2] (see section 3.4.1.1), a three-step procedure was carried out. First, the mean votes of acceptability of air polluted by 2-propanone were transferred into percentage of dissatisfied by plotting mean votes of acceptability against the percentage of dissatisfied calculated by dividing the sum of votes in the non-acceptable part of the continuous scale (Gunnarsen and Fanger, 1989) by the total number of votes. The percentage of dissatisfied was then transferred into decipol using the relationship of Fanger (1988). Finally, the perceived air quality in decipol was regressed against the concentration of 2-propanone over background.

To check for the above-mentioned errors, the original data from the experiment of

Bluyssen were re-analysed, using the methodology described in section 3.4.6.2, and the following model was fitted (r^2=0.87):

$$ACC_{Bl} = 0.58 - 0.48 \cdot \log\Delta C \qquad [3.5.11]$$

The model is plotted in the left chart of Fig. 3.5.7 and compared with the model developed using the data obtained in the present experiment:

$$ACC_{War} = 1.24 - 0.85 \cdot \log\Delta C \qquad [3.5.12]$$

where:
ACC = mean perceived acceptability of air polluted by 2-propanone assessed by a panel of untrained subjects using the continuous acceptability scale;
ΔC = 2-propanone concentration over background, ppm;
Bl, War = indexes indicating that the models were developed using the data of Bluyssen (previous experiment) and Wargocki (present experiment), respectively.
Note that the model [3.5.12] is different from that shown in Table 3.4.5, because the concentration of 2-propanone over background was used as an independent variable. This was done to make it possible to compare this model with the model developed by Bluyssen.

Models [3.5.11] and [3.5.12] were transformed into decipol using relation [3.4.7] and are compared in the right chart of Fig. 3.5.7 with the original relationship [3.4.2] developed by Bluyssen.

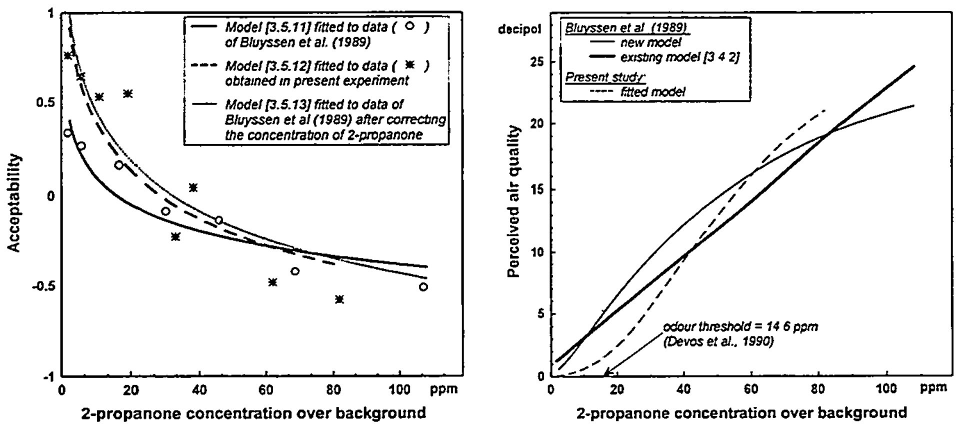


Figure 3.5.7 Exposure-response relationships between the perceived air quality expressed as acceptability (left chart) and in decipol (right chart) and the concentration (over background) of 2-propanone. Each point in the left chart is a mean of 43 votes as regards the present study and 265 votes as regards the experiment of Bluyssen et al. (1989)

The left chart in Fig. 3.5.7 shows that the model developed using sensory evaluations of air quality collected in the present experiment is different from that developed using the data of Bluyssen only at the low concentrations of 2-propanone. This difference cannot be explained by the procedure used to transform mean acceptability votes into decipol because the same modelling of the data of Bluyssen and the present data did not produce similar relationships. The right chart in Fig. 3.5.7 shows that at the odour detection threshold of 2-propanone (Devos et al., 1990), the perceived air quality would be ca. 4 decipol according to the model of Bluyssen, but it would be below 0.6 decipol according to the present data. Since 4 decipol corresponds to 40% dissatisfied (Fanger, 1988), and the detection threshold is the concentration of a compound that can be detected by 50% of human judges (Cain, 1988; WHO, 1989), it is hypothesized that the reason for the discrepancies observed in Fig. 3.5.7 could be due to the measuring error in the study of Bluyssen or due in general to poor quality of the air used to dilute 2-propanone in that study. The latter option is, however, difficult to verify at present.

To study the extent to which the error of measuring 2-propanone concentration could influence the results of Bluyssen, it was assumed that a systematic error occurred, resulting in too low concentrations for the whole measuring range. Accordingly, each of the concentrations of 2-propanone measured by Bluyssen were elevated by 1, 2, 3, etc. ppm, and the models were fitted for these new concentrations. At a concentration of 2-propanone increased by 10 ppm, this procedure yielded a model almost identical to that developed using the data from the present experiment (see left chart of Fig. 3.5.7). This model has the following form:

$$ACC_{Bl}{}^{*} = 1.33 - 0.88 \cdot \log\Delta C^{*};\ \Delta C^{*} = \Delta C + 10 \qquad [3.5.13]$$

where:

ACC = mean perceived acceptability of air polluted by 2-propanone assessed by a panel of untrained subjects using the continuous acceptability scale;

ΔC^{*} = 2-propanone concentration over background, ppm;

ΔC = 2-propanone concentration over background used for modelling the data in the original study of Bluyssen et al. (1989), ppm;

This result implies that a systematic measuring error of ÷10 ppm may have occurred in the study of Bluyssen. An additional experiment would be required, however, to verify this hypothesis. No study has yet verified that the relationship between the perceived air quality in decipol and the 2-propanone concentration developed by Bluyssen et al. (1989) is properly established (Groes, 1995).

The results shown in the right chart of Fig. 3.5.7 can also explain why, at good perceived air quality (low decipol levels) which is usually expected outdoors, trained panels assess the air quality to be rather poor. This is due to barely perceptible concentrations of 2-propanone at levels below 4 decipol because they are close to or below the odour detection threshold. This observation can be used further to explain why, in the "European Audit Project to Optimise Indoor Air Quality and Energy Consumption in Office Buildings" carried out in 56 office buildings in 9 European countries (Bluyssen et al., 1996), the trained panels assessed the perceived quality of outdoor air to be on average 1.9 decipol.

<u>Psychophysical phenomenon.</u> The discrepancy between assessments of air quality made by trained and untrained panels can also have a psychophysical origin, i.e., the

subjects trained using 2-propanone can have difficulties in rating the annoyance of other pollution sources in comparison to 2-propanone. Although 2-propanone was selected as one of human bioeffluents occurring most frequently and is often present in indoor climates (section 3.3.2), its odour is quite distinct from the odour of air polluted by building materials. In addition, it is also found by some people to be pleasant, which can confound subjects' perceptions even more, since their task is to rate the annoyance of the polluted air in comparison to the annoyance produced by 2-propanone. Consequently, trained subjects may rate mainly the intensity of odour and not the annoyance of air comprising simultaneously other sensory impressions (e.g., irritation), as this sensation seems to be rather easy to comprehend.

The existence of a psychophysical phenomenon has actually been indicated in previous studies with trained panels. For example, Groes (1995) showed that the excellent performance of the trained subjects as regards the assessments of air polluted by 2-propanone does not guarantee excellent performance as regards the assessments of the quality of air containing more complex sensory mixtures of pollutants. These results also suggest that the trained subjects may rate mainly the odour intensity. Additionally, it was observed in the present experiment that, depending on the type of exposure, the sensory evaluations made by a trained panel can very considerably. As seen in Fig. 3.5.1, for the constant acceptability of air, which can be considered as a "true" primary psychophysical judgement of air quality, the perceived air quality assessed by a trained panel can vary with about 5 decipol.

However, the effect of psychophysical phenomena on the sensory evaluation was not studied in the present experiment. If these effects are significant, they can preclude the use of a panel trained to assess the perceived air quality using only one reference exposure, and can indicate that there is a need to use many reference exposures. To study psychophysical phenomena, the panels should be trained using different reference exposures, e.g., using the models developed in section 3.4.7 of the present thesis. These different trained panels should then evaluate the perceived quality of air polluted by a wide range of sources directly in decipol, and their assessments should be compared to see whether they match. The difference in the assessments should account for the psychophysical effect.

If a psychophysical phenomenon is disregarded and the existence of a systematic measuring error in the original study of Bluyssen (1990) is accepted, then the model shown in Table 3.4.5 can be used in future to train subjects to assess the perceived air quality in decipol using 2-propanone as a reference exposure.

3.5.4.2 Consequences of the Discrepancy between Sensory Evaluations of Trained and Untrained Subjects

The results of the present experiment have an important implication for studies in which trained sensory panels are used to assess the air quality by comparing with a reference of 2-propanone. Firstly, they show that sensory ratings made by a trained panel can be used as the entry values in the comfort model of Fanger (1988) only when they are transferred into the corresponding assessments of air quality made by untrained subjects, using the laboratory and field transfer models that compare the sensory evaluations of both panels. Secondly, they show that if the uncorrected sensory ratings of a trained panel were used to calculate the required ventilation rates for acceptable indoor air quality, this would result in a significant oversizing of the airflow.

Table 3.5.3 Comparison of the perceived air quality in three categories of spaces proposed in prENV 1752 (1997) if they were designed using the sensory evaluations made by untrained or trained subjects

Perceived air quality (decipol)			
Untrained panel		Trained panel	
		Laboratory transfer model	Whole-body field transfer model
Category A	(1.0 decipol)	3.4	2.5
Category B	(1.4 decipol)	4.1	2.9
Category C	(2.5 decipol)	5.3	3.6
Laboratory transfer model	Whole-body field transfer model		
0.3	0.1	Category A	(1.0 decipol)
0.4	0.3	Category B	(1.4 decipol)
0.6	1.0	Category C	(2.5 decipol)

In the proposal of the European draft pre-standard prENV 1752 "Ventilation for buildings: Design criteria for the indoor environment" (prENV 1752, 1997), three categories of air quality in spaces were recommended, corresponding respectively to 1, 1.4 and 2.5 decipol when assessed by untrained judges. If judges trained to assess the perceived air quality in reference to 2-propanone were used, then, as seen in Table 3.5.3, the levels of perceived air quality in these three categories would have to be elevated. On the other hand, if the perceived air quality assessed by trained subjects were used to design acceptable indoor air quality in these three categories of spaces (Table 3.5.3), ventilation rates would be oversized, as the actual levels of the perceived air quality would be much lower.

3.5.4.3 Methodological Issues and Suggestions for Future Experiments

In the laboratory transfer model comparing the sensory evaluations of untrained and trained panels, the variation in sensory votes of both panels was taken into account. This model was developed by comparing non-linear perception models relating the perceived air quality to the concentration of air pollutants (8 single VOCs and 3 mixtures of VOCs), in which the variation of sensory votes was accounted for during regression analysis carried out separately for the assessments of untrained and trained subjects. This variation can be quite large because untrained panels assess the air quality with the average standard deviation of ca. 0.45 units on a continuous acceptability scale, whereas for trained panels the standard deviation is ca. 4 decipol (Gunnarsen and Bluyssen, 1994). When field transfer models were developed, untrained panel votes were regressed against trained panel assessments, hence only variation of the sensory ratings of untrained subjects is accounted for in these models, as well as in the transfer model developed by Jørgensen et al. (Fig. 3.5.6).

For field validation of the laboratory transfer model, tobacco smoke was passively produced inside the offices prior to sensory assessments. Smoking had ceased and the sensory evaluations were completed after ca. 20 min. It is expected that during this time, the intensity of tobacco smoke odour in the office stayed at the same level since the infiltration of outdoor air into the offices was low (0.15 h^{-1}).

For whole-body assessments, subjects in succession entered three offices in three groups of 15 people each. The offices were landscaped and thereby could accommodate this number of subjects during sensory evaluations. It can be anticipated that the perceived air quality in the offices worsened as the experiments progressed, due to bioeffluents produced by the previous groups of subjects entering the offices. However, as the subjects stayed in the office for a very short time (less than 1 minute), it is expected that the contribution of bioeffluents to the sensory pollution load on the air could be disregarded.

It has been shown in the present experiments that sensory evaluations made during face and whole-body exposures were different. Recently, Fang et al. (1998b) and Jørgensen and Vestergaard (1998) observed a similar phenomenon. This difference is most likely due to the duration of exposure. During face exposures, subjects assess the air quality after taking 1 to 2 inhalations of polluted air, which takes less than 10 seconds. During whole-body exposures, subjects assess the air quality on average after ca. 30 seconds, and they may take up to 10 inhalations. During this time, strong adaptation can occur (Cain, 1974), modifying the magnitude of perception. In future, dynamic characteristics of the sensory response in relation to the time of exposure should be developed for common indoor air pollutants. These characteristics will enable comparisons to be made of the sensory evaluations from face and whole-body exposures and, in addition, the unadapted and self-adapted perceptions.

Other reasons for the difference in sensory evaluation made during face and whole-body exposures may be the high air velocities passing the face and eyes during face exposures, and the ability to compare the air presented during face exposures with the ambient air, which is otherwise impossible during whole-body exposures. These two effects may consequently exacerbate the perception of pollutants in air. It is therefore recommended that they be eliminated in future by changing the mode of presentation of air during face exposures. For example, special systems, such as head-sized exposure chambers (e.g., helmets with a clear view of the surroundings, modelled on the basis of motorcycle helmets) can be devised in which the air passes at low velocity along the subject's head so that he or she cannot compare this air with the ambient air. In addition, helmets of this kind would be ideal for field work in real buildings, as the subject's view of the surroundings he/she is judging could be temporarily obscured, both in transit and while judging the air in a given room; moreover, reference air (e.g., outside air) could be piped to the helmet from portable cylinders or from ducts drawing air from outside the building, without subjects having to leave the room and go outside for that purpose.

The transfer model comparing sensory evaluations made by untrained and trained subjects was developed using sensory ratings of the quality of air polluted by common VOCs. An extension of the model for building materials would be required. Such an extension for 10 common building materials can be obtained using the data of the previously mentioned experiments of Jørgensen et al. (1997). Field validation of the laboratory transfer model was made only in a few office spaces. Further validation studies are thus recommended in a wider range of indoor spaces, not only polluted by the emissions from building materials and tobacco smoke (as in the present experiment), but also by bioeffluents and the pollutants introduced with the air supplied by the HVAC system.

3.6 Conclusions

- The literature reporting chemical measurements in indoor climates was reviewed. The review showed 133 different VOCs with measured concentrations, among which the most prevalent was toluene. Ethanol was the compound having the highest mean concentration measured indoors, and only 3 compounds had a mean concentration higher than their odour detection threshold. Aldehydes and organic acids were among the compounds having the highest potency and the power to evoke sensory sensations in humans at the concentrations measured in indoor environments.

- Eight volatile organic compounds were selected as candidates for the sensory reference atmospheres. These compounds are: n-butanol, n-decane, ethylbenzene, n-hexane, 2-propanone, toluene, 1,2,4-trimethylbenzene and m-xylene. They are the compounds that are most frequently measured indoors, have the highest measured concentration and have the highest sensory impact on humans at the concentrations measured in indoor climates. None of the VOCs selected is harmful to people or the environment in the concentrations occurring normally in indoor environments.

- Three mixtures containing 8, 19 and 22 different VOCs frequently occurring in indoor environments were selected as candidates for the sensory reference atmospheres. The mixture of 22 VOCs was previously used as an exposure for investigating the effects of air pollutants on humans, whereas the mixtures of 8 and 19 VOCs are the daughters of this mixture.

- For eight selected VOCs and three mixtures of VOCs, the exposure-response relationships were developed. They can be used to train people to assess the perceived air quality directly in decipol.

- Odour intensity was strongly negatively correlated with the air acceptability. The correlation did not depend to any great extent on the type of exposure.

- Odour intensity of the VOCs below their odour thresholds was enhanced when the VOCs were in a mixture.

- Sensory pollution loads on the air caused by VOCs were not constant and depended on the concentration of VOCs in air.

- Substantial discrepancies were observed between the sensory ratings of the perceived quality of air made by panels of untrained subjects and of the subjects trained to assess the perceived air quality directly in decipol in reference to 2-propanone.

- The difference between the assessment of air quality made by untrained and trained panels is probably caused by a measuring error of 2-propanone concentration and/or the difference in the sensation produced by 2-propanone and by the air polluted by other indoor pollution sources.

- A transfer model relating the sensory evaluations of trained and untrained panels was established and validated in the field.

- Before the results of trained panels are used to estimate the percentage of persons dissatisfied with the air quality, the required ventilation rates or the sensory pollution loads, they should be corrected using the transfer model [3.5.4] or [3.5.10], depending on whether the exposures were face or whole-body, respectively.

- Assessments of the air quality made during face and whole-body exposures were found to be different. In future, dynamic characteristics for a wide range of common indoor air pollutants should be studied, describing the change in sensory response with time of exposure.

- Further field validation of the transfer model developed is recommended for a wider range of indoor spaces polluted by the building, people, tobacco smoke and HVAC systems.

CHAPTER 4

Impact of Emissions from a Carpet on Perceived Air Quality, SBS-Symptoms and Productivity

4.1 Background

Several studies have documented that different environmental parameters have an impact on comfort, health and productivity of people in indoor climates. Among these parameters are pollutants emitted by building materials (Mølhave et al., 1986; Fanger et al., 1988a; Thorstensen et al., 1990; Pejtersen et al., 1991; Berglund et al., 1992b; Bluyssen et al., 1996), air-conditioning, carpets, the number of people occupying a space, VDT-use and ventilation rates at or below 10 L/s per person (Mendell, 1993). All these factors can reduce the health and comfort conditions of humans, both by increasing the sensory pollution load on the indoor air and by increasing the prevalence of health symptoms, usually referred to as the Sick Building Syndrome (SBS) (WHO, 1982).

4.1.1 Carpets and SBS-Symptoms

Floor materials in particular can have a negative impact on perceived air quality and health symptoms. A review of epidemiological literature (Mendell, 1993) revealed that carpets were consistently associated with an increased prevalence of symptoms among occupants in office buildings. This conclusion was based on the results derived from six investigations, among which five showed a strong association (Norbäck and Torgén, 1989; Skov et al., 1990; Norbäck et al., 1990b; Fisk et al., 1993 and Menzies et al., 1992) and only one failed to show any association (Zweers et al., 1992).

In the study carried out in Swedish schools (Norbäck and Torgén, 1989), a higher prevalence of mucosal, cutaneous and general symptoms was observed among personnel working in schools with wall-to-wall carpet, as compared to schools with a hard floor covering. The presence of wall-to-wall carpets in the working environment but not in dwellings was related to a higher incidence of chronic symptoms (Norbäck et al., 1990b). In the Danish Town Hall study (Skov et al., 1990), the presence of needle-felt carpet and loop-woven carpet increased work-related mucosal irritation, as compared to offices with bare floors. The presence of any carpet in spaces investigated in Californian office buildings (Fisk et al., 1993) increased mucosal irritation and the frequency of headaches. In a case-control study in office buildings in Canada (Menzies et al., 1992), workers who reported frequent work-related symptoms and upper and lower respiratory tract symptoms were more likely to have carpets in their office. Thorstensen et al. (1990) showed that the prevalence of mucosal irritation among Danish pupils was higher in schools with carpet as compared to schools with linoleum, and they found larger amounts of immunogenic dust contained in the floor dust in carpets.

In contrast, Zweers et al. (1992) did not observe an increased prevalence of SBS symptoms among office employees in the Netherlands working in carpeted offices. However, the presence of carpets was grouped by Zweers et al. together with the presence of curtains and open shelves as "fleecy materials", which according to the review of Mendell is not a causative workspace factor as regards the occurrence of SBS symptoms, although the Danish Town Hall study (Skov et al., 1990) found it to be so. Also in the study in offices of Northern Sweden (Sundell, 1994) no consistent associations were observed between SBS-symptoms among video display terminal workers and fleece factors or floor materials. Similarly, in the European Audit project among office workers in nine countries, carpets were not identified as a risk factor for SBS symptom occurrence (Groes et al., 1996). Consistent with the findings described above are the results obtained in the laboratory study (Pejtersen et al., 1998) with 20 subjects occupying climate chambers in which the impact of new linoleum, old carpet and new low-polluting vinyl were studied one by one: the magnitude of symptoms experienced by subjects after 6 hours of occupation was very low and independent of the three floor materials. This occurred in spite of the fact that measurements of perceived air quality upon entering the chamber showed the low-polluting vinyl to cause the least number of dissatisfied.

4.1.2 Effect of Renovation of Floor Material on PAQ and SBS-Symptoms

When there is pollution from building materials, it is recommended that the total outdoor air rate be increased and/or that polluting materials be replaced with low-polluting alternatives (ECA, 1992; ASHRAE 62-1989R, 1996; prENV 1752, 1997). An increase of ventilation rates can be costly since larger air volumes must be conditioned. Godish and Spengler (1996) reviewed the literature concerning relationships between ventilation rates and air quality, and argue that increasing outdoor air rates above 10 L/s per person may not have any positive effect on decreasing SBS-symptoms among occupants. In the European Audit project (Groes et al., 1996), too little outdoor air supply was found to be a causative factor of a higher incidence of SBS-symptoms among office workers. On the other hand, controlling pollution by avoiding pollution sources is a rather simple (Pettenkofer, 1858) and energy-efficient means of improving the air quality in buildings, although rather limited experimental data exist on how effective this measure can be.

In a naturally ventilated office building in Denmark that had been identified as a problem building, polyamide floor carpet (bouclé) was found to be an important source of sensory pollution and was replaced by flooring made of polyolefine tiles, selected in laboratory experiments to be the lowest polluting floor materials among nine different floor coverings investigated (van Beuningen et al., 1994). Following the intervention, the sensory pollution load of the building (i.e., building materials and furnishings in renovated spaces) was found to be significantly reduced, when measured by a sensory panel of subjects trained to assess the air quality using 2-propanone as a reference (Bluyssen et al., 1989). Moreover, air quality caused less dissatisfaction among occupants after the renovation, even though the outdoor air rate was reduced after renovation.

In a longitudinal study of school personnel in Sweden (Norbäck and Torgén, 1989), wall-to-wall carpet in two mechanically ventilated schools was removed and replaced by hard PVC floor coating. Following this intervention, the prevalence of eye symptoms, face rashes, headache and abnormal tiredness decreased to the levels found in two naturally and two mechanically ventilated schools with hard floor covering. However, for airway symptoms, no effect of removing the wall-to-wall carpet was observed.

In a naturally ventilated office building, offices with three different types of floor material (a felt carpet, and linoleum and floor tiles made of polyolefine, which both replaced a felt carpet previously used all over the building) were occupied by recruited impartial subjects, who assessed indoor air quality both as visitors, upon entering offices, and as occupants, after 1 hour occupation of offices (Wargocki and Fanger, 1997). This new experimental approach was intended to model real-life conditions in the office building, and was carried out on a day when normal occupants were absent. Substitution of the felt carpet by low-polluting polyolefine significantly improved perceived air quality in offices ventilated with similar outdoor air rates. Preference votes showed only modest differences between offices, possibly due to the simultaneous presence of bioeffluents in the offices and the subjects' expectation. No associations were made between floor type and prevalence of symptoms but probably a one-hour exposure was too short for symptoms to develop.

In the study carried out within the frame of the Healthy Buildings research programme (Pejtersen et al., 1998), an office building in Denmark was renovated by replacing an old carpet with new low-polluting vinyl and by renovating a ventilation system by increasing the outdoor air rate and the ventilation effectiveness. A significant decrease of many SBS-symptoms was observed among 50 occupants after renovation. However, no clear distinction could be made as to whether this decrease was due to changes in the ventilation system or to the substitution of floor covering, as both remedies were introduced simultaneously. No change in magnitude of symptoms was observed among 50 occupants in a control group in offices in which the intervention was not carried out. In a follow-up study (Falk Nyboe et al., 1997) in the above-mentioned office building, renovated and non-renovated offices were occupied for 2.5 hours by 32 impartial observers on a day when normal occupants were absent (similar to the procedure in the above-mentioned study by Wargocki and Fanger (1997)). No significant difference was observed between renovated and non-renovated offices as regards the perceived air quality and prevalence of symptoms. Symptoms experienced were actually at a very low magnitude, perhaps because people were relaxing and were not asked to perform any specific job.

4.1.3 SBS-Symptoms and Productivity

Poor indoor climate may contribute to the occurrence of health and comfort problems, which in turn may diminish human performance and cause substantial economic losses (Fisk and Rosenfeld, 1997). The effects of the indoor environment on productivity were summarized by Wyon (1996), who concluded that poor air quality causing fatigue and headaches may negatively affect human performance. In the review made by Leinster and Mitchell (1992), building-related symptoms were found to negatively affect productivity when they averaged two per person or more.

Different measures have been used to evaluate productivity of people under various environmental conditions. These measures generally include special neurobehavioural tests administered to subjects (Baker et al., 1985), estimates of quantity and quality of work performed, as well as measures of self-reported productivity and absenteeism (Sensharma et al., 1998). The measurements of productivity are made both under laboratory conditions as well as in the field. The following paragraphs summarize selected experiments, using the above methods to investigate the cause-effect link between occurrence of SBS-symptoms and human performance.

Mølhave et al. (1986) exposed 62 healthy subjects, who claimed to report SBS-symptoms at the workplace, to the complex mixture of 22 volatile organic compounds (VOCs) characteristic of pollutants emitted from building materials in Denmark (Mølhave and Møller, 1978; Mølhave, 1982; Chapter 3 of the present thesis). Two concentrations were used: 5 and 25 mg/m^3; the latter is the highest measured concentration in new Danish houses (Mølhave and Møller, 1978). Subjects were exposed in the climate chamber for 2.75 hours. A significantly decreased memory for digits in a standard digit span test was observed. Conversely, in the chamber experiment of Otto et al. (1992) with the same duration and type of VOC exposure, 66 healthy young males did not show impaired performance on 13 administered neurobehavioural tests (Baker et al., 1985) during exposure to a mixture constituting 22 VOCs at the total concentration of 25 mg/m^3, as compared to the exposure to clean air. However, subjects expressed increased mental confusion and fatigue, as opposed to the results of Mølhave et al. (1993) with the same VOC mixture but at the concentration of 10 mg/m³ and three different air temperatures (18, 22 and 26°C). In another study, no impaired performance was observed among 26 male and 15 female subjects during a 4-hour chamber exposure to 22 VOCs at a concentration of 25 mg/m³ (Otto et al., 1993). Again, significant effects were observed only for confusion, fatigue, depression and tension.

In a field experiment, Nunes et al. (1993) administered two neurobehavioural tests among 47 employees in a mechanically ventilated building; both tests were completed by subjects at their work sites during a working day over three consecutive weeks. The results showed that workers who reported any SBS-symptom performed significantly worse on a continuous performance task and with the increased error rate in a symbol-digit substitution test. Conversely, in another study in Sweden (Berglund et al., 1992a), no differences were observed as regards performance on four diverse psychological tests measuring reaction time, short-term memory, vigilance and hand steadiness of 48 impartial subjects who were exposed for 5 hours to diagnosed "sick" and "healthy" Swedish pre-schools. This happened most likely since no significant difference was observed between symptom prevalences among subjects exposed to "sick" and "healthy" buildings.

Preller et al. (1990) observed that absenteeism (due to sick leave) among 7000 office workers in 61 office buildings in the Netherlands was related to several building- and work-related factors: in particular, stronger significant associations were found for sick leave due to SBS-symptoms. Self-reported productivity was found to be linked to symptoms, comfort and the perception of the environment in the questionnaire survey among 4373 workers in 46 office buildings in the UK (Raw et al., 1990). Mucosal symptoms accounted for 18% and all work-related symptoms for 30% of the variance in self-reported productivity among 3000 workers in an office building in the USA (Hall et al., 1991). However, no study has validated the accuracy of self-reports of productivity made by building occupants.

4.1.4 Rationale

Most of the literature describing SBS-symptoms among office workers in indoor climates is based on epidemiological studies in a large numbers of buildings in which it is difficult to control the environmental parameters. Furthermore, human subjective votes concerning environmental factors are confounded by social factors such as type of work or job satisfaction. Sometimes an effort has been made to study the impact of these confounding factors by sophisticated multivariate statistical analyses.

Confounding factors may have contributed to some conflicting findings concerning the impact of carpets on the well-being of occupants in indoor climates (see section 4.1.2). In brief, studies in which impartial observers were recruited (Wargocki and Fanger, 1997; Falk Nyboe et al., 1997; Pejtersen et al., 1998) could not detect the effect of the intervention on the prevalence of symptoms, whereas when occupants of the building were asked to judge their symptoms (Norbäck and Torgén, 1989; Pejtersen et al., 1998), a decrease in symptom occurrence was observed. The most likely reasons for the above discrepancy are: a lack of blinding and occupants' expectation of improved air quality after renovation; the selection of young students (mainly males) as impartial observers, i.e., a sub-population that is not representative of office workers; carrying out experiments in windowless stainless steel climate chambers that are markedly different from typical office environments; too short exposures; simultaneous implementation of many intervention measures precluding separation of the effects for single factors; and finally, the fact that the impartial observers employed did not perform typical office jobs during field exposure.

As regards productivity, a considerable amount of work has been done on studying the effects of thermal conditions on human performance (Wyon, 1996) but little information is available on the effects of air pollutants on productivity under realistic environmental conditions in the field (see section 4.1.3).

In conclusion, a systematic study should be carried out to investigate the extent to which floor materials can influence comfort, health and performance of the occupants of buildings. The study should be performed under well controlled conditions in an office-like environment with impartial subjects performing simulated office work. Used carpet should be selected as the odour source used to degrade the perceived air quality in the office since from the epidemiological studies it is hypothesised that used carpet will increase SBS-symptom intensity and from other field studies it is hypothesised that this will reduce performance. The subjects should be females, taking into account that women are an important risk group in indoor climates, consistently reporting more SBS-symptoms than men (Mendell, 1993). With the experimental design described above, the job, personal and building-related factors that usually are confounded in SBS-studies can be eliminated.

4.2 Objective

The purpose of the present study is to investigate whether air pollutants emitted from a carpet have a negative effect on perceived air quality, resulting in increased prevalence of SBS-symptoms and reduced productivity.

4.3 Methods and Materials

4.3.1 Experimental Plan

The air pollution level in an office space with low-polluting floor covering was modified by placing a sample of old, used carpet behind a partition, all other environmental parameters being kept unchanged. The office with and without carpet placed behind a partition was occupied by impartial female subjects who were unaware that an intervention took place.

The subjects assessed the perceived air quality, indoor climate and SBS-symptoms upon entering the office and on several occasions during occupation of the office. Subjects performed several tasks simulating office work and were exposed to a diagnostic psychological test battery measuring their performance while occupying the office. These measures were used to estimate the productivity of subjects under different loads of air pollution. During office occupation, subjects were kept thermally neutral as they were asked to adjust their clothing. Following the occupation period, the subjects left the office and re-entered it after a short time to evaluate again the perceived air quality.

4.3.2 Facilities

4.3.2.1 Office Characteristics

The study was carried out in a 25-year-old cellular office space with two-module windows facing east, each module being 3 m wide. The office had a floor area of 36 m^2 and a volume of 110 m^3 (LxWxH = 6x6x3 m). Two-and-a-half years previously, the office had been renovated: the walls and ceiling had been painted and felt carpet was replaced by floor tiles made of polyolefine, known from previous studies to be a low-polluting floor material (van Beuningen et al., 1994; Jørgensen et al., 1997). A schematic diagram of the office is shown in Fig. 4.3.1.

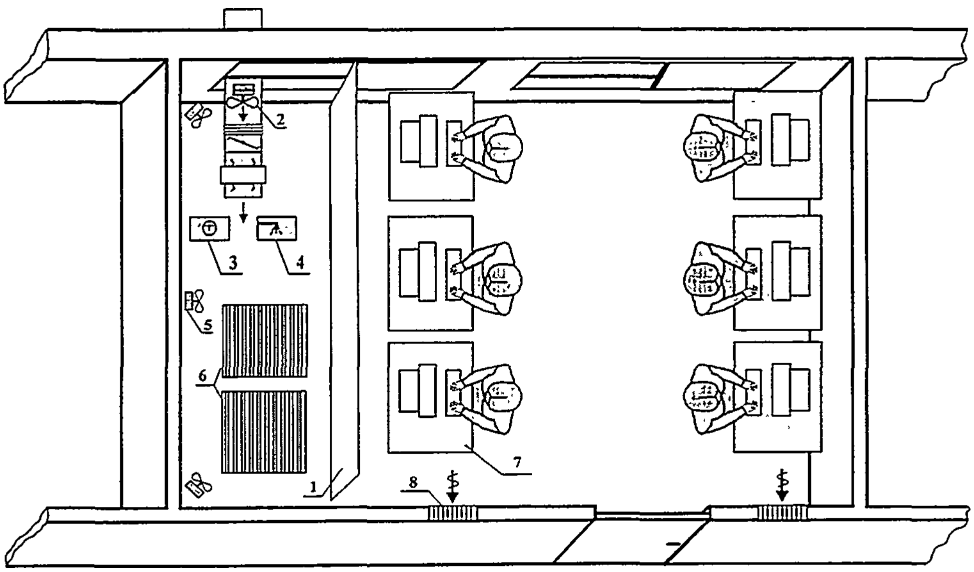


Figure 4.3.1 Experimental set-up in the office in which the investigation was carried out: 1-partition, 2-axial fan with damper and silencer, 3-electric heater, 4-electric steam humidifier, 5-mixing fan, 6-samples of carpet hanging on the stainless steel racks, 7-workstation consisting of a table, a lamp, a personal computer and a chair, 8-exhaust ventilation grills. In the figure, the office is occupied by the subjects and the carpet is placed behind a partition

The office was divided into two smaller spaces by means of a partition made of laminated wooden panels. The partition was 2 m high so that the air from one space could easily mix with the air from the other, and at the same time a sight-barrier was created, preventing people occupying one space from seeing what was placed behind the partition in the other space. The partition was placed perpendicular to the windows so that both spaces had access to them. One space in the office was occupied by subjects. Six workstations were created in this space. Each workstation consisted of a table, a lamp having a low-energy bulb of 9 W, a personal computer (PC) and a chair. The tables were placed along the wall and along the partition, at right-angles to the window. The other space was used to accommodate the equipment conditioning the air, axial fans, fans mixing the air, as well as stainless steel racks on which samples of carpet were hung. No other equipment or furnishing was placed in the office during the experiment, except for wooden stairs used for a two-step exercise during the experiment.

4.3.2.2 Ventilation

An axial fan was mounted in the window to supply outdoor air to the office. The air was exhausted naturally through the existing exhaust ventilation system and a slot between the floor and the door to the corridor outside the office. Several small fans were located in the office to ensure that the air was well mixed. When locating small fans, special care was taken to avoid creating draught risk for people occupying the office on the other side of the partition. Special care was taken also to reduce the noise level produced by the equipment: a silencer was mounted on a supply fan and transformers were used to reduce the rotation speed of the small fans.

4.3.2.3 Air-Conditioning

Electric oil-heaters of 4 kW total power were used to condition the air to the required temperature. A steam humidifier with a maximum output of 0.6 L H_2O/h provided the required relative humidity inside the office. The heater and humidifier were controlled by a PID-controller together with the calibrated temperature and relative humidity sensor (Vaisaala HMP 131) located centrally in the space occupied by subjects.

Heating and humidifying equipment were carefully cleaned before the experiment and maintained in a clean condition during the entire experiment to ensure that no pollution was created while conditioning the air.

4.3.3 Subjects

Thirty female subjects participated in the present experiment; some characteristics of subjects are presented in Table 4.3.1. They were recruited among 58 applicants replying to the advertisements distributed in colleges and universities of the Greater Copenhagen area and those responding to the preliminary questionnaire requesting information on age, occupation, smoking habits, general health and SBS-history. Criteria for recruitment included subjects' availability to participate in the experiment, acquaintance with a PC, absence of chronic diseases, as well as absence of asthma, allergy or hay-fever; these data was obtained from the above-mentioned questionnaire and no medical examination of the subjects was made. Among selected subjects, a few dropped out prior to commencement of the experiment, and to complete the group, it was necessary to include one subject with asthma and one with hay-fever (see Table 4.3.1). Another recruitment criterion was subjects' impartiality to the building in which the office was located: the subjects selected should not have worked or studied in that building prior to the experiment. No restriction was placed on subjects' age or occupation.

Table 4.3.1 Some characteristics of n=30 subjects participating in the present experiment. The data were obtained from the preliminary questionnaire pertaining to applicants' personal characteristics; this questionnaire was filled out by applicants during recruitment

Age:	20÷31 years old (mean=24, st.dev.=3)
Height:	153÷182 cm (mean 169; st.dev.=7)
Weight:	50÷90 kg (mean=64; st.dev.=9)
Average DuBois body surface:	1.72 m^2
Occupation:	students
Number of non-smokers (never-smokers):	23 (19)
Number of asthmatic subjects:	1
Number of subjects with hay fever:	1
Number of subjects with skin easily burned or eczematized by sunlight:	10
Number of subjects often experiencing "dry air" at home or at work (school):	6
Number of subjects considering themselves as more sensitive to poor air quality:	11
Number of subjects with SBS-history*:	23

* subjects who within a year prior to the experiment experienced at least twice per month one mucosal, cutaneous or general symptom

During the week preceding the main experiment in the office, subjects received 5 hours' training in performance tasks and the performance test battery, which were both used during later exposure in the office. They were also instructed on how to use questionnaires for measuring subjective responses. During training sessions, subjects were kept blind to the experimental office; training sessions were carried out in another mechanically ventilated office space used as a waiting room during the main experiment. Furthermore, subjects were not informed that these training sessions were only for practice. Recruited subjects took also an olfactory test comprising a ranking test with n-butanol at 4 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 8587 (1988) and ISO 8586-1 (1993). Subjects had on average 82% correct ranking and 78% correct matching.

The people recruited occupied the office in 5 groups, each comprising 6 subjects (Fig. 4.3.1). The training sessions described above were also carried out separately for each of the 5 groups of subjects.

Recruited subjects were paid a salary for participation in the experiment on a rate per hour basis. As a source of motivation, they were also paid a bonus of up to 20% of the total salary, depending on their performance.

4.3.4 Test Conditions

4.3.4.1 Air Pollution

To modify the air pollution level in the office, samples of carpet were placed inside the office behind the partition (Fig. 4.3.1) or removed from the office. In this way, two exposure conditions were created: (1) office without carpet = building materials, 6 workstations each consisting of a table, a chair, a lamp and a PC, and equipment used to condition the air inside the office, and (2) office with carpet = the office as above plus carpet. These two experimental conditions will hereafter be referred to as "office without carpet" (w/o carpet) and "office with carpet", respectively. Except for placing and removing carpet in the office, no other changes to the office equipment, furnishing or building materials were made during the experiment.

The carpet from which samples were made was a tufted bouclé with 100% polyamide fibres and latex backing. It was collected from an office building in Denmark (Pejtersen et al., 1998) where it had been situated for 20 years. The samples of carpet were attached back-to-back and the edges were protected so that the backing of the carpet was not exposed during experiments. The samples hung on stainless steel racks while placed in the office. The area of carpet was 36 m^2, thus corresponding to the floor area of the office.

4.3.4.2 Ventilation Rates

During the experiment, the office was ventilated with a constant outdoor air supply corresponding to 10 L/s per person. This ventilation rate was reported by Mendell (1993) and Godish and Spengler (1996) to be a border rate above which no positive effect in decreasing the number of SBS-symptoms among occupants of office buildings can be obtained with increasing rates of outdoor air supply. Conversely, Sundell (1994) showed that increasing the ventilation rate up to 50 L/s per person has a positive effect on decreasing the odds ratio of SBS.

A ventilation of 10 L/s per person was selected as this is currently required by ASHRAE Standard 62 (1989). This ventilation rate was selected for a practical reason also: since the experiment was carried out in the beginning of June and no cooling device was installed in the office, a high ventilation rate was needed in order to maintain the air temperature in the office at the designed value.

Since six people occupied the office, total outdoor air supply was 60 L/s, or 1.7 L/s per m^2floor, or 2 air changes per hour.

4.3.4.3 Thermal Parameters, Noise and Illumination

The designed temperature and relative humidity of air in the office were respectively 24°C and 50% rh. They both lie within the limits of the range required for thermal comfort of people performing light, mainly sedentary activity under summer conditions (ISO 7730, 1993), assuming that the operative temperature equals the air temperature. These conditions were not changed in the office with and without carpet. The air velocity at the workstations was designed to be at or below 0.2 m/s.

The noise level in the office without occupants but with fans and computers switched on was designed to be ca. 42 dB(A), for exposures both with and without carpet. This level is slightly higher than 35 dB(A) required for cellular offices and 40 dB(A) for landscaped offices (prENV 1752, 1997; Category B). It was, however, the lowest possible level to be obtained in the office with all equipment in operation.

No control of the illumination level in the office was made. The office was illuminated by day-light through the windows with a glazing surface of 6 m^2. Since the experiments were carried out in the afternoon and the windows faced east, there was no direct sunlight entering the office when it was occupied by the subjects. If the subjects felt it was too dark, they used a lamp attached to the table at each workstation.

4.3.5 Measurements

4.3.5.1 Physical Measurements

Temperature and relative humidity of air were continuously measured at each workstation by calibrated temperature and relative humidity sensors (Vaisaala HMP 131) located close to the breathing zone of the subjects. The measurements were logged through the data acquisition system and stored on the computer. In addition, temperature, relative humidity and air velocity were continuously measured using a Brüel & Kjær Indoor Climate Analyzer Type 1213. Sensors were located 1.1 m above the floor centrally in the space occupied by the subjects and close to the sensor controlling the relative humidity and temperature in the office. Spot measurements of the outdoor temperature and relative humidity were made in the beginning and at the end of the experiment.

Ventilation measurements were made several times during the experiment, using a Brüel & Kjær Multi-Gas Monitor Type 1302 connected with a Brüel & Kjær

Multipoint Sampler and Doser Type 1303. A constant concentration method was used: a tracer gas (SF_6) was dosed to the inlet of an axial fan supplying outdoor air into the office and its concentration was maintained at 1 ppm at one workstation, while concentrations of SF_6 at the remaining five workstations were monitored. Sampling of the air at the workstation was made close to the breathing zone of the subject. Based on the amount of tracer gas dosed into the office, the rate of outdoor air supplied to the office was calculated. Measured concentrations of tracer gas at each workstation were used to evaluate ventilation efficiency, i.e., whether the air was well mixed inside the office and hence, whether each subject received similar exposure.

During experiments, concentrations of carbon dioxide (CO_2) and a toluene equivalent total concentration of volatile organic compounds (TVOC toluene-equivalent) were continuously measured inside the office and outdoors. Outdoor air was sampled at the inlet of the axial fan supplying outdoor air to the office. Office air was sampled at each workstation close to the breathing zone of the subject and in the slot between the door and the floor through which the air was exhausted from the office. Measurements were made using a Brüel & Kjær Multi-Gas Monitor Type 1302.

Noise measurements were made continuously during the experiment using a Brüel & Kjær Sound Level Meter Type 2218 located at the centre point of the space occupied by subjects.

Parallel to chemical measurements, spot measurements of ozone concentration were made on two experimental days in the beginning and at the end of the occupation period. Measurements were made at the centre point of the space occupied by subjects (office air) and in the inlet of the axial fan supplying outdoor air into the office (outdoor air). A portable Ozone Analyzer Type 550 (Thermo Electron Instruments) was used. It functions on the chemoilluminance principle, i.e., measurement of the light produced by the chemical reaction between ozone and ethylene.

4.3.5.2 Chemical Measurements

Measurements of formaldehyde and VOCs in the office air and outdoors were made on two successive experimental days in the office with and without carpet. Formaldehyde was sampled on a silica gel tube coated with 2,4-dinitrophenylhydrazin with a flow of 80 ml/min. VOCs were sampled on Tenax-TA tubes with a flow of 30 ml/min. The air was sampled in the inlet of the axial fan supplying the air into the office (outdoor air) and centrally in the space occupied by subjects (office air). Parallel 5-hour sampling was made when people occupied the office. When sampling was completed, tubes were sent for further chemical analysis to the laboratory (Miljø-Kemi A/S, Galten, Denmark). They were analysed with an accuracy of ±10% and the detection limits of 5 $\mu g/m^3$ for formaldehyde and $1 \mu g/m^3$ for VOCs. Twenty-five VOCs with the highest concentrations were quantified.

In addition to chemical analysis of air described above, samples of carpet used to modify the air pollution in the office were sent to the laboratory (Miljø-Kemi A/S, Galten, Denmark) in order to estimate the chemical emission rate from the carpet used during experiments. Two specimens of carpet were prepared and sent for analysis: a specimen prepared from the carpet unexposed to the office air during the experiment and a specimen prepared from the carpet that was exposed to the office air during experiment. Chemical emissions from the carpet were measured using Field and Laboratory Emission Cell - FLEC (Wolkoff et al., 1993) at a temperature of 23°C, a relative humidity of 50% rh, and an airflow of 250 ml/min. Thermal conditions were thus similar to those in the office air. The air from FLEC was sampled on Tenax-TA tubes and 25 VOCs with the highest concentration were quantified with an accuracy of ±15%. Parallel sampling of the air from FLEC was made.

4.3.5.3 Subjective Measurements

The questionnaire used for subjective measurements included questions regarding perceived air quality, general perceptions of the environment, SBS-symptoms, thermal comfort and self-performance. In addition, each day before entering the office, subjects filled in a questionnaire recording information concerning their personal hygiene, medication and health condition on the experimental day, as well as their activities on that day (in the morning) prior to the experiment. Finally, when occupation of the office ended, subjects recorded their clothing using a standardized questionnaire.

To assess the perceived air quality, subjects used continuous scales describing acceptability of air, as well as intensity of odour and irritation of eyes, nose and throat; the scale for acceptability is a slightly modified continuous scale introduced by Gunnarsen and Fanger (1989) and the scales for measuring perceived odour intensity, irritation of eyes, of nose and of throat are similar to those used by Yaglou (1955). The questionnaire for measuring the perceived air quality is shown in Figure 4.3.2.

To assess general perceptions of the environment, symptoms and self-performance, visual- analogue scales (VAS) were used (Wyon, 1994; Wyon et al., 1995). A set consisting of 26 scales was used and is shown in Figure 4.3.3. Each scale was a 100 mm long horizontal line without graduation with two vertical dash lines marking extreme points of the scale with defined end labels. The subjects marked on a scale to indicate the intensity of a symptom or perception. The following perceptions were measured: air dryness, air freshness, illumination, noise and office cleanliness. The following symptoms were measured: nose congestion, nose dryness, throat dryness, mouth dryness, lip dryness, skin dryness, hair dryness, nail brittleness, eye dryness, smarting eyes, aching eyes, eye grittiness, headaches, difficulty to think clearly, dizziness, well-being and depression.

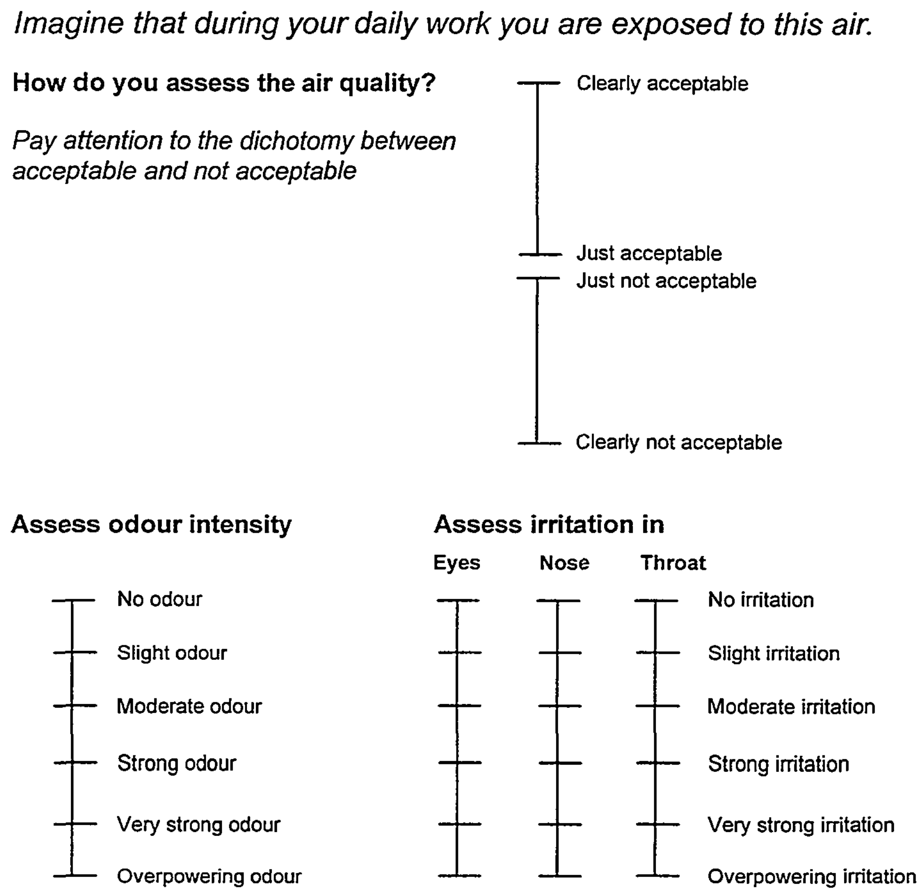


Figure 4.3.2 Questionnaire used to assess the perceived air quality in the office

To assess thermal comfort, subjects filled in a questionnaire including questions regarding thermal sensation and draught. Thermal sensation was measured using a 7-point thermal sensation scale (ASHRAE Handbook, 1997), and questions were asked regarding acceptability of the thermal climate (marked on a continuous acceptability scale similar to that used during evaluations of the perceived air quality) and the preference of temperature, i.e., whether subjects would prefer a higher, an unchanged or a lower temperature during occupation. Draught was measured by asking people whether they could feel air movement and whether this sensation was acceptable or not (marked on a continuous acceptability scale similar to that used for assessments of the perceived air quality), so that the number of subjects who actually sensed draught could be estimated. In addition, subjects were asked about their preference as regards air movement, i.e., whether they would prefer more, unchanged or less air movement.

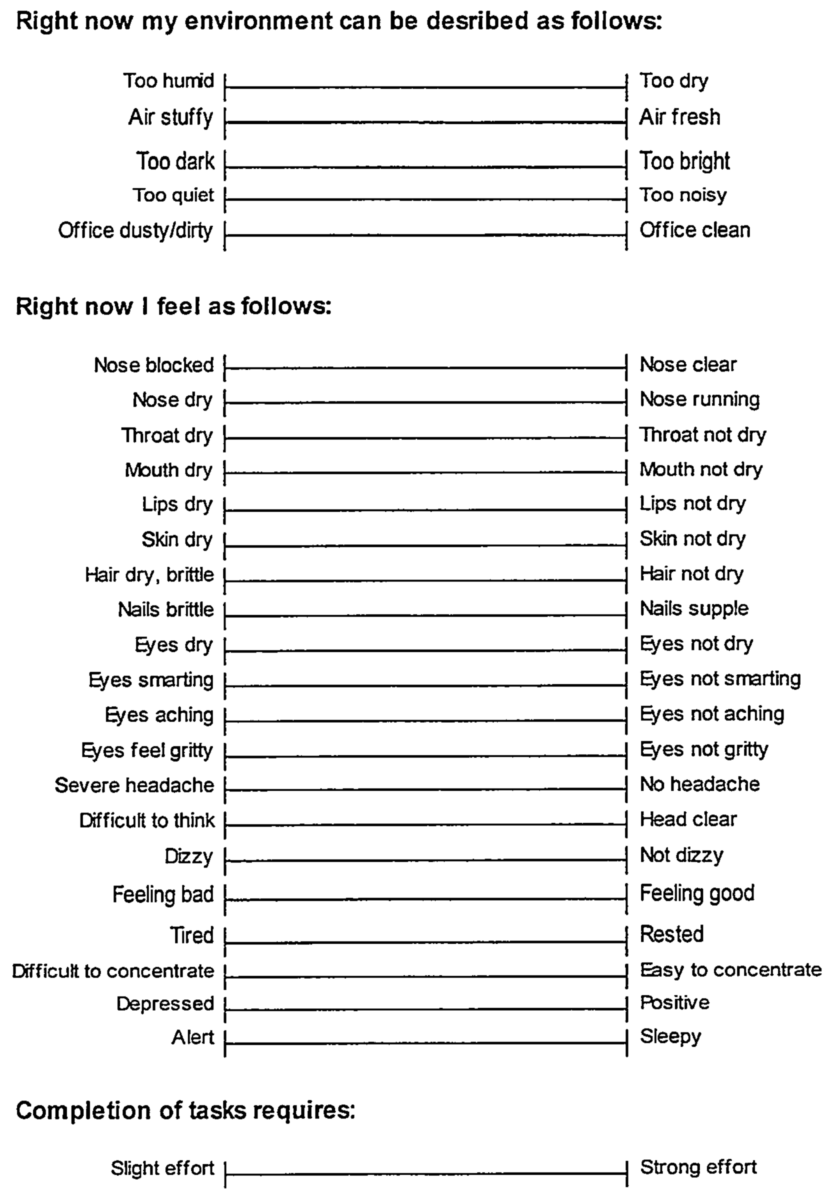


Figure 4.3.3 Visual-analogue scales used to measure general perception of the environment, SBS-symptoms and self-performance

4.3.5.4 Measurements of Performance

The present study investigated only the effects of air pollution on performance. The potential whole-body thermal effects on performance were minimized by encouraging the subjects to change their clothing so that they felt thermally neutral during occupation of the office.

Three methods were used to estimate the performance of subjects occupying the office: performance of subjects exposed to psychological tests, performance of subjects engaged in simulated office work, and subjective evaluation of self-performance. Psychological tests of short duration test specific skills and can thus be very sensitive. However, they exhibit large inter-individual differences (as they are designed to examine such differences rather than environmental effects), which reduce their ability to reveal environmental effects. Furthermore, they are unrealistic and unrepresentative of anything anybody does all day at work. In addition, due to their very short duration, it is possible for subjects to temporarily exert enough effort to overcome any negative effects of the environment. Simple performance tests used to simulate office work are of relatively long duration and thus have none of the disadvantages of the psychological tests, particularly if subjects are all trained to perform them in the same way. Subjective evaluation of self-performance, on the other hand, is largely influenced by expectation, which may be mistaken. As a matter of fact, subjects can fail to perceive even a 30% decrease in actual performance if it is caused by external factors (Kroner et al., 1992). In the following, a detailed description of the tests applied in the above three-fold approach to performance evaluation is given.

Psychological tests. A Danish version of the Walter Reed performance assessment battery - PAB (Thorne et al., 1985) was used. PAB is a computerized psychological test battery designed to examine the effects of various state-variables on a representative sample of normal psychomotor, perceptual and cognitive tasks and it has been frequently used as a relatively powerful measure of the effects of, e.g., sleep deprivation and drugs.

The battery, comprising 8 tasks, was compiled for the present experiment. The tasks were presented to subjects on a computer screen. Their description is given in the following in the order in which they were presented to subjects:

1. *Two-letter search* A visual search and recognition task in which subjects are to decide whether two letters presented at the top of the screen are among the string of 20 characters presented in the middle of the screen. Ten pairs of letters were presented to subjects.
2. *Two-column addition* A subject-paced mental arithmetic task, in which five two-digit numbers are presented simultaneously in the column and subjects are to determine their sum. When the result of the addition is entered into the computer, the column with numbers disappears (after entering the first digit) hence no corrections can be made. Ten columns with digits were presented to subjects.
3. *Logical reasoning* An exercise of transformational grammar (Baddeley, 1968). The letter pair "AB" or "BA" is displayed along with the statement that correctly or incorrectly describes the order of letters within the pair (e.g., "B follows A" or "A is not preceded by B"). The subject decides whether the statement is true (same) or false (different). Thirty-two pairs with A and B letters were presented to subjects.

4. *Serial addition/subtraction* A machine-paced mental arithmetic task requiring sustained attention, in which two randomly selected digits and either a plus or minus sign are displayed sequentially for ca. 250 msec. with 200 msec. break in between in the same screen location, followed by a prompt symbol. The subject performs the indicated addition or subtraction and enters the least significant digit of the result (e.g., 5 7 + equals 12, so enter 2). If the result is negative, the subject adds 10 to it and enters the positive single digit remainder (e.g., 5 7 - equals -2, enter 8). Fifty pairs of sequentially displayed digits were presented to subjects.

5. *Stroop* A test of response competition due to perceptual/linguistic interference. Words are displayed on the screen, one at a time, each word being in a different colour, either red, blue or green. The colour of the word has to be determined and the appropriate key pressed, e.g., for the word "red" displayed in blue, the subject has to press the key assigned to the colour blue (incongruent trial), for the word "house" in green, the subject has to press the key assigned to the colour green (normal trial). Forty-eight trials were presented to subjects, among which 24 were incongruent.

6. *Running memory* A measure of immediate or working memory with a distractor. Single digits are displayed on the screen, one at a time, successively. The task for the subject is to memorize the displayed digit, but to enter the one which preceded the digit displayed on the screen. Forty-eight digits were displayed to subjects during this task.

7. *Six-letter search* A visual search and recognition task in which subjects are to decide whether six letters presented at the top of the screen are among the string of 20 characters presented in the middle of the screen. Ten pairs of letters were presented to subjects.

8. *Code substitution* A paired associate learning task from the Wechsler Adult Intelligence Scale evaluating speed and coding ability in which subjects are to press the digit keys corresponding to a reordered test set of nine symbols, which are paired with nine digits in a table at the top of the screen. Pairing of the symbols and digits should be memorized since the table shown at the top of the screen disappears after some trials. Subjects can of course then look it up, but at the cost of reduced accuracy. Fifty-four digit-symbol pairs were displayed to subjects, among which 27 were displayed in the second part of the task without a table showing pairing of symbols and digits.

The entire battery took approx. 20 minutes to complete. Four different sets of batteries each consisting of the 8 tasks described above, were administered to subjects during exposure in the office. Both speed (using a special timer card installed in the computer measuring reaction time, interstimulus interval and stimulus duration) and accuracy (number of errors) were registered by the computer and used later as measures of subjects' performance.

In order to reach stability and minimize learning effects, subjects received ten practice sessions with a performance assessment battery in the week prior to exposure in the office.

<u>Simulation of office work.</u> In general, office work covers a wide range of tasks. A few, however, are common to most office workers, i.e., working with a PC, word-processing, making calculations, reading and proof-reading, paper handling, etc. All these tasks require a certain level of manual and intellectual skills, as well as creative thinking. In the present study, three tasks were selected for simulation of office work, namely: typing text on a PC, addition of numbers and creative thinking. The selected tasks are described in the following:

1. *Word processing* Subjects typed a text into a PC using Microsoft Word for Windows 95, version 6.0 text editor. Four different texts of similar difficulty were prepared for typing and distributed to subjects on paper. These texts were articles from a Danish magazine on popular science. The texts that were presented to subjects were printed with a 12-point Times New Roman font and with triple line spacing. Subjects typed the texts at their own pace. They had 47 minutes to type each text. Two measures of subjects' performance were used: number of characters typed per minute (registered by the text editor) and total number of errors: misspellings, typing errors, etc. (checked manually). These measures characterize speed and accuracy.

2. *Addition of numbers* Subjects added five two-digit numbers, excluding zeros, printed in a column one below another (Wyon et al., 1975). Four different sets of numbers were prepared for subjects and distributed to them on paper. Subjects attempted to complete as many units (a column with two-digit numbers) as possible during a 25-minute period. Two measures of performance were used: speed, i.e., the total number of units completed per hour, and accuracy, i.e., the percent of correctly executed operations.

3. *Creative thinking task* Four open-ended thinking tests (with question to which there are an almost unlimited number of correct answers) were used. All tests were especially created for repeated-measures design. Subjects had to write familiar Danish male names beginning with either the letter E or Ø (test CT-1), or either letter S or U (test CT-2), or familiar Danish female names beginning with either letter A or U (test CT-3), or either letter J or N (test CT-4). Using a Danish name lexicon (Søndergaard, 1991), each version should have produced a similar number of "correct" answers, i.e., 31 names. No time restriction was made: 25 min was nevertheless assigned to the task, as it was felt to be sufficient for its completion. To measure subjects' performance, originality of answers was used rather than speed and accuracy appropriate for measuring performance on tasks requiring logical thinking. This was accomplished by transforming the score of each subject into bits (Wyon, 1969) (see section 4.3.7.4). A restriction was made for the analysis as regards the names provided by subjects: only those names were accepted which were correctly identified as male or female names by >95% of the same group or an equivalent group selected at random from the same underlying population of potential subjects. Incorrectly spelled names were accepted if the intention was clear.

Text processing and addition are simple tasks only little affected by learning. Being regarded as well-practised in daily life, a long training session was considered to be quite unnecessary. A short familiarization session was nevertheless made in the week preceding the experiment, during which subjects were informed about their tasks, were introduced to the materials, and could practise for approx. 10 minutes with both the addition and text typing task. No practise sessions were carried out for the creative thinking task.

To avoid a decrease in workrate due to boredom, financial motivation was provided for the subjects. They were paid 20% of the total payment on the basis of the amount of work done.

Self-performance. Subjective judgements of performance were made using four continuous VAS scales describing fatigue (tired/rested), concentration (difficult/easy to concentrate), arousal (alert/sleepy) and effort required for completion of tasks simulating office work (slight/strong) (Langkilde et al., 1973; Wyon et al., 1975). They were all included in the questionnaire measuring SBS-symptoms and general perceptions of the environment and are shown in Fig. 4.3.3. VAS scales are described in section 4.3.5.3.

4.3.6 Procedure

The experiment was made during two consecutive weeks in June 1998, each week on five days from Monday to Friday, and each day for ca. 5 hours in the afternoon, from 1300 to 1800 hours. Each weekday a different group of 6 subjects participated in the experiment. Each subject was randomly assigned to the same weekday in two experimental weeks to avoid confounding of experimental condition with weekday. Furthermore, each subject occupied the office with one week break in between two exposure conditions: with and without carpet in the office, so that carry-over effects could be avoided.

The exposures in the office were completely randomized during two weeks of experiments to avoid bias of results with the exposure condition. Hence, three groups of subjects were exposed to the office without carpet in the first week and to the office with carpet in the second week, conversely to the exposure of two other groups of subjects. Also performance tests and tasks simulating office work were presented to subjects completely at random way in order to balance out possible bias due to confounding of the test version with the exposure condition. Appendix 5 shows the randomization of performance tasks and the order in which groups of subjects occupied the office.

One experimental session on one weekday consisted of three periods (Fig. 4.3.4): pre-exposure, exposure in the office and post-exposure. They are described in the following.

4.3.6.1 Pre-Exposure

Upon arrival, subjects assembled in a mechanically ventilated space (called thereafter a waiting room) which was located close to the experimental office; this space was also used by subjects for training and practise sessions with performance tests prior to the experiment. Subjects spent approx. 10 min in the waiting room during which they completed the questionnaire describing their exposures and activities prior to arrival. After this period, subjects went outdoors and assessed the perceived quality of outdoor air. Immediately thereafter, subjects were led to the experimental office. The above routine was repeated for each group of subjects to ensure that they received similar pre-exposure immediately before they entered the experimental office.

4.3.6.2 Exposure in the Office

Subjects entered the experimental office and stayed inside for 4 hours and 25 minutes (=265 min) excluding short periods during which they went out to the toilet. During occupation of the office, subjects took the performance battery test (PAB), completed several tasks used to simulate office work, and on several occasions made subjective evaluations of the indoor environment according to the schedule presented in Fig. 4.3.4.

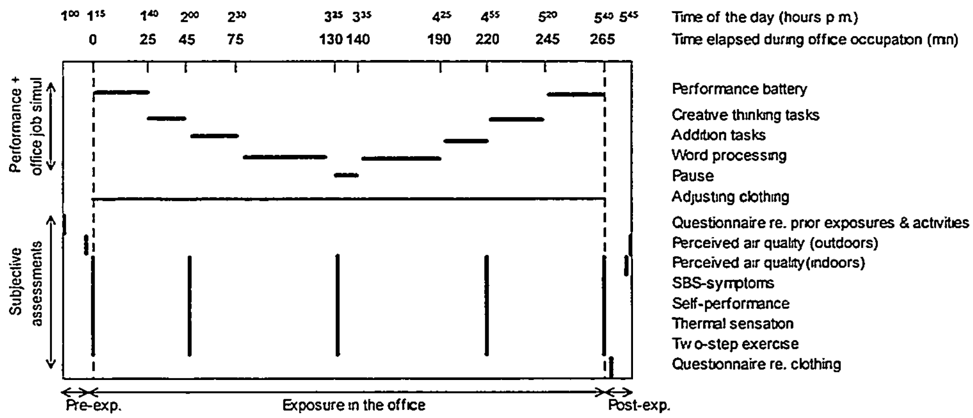


Figure 4.3.4 Schedule of events taking place during one experimental session

In brief, immediately upon entering the office, subjects approached their workstation and assessed the perceived air quality. When seated, they then answered the remaining questionnaires describing general perception of the environment, SBS-symptoms, self-performance and thermal sensations. The above evaluations were thereafter repeated four times (about 45 min, 125 min, 215 min and 265 min after entering the office) by subjects seated at their workstations. In the first 20 min of occupation, subjects took the performance assessment battery (PAB), then completed the creative thinking task (25 min), followed by the addition (25 min) and text typing (47 min) tasks. In the middle of exposure, subjects had a short 10 min break. During the break, subjects stayed inside the office and left it only if it was necessary to do so. Following the break, another range of tasks including text typing, addition, creative thinking tasks and PAB were presented to subjects. The order of presentation was reversed, however, from that used before the pause (Fig. 4.3.4).

In order to avoid only sedentary occupation and to obtain an average metabolism of 1.2 met, every time subjects filled out the set of questionnaires used for subjective measurements, they had to get up and walk to the ballot box, taking four steps of 0.2 m height on their way. After placing the questionnaire in the ballot box, subjects returned to their workstation, taking also four steps of 0.2 m height and sat down on their chair. Energy produced by this exercise was calculated as follows (Arens et al., 1998): for an average female subject participating in the experiment, having a body surface area of 1.72 m^2 and a weight of 64 kg, the 10 step-exercise (4 steps on the way to the ballot box + 4 steps when returning + equivalent of 2 steps when getting up and sitting down on the chair) corresponds to a total energy of 2.3 W, assuming a muscular efficiency of 15%. Energy produced by other tasks carried out by subjects during occupation can be calculated as follows (ISO 8996, 1990; ASHRAE Handbook, 1997): creative thinking and addition tasks as well as the performance battery, and filling in questionnaires requires energy of 1 met x 1.72 m^2 x 58.2 W/m^2 = 99.9 W. Typing requires energy of 1.1 met x 1.72 m^2 x 58.2 W/m^2 = 110.1 W. Walking requires energy of 1.9 met x 1.72 m^2 x 58.2 W/m^2 = 190.2 W. Finally, averaging over time and adding energy required for steps yields: 110.1. x 0.35 + 99.9 x 0.64 + 190.2 x 0.01 + 5 x 2.3 = 115.8./(58.2 x 1.72) ≈ 1.16 met, which is slightly lower than a typical activity level found in offices. However, in the above calculation, the metabolic rate of 58.2 W/m^2 was used for estimating the energy produced by the subjects performing the creative thinking and addition tasks, and exposed to the performance battery. This metabolic rate is for sedentary persons performing no mental work and it may increase during the performance of concentrated mental work by 20-30% due to an unconscious increase in muscle tonus (Wyon et al., 1975); an increase of 20% would result in the activity level in the office being at 1.2 met.

During occupation, the subjects were asked to adjust their clothing so that they at all times felt thermally neutral when staying in the office. Whenever thirsty or hungry during occupation of the office, subjects could consume CO_2-free water and digestive biscuits supplied at each workstation.

4.3.6.3 Post-Exposure

Following 265 min occupation in the office, subjects returned to the waiting room that they occupied before entering the office. They spent 5 min in the waiting room, during which they completed a questionnaire describing their clothing. Thereafter, they re-entered the experimental office and after approaching their workstations, they immediately assessed the perceived air quality. After this evaluation, subjects went outdoors to make an assessment of the perceived quality of outdoor air.

4.3.7 Data Analysis

4.3.7.1 Coding Subjective Ratings on Questionnaires

Linear scales used for measuring perceived air quality were coded as follows:

- acceptability scale: "clearly not acceptable" = -1; "just not acceptable/just acceptable" = 0; "clearly acceptable" =1;
- odour intensity scale: "no odour" = 0, "slight odour" = 1, "moderate odour" = 2, "strong odour" = 3, "very strong odour" = 4, "overpowering odour" = 5;
- scales 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 end-points on the visual analogue scales were coded by 0 (left end of the scale) and 100 (right end of the scale).

The seven-point ASHRAE thermal sensation scale was coded as follows: "hot" = 3, "warm" = 2, "slightly warm" = 1, "neutral" =0, "slightly cool" = -1, "cool" = -2, "cold" = -3.

4.3.7.2 Calculation of the Perceived Air Quality in the Office

Two measures of the perceived air quality in the office were calculated: percentage of dissatisfied and perceived air quality expressed in the decipol unit introduced by Fanger (1988).

To calculate the percentage of dissatisfied with the air quality, mean ratings of acceptability were transformed using a logit curve fitted to the data of Gunnarsen and Fanger (1992):

$$PD = \frac{\exp(-0.18 - 5.28 \cdot ACC)}{1 + \exp(-0.18 - 5.28 \cdot ACC)} \cdot 100 \qquad [4.3.1]$$

where:
PD = percentage of dissatisfied with the air quality, %;
ACC = mean vote of air acceptability.

To calculate the perceived quality of air expressed in decipol, the following formula was used (Fanger, 1988):

$$C = 112 \cdot [\ln(PD) - 5.98]^{-4} \qquad [4.3.2]$$

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

4.3.7.3 Calculation of Sensory Pollution Loads

Total sensory pollution loads in the office with and without carpet were calculated similarly to the method described in detail in Chapter 2 of the present thesis. Briefly, sensory assessments of acceptability of air made by subjects upon entering the office and sensory rating of acceptability of outdoor air were first transferred into corresponding levels of the percentage of dissatisfied [4.3.1] and the perceived air quality expressed in the decipol unit [4.3.2]. With the comfort model (Fanger, 1988) and the measured ventilation rate, total sensory pollution load on the air in the office was calculated.

The sensory pollution load on the air from people occupying the office was predicted using measurements of carbon dioxide (CO_2) concentrations similarly to the method described in section 2.4.1.6 of the present thesis:

$$G_P = \frac{3.6 \cdot 10^{-3} \cdot \Delta CO_2 \cdot Q}{\sum G_{CO_2}} \qquad [4.3.3]$$

where:

G_P = predicted sensory pollution load from people in the office, olf;
ΔCO_2 = measured CO_2 concentration over background outdoors, ppm;
Q = measured ventilation rate, L/s;
$\sum G_{CO2}$ = total production of CO_2 by all persons in the office, L/h.

Production rate of carbon dioxide (CO_2) from one person was estimated by (ISO 8996, 1990):

$$G_{CO_2} = \frac{RQ}{(0.23 \cdot RQ + 0.77) \cdot 5.88} \cdot M \cdot A_{DU} \qquad [4.3.4]$$

where:

G_{CO2} = production rate of CO_2 by one person, L/h per person;
RQ = respiratory quotient, estimated at 0.85 (ISO 8996, 1990);
M = metabolism, for sedentary office work (ISO 7730, 1993) =1.2*58.2 = 69.8, W/m^2;
A_{DU} = DuBois body surface area, m^2, calculated with the following formula:

$$A_{DU} = 0.202 \cdot H^{0.425} \cdot W^{0.725} \qquad [4.3.5]$$

where:

H = height of a person, m;
W = weight of a person, kg.

4.3.7.4 Analysis of Performance

<u>PAB, addition task and text typing.</u> Subjects took performance tests on two exposure days with one week break in between and twice on each day. This design was completely balanced. Considering the order in which tasks were presented to subjects, learning effects were calculated for the whole period of experiments as well as both *within exposure days*, i.e., comparing the first test completion (try-1) with the second one (try-2) on each of two exposure days (day-1 and day-2), and *between days*,

i.e., comparing the first test completion (try-1) on the first day (day-1) with the first test completion (try-1) on the second day (day-2) and accordingly for the second test completion (try-2). The effects of the air pollution on subjects' performance were calculated in a similar way as learning effects, i.e., within and between exposure days; however, the exposure in the office (with and without carpet) and not the order of presentation was a grouping factor for the results of performance tests. Learning effects and effects of exposure were calculated both for the results describing speed as well as accuracy.

Creative thinking task. Each of the four versions of the creative thinking task used were scored independently across all subjects regardless of the exposure and the time it was completed. For each name in each version, the probability of its occurrence was calculated by dividing the number of times it was given by different subjects by the total number of subjects. This probability was then used to derive the so-called C-Score in bits according to an information theory (see Wyon, 1969 for details):

$$\mathrm{C-Score} = \log_2(1/P) = \log_2(N/n) \qquad [4.3.6]$$

where:

C-Score = information conveyed by the given name, bits;

P = probability of the name occurrence;

N = number of subjects participating in the experiment;

n = number of times a name was given by different subjects.

It can be seen that the name given by all subjects carries a score of zero (no information). Within each version, total C-Scores were then calculated for each subject by cumulating C-Scores from all the answers (names) given by the subject.

The effects of the air pollution on creative thinking of the subjects (C-Score) were calculated in a similar way as the effects for the other performance tasks, i.e., during occupation of the office separately for the exposure with and without carpet (fatigue during exposure), and between occupation of the office with and without carpet separately for the beginning and the end of occupation (effect of exposure). Statistical analysis was made on normalized total C-scores (Normal C-Scores): total C-Score of each subject in each version was divided by that subject's average score on all versions of the test.

4.3.7.5 Statistical Analysis

Subjective assessments and the results of performance tasks were first tested for normality using Shapiro-Wilks' W test; the rejection region was set to be $p<0.01$. Normally distributed data was subjected to analysis of variance in repeated measured design using subjects as their own control (the interaction of subject-by-factor was used as an error term to remove the main effect of subject) or to paired t-tests (Montgomery, 1991). Not normally distributed data was analysed using Friedman two-way analysis of variance by ranks or Wilcoxon matched-pairs signed-ranks test for related samples, and Mann-Whitney U test for independent samples

(Siegel and Castellan, 1988). Correlations were made by calculating the Spearman correlation coefficient.

4.4 Results

4.4.1 Conditions of Indoor Climate inside the Office

Results of measurements of general parameters describing indoor climate inside the office during experiments are shown in Table 4.4.1. Unless indicated, these values are means of continuous measurements carried out in the office with and without carpet for each of 5 groups of subjects occupying the office in these two exposure situations. Also indicated are selected parameters of outdoor air supplied to the office by ventilation. Designed parameters of the climate inside the office did not deviate from those measured in the office.

Table 4.4.1 Average parameters of the outdoor air supplied to the experimental office (supply air) and the air inside the office (office air) on days when the carpet was not placed in the office (w/o carpet), and on days on which carpet was placed inside the office (with carpet)

Parameter	Office w/o carpet		Office with carpet	
	supply air	office air	supply air	office air
Temperature† (°C)	16.5	24.1	17.4	24.3
Relative humidity† (%)	68	51	57	49
Air velocity ± SD† (m/s)	-	0.13±0.07	-	0.14±0.06
Sound pressure†† (dB(A))	-	53	-	52
Outdoor air supply* (L/s)	-	59.7	-	59.7
CO_2‡ (ppm)	406	964	407	953
TVOC-toluene equivalent (ppm)	1.98	2.34	1.97	2.35
Ozone* (ppb)	28	8	40	20
Formaldehyde** (μg/m³)	4.70	16.85	3.65	14.40

† measured at the central point of the space occupied by subjects; †† 5-hour weighted average with occupants inside the office; ‡ concentration after steady-state level was obtained; * few measurements taken during experiments; ** measurements were performed only on one experimental day w/o carpet and on one day with carpet placed inside the office

The time-profile of temperature measured at the central point of the space in the office occupied by the subjects is shown in the left chart of Fig. 4.4.1. Air temperature increased by ca. 1°C during the first 2.5 hours of occupation to the level of ca. 24.5°C and did not change during the remaining occupation period. Temperature growth was caused by the additional heat production inside the office - people occupying the office. It could not be quickly compensated for, since cooling capacity of the supplied outdoor air was low (Table 4.4.1) and there was no cooling device installed in the office. Nevertheless, a similar profile of temperature change was observed under both experimental conditions: office with and without carpet. Hence, it is expected that the rising temperature had a similar impact on symptoms, perception of the environment and perceived air quality, if any, under both exposures studied inside the office. It should also be noted that the temperature in the office with carpet was marginally higher by ca. 0.2°C, which is within the measurement error of the temperature measurement system used. Nevertheless, this difference was consistent.

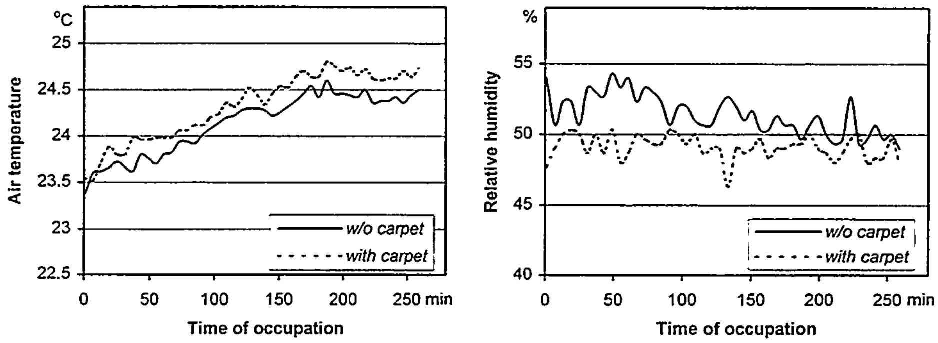


Fig. 4.4.1 Time-course of temperature (left) and relative humidity (right) of air in the office with and without carpet occupied by people; average data are presented and were obtained by the measurements taken on 5 days for each exposure situation in the office

The time-course of relative humidity of air measured at the central point of the space in the office occupied by the subjects is shown in the right chart of Fig. 4.4.1. Relative humidity was generally constant and close to the designed value of 50% rh. A 2-3% consistently lower humidity in the office with carpet was probably due to a slightly higher temperature in this office as compared with the office without carpet (left chart of Fig. 4.4.1). The fact that there was no variance in the dew-point temperature measured at both pollution levels in the office confirms this observation.

The air velocity measured at each workstation was in the range 0.14÷0.23 m/s (average 0.20 m/s), while the standard deviation ranged from 0.04 to 0.10 m/s (average 0.06 m/s). A slightly lower mean air velocity was obtained using continuous measurements at the central point of the space occupied by the subjects in the office, whereas standard deviation of measured air velocity was similar (Table 4.4.1). With velocities measured at each workstation, the percentage of people disturbed by draught was predicted to amount to ca. 15% (Fanger et al., 1988b). As shown in Fig. 4.4.2, the actual percentage of people complaining due to draught was lower, generally below 7% (i.e., 2 people out of 30).

Consistent with temperature measurements is the thermal sensation voted by subjects during occupation (Fig. 4.4.3). Even though air temperature increased by 1°C in the office (Fig. 4.4.1), the thermal vote remained almost unchanged, indicating that subjects adjusted their clothing during occupation as instructed. The thermal vote was slightly higher than neutral, i.e. on the warmer side of the sensation scale. The average metabolic rate of subjects was ca. 1.3 met and it was calculated using measured CO_2 concentration in the office (Table 4.4.1). It was higher than the estimated metabolic rate of 1.16 met (section 4.3.6.2), most likely due to a ca. 30% increase in metabolic rate during mental work (addition, creative thinking, performance assessment battery) (Wyon et al., 1975).

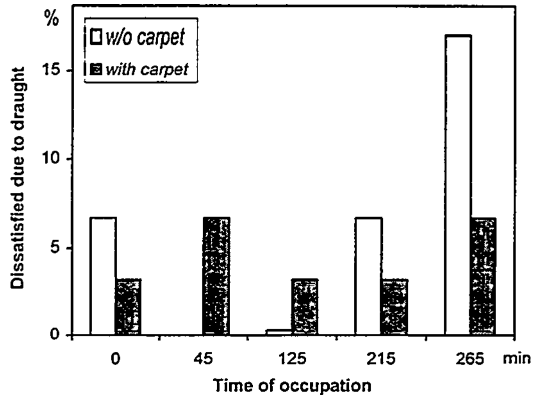


Fig. 4.4.2 Percentage of people complaining due to draught as a function of time of occupation of office with and without carpet

Using the results of temperature and relative humidity measurements inside the office at the end of occupation (Fig. 4.4.1), mean air velocity (Table 4.4.1), calculated average metabolic rate of subjects (ca. 1.3 met), estimated resistance of clothing (using the clothing questionnaire filled out by subjects after occupation of the office - 0.68 clo in the office with and without carpet), and assuming that radiant temperature equalled air temperature, the predicted mean vote (PMV) of subjects occupying the office was calculated (Fanger, 1970). In the office with and without carpet, the calculated PMV equalled 0.14, and was thus in excellent agreement with the thermal sensation rated by the subjects (see Fig. 4.4.3).

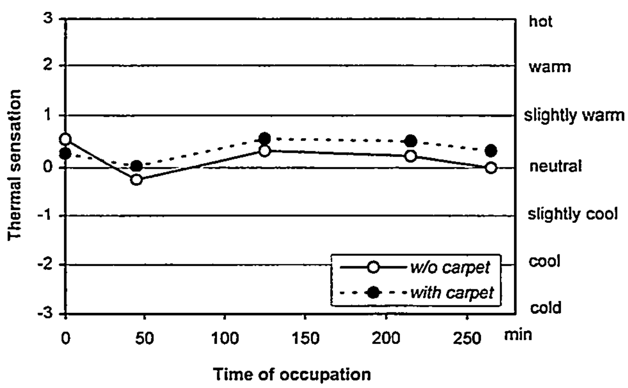


Fig. 4.4.3 Thermal sensation as a function of time of occupation of office with and without carpet

A five-hour weighted average of sound pressure level measured in the office with occupants was 52 dB(A) (Table 4.4.1). It was ca. 10 dB(A) higher than the designed value of 42 dB(A) in the office without occupants. The increase in noise level was caused by the activities taking place inside the office: subjects typing text on the computer, walking over an exercise step to the ballot-box, etc.

The measured outdoor air supply was 59.7 L/s, and was thus similar to the designed value. Measurements of ventilation effectiveness showed that the air was well mixed inside the office and no significant difference in the age of air between workstations was observed. This is consequently confirmed by the measurements of carbon dioxide (CO_2) concentration inside the office occupied by subjects. As shown in Fig. 4.4.4, similar concentrations of CO_2 were measured at each workstation as well as in the air exhausted from the office.

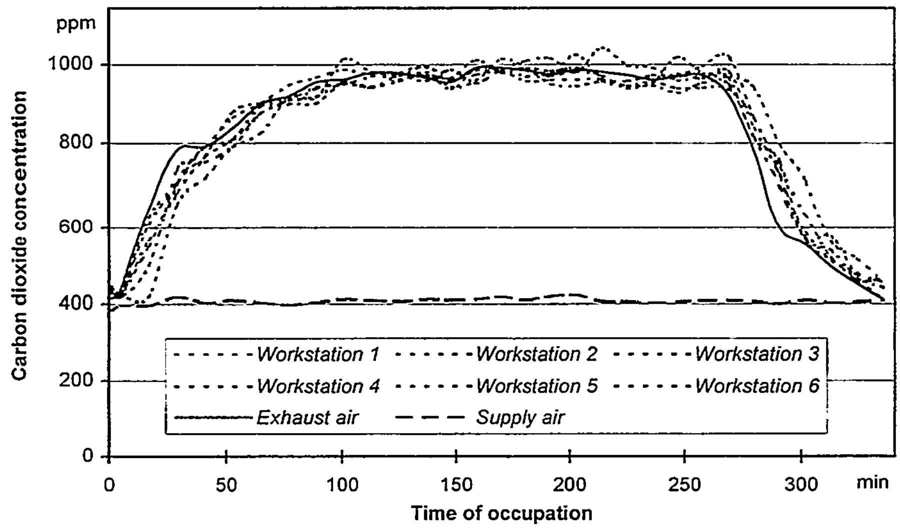


Fig. 4.4.4 Typical time-course of carbon dioxide (CO_2) concentration in the office occupied by subjects. Measurements made at 6 workstations, close to the breathing zone of the subjects, are presented together with CO_2 concentration of outdoor air supplied by the fan and of the air exhausted from the office

The measured outdoor ozone concentration was lower on a day when no carpet was placed in the office (28 ppb) as compared to the measurement on a day with carpet inside the office (40 ppb) (Table 4.4.1). This difference was probably caused by different weather conditions: the day without carpet inside the office was cloudy. Indoor ozone removal was slightly higher in the office without carpet: the ratio of indoor to outdoor (I/O) ozone concentration was 30% during that exposure, whereas in the office with carpet the I/O ratio was 50%. Both values are close to the typical I/O ratio which is 35% in the spaces ventilated with 2 air changes per hour (Weschler et al., 1992).

No difference was observed in the TVOC-toluene equivalent concentration (Table 4.4.1) and the total concentration of VOCs (Table 4.4.2) measured in the office with and without carpet. Formaldehyde concentration was also generally the same in the office with and without carpet, but slightly higher in the office without carpet when adjusted for the concentration in the air supplied by the ventilation (Table 4.4.1).

Among chemical compounds measured in indoor air (Table 4.4.2) there were aldehydes (C_5-C_{10}, undecanal, benzalaldehyde), ketones (acetone) and organic acids (acetic, benzoic, hexanoic, octanoic, nonanoic and decanoic) which constituted 60% to 70% of the total sum of compounds measured inside the office. These compounds are expected to be products of ozone reaction indoors (Weschler and Schields, 1997). In the experiment of Weschler et al. (1992), aldehydes were produced by the reaction of the emissions from carpets with ozone at moderate concentrations (30÷50 ppb), they were thus similar to ozone concentrations measured in the present experiment (Table 4.4.1). Table 4.4.2 reveals that similar aldehydes, organic acids and ketones were measured in the air of the office with and without carpet, indicating that these compounds could adsorb on the surfaces in the office. Slightly higher concentrations were nevertheless measured in the office with carpet, especially for acetic acid, and C_6 to C_{10} aldehydes (after adjusting for the concentrations measured in outdoor air). Two VOCs contributed most to the chemical pollution of air, and these were acetone and acetic acid.

FLEC measurements of VOC emissions from carpet (Table 4.4.3) showed higher emissions for carpet exposed in the office than for unexposed carpet. Exposed carpet is a carpet that was used to modify the pollution level in the office. Hence this carpet was in contact with the office air and the ozone, unlike the unexposed carpet which was wrapped in aluminium foil and not used in the present experiment. A few compounds emitted from the carpet were not measured in the office air (α-pinene, a few alcohols including n-butanol and 2,2,4,6,6-pentamethylheptane), whereas a few organic acids, undecanal and heptanal, were only identified in the office air. Other compounds emitted from the carpet were measured in the office. The concentration of total VOCs from exposed carpet were significantly higher than TVOC measured for unexposed carpet, indicating that chemical reactions may have taken place inside office. This issue is further elaborated in section 4.5.3.

Table 4.4.2 Chemical measurements of outdoor air supplied to the office and the office air during two exposure situations: without and with carpet inside the office. Concentrations in brackets are the detection limits; they were not measured and are only estimates of the concentration calculated on the basis of relative response factors applied during analysis of sampled air; they were derived in order to estimate I/O-ratio; n.i.-not identified

Compound	Office w/o carpet			Office with carpet		
	Concentration (μg/m³)			Concentration (μg/m³)		
	outdoor air (O)	office air (I)	I/O-ratio	outdoor air (O)	office air (I)	I/O-ratio
decane	*n.i.*	*n.i.*	-	1.55	2.3	1.48
benzene	3.25	8.5	2.62	3.25	7.15	2.2
ethylbenzene	4.05	3.8	0.94	8.4	8.2	0.98
toluene	9.25	10.5	1.14	13	13	1.0
trimethylbenzene	(1.81)	1.25	(0.69)	1.5	1.4	0.93
xylene	9.95	9.9	0.99	24.5	26	1.06
styrene	2.6	2.35	0.90	2.7	2.75	1.02
limonene	(2.0)	5.15	(2.58)	(1.88)	3.05	(1.62)
butylglycol	(4.04)	2.6	(0.64)	(3.80)	3	(0.79)
butyldiglycol	(3.95)	9.1	(2.3)	(3.72)	9.65	(2.60)
phenol	1.9	2.55	1.34	2.85	3.5	1.23
propyleneglycol	(9.65)	41	(4.25)	*n.i.*	*n.i.*	-
texanol	(2.17)	3.2	(1.47)	*n.i.*	*n.i.*	-
acetone	60	75	1.25	135	125	0.93
acetic acid	24.5	39	1.59	29	60.5	2.09
benzoic acid	11	9.4	0.85	19.5	9.9	0.51
hexanoic acid	1.2	2.6	2.17	7.1	1.55	0.22
hexadecanoic acid	*n.i.*	*n.i.*	-	2.85	(1.61)	(0.56)
octanoic acid	(1.74)	3	(1.72)	(1.63)	3.2	(1.96)
nonanoic acid	3.15	3.45	1.1	1.5	3.05	2.03
decanoic acid	1.5	1.45	0.97	1	(1.61)	(1.61)
isopentanal	1.75	(1.60)	(0.92)	1.75	2.5	1.43
hexanal	4.05	5.7	1.41	4.8	6.85	1.43
heptanal	*n.i.*	*n.i.*	-	(2.82)	3.05	(1.08)
octanal	4.65	6.5	1.4	4.25	6.35	1.49
nonanal	14.5	18	1.24	9.75	16	1.64
decanal	9.55	11.5	1.2	6.3	10	1.59
undecanal	(1.74)	1.95	(1.12)	*n.i.*	*n.i.*	-
benzaldehyde	4.95	4.9	0.99	5.75	5.35	0.93
butylacetate	*n.i.*	*n.i.*	-	1.7	(1.87)	(1.10)
butyldiglycolacetate	(1.34)	4.3	(3.22)	(1.26)	5.1	(4.05)
halogenated hydrocarbons	1.8	6.3	3.5	3.2	9.55	2.98
acetophenone	2.8	3.1	1.11	2.8	2.75	0.98
benzamide	*n.i.*	*n.i.*	-	1.75	(1.61)	(0.92)
dibuthylphtalate	*n.i.*	*n.i.*	-	2.4	(1.24)	(0.52)
diethylphtalate	(1.74)	2.7	(1.55)	*n.i.*	*n.i.*	-
isopropylmirystate	*n.i.*	*n.i.*	-	(1.09)	1.15	(1.06)
6-methyl-5-hepten-2-one	(1.74)	2.9	(1.67)	2.15	3.6	1.67
phthalacidanhydride	2.1	1.3	0.62	1.75	(1.61)	(0.92)
siloxane	(1.74)	2.3	(1.32)	*n.i.*	*n.i.*	-
total VOCs	165	195	1.18	220	195	0.89

Table 4.4.3 FLEC measurements of the source strength of carpet unexposed to the office air and the carpet exposed to the office air; compounds not identified in the office air are italicized. Exposed carpet is the carpet used to modify the pollution level in the office, hence being in contact with ozone. Unexposed carpet is the carpet that was wrapped in aluminium foil and was not used in the present experiments; n.i. - compound not identified in the sample

Compound	Source strength ($\mu g/m^2 \cdot h$)		
	not exposed carpet (NEC)	exposed carpet (EC)	EC/NEC-ratio
benzene	1.7	4.25	2.5
ethylbenzene	2.2	*n.i.*	-
toluene	13.5	24.5	18.1
xylene	9.6	*n.i.*	-
limonene	3.3	5.7	1.73
*α-pinene**	*n.i.*	5.0	-
*2-butanol**	*n.i.*	9.2	-
butyldiglycol	*n.i.*	10.4	-
*ethanol**	*n.i.*	9.25	-
*1-ethoxy-2-propanol**	6.2	12.5	2.02
*1-methoxy-2-propanol**	8.3	*n.i.*	-
acetone	12	18	1.5
*2-buten-2-one**	*n.i.*	11.5	-
acetic acid	37	65.5	1.77
benzoic acid	<0.5	1.5	3.0
hexanoic acid	*n.i.*	3.5	-
pentanal	2.4	4.95	2.06
hexanal	12.75	22	1.73
nonanal	2.05	6.1	2.98
decanal	0.8	1.85	2.31
benzaldehyde	4.35	8.2	1.89
*2-hydroxy-benzaldehyde**	*n.i.*	3.6	-
butylacetate	4.2	*n.i.*	-
butyldiglycolacetate	2.85	8.8	3.09
*ethylacetate**	*n.i.*	8.3	-
acetophenone	*n.i.*	3.95	-
*2,2,4,6,6-pentamethylheptane**	7.35	5.3	0.72
*benzothiazol**	*n.i.*	3.8	-
*1,2-propanediol**	30	*n.i.*	-
not identified	9.59	21.5	2.24
total VOCs	11.9	127	10.67

4.4.2 Perceived Air Quality in the Office

4.4.2.1 Visitors' Assessments of the Perceived Quality of Air

As visitors to a space, subjects assessed perceived quality of air inside the office at four exposures: the office without carpet and office with carpet (upon entering the office for the first time) and the office without carpet plus bioeffluents and with carpet plus bioeffluents (upon re-entering the office after leaving it for a short time at the end of the occupation period). Results of air acceptability ratings and calculated perceived quality of air in the office at these four exposures are shown in Table 4.4.4. Perceived quality of air assessed upon entering the office caused 15% dissatisfied in the office without carpet and 22% in the office with carpet; however, this difference was not at a statistically significant level ($p<0.33$). The air in the office without carpet plus bioeffluents caused 25% dissatisfied whereas with carpet plus bioeffluents 68% were dissatisfied; this difference was statistically significant ($p<0.0001$). The perceived quality of outdoor air caused on average 2% dissatisfied. However, on days without carpet in the office it was perceived to be significantly worse ($p<0.03$) than on days with carpet. Hence, when calculating sensory pollution loads inside the office, assessments of perceived quality of outdoor air were not averaged but treated separately for each exposure situation. Perceived quality upon entering the waiting room caused ca. 15% persons to be dissatisfied.

Table 4.4.4 Perceived quality of air measured upon entering the office as a function of absence or presence of carpet in the office with and without bioeffluents

Perception	Office w/o carpet	Office with carpet	t-test*
	Office without bioeffluents		
Acceptability† of air (± sd‡)	0.29 (±0.42)	0.21 (±0.45)	$p<0.33$
Percentage dissatisfied (%)	15	22	
Perceived air quality (decipol)	1.0	1.6	
	Office with bioeffluents		
Acceptability of air (± sd)	0.18 (±0.44)	-0.18 (±0.51)	$p<0.0001$
Percentage dissatisfied (%)	25	68	
Perceived air quality (decipol)	1.9	11.6	

† scale coded: -1=clearly not acceptable; 0=just not acceptable/just acceptable; 1=clearly acceptable; ‡ sd=standard deviation; * office with carpet vs. office w/o carpet;

As seen in the left chart of Fig. 4.4.5, acceptability of air worsened with more pollution sources in the office. The right-hand chart of Fig. 4.4.5 shows that odour intensity and perceived intensity of nose irritation were similarly affected. When bioeffluents were present in the office, the acceptability of air decreased, and consequently the perceived quality of air (i.e., % dissatisfied and decipol) approached significance in the office without carpet ($p<0.08$) and was significant in the office with carpet ($p<0.007$). This, in turn caused sensory pollution loads on the air in the office to increase (Table 4.4.5), since the supplied outdoor air rate was constant.

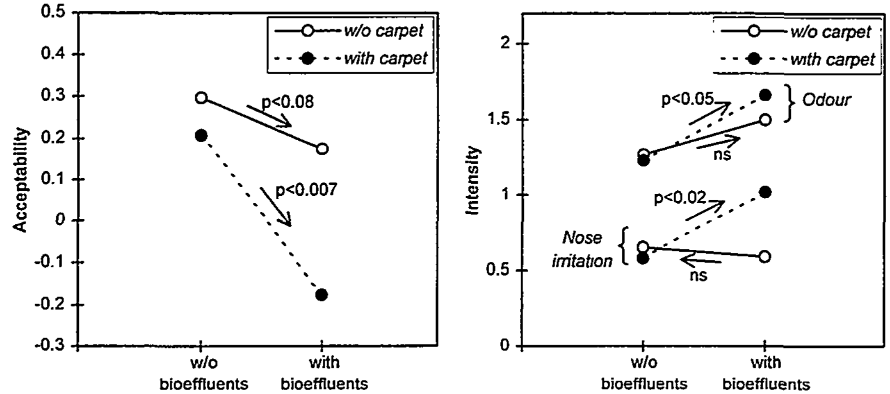


Figure 4.4.5 Change of the perceived acceptability of air (left chart), odour intensity and irritation of nose (right chart) as a function of absence or presence of bioeffluents in the office with and without carpet

4.4.2.2 Sensory Pollution Loads in the Office

Table 4.4.5 reveals that total sensory pollution loads in the office increased when additional pollution sources (carpet or people) were introduced into the office. The presence of carpet inside the office increased the sensory pollution load by 0.11 olf/m^{2}floor, which is equivalent to a source strength of 4 olfs (standard persons). The presence of 6 people inside the office without carpet increased the sensory pollution loads by 0.17 olf/m^{2}floor, which corresponds to 6 extra olfs in a space, and agrees excellently with the predicted sensory pollution load from people (the average person participating in the present experiment was estimated to emit on average 1 olf). In the office with carpet plus bioeffluents, the measured total sensory pollution load was much higher than the sensory pollution load predicted by adding measured sensory pollution load in the office with carpet and predicted sensory pollution load from people. The above discussions indicate that adding sensory pollution loads of individual sources in the office does not overrate measured total sensory pollution load (Fig. 4.4.6).

Table 4.4.5 Sensory pollution loads in the office

	Sensory pollution loads in the office (olf/m^{2}floor)	
	w/o carpet	with carpet
Office w/o bioeffluents	0.14	0.25
Office with bioeffluents	0.31	1.92

It should also be noted that although the floor material in the experimental office was low-polluting polyolefine, the office cannot be classified as a part of a low-polluting building (<0.10 olf/m²floor according to ECA, 1992), most likely due to emissions from six running personal computers inside the office.

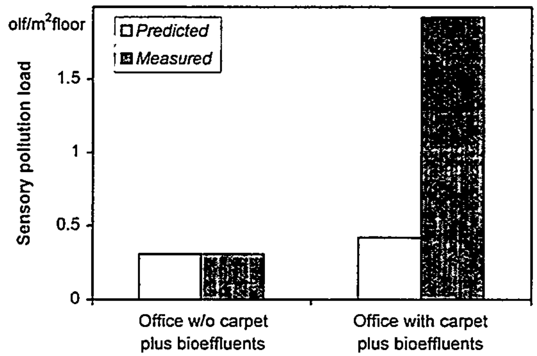


Fig. 4.4.6 Total measured sensory pollution loads in the office without carpet plus bioeffluents and with carpet plus bioeffluents compared with the total sensory pollution load predicted by adding measured sensory pollution loads on the air in the office with and without carpet, and predicted sensory pollution loads from occupants (subjects occupying the office)

4.4.2.3 Occupants' Assessments of the Perceived Air Quality

During occupation of the office with and without carpet, subjects assessed the air quality on 4 occasions: at 45, 125, 215 and 265 minutes after entering the office.

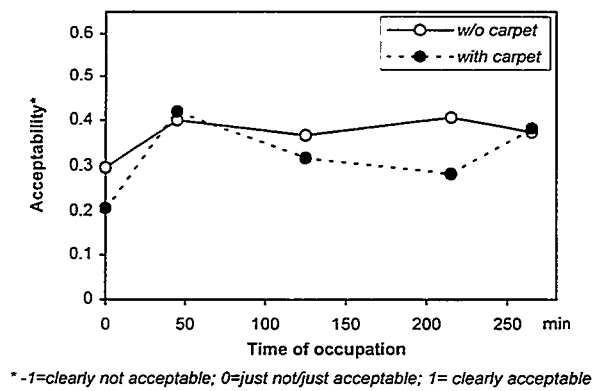


Fig. 4.4.7. Time-course of the perceived acceptability of air during occupation of the office with and without carpet

Sensory evaluations of acceptability of air made during occupation of the office are shown in Fig. 4.4.7. Acceptability of air was generally lower in the office with carpet, but the difference was very modest. Consequently, the percentage of dissatisfied occupants in the office with and without carpet were on average 12% and 10%, respectively. The perceived acceptability of air in the office with carpet fluctuated.

Increased acceptability at minute 45 was possibly due to falling odour intensity (Fig. 4.4.8), as it occurred both in the office with and without carpet. No apparent reason can be given for growing acceptability in the last hour of exposure (between minute 215 and 265) in the office with carpet. Excluding these two assessments, the percentage of dissatisfied with the air quality in the office with carpet increased to 15%, whereas in the office without carpet it remained unchanged at 10%. None of the above-mentioned differences in quality of air perceived by occupants in the office with and without carpet were at a statistically significant level.

Comparing with the assessments of visitors upon entering the office (Table 4.4.4), the assessments of acceptability of air made by occupants were slightly higher. Accordingly, air quality in the office with and without carpet caused on average 5% fewer dissatisfied occupants than visitors. This modest difference may indicate that adaptation to air pollution occurred, but not enough to be statistically significant.

Odour intensity assessed by visitors was significantly higher than that evaluated by occupants (Fig. 4.4.8), as a result of a significant decrease in the odour intensity ($p<0.00001$) during the first 45 minutes of occupation in both the office with and without carpet. This result is in agreement with a well-described mechanism of prompt adaptation to odours (Cain, 1974). In the second half of exposure, minutes 125 to 265, a moderate increase of odour intensity was observed in the office with carpet ($p<0.11$), whereas in the office without carpet it remained unchanged. As a result, odour intensity was higher in the office with carpet after 2 hours of occupation.

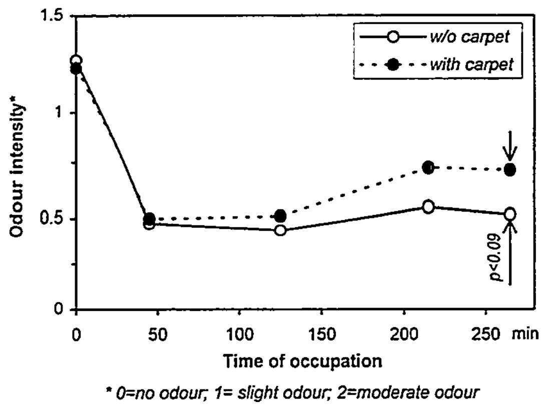


Fig. 4.4.8. Odour intensity as a function of time of occupation of office with and without carpet

The intensity of eye irritation was very low, below slight; however, as shown in Fig. 4.4.9, it was generally higher in the office with carpet. No difference in irritation was seen upon entering the office. In both the office with and without carpet, the intensity of irritation increased ($p<0.02$) during the first half of occupation, up to minute 125, and remained unchanged during the last two hours of occupation.

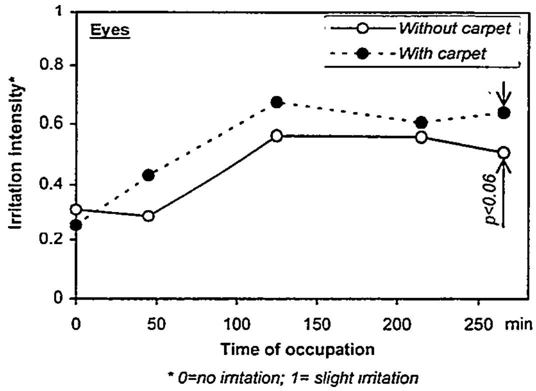


Fig. 4.4.9. Time-course of the perceived intensity of irritation of eyes during occupation of the office with and without carpet

The intensity of irritation of the nose and throat was very low, much below slight irritation. Moreover, it did not differ as assessed by occupants in the office with carpet and without carpet. Nevertheless, nose irritation decreased significantly ($p<0.03$) under both exposures in the office in the beginning of occupation, most likely due to falling odour intensity.

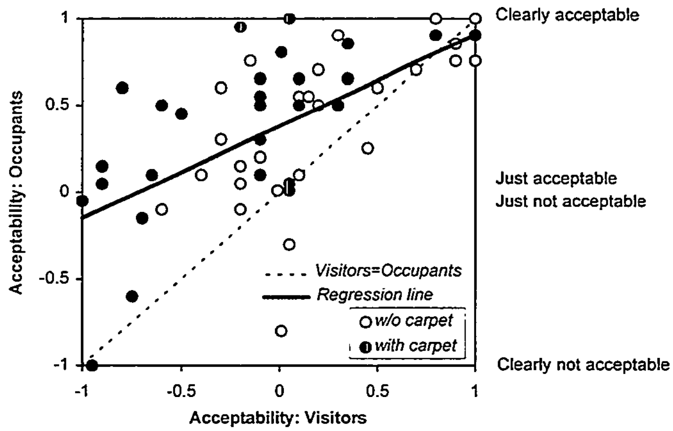


Fig. 4.4.10 Occupants' assessments of acceptability of air polluted by the building plus bioeffluents plotted against visitors' assessments of this air; each point represents sensory evaluation made by one subject. Regression is performed on all sensory assessments made in the office with and without carpet

4.4.2.4 Sensory Ratings of Visitors' vs. Occupants' Assessments

In order to compare the sensory assessments of the perceived quality of air made by visitors to spaces and those made by occupants, acceptability of air evaluated by each subject upon re-entering the office polluted by the building (office with or without carpet) plus bioeffluents were plotted against acceptability of air rated by the same subject at the end of occupation of the office (min 265). The results (Fig. 4.4.10) show a highly significant ($F(1,58)=33.2$, $p<0.0001$) correlation ($r^2=0.36$) between these two assessments. As expected, perceived quality of air is assessed by occupants to be better (higher acceptability).

4.4.3 Perceptions of Indoor Climate and SBS-Symptoms

Preliminary analysis of all results showed that only the perceived level of illumination ($p<0.002$), the severity of headaches ($p<0.025$) and dizziness ($p<0.025$) were significantly different in the office with and without carpet. The time course of these perceptions during occupation of the office is shown in Figs. 4.4.11 to 4.4.13, respectively; results of detailed analysis of these symptoms are summarized in Table 4.4.6. No significant differences in magnitude of all other symptoms or perceptions of the environment were observed between the office with and without carpet.

Table 4.4.6 Significant effects on perceptions and symptoms during occupation of the office with and without carpet

Perception or symptom	Period of occupation	Means in office		Statistical test	Scale description
	(min)	w/o carpet	with carpet	p	
Illumination	45-265	37	43	<0.0006	0 = too dark 100 = too bright
Headache	125-215	75	66	<0.04	0 = severe headache 100 = no headache
Dizziness	0-45	95	90	<0.02	0 = dizzy 100 = not dizzy

Fig 4.4.11 shows that during the whole period of occupation, the subjects regarded the office without carpet as being darker than the office with carpet. This is perhaps a strange result considering that the carpet, when present, was placed behind a screen, and so could not affect the level of illumination at the workstations, and that each workstation was equipped with an individually controlled table lamp that could be, and actually was used by subjects during occupation.

Severity of headaches increased in the office with carpet, especially during periods when people occupying the office were performing simulated office work by adding numbers and processing the text. These two tasks were perhaps more demanding than creative thinking tasks or the performance assessment battery (PAB), since during the period when subjects performed creativity tasks and were exposed to PAB (minute 215-265), alleviation of headache severity was observed in the office with carpet to the level of that in the office without carpet (Fig. 4.4.12). Headache due to polluted air was thus more pronounced during tasks requiring concentration.

Fig. 4.4.13 shows that subjects were more dizzy in the office with carpet only during the first hour of exposure, indicating that this effect was probably not caused by exposure to air pollution inside the office.

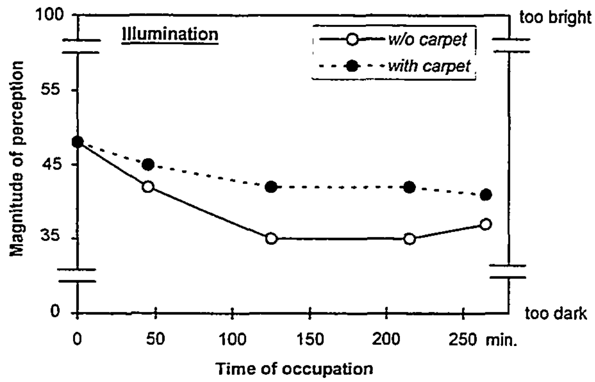


Fig. 4.4.11 Perceived illumination in the office with and without carpet as a function of time of occupation

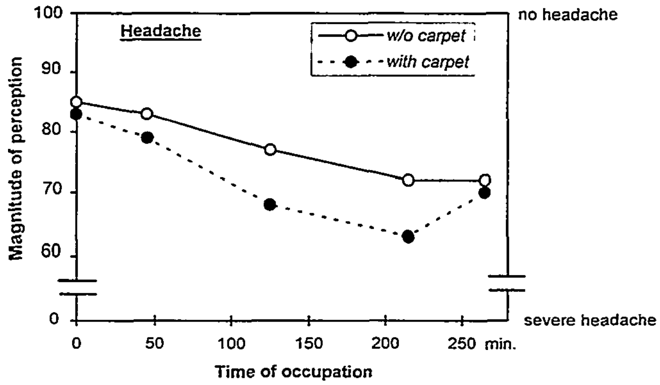


Fig. 4.4.12 Severity of headaches in the office with and without carpet as a function of time of occupation

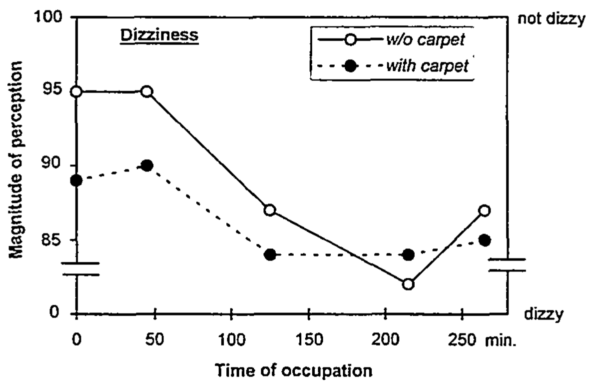


Fig. 4.4.13 Time-course of dizziness during occupation of the office with and without carpet

Table 4.4.7 specifies perceptions and symptoms for which significant change in magnitude was observed with time of occupation in the office with and without carpet. It shows that in the office with carpet, perceived dryness of air increased in the last hour of occupation. Also, in this period, subjects reported increased dryness of nose in the office with carpet. At the same time no change of both sensations of dryness was observed in the office without carpet. The magnitude of most general symptoms (headache, difficulty in thinking clearly), well-being and depression experienced in the office with and without carpet showed significant time trends. The severity of these symptoms built up during occupation, especially in the mid-periods of occupation when subjects were performing simulated office work by adding numbers and typing the text. After this build-up, almost no change in magnitude of these symptoms was observed in the last hour of occupation. The trends observed in the SBS-symptoms - a decrease as an exposure progressed and recovery towards the end of the exposure - can plausibly be attributed either to the work schedule, as was mentioned earlier, or to a fairly trivial mechanism of fatigue, which is counteracted by a positive mood change in anticipation of the end of session. The latter has often been observed previously while testing various types of performance.

Table 4.4.7 Effects of time on perceptions and symptoms in the office with and without carpet

Perception or symptom	Exposure type	Period* during occupation (min)	Effect at the end of the period	Stat. test†
Air dryness	with carpet	from 215 to 265	air more dry	+
Nose dryness	with carpet	from 215 to 265	nose more dry	+
Illumination	w/o carpet	from 0 to 125	} less bright	++
	with carpet	from 0 to 125		+
Headache	w/o carpet	from 45 to 125	} more severe	++
	with carpet	from 45 to 215		++
	with carpet	from 215 to 265	less severe	±
Difficulty to think clearly	w/o carpet	from 0 to 215	} more difficult	++
	with carpet	from 0 to 215		++
Dizziness	w/o carpet	from 45 to 215	} more dizzy	++
	with carpet	from 45 to 215		±
Well-being	w/o carpet	from 0 to 215	} feeling worse	++
	with carpet	from 0 to 215		++
Depression	w/o carpet	from 0 to 265	} more depressed	++
	with carpet	from 0 to 265		++

* period during occupation of the office in which a change was observed in magnitude of sensation with time

† significance of statistical test:: ++ = $p \leq 0.01$; + = $0.01 < p \leq 0.05$; ± = $p \leq 0.10$

4.4.4 Performance

4.4.4.1 Objective Measures of Performance

During occupation of the office, subjects were repeatedly exposed to several performance tasks. These tasks were presented in a completely balanced design with respect to the test version and the exposure condition (Appendix 5) and the results were subsequently used to analyse subjects' performance. As the work schedule effects were confounded with time (see discussion on time trends in section 4.4.3), it was not possible to test the data describing subjects' performance in any way that would discriminate between the two. The results of the analysis for the performance assessment battery, addition task and text typing are summarized in Tables 4.4.8 and 4.4.9 for the learning effects and the effects of exposure respectively. The results of the creative thinking task are presented in Fig. 4.4.20. The way the analysis was carried out is described in section 4.3.7.4. A short description of the observed effects is given in the following, separately for each performance task.

Performance assessment battery (PAB). The tasks from the performance assessment battery (PAB) were administered to subjects in the beginning of exposure (between ca. 5 and 25 min of occupation) and at the end of occupation (between ca. 245 and 265 min of occupation). Consequently, the first completion of PAB under each exposure in the office was considered as a control, with which changes in performance during second completion (at the end of occupation) were compared, considering both changes within exposure due to fatigue, and changes between exposure due to presence or absence of carpet. In addition, a new dependent variable ("modifier") was defined to test the change in performance between successive tests. It was derived for both speed and accuracy at which the tests were performed, by subtracting the performance measure at the start of occupation from the performance measure at the end of occupation separately for each exposure (i.e., the office with and without carpet). The results of performance for each particular task in PAB are summarized in Tables 4.4.8 and 4.4.9. A short description of the findings is given in the following:

1. No learning effects for speed and accuracy were observed for *two-letter search*. Speed was, however, lower in the office with carpet ($p<0.10$). It was consistently lower at the beginning and at the end of exposure; therefore this effect was probably not due to the absence or presence of carpet inside the office. This is confirmed by the results on accuracy, which show modestly higher accuracy in the office without carpet at the beginning of exposure ($p<0.10$) but no difference at the end of occupation. The changes of speed and accuracy (defined by the variable "modifier") in the office without carpet were not significantly different from those in the office with carpet.

2. A significant learning effect was observed for *column addition*: in the beginning of the second day of exposure subjects were adding quicker compared to adding speed in the beginning of the first day of exposure ($p<0.08$). While occupying the

office without carpet, subjects completed this task significantly quicker at the end of occupation as compared with the speed at the beginning of occupation ($p<0.02$). No such improvement in performance was observed while they occupied the office with carpet. The changes of speed and accuracy (defined by the variable "modifier") in the office without carpet were not significantly different from those in the office with carpet.

3. Similar effects to those observed for column addition were also observed for *logical reasoning*. The speed of executing this task was significantly affected by learning ($p<0.05$); however, as regards the type exposure, a significant increase in speed was observed only while subjects occupied the office without carpet ($p<0.006$). No change in speed from the beginning to the end of occupation was seen in the office with carpet. The number of correctly completed trials by subjects fell during occupation of the office with carpet whereas it remained unchanged in the office without carpet. The effect on accuracy could, however, be due to strong fatigue ($p<0.007$) observed when subjects performed this task while occupying the office for the second time (see Table 4.4.8). Increase of speed (defined by the variable "modifier") in the office without carpet was moderately higher ($p<0.08$) than the increase observed in the office with carpet (Fig. 4.4.14). This result may indicate a worse performance in the office with carpet. However, no such effect was observed as regards the change of accuracy, also defined by the variable "modifier".

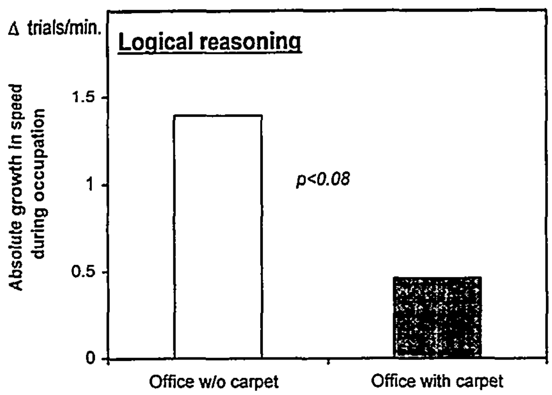


Fig. 4.4.14 Comparison of absolute growth in speed (number of trials taken per minute) of performing the logical reasoning task from the beginning to the end of occupation in the office without and with carpet

4. Generally, no effects on speed could be observed for *serial addition*. Although increase in speed was shown, it occurred both in the office without ($p<0.10$) and with ($p<0.08$) carpet. Some effects could nevertheless be shown on accuracy for which no learning took place. Even though subjects added more accurately at the beginning of occupation in the office with carpet ($p<0.03$), the percent of correctly

added numbers fell during occupation of this office and this effect approached significance ($p<0.06$). Consequently, the change of accuracy defined by the variable "modifier" was lower ($p<0.06$) in the office with carpet (accuracy decreased) as compared to the office without carpet (Fig 4.4.15). At the same time, the number of correctly completed additions remained at the same level in the office without carpet. This result may indicate decreased performance in the office with carpet. The change of speed (defined by the variable "modifier") in the office without carpet was not significantly different from that in the office with carpet.

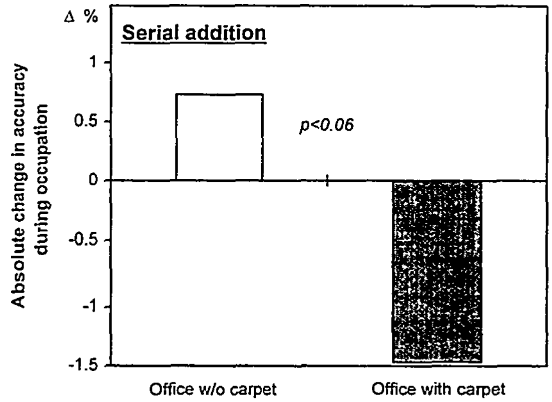


Fig. 4.4.15 Comparison of absolute change in accuracy (% correctly added numbers) of performing the serial addition task from the beginning to the end of occupation in the office without and with carpet

5. The effects on performance of *stroop* were analysed separately for all trials, neutral trials (no perceptual/linguistic interference) and incongruent trials (with linguistic/perceptual interference). Only speed was affected. During occupation of the office without carpet, the speed of completing all trials increased significantly ($p<0.002$). Although no difference in speed was observed at the beginning of occupation in the office with and without carpet, at the end of occupation, the speed of completing all trials was higher ($p<0.04$) in the office without carpet (Fig. 4.4.16). Consequently, increase of speed defined by the variable "modifier" was lower ($p<0.10$) in the office with carpet as compared to the office without carpet. Learning effect on speed occurred only during the second day of exposure ($p<0.04$). The effects observed for all trials were probably due to effects on neutral trials for which similar effects to those described above were observed, while on the contrary, almost no effects were seen on incongruent trials.

6. Speed of completing the *running memory* test increased significantly during occupation of both office without carpet ($p<0.0003$) and office with carpet ($p<0.06$). These two effects were probably the result of a learning effect ($p<0.0005$) and not due to exposure. The changes of speed and accuracy (defined by the variable "modifier") in the office without carpet were not significantly different from those

in the office with carpet.

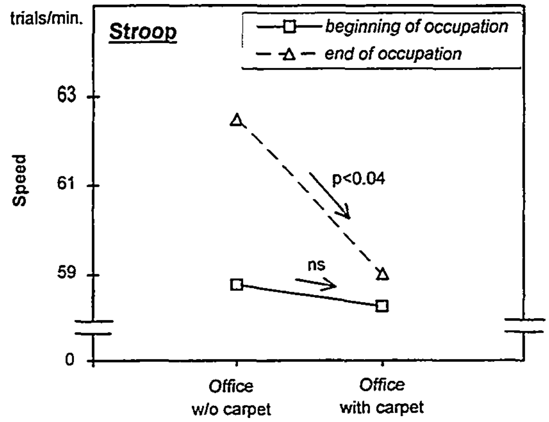


Fig. 4.4.16 Speed of performing the stroop task (number of trials taken per minute) in the beginning and the end of occupation as a function of presence or absence of carpet in the office

7. No effects were observed for the *six-letter search.* The change of speed and accuracy (defined by the variable "modifier") in the office without carpet were not significantly different from those in the office with carpet.

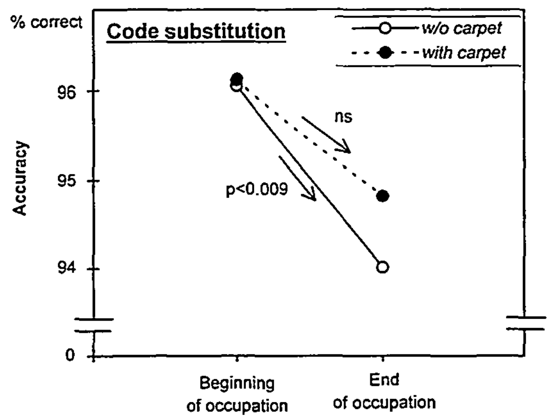


Fig. 4.4.17 Accuracy of performing the code substitution task (% correctly matched letter-digit pairs) in the office with and without carpet as a function of time of occupation

8. Generally, no relevant effects on speed were observed for *code substitution.* A moderately higher speed in the beginning of occupation in the office with carpet ($p<0.06$) remained higher, but not significantly, also at the end of occupation. It was thus not affected by the type of exposure. As regards accuracy, it decreased significantly during occupation of the office without carpet ($p<0.009$), whereas decrease of accuracy in the office with carpet did not approach significance (Fig. 4.4.17). This effect is opposite to that observed for other performance tasks. The

changes of speed and accuracy (defined by the variable "modifier") in the office without carpet were, however, not significantly different from those in the office with carpet.

Table 4.4.8 Results of performance tests describing ***learning effects*** *on speed and accuracy at which particular tasks were completed by subjects (see section 4.3.7.4 for further explanations on the way the analysis was carried out). Direction of change in performance is shown only for significant effects*

Performance tasks	Speed				Accuracy			
	within days[†] try-2 (wrt try-1)		between days day-2 (wrt day-1)		within days[†] try-2 (wrt try-1)		between days day-2 (wrt day-1)	
	day-1	day-2	try-1	try-2	day-1	day-2	try-1	try-2
PAB tasks:								
Two-letter search	-	-	-	-	-	-	-	-
Column addition	-	-	± (⇧)	-	-	-	-	-
Logical reasoning	± (↑)	± (↑)	-	-	-	++ (↓)	-	-
Serial addition	-	+ (↑)	-	-	-	-	-	-
Stroop:								
all trials	-	+ (↑)	-	-	-	-	-	-
neutral trials	-	± (↑)	-	-	-	-	-	-
incongruent trials	± (↑)	-	-	-	-	-	-	-
Running memory	++ (↑)	+ (↑)	-	-	-	-	-	-
Six-letter search	-	-	-	-	-	-	-	-
Code substitution	-	+ (↓)	-	-	+ (↓)	-	-	-
Addition task	++ (↑)	++ (↑)	± (⇧)	± (⇧)	-	-	+ (⇧)	-
Text typing	-	-	-	-	± (↓)	± (↓)	-	-

Legend: ++ = p≤0.01; + = 0.01<p≤0.05; ± = p≤0.10; - = not significant (p>0.10);
(↑) = higher in try-2 than in try-1; (↓) = lower in try-2 than in try-1;
(⇧) = higher in day-2 than in day-1; (⇩) = lower in day-2 than in day-1; [†]wrt = with reference to;
try-1 took place: for PAB tasks between ca. 5 and 25 min of occupation, for addition task between ca. 50 and 80 min of occupation and for typing text between ca. 80 and 125 min of occupation;
try-2 took place: for PAB tasks between ca. 245 and 265 min of occupation, for addition task between 190 and 215 min of occupation and for text typing between 140 and 190 min of occupation.

Table 4.4.9 Results of performance tests describing effects of exposure (office with carpet vs. office without carpet) on speed and accuracy at which subjects performed particular tasks (see section 4.3.7.4 for further explanations on the way the analysis was carried out). Direction of change in performance is shown only for significant effects

Performance tasks	Speed				Accuracy			
	within exposures† try-2 (wrt try-1)		between exposures with carpet (wrt w/o carpet)		within exposures† try-2 (wrt try-1)		between exposures with carpet (wrt w/o carpet)	
	w/o carpet	with carpet	try-1	try-2	w/o carpet	with carpet	try-1	try-2
PAB tasks:								
Two-letter search	-	-	± (⇩)	± (⇩)	-	-	± (⇩)	-
Column addition	+ (↑)	-	-	-	-	-	-	-
Logical reasoning	++ (↑)	-	-	-	-	+ (↓)	-	-
Serial addition	± (↑)	± (↑)	-	-	-	± (↓)	+ (⇧)	-
Stroop:								
all trials	++ (↑)	-	-	+ (⇩)	-	-	-	-
neutral trials	++ (↑)	-	-	+ (⇩)	-	-	-	-
incongruent trials	± (↑)	-	-	-	-	-	-	-
Running memory	++ (↑)	± (↑)	-	-	-	-	-	-
Six letter search	-	-	-	-	-	-	-	-
Code substitution	-	-	± (⇧)	-	++ (↓)	-	-	-
Addition task	++ (↑)	++ (↑)	-	-	-	-	-	-
Text typing	-	-	++ (⇩)	+ (⇩)	-	+ (↓)	-	± (⇩)

Legend: ++ = p≤0.01; + = 0.01<p≤0.05; ± = p≤0.10; - = not significant (p>0.10);
(↑) = higher in try-2 than in try-1; (↓) = lower in try-2 than in try-1;
(⇧) = higher in the office with carpet than in the office w/o carpet; (⇩) = lower in the office with carpet than in the office w/o carpet; † wrt = with reference to;
try-1 took place: for PAB tasks between ca. 5 and 25 min of occupation, for addition task between ca. 50 and 80 min of occupation and for typing text between ca. 80 and 125 min of occupation;
try-2 took place: for PAB tasks between ca. 245 and 265 min of occupation, for addition task between 190 and 215 min of occupation and for text typing between 140 and 190 min of occupation.

Addition task. Addition tasks were given to subjects twice during occupation, ca. 45 min and ca. 190 min after entering the office. On both occasions, subjects had exactly 25 min to complete each task. As shown in Table 4.4.8, there were significant learning effects on speed ($p<0.00001$), i.e., the rate of completed units increased during experiment. These effects were significant both during exposure days and between exposure days. As a result of learning, the total number of units added by subjects increased during occupation of the office with carpet ($p<0.01$) and without carpet ($p<0.008$). Similar learning effects were observed for column addition in PAB. Additional analysis was made to study whether absolute growth in speed was different as regards the office with and without carpet; absolute growth was calculated separately for each exposure in the office by subtracting the number of units added during the first and the second presentation of a task (as it was done while defining the variable "modifier" in the case of PAB). The results shown in Fig. 4.4.18 indicate that speed growth was significantly lower in the office with carpet ($p<0.05$), which may indicate decreased performance under this type of exposure. Accuracy of adding numbers was generally not affected (Table 4.4.9).

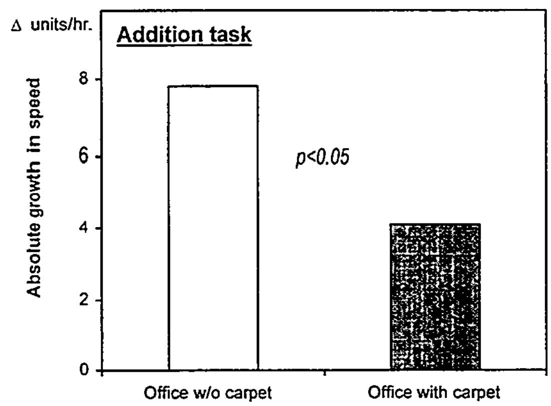


Fig. 4.4.18 Comparison of absolute change in number of units completed per hour while performing an addition task for the first and the second time in the office with and without carpet

Text typing. Subjects began to type text on a PC after ca. 78 and ca. 140 minutes of occupation. On both occasions they typed exactly for 47 minutes. Strong effects on typing speed were observed, depending on type of exposure: subjects typed fewer characters per minute when occupying the office with carpet as compared to the office without carpet (Table 4.4.9). This effect was significant ($p<0.003$) and occurred repeatedly when subjects typed text for the first and the second time during occupation of the office (Fig. 4.4.19). At the same time, there was no learning effect on typing speed (Table 4.4.8). In addition (Table 4.4.9), accuracy of typing decreased significantly ($p<0.03$) during occupation of the office with carpet ($p<0.03$). As a result, the total number of typing errors made by subjects increased ($p<0.10$) in the office with carpet, as compared to the office without carpet. This effect could, however, be due to the fact that the number of typing errors generally increased during occupation of the office for the first ($p<0.09$) and the second ($p<0.07$) time, independent of exposure (see Table 4.4.8).

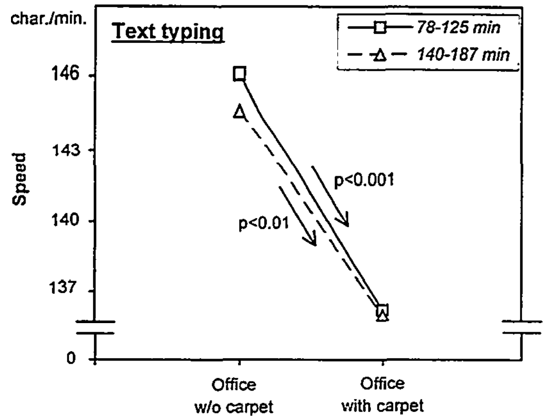


Fig. 4.4.19 Speed of typing during first (78-125 min) and second (140-187 min) presentation of the text typing task to subjects, as a function of presence or absence of carpet in the office. Subjects typed 6.5% fewer characters in the office with carpet than in the office without carpet

It was observed that the versions of texts presented to subjects for typing may have differed in difficulty ($p<0.10$): subjects typed version one of the text quicker than all remaining 3 versions. Additional analysis was therefore carried out to examine whether excluding version one of the text would change the observed tendency of decreased performance in the office with carpet. This analysis showed that both during the first and the second period of text typing, subjects typed fewer characters in the office with carpet ($p<0.10$ and $p<0.06$, respectively). It should be emphasized, however, that this analysis is much weaker than analyses with all results for the whole group of n=30 subjects, since it was performed with the total number of observations of typing speed reduced to half, i.e., from only n=15 subjects.

<u>Creative thinking task.</u> Crude adjustments were made to the names given by the subjects. Obviously nonexistent names, repeats, names created by joining two names, e.g., Annemarie, or non Danish names were excluded, whereas wrongly spelled names were classified into one group. Next, Normal C-Scores were calculated according to the methodology described in Section 4.3.7.4. They are called Crude Normal C-Scores since acceptance of names provided by the subjects was not restricted to those which were correctly identified as male or female names by >95% of the equivalent group selected at random from the same underlying population of potential subjects. This analysis will be performed later.

Although intended to produce a similar number of answers, the versions differed significantly from each other ($p<0.00001$). Two versions of the task with male names produced approximately a similar number of names: 41 (E=39 and Ø=2) and 44 (S=39 and U=5), respectively, and they were not statistically different from each other. In the versions with female names, discrepancy was large: 65 names (A=59 and U=6) vs. 83 names (J=50 and N=33). It was therefore decided to carry out a separate analysis for all 4 versions of the task and for the versions with the male names only. In addition, statistical analysis of the results was carried out only for the difference in Crude Normal C-Scores obtained by the subjects in the office with and without carpet separately in the beginning and in the end of occupation. The analysis of fatigue occurring during occupation (i.e., testing of the change in Crude Normal C-Score during occupation of either the office with or without carpet) was not carried out. Due to an observed discrepancy between versions of creative thinking tasks and randomization (versions with female names presented close to the beginning of occupation and with male names close to the end of occupation, or vice versa, see Appendix 5), it was felt that this analysis would produce unreliable results.

Fig. 4.4.20 shows that subjects' creativity was not affected by exposure to the pollutants from the carpet. The left chart of Fig. 4.4.20 may indicate that in the office with carpet, at the end of occupation, subjects could be more fatigued and thus less creative. But this effect could also be a consequence of the above-mentioned discrepancy between the versions of the task. The right chart of Fig 4.4.20 shows that for 2 versions of the task with male names, higher Normal Crude C-Scores were obtained in the office with carpet; this analysis is less strong, however, than for all versions of the task, since it was carried out on half the total number of answers given by the subjects. None of the effects presented in Fig. 4.4.20 were at statistically significant level (p>0.20).

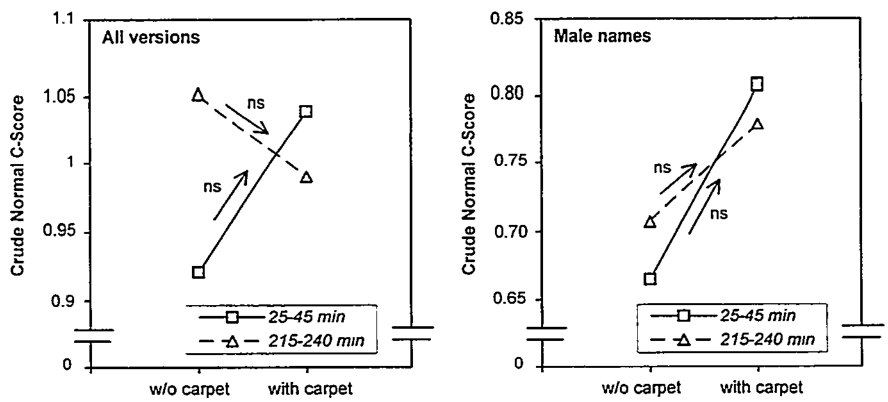


Fig. 4.4.20 Crude Normal C-Scores obtained by subjects in the office with and without carpet for the first (ca. 20-45 min of occupation) and the second (ca. 215-240 min of occupation) presentation of the creative thinking task; a higher C-Score means higher creativity. In the left chart the results from all 4 versions of the creative thinking task are presented whereas the right chart shows the results from 2 versions with male names

4.4.4.2 Self-Estimates of Performance

Statistical analysis showed that among 4 symptoms relevant to performance - fatigue, concentration, arousal and effort - only effort required to complete performance tasks was significantly different in the office with and without carpet ($p<0.04$). A detailed analysis showed that subjects required less effort to complete tasks in the office with carpet (Fig. 4.4.21), especially between 45 and 215 minutes of occupation ($p<0.02$), i.e. at the time they performed simulated office work. In this period, subjects' performance on the text typing task was significantly affected ($p<0.003$) in the office with carpet. These results indicate that subjects performed less well in the office with carpet because they exerted less effort.

A change of reported self-performance with time of occupation is studied in Table 4.4.10. Self-estimated effort in the office with and without carpet increased moderately but generally only to the moment when subjects finished performing simulated office work (minute 215). Subjects felt more fatigued and more sleepy at the end of occupation under both exposures in the office. Difficulty in concentrating changed with time generally only during periods when subjects performed simulated office work. In the last hour of exposure, difficulty in concentrating decreased only modestly in the office with carpet, whereas in the office without carpet, subjects reported that it was easier to concentrate at the end of exposure (min 265) than just after the period when they performed simulated office work (min 215). This could indicate that creative thinking tasks and PAB were easier to complete than addition and text typing.

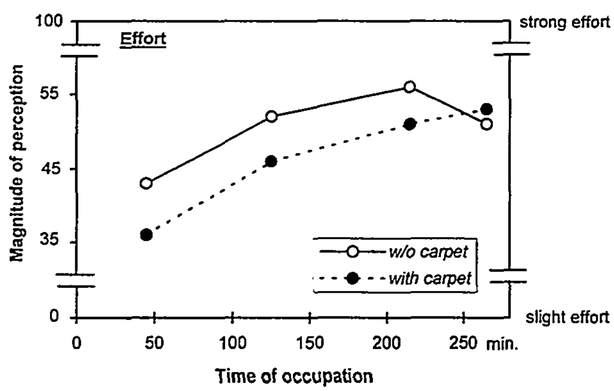


Fig. 4.4.21 Self-estimated effort required to complete performance tasks in the office with and without carpet as a function of time of occupation

Table 4.4.10 Effect of time on descriptors of self-performance in the office with and without carpet

Perception or symptom	Exposure type	Period* during occupation (min)	Effect at the end of the period	Stat. test†
Fatigue	w/o carpet	from 0 to 265	} more tired	++
	with carpet	from 0 to 265		++
Concentration	w/o carpet	from 0 to 215	} more difficult to concentrate	++
	with carpet	from 0 to 215		++
Arousal	w/o carpet	from 0 to 265	} more sleepy	++
	with carpet	from 0 to 265		++
Effort	w/o carpet	from 45 to 215	} more effort	+
	with carpet	from 45 to 265		++

* period during occupation of the office in which a change was observed in magnitude of sensation with time; † significance of statistical test:: ++ = $p \leq 0.01$; + = $0.01 < p \leq 0.05$

4.4.5 Influence of Personal Characteristics on SBS-Symptoms, Perceptions, Self-Performance and Perceived Air Quality

Epidemiological studies indicate that personal factors are important when SBS-symptoms are evaluated (Mendell, 1993). Consequently, it was examined whether any relations can be observed in the present experiments between personal characteristics of subjects and reported symptoms and perceptions. Using personal data from the questionnaire completed during recruitment (see section 4.3.3), subjects were divided into three groups:

1. subjects considering themselves as more sensitive to poor air quality (n=11 subjects);
2. subjects with SBS-history, i.e., subjects having at least one either mucous membrane or cutaneous or general symptom occurring at least twice per month during 12 months prior to the experiment (n=23 subjects);
3. subjects often experiencing dry air at home or at work and subjects reporting that their skin is easily burned or eczematized by sunlight (n=14 subjects).

Grouping of subjects under items 2 and 3 was suggested as it was used previously in other SBS studies (Mølhave et al., 1986; Sundell, 1994, respectively).

A separate analysis was carried out on subjective ratings of perceptions of indoor climate, SBS-symptoms and self-performance (VAS scales presented in Fig. 4.3.3) for each of the above three groups of subjects. Additionally, for people considering themselves as more sensitive to poor air quality, analysis was made on subjective assessments of the perceived quality of air (scale presented in Fig. 4.3.2). The above-mentioned analyses were performed on particularly sensitive subjects who, because they were "blinded", could have no preconception of how they would respond in any given exposure. The results of the analyses are presented in the following.

4.4.5.1 Subjects Sensitive to Poor Air Quality

The analysis of the subjective assessments of people sensitive to poor air quality - "sensitive" subjects (n=11), showed significant differences between the office with and without carpet for the following SBS-symptoms, perceptions and estimates of self-performance: air stuffiness ($p<0.02$), aching eyes ($p<0.07$), headache ($p<0.10$) and fatigue ($p<0.06$). All significant effects were in the expected direction, and, except for headache, were not observed in the counterpart group of subjects considering themselves as not especially sensitive to poor air quality (n=19).

Table 4.4.11 Significant effects on perceptions, symptoms and self-performance during occupation of the office with and without carpet for people considering themselves as sensitive to poor air quality - "sensitive" subjects (n=11)

Subjective rating	Period of occupation (min)	Means in office		Statistical test	Scale description
		w/o carpet	with carpet	p	
Stuffy air	0-265	38	28	<0.02	0 = stuffy 100 = fresh
Dry eyes	215-265	68	54	<0.06	0 = dry 100 = not dry
Aching eyes	0-265	76	61	<0.07	0 = aching 100 = not aching
Headache	125-215	59	42	<0.10	0 = severe 100 = no
Difficult to think clearly	265	49	36	<0.06	0 = difficult 100 = easy
Fatigue	215-265	58	35	<0.06	0 = tired 100 = rested
Difficult to concentrate	265	81	72	<0.09	0 = difficult 100 = easy

Detailed results are shown in Table 4.4.11. Similar to the effects for the whole group of subjects, "sensitive" people reported more headaches in the office with carpet. Additionally, they reported increased difficulty in thinking clearly and difficulty to concentrate in the office with carpet in the last hour of occupation; similar effects were observed also for the whole group, but they did not reach significance. Although "sensitive" subjects reported that their eyes were aching more in the office with carpet, this effect may not be due to air pollution in the office since their eyes ached also more in the beginning of occupation. The air in the office with carpet was assessed as being more stuffy and it caused increased dryness of eyes for "sensitive" subjects. "Sensitive" subjects reported also increased dryness of air, nose and throat in the office with carpet. These effects did not, however, reach significance. As shown in Fig. 4.4.22, dryness of mucous membranes (eyes, nose, throat) and the perception of dry air increased progressively during occupation of office with carpet as assessed by "sensitive" people, but not by all subjects participating in the present experiment.

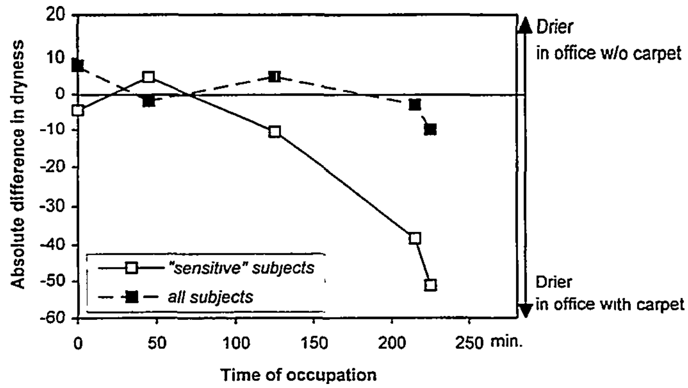


Fig. 4.4.22 Absolute difference in dryness of air, nose, throat and eyes between the office with and without carpet as a function of time of occupation for people considering themselves as more sensitive to poor air quality ("sensitive" subjects) and for all subjects participating in the experiment

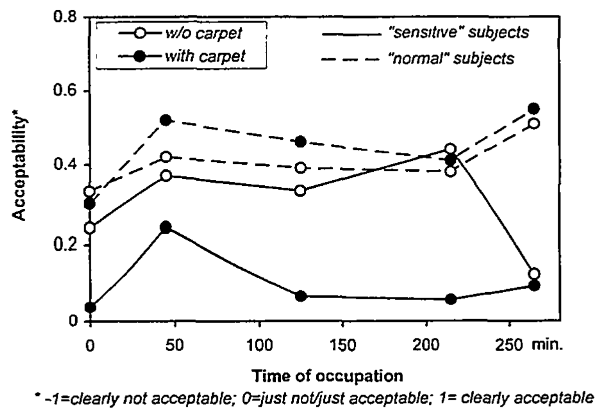


Fig. 4.4.23 Acceptability of air assessed by subjects considering themselves as sensitive to poor air quality ("sensitive" subjects) and those who did not regard themselves as being so ("normal" subjects) as a function of time of occupation of office with and without carpet

It was also studied whether the perceived quality of air (assessed in terms of air acceptability), odour intensity and irritation of eyes, nose and throat differed when assessed by "sensitive" subjects and by subjects who did not regard themselves as being sensitive to poor air quality - "normal" subjects, both on entering the office and during occupation. The results of acceptability ratings (Fig. 4.4.23) show that "normal" subjects did not differentiate the office with and without carpet: under both conditions ca. 15% persons were dissatisfied with the perceived air quality. "Sensitive" subjects assessed the air in the office without carpet to be slightly worse as ca. 20% was dissatisfied. The air quality in the office with carpet was rated by "sensitive" subjects to be significantly worse ($p<0.00001$) than in the office without carpet and it caused ca. 40% dissatisfied. As shown in Fig. 4.4.24, "sensitive" subjects reported higher irritation of eyes compared to "normal" subjects. Intensity of nose and throat irritation, as well as the odour intensity tended to be marginally higher for "sensitive" subjects.

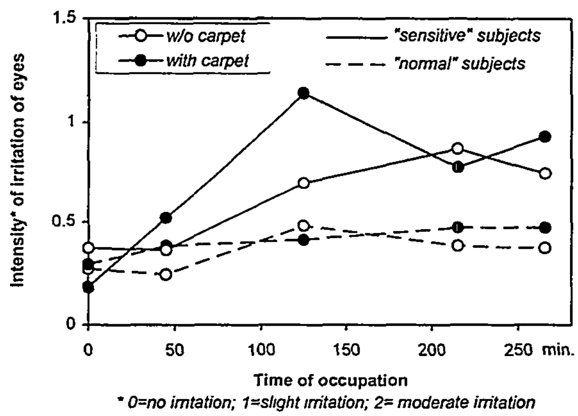


Fig. 4.4.24 Intensity of irritation of eyes evaluated by subjects considering themselves as sensitive to poor air quality ("sensitive" subjects) and those who did not regard themselves as being so ("normal" subjects) as a function of time of occupation of office with and without carpet

4.4.5.2 Subjects with a History of SBS-Symptoms

Analysis of the subjective assessments of people with SBS-history (n=23) showed significant differences between the office with and without carpet for the following SBS-symptoms, perceptions and estimates of self-performance: dizziness ($p<0.006$), headache ($p<0.02$) and illumination ($p<0.04$). All significant effects were in the expected direction, and, except for self-estimated effort required to complete performance tasks, they were not observed in the group of subjects without SBS-history (n=7).

Detailed analysis (Table 4.4.12) showed that after 2 hours of occupation, subjects with SBS-history assessed the air in the office with carpet to be more stuffy. As regards other effects for these subjects, they were similar to those observed for the whole group (section 4.4.3), perhaps due to fact that almost all subjects (23 out of 30) had SBS-history.

Table 4.4.12 Significant effects on perceptions, symptoms and self-performance during occupation of the office with and without carpet for people with SBS-history (n=23)

Subjective rating	Period of occupation (min)	Means in office		Statistical test p	Scale description
		w/o carpet	with carpet		
Stuffy air	125-265	39	33	<0.09	0 = stuffy 100 = fresh
Illumination	45-265	36	40	<0.01	0 = too dark 100 = too bright
Headache	125-215	71	58	<0.009	0 = severe 100 = no
Dizziness	0-265	89	83	<0.006	0 = dizzy 100 = not
Effort	45-125	53	46	<0.07	0 = slight 100 = strong

4.4.5.3 Subjects Complaining of Dry Air and Having Sensitive Skin

Analysis of the subjective assessments of people complaining often of dry air at home or at work and people with skin sensitive to sunlight (n=14) showed significant differences between effects in the office with and without carpet for the following SBS-symptoms, perceptions and estimates of self-performance: cleanliness of office ($p<0.09$), aching eyes ($p<0.05$), headache ($p<0.03$) and effort ($p<0.06$). All significant effects were in the expected direction and they were not observed for subjects not in the above category (n=16). In addition, detailed analysis in Table 4.4.13 showed that subjects with sensitive skin and experiencing dry air assessed the air in the office with carpet to be more stuffy.

Table 4.4.13 Significant effects on perceptions, symptoms and self-performance during occupation of the office with and without carpet for subjects experiencing often dry air at home or at work and those reporting that their skin is sensitive to sunlight (n=14)

Subjective rating	Period of occupation (min)	Means in office		Statistical test p	Scale description
		w/o carpet	with carpet		
Office cleanliness	215-265	75	70	<0.04	0 = dirty 100 = clean
Air stuffy	45-265	45	34	<0.04	0 = stuffy 100 = fresh
Aching eyes	0-265	79	70	<0.05	0 = aching 100 = not aching
Headache	125-215	74	58	<0.03	0 = severe 100 = no
Effort	45-215	53	45	<0.04	0 = slight 100 = strong

4.5 Discussion

The main hypothesis of the present study was that due to elevated pollution load on the air in the office with carpet, the perceived quality of air would decrease, the prevalence of health symptoms - referred to as Sick Building Syndrome (SBS) symptoms - would increase, and that consequently the productivity of people occupying the office would fall. The results of the experiments indicate that this hypothesis was correct. The office with carpet caused a greater number of people who were dissatisfied with the perceived air quality and an increased severity of headaches among subjects who occupied this office. Subjects in the office with carpet were less inclined to exert effort. This is probably the reason why the occupants in the office with carpet typed less text.

These results were obtained in a real office with windows and access to daylight. Impartial subjects occupied this office for 4.4 hours and performed simulated office work including typing text, adding numbers and performing a creative thinking task, all tasks being typically performed in normal offices. They also took a battery of psychological tests. Female subjects were selected as they constitute an important risk group in indoor climate field studies, consistently reporting more SBS-symptoms than men (Skov et al., 1989; Mendell, 1993; Stenberg and Wall, 1993; Sundell, 1994; Groes et al., 1996). The air pollution level in the occupied office was changed by placing or removing the carpet. At the same time, all other parameters of indoor climate in the office, including air temperature, relative humidity, air velocity, noise level and ventilation rate, had similar levels whether the carpet was present or not. Subjects remained blind to the intervention so their expectations did not influence the observed effects.

4.5.1 Effects of Pollution Sources on the Perceived Air Quality and Ventilation Demand

The perceived quality of air as assessed upon entering the unoccupied office complied with present ventilation standards (ASHRAE, 1989). In the office without carpet it caused 15% to be dissatisfied, while 22% were dissatisfied when the carpet was present. According to the proposed European prestandard "Ventilation for Buildings: Design Criteria for the Indoor Environment" (prENV 1752, 1997), the quality of air in the office without carpet met criteria of category A, while in the office with carpet the criteria of category B were not met. The perceived air quality in the office was quite good and not as unrealistically poor as e.g., in the experiments with volatile organic compounds (VOCs) where the subjects were exposed to total concentrations of VOCs as high as 25 mg/m^3 (Mølhave et al., 1986; Otto et al., 1993), which actually rarely occur in non-industrial environments (Brown et al., 1994; Wolkoff, 1995; Chapter 3 of the present thesis). Perceived air quality assessed by visitors in the office with carpet was only slightly worse than in the office without carpet. But this difference was consistent, causing more dissatisfied occupants, higher odour intensity and eye irritation in the office with carpet.

Good air quality in the office was maintained by an airflow rate of 10 L/s per person (or 1.7 L/s per m^2floor), and was thus equal to or slightly higher than the airflow rates recommended by the above-mentioned standards. However, this flow rate of outdoor air was only sufficient to handle sensory pollutants emitted by building materials in the office. In the presence of occupants, the perceived quality of air decreased significantly and caused 25% to be dissatisfied upon entering the office without carpet but with bioeffluents, while 68% were dissatisfied upon entering the office with carpet and bioeffluents. Concurrently with the reduced perceived air quality in the office with bioeffluents, the intensity of odour and irritation of the nose also increased significantly. Decreased perceived air quality in the office with bioeffluents as compared to the office without bioeffluents was partially due to a 1°C higher air temperature (Fang et al., 1998a, 1998b; Toftum et al., 1998). But this effect accounts only for ca. 20-25% of the observed change, implying that worsening of the air quality was mainly due to the presence of and additional pollution source (bioeffluents) in the space. To raise the perceived air quality evaluated upon entering the office with bioeffluents to the level that was assessed by the subjects upon entering the office without bioeffluents, the ventilation rate would have to be doubled in the office without carpet plus bioeffluents and increased by ca. 10 times in the office with carpet plus bioeffluents. These results suggest that adding ventilation rates required to handle separately each of the pollution sources in a space can be a reasonably good solution to maintain the perceived air quality at the required level. They confirm the results obtained in previous field experiments on addition of sensory pollution sources in spaces, where the perceived air quality caused less than 25% persons to be dissatisfied. These experiments were performed while the prevailing air quality was rather poor (Wargocki. et al., 1996a; Chapter 2 of the present thesis)

Detailed analysis of results indicated that mainly people regarding themselves as more sensitive to poor air quality (self-reported sensitivity) assessed the air quality in the office with carpet to be worse. These persons constituted 1/3 of the whole group and apparently demonstrated a higher sensitivity to the air they were breathing. Other subjects did not assess the quality of air in the office with carpet to be worse as compared to that in the office without carpet. This difference suggests that the airflow rates calculated, based on the average perceived air quality in the office evaluated by the whole group, may not be high enough to satisfy the most sensitive individuals. In order to improve the air quality in the office with carpet and reach a percentage of dissatisfied comparable to the level in the office without carpet, sensitive people would require ca. twice as much ventilation as other people occupying the office. Consequently, if the ventilation rates were designed for sensitive persons, extra costs would be incurred. This may be avoided by using individually controlled workstations where each person can adjust the airflow rate according to her/his needs. The expenses required for conditioning and supplying ventilation air can further be diminished by reducing the pollution load on the indoor air, instead of increasing the ventilation rates. This issue will be addressed later.

Just as for visitors, the perceived quality of air in the office with carpet was also assessed by occupants to be worse when compared to the air quality in the office without carpet. However, the perceived air quality assessed by occupants and expressed in the decipol unit (Fanger, 1988) was only about 60% of that assessed by visitors, implying that occupants of the office with and without carpet would need only 60% of the airflow rate required for the visitors to these offices. Similar effects, although greater in magnitude, were observed in the laboratory experiments of Gunnarsen (1990). During exposures to the pollutants emitted from carpets, the adapted ratings of the air quality made by a trained panel of subjects were nearly half the initial ("first exposure") values. Improvement of the perceived air quality as assessed by occupants in the present study was probably due to moderate adaptation to the pollutants emitted from building materials. This adaptation occurred mainly during the first hour of occupation and reflected most likely a strong adaptation to odours. These results imply that the air in the office was mainly judged in terms of its ability to control odour rather than to cause irritation (only little irritation of the eyes was observed, and airways symptoms occurred only among people reporting sensitivity). Nevertheless, evoked irritation caused adaptation to air pollutants to be only moderate and not as strong as for odour intensity. Present findings do not contradict the results of Gunnarsen and Fanger (1992) who showed that no adaptation to the emissions from building materials would occur as long as they comprised large fractions of irritants. It was also confirmed that people adapt to bioeffluents (Gunnarsen and Fanger, 1989). Sensory ratings of visitors to the office with carpet plus bioeffluents and in the office without carpet plus bioeffluents were higher than those of occupants, indicating that occupants lacked the ability to sense their own pollutants. This potentially important finding, implying reduction of ventilation demand for occupants and maintaining it only at the level required mainly to dilute the emissions from building materials, was previously discussed by Gunnarsen and Fanger (1992).

In the European Audit Project (Bluyssen et al., 1996), no correlation could be made between immediate assessments of the air quality made by the independent panel of trained human subjects and the assessments of the air quality made by occupants (Groes, 1995). In the present study, visitors' and occupants' assessments of the air quality were significantly correlated. Lack of correlation in the Audit Project could be the consequence of only a few assessments having been made by the sensory panels at certain locations in the building but these assessments were compared with the perceptions of 200-500 occupants distributed all over the building. It could also be due to discrepancy between sensory assessments made by a trained panel on the decipol scale and those made by occupants on the acceptability scale (see Chapter 3 of the present thesis). On the other hand, the correlation in the present study was made using dependent sensory evaluations - visitors and occupants were actually the same group of judges. Additionally, visitors assessed the quality of air polluted by their own bioeffluents produced when they occupied the office. The correlation between visitors' and occupants' assessments of the air quality should be investigated further in future.

In the present study, the occupants reporting increased dryness of air affecting airways and eyes in the office with carpet (people regarding themselves as more sensitive to poor air quality) were also more dissatisfied with the perceived air quality. This result supports the hypothesis that a correlation exists between the perceived air quality and mucous membrane symptoms, as observed in the European Audit project (Groes et al., 1996) and the Danish Healthy Building project (Pejtersen et al., 1998).

4.5.2 Mitigation of Sensory and Chemical Pollution Loads on the Air by Source Removal

Improved perceived quality of air in the office without carpet was a consequence of the reduced sensory pollution load caused by the room when the carpet was removed, from 0.25 olf/m^{2}floor in the office with carpet down to 0.14 olf/m^{2}floor in the office without carpet. This reduction in sensory pollution load was exclusively the result of carpet removal since the ventilation rate in the office with and without carpet was unchanged. Analogous results were obtained in the office building studied by van Beuningen et al. (1994), in which bouclé carpet was substituted by floor covering made of polyolefine, both materials being similar to those used in this investigation. A significant reduction of sensory pollution load on the air was observed. Their panel of trained subjects, however, was not blind to the intervention taking place, unlike the subjects in the present experiment. Both studies have experimentally documented that removing superfluous pollution sources in indoor climates will improve the air quality. Source removal involves also economic benefits due to the fact that perceived air quality is improved without incurring additional costs for operating the ventilation system.

Chemical measurements (GC/MS analysis) revealed that slightly higher concentrations of VOCs were measured in the office with carpet than in the office without carpet. This concerns especially aldehydes, organic acids and ketones which are potential products of the reaction between pollutants emitted by the carpet and ozone (Weschler et al., 1992) and are not measured in the emissions from carpets in climate test chambers at zero air exchange rate (Sollinger et al., 1994). These results imply that reactions with ozone may have occurred in the office. The carpet in the office could thereby serve as a source of pollutants activating chemical reactions, which may have increased concentrations of aldehydes that are strong odorants (Devos et al., 1990) and suspected strong irritants (Wolkoff et al., 1997). At the same time, chemical analysis of the emissions from carpet (using FLEC) suggested that the carpet could also act as a sink. The carpet exposed to the office air (i.e., the one that had contact with the office air and with ozone) had higher emissions of aldehydes, ketones, organic acids and total concentration of VOCs, than unexposed carpet (i.e., the one that had no contact with the office air, neither with ozone). As a result, the presence of carpet could reduce the concentration of VOCs in the air and thereby diminish the difference in the perceived air quality between the office with and without carpet. In fact, the concentration of total volatile organic compounds did not differ in the air of the office with and without carpet as measured using both the photo-acoustic principle (toluene equivalent) and quantified with GC/MS analysis. But the sorption potential of the carpet should not be overestimated. As mentioned earlier, pollutants emitted from carpet, together with ozone, can trigger chemical reactions resulting in sensorily potent compounds (Wolkoff et al., 1997, Weschler and Schields, 1997), indicating that removal of carpet would be desirable.

It should furthermore be emphasized that even though the chemical measurements indicated an extremely small difference between the condition with and without carpet in the office, there was a measurable effect on performance (see section 4.5.4).

4.5.3 Risk Factors for SBS-Symptoms

4.5.3.1 Presence of Carpets in the Environment

The results of the present study indicate the positive effect of carpet removal on health. Occupants of the office without carpet experienced significantly lower severity of headaches than occupants of the office with carpet ($p<0.04$). Similar results were observed in other field studies. Norbäck and Torgén (1989) showed increased prevalence of headaches ($p<0.009$) among the personnel of schools with wall-to-wall carpet; headaches disappeared when carpet was removed. In the Californian Healthy Building study (Fisk et al., 1993), the odds ratio (OR) for prevalence of headaches was significantly higher in the carpeted offices (OR=2.0 with 95% confidence interval of 1.1÷3.4). No such associations, however, could be made in the Danish Town Hall study (Skov et al., 1990) or in the Danish Healthy Buildings project (Pejtersen et al., 1998). These two surveys, on the other hand, showed elevated prevalence of mucous membrane symptoms in the presence of carpet, which was not observed in the present experiment.

A higher prevalence of headaches has been associated with occupants working many hours at video display terminals (Groes, 1995). In the present experiment, subjects worked on PCs when typing the text for about 2 hours (with a 15 min break in the middle of the typing period) and during this time the severity of headaches increased. It was much higher in the office with carpet, implying that the exposure to carpet was a more important risk factor in the present study than the PC-work.

4.5.3.2 Workload

In the Swedish Office Illness study, Stenberg et al. (1993) showed that the odds ratio for SBS-symptoms increased significantly with the psychosocial workload, i.e., the workload associated with job satisfaction, position in the office, opportunity to influence working conditions, etc. Results of the present study are in close agreement with the Office Illness study. An interaction was observed between the prevalence of SBS-symptoms, the workload and the exposure. While subjects were performing simulated office work, the severity of many general symptoms, such as fatigue, discomfort, difficulty to concentrate, etc., increased significantly with time, independent of whether the carpet was present or not, whereas the severity of headaches was elevated by the presence of carpet when subjects typed text on the computer and added numbers. These results suggest that typing and addition, which require increased concentration, logical thinking and manual skills, are more sensitive to poor air quality than creative thinking tasks and the tasks from the performance assessment battery. In addition, the results clearly show that, depending on the work strain, the severity of symptoms can fluctuate and has a tendency to increase during the working day.

4.5.3.3 Self-Reported Sensitivity

Previous SBS-studies showed that personal factors can play an important role in the assessment of the working environment and the prevalence of health symptoms (Mendell, 1993; Sundell, 1994). Also in this experiment relationships between personal factors, symptoms and perceptions of the environment were found. These effects were observed for a rather small number of subjects and the statistical significance is therefore rather weak. Moreover, personal characteristics of subjects with skin problems was based on self-reports rather than on physical examination. To study the impact of personal factors on symptom prevalence, subjects participating in the present experiments were divided into three groups: people more sensitive to poor air quality (sensitive people), people with SBS-history, and people with easily eczematized skin or who often perceived dry air at home or at work. The results obtained for each of these groups as well as for all subjects are summarized in Table 4.5.1.

Table 4.5.1 The effects on perceptions and symptoms observed for subjects with different personal characteristics compared to the effects observed for the whole group of subjects; + indicates that the symptom or perception was worse in the office with carpet (at min. $p<0.10$); - indicates no significant effect

Symptom or perception	People sensitive to poor air quality	People with SBS-history	People with eczematized skin and/or often perceiving dry air	Whole group
Air stuffiness	+	+	+	-
Increased dryness of air, airways and eyes	+	-	-	-
Illumination	-	+	-	+
Office cleanliness	-	-	+	-
Headache	+	+	+	+
Difficult to think	+	-	-	-
Fatigue	+	-	-	-

The results indicate that sensitive people generally experienced more symptoms, implying that they were a risk group in the present experiment. These people reported increased dryness of nose, throat and eyes as well as increased perception of dry air in the office with carpet after ca. 3.5 hours of occupation. This effect was not observed for other subjects participating in the present experiment. Self-reported sensitivity was found to be significantly associated, at $p<0.001$ level, with increased prevalence of symptoms among personnel in the 11 sick office buildings in Sweden (Norbäck et al., 1990a).

SBS-history was not found to be a risk factor for SBS-symptom prevalence in the present experiment as nearly all subjects (all but 7) had such a history, and no conclusions could be drawn. Whether SBS-history is an indicator for increased sensitivity should be investigated further in future.

Perception of dry air and skin sensitive to sunlight were suggested by Sundell (1994) as risk factors for the prevalence of SBS-symptoms, but were not found to be so in the present study. This happened probably due both to lack of cutaneous symptoms experienced by subjects (expected for people with easily eczematized skin) as the exposure was perhaps too short, and to the small number of subjects (6 out of 30) frequently experiencing dry air at home or at work, thereby precluding consistent associations.

4.5.4 Reduced Productivity Due to Prevalence of Symptoms and Increased Pollution of Air

The effects on subjects' performance are summarized in Table 4.5.2 for the tasks for which significant changes were observed ($p<0.05$), or for which the effects approached significance ($0.05<p<0.10$).

The strongest effect was observed for the task involving text typing, which is a typical office task; the relevance of this finding is thus very high. Subjects typed 6.5% fewer characters in the office with carpet than in the office without carpet and this effect was highly significant ($p<0.003$). At the same time there was no learning effect: subjects typed the same number of characters independent of whether typing for the first, second, third or the fourth time in a completely balanced design. Considering that the average typing speed of subjects during occupation of the office with carpet was ca. 136 char./min and that subjects typed ca. 440 characters more in the office without carpet, it can be estimated that for the average subject it would have taken ca. 50 min to continuously type the text in the office with carpet compared to 47 min required to type the text in the office without carpet. This estimate does not take into account extra time required for proof-reading, which also would be longer in the office with carpet considering that the number of typing errors in this office was on average ca. 5% higher than in the office without carpet.

In the present study, subjects typed less when the severity of headaches increased. However, not only fatigue or headaches (Wyon, 1996), but also the presence of any symptom can negatively affect the performance. This was demonstrated by Nunes et al. (1993) among office workers in Canada for whom a response time on a continuous performance test was significantly lower ($p<0.001$) and the error rate on a code substitution test approached significance ($p<0.07$) if only they reported at least one symptom. Both the results of the present study and the study of Nunes et al. suggest a mutual interaction between SBS and productivity, implying that increased prevalence of symptoms can reduce productivity and vice versa.

Some effects were also observed on other performance tasks administered to subjects. These tasks were stroop, logical reasoning and serial addition from the performance assessment battery and the addition task (Table 4.5.2). Significant ($p<0.05$) or near-significant ($p<0.10$) improvement in performance ("learning") on these tasks was observed among people occupying the office without carpet as compared to such improvement in performance among people occupying the office with carpet. These effects were not accompanied by the difference in symptoms severity between the office with and without carpet, which may have occurred due to less effort required to complete these tasks compared to text typing. Nevertheless, they point in the expected direction, implying negative impact of elevated sensory pollution load in the office with carpet on subjects' productivity.

Table 4.5.2 Summary of the effects on performance during occupation of the office with and without carpet; all effects show impaired performance in the office with carpet

Task	Effect	Description	p-value
Logical reasoning	3.4%	higher growth of reaction time in the office without carpet as compared to the growth in the office with carpet	<0.08
Serial addition	2.5%	higher increase of accurately added digits in the office without carpet as compared to increase in the office with carpet	<0.06
Stroop	3.1%	higher increase of reaction time during occupation of the office without carpet as compared to the increase of reaction time in the office with carpet	<0.10
Addition	3.8%	higher increase of the number of added units in the office without carpet as compared to the increase of added units in the office without carpet	<0.05
Text typing	6.5%	higher number of typed characters in the office without carpet as compared to the number of characters typed in the office with carpet	<0.003

Subjects reported that the effort required to type was lower in the office with carpet. This may imply that subjects were disinclined to exert effort in the office with carpet and this is perhaps why they performed less well under this condition. Similar effects occurred in the study of Pepler and Warner (1968) investigating the effects of moderate heat stress on the performance of subjects doing mental work. At 27°C, the temperature at which most of the subjects in the study of Pepler and Warner felt thermally comfortable, their subjects exerted the least effort and performed least work. These results indicate further that it may be difficult to make meaningful assessments of subjectively estimated self-performance. Therefore, if possible, objective methods should be used to examine the effects of environmental factors on productivity.

Fisk and Rosenfeld (1997) estimated that annual costs of SBS for office workers due to decreased productivity amount to $50 billion in the USA. This estimate was calculated assuming a 2% decrease in productivity due to SBS and taking into account that this value is quite uncertain, as it is derived mainly from the self-reported productivity decrement (see also the above paragraph). In the present study, typing text, being an objective task and probably the most common one in offices, took ca. 6% longer when the severity of headaches was elevated in the office with carpet. The arguable Fisk and Rosenfeld estimate of productivity costs due to SBS should be increased by a factor of 3.

4.5.5 Methodological Issues in the Context of Future Experiments

In the present experiment, old bouclé carpet was used to modify the pollution load on the air in the office; carpet was selected as it is a risk factor for the prevalence of SBS-symptoms (Mendell, 1993). The carpet was hung on stainless-steel racks and placed behind the screen. A disadvantage of this method is the unnatural exposure of the carpet surface towards the ventilation air - normally carpets lie on the floor and the carpet surface is not fully exposed to the office air due to, e.g., obstruction by furniture, poor air distribution, etc. The above solution was used as it was crucial to prevent people from seeing the carpet. The main objective of the present study was to investigate the effects on people of sensory pollutants emitted from the carpet. However, since the carpet was not vacuum-cleaned before the experiment it might also be a source of other pollutants, such as e.g., dust or microorganisms. The significance of these other pollutants for the prevalence of SBS-symptoms and the productivity of humans should be studied in future experiments.

The office occupied by subjects in the present experiment had a floor made of low-polluting polyolefine (van Beuningen et al., 1994; Wargocki and Fanger, 1997). Nevertheless, the office without carpet could not be categorized as low-polluting (ECA, 1992), since the sensory pollution load on the air caused by the building was higher than 0.1 olf/m^{2}floor. Elevated sensory pollution loads in the office with low-emitting polyolefine could be caused by the equipment inside the office which included six personal computers, tables and chairs, and also by a ceiling made of a compressed mineral wool. In addition, sorption effects could occur inside the office: the pollutants from carpet could adsorb on surfaces during periods when the carpet was placed inside the office and they could consequently desorb in the periods without carpet, thereby increasing the pollution load on the air. An interim period of 19 hours between exposures with and without carpet may not be long enough to remove pollutants desorbing to the office air. Chemical measurements revealed that similar compounds were present in the office air whether the carpet was present or not and indicated that sorption may have occurred. In future studies, sorption effects may be minimized by, e.g., extending the time between exposure with and without carpet in the office, or by additional ventilation during the intervening nights to remove adsorbed substances.

The difference in the perceived air quality between the office with and without carpet in the present study was not at a statistically significant level. The reason is a substantial variation in air acceptability ratings from which the percentage of dissatisfied was derived. On average, the standard deviation of the acceptability vote lies around 0.45 on the scale with endpoints coded -1 and 1 (see also Gunnarsen and Bluyssen, 1994). With this variance, the office with carpet would have to produce at least 30% dissatisfied, or 140 subjects would be required to participate in order to make the difference in perceived air quality in the office with and without carpet significant (at $p<0.05$ and one-tailed region of rejection). It is thus suggested that slightly stronger sources be used in future experiments. It is also worth mentioning that higher levels of source strength may increase the number of significant effects on performance, but these effects would not be due to blind comparisons and they could be interpreted as being due to subjects' expectations. In the present study, the small and statistically non-significant difference between the office with and without carpet in the quality of air perceived by occupants (12% vs. 10% of persons dissatisfied, section 4.4.2.3), makes the comparison in terms of performance one that is almost a blind comparison. Hence, it is unlikely that subjects' expectations could have affected the performance results.

The intention was that the temperature should be constant at 24°C during occupation of the office. Ca. 1°C increase of temperature was nevertheless observed, from ca. 23.5°C to 24.5°C, as a result of no cooling device in the office and low cooling capacity of the supplied air. Increased temperature and the difference in temperature between the office with and without carpet could increase the severity of symptoms, since the prevalence of headaches, fatigue and other SBS-symptoms can be considerably affected by a temperature increase from 20-21°C to 24.5°C (Wyon, 1996). Consequently, it was examined whether each group of subjects was exposed to similar thermal conditions when occupying the office. This analysis showed no significant differences in the air temperature between the office with and without carpet and a similar pattern of rising temperature under both exposures. A 1°C growth of air temperature in the office with and without carpet is not expected to influence the productivity of subjects, as they felt thermally neutral during occupation and only a few reported draught. Under conditions of thermal comfort, Wyon et al. (1975) found that changing the air temperature did not affect the performance of widely different kinds of mental task. In future experiments, an air-conditioner with low noise and min. 2 kW cooling capacity will be installed in the office in order to reduce the heat loads from occupants and equipment, thereby enabling better control of the air temperature.

The level of illumination was not measured inside the office but no differences were believed to have occurred between occupation of the office with and without carpet. Subjects reported, however, that in the office without carpet it was perceived significantly darker than in the office with carpet. This finding is unexpected and rather difficult to explain, especially considering that the carpet was placed behind a screen and could not influence the illumination level, and that subjects could individually control the level of artificial lighting in the office using a lamp attached to each workstation, and many of them did so. On the other hand, the perception that it was darker when the air was less polluted may simply indicate that subjects felt more relaxed and incorrectly attributed this feeling to a difference in illumination level, bright light being familiar as a powerful arousing factor. Or they could merely be more attentive to the environment, because the pollution level in the office without carpet was lower. In future experiments the level of illumination should be well controlled.

Whether perceived lower illumination in the office without carpet influenced subjects' productivity is unclear. No documentation exists on the potential significant improvement of productivity with lighting level (Fisk and Rosenfeld, 1997). Moreover, in the experiment of Banhidi et al. (1996), no decreased performance among subjects typing text using an MS-word processor (similar to the task used in the present experiment) was found when the artificial lighting was changed from 290 and 920 lux, although it decreased when the temperature of air increased from 20°C to 30°C and simultaneously the level of artificial lighting increased, too. Even perceived illumination had affected subjects' performance, it is expected that it would have enhanced the performance in the office with carpet, and the true negative effect of air pollution on productivity would have been greater than measured.

Simulation of office work proved to be successful - subjects reported increased fatigue during occupation of the office. A similar effect was observed during field studies. In future experiments, tasks used to simulate office work in the present experiment may be supplemented with other tasks such as proof-reading, number checking, checking names and addresses in a telephone book, etc. No effects, however, were shown for the creative thinking task, possibly because no proper reference for inclusion or exclusion of the names was used, resulting in rather ambiguous analysis. The results of this task should therefore be analysed once more, restricting the acceptance of names to those correctly identified as male or female names by >95% of people selected at random from the same population as subjects recruited in this study. This restriction was not fulfilled when analysing the results of the creative thinking task in the present experiment. Some effects were observed for a few tasks from the performance assessment battery including serial addition, logical reasoning and stroop. In a longer version (increased number of trials, extended duration), they can be recommended for use in future experiments. It should nevertheless be remembered that tasks from the performance assessment battery are only diagnostic psychological tools intended to be performed for a very short time; they do not resemble typical office work. On many occasions, the strength of these tasks can be too low when used for weak stimuli occurring in indoor climates (Berglund et al., 1992a). In the present study, the results of performance on the battery of tests used did not correlate with the subjective assessments of symptoms. Fatigue, sleepiness, difficulty to concentrate and other symptoms increased in severity during occupation, but performance on PAB rather than declining actually improved at the end of occupation compared to the performance of subjects just after entering the office.

All statistical analyses of the performance tests were carried out as within-subject designs, i.e., between-subjects variance, and consequently the difference in subjects' experience, training, typing and intellectual skills, educational background, etc., were excluded from the main effects observed. To minimize the learning effects using a performance assessment battery, subjects received training comprising 10 practise sessions with a complete set of psychological tests in a neutral environment. During this time, significant learning effects were observed, and they were much higher than those observed during occupation of the office with and without carpet. The addition task was also very much influenced by the learning effect, and in future experiments further practise sessions with this task are recommended prior to the experiments.

Due to considerable learning taking place in most of the performance testing, which led to a much more complex analysis and to much more tentative conclusions as a result, it could be considered in future experiments to use an independent measures design. In such a design, learning cannot affect a comparison between conditions; however, between-subjects variance would mean that a greater number of subjects than used in the present study would be required to participate. For example, to make the difference in typing speed in the office with and without carpet significant (at $p<0.05$ and one-tailed region of rejection), more than 120 subjects would have had to participate in the present experiments, if the design had been the independent measures. Increasing the number of subjects would, on the other hand, have the advantage of increasing the number of subjects in the sub-groups (people sensitive to poor air quality, people with SBS-history, atopic people, etc.), which could lead to more powerful analysis of the effects of personal factors on the prevalence of symptoms compared to such analyses performed in the present experiment, which were rather weak.

A limitation of the present experiment is that only young, generally healthy, female subjects were recruited. In addition, they were students, thereby not a representative subpopulation of office workers. In future experiments, another subpopulation of subjects may be selected. This concerns both the age of subjects, their health and occupation; however, female subjects should still be recruited. Epidemiological studies generally do not find strong associations between the age of women and the prevalence of symptoms (Mendell, 1993; Groes, 1995). Nevertheless, in the experiment of Wyon et al. (1995), older female drivers (>40 years old) experienced significantly more eye discomfort, headache and fatigue when compared to young drivers (<40 years old) when driving a car for one hour in city traffic during periods of ionization of air (i.e., altering the airborne particulate concentration) inside the vehicle. Also in dry office air in winter, without humidification, a significantly higher proportion of older men and women (>35 years old) complained of low humidity in comparison with the younger group; concurrently, more women complained of low humidity, in comparison with men (Andersson et al., 1975). Conversely, in the survey in 47 office sites in the UK (Hedge et al., 1989), workers who were 30 and younger rated the environment less favourably, but at the same time they reported less job stress than older workers. In the present experiment, subjects were below 31 years old. In future studies, the use of other age groups may be considered.

Atopic people suffering from asthma, hay fever, allergy, chronic bronchitis or eczema have often been reported as having more symptoms than people with normal sensitivity (Sundell, 1994). Also, subjects performing clerical and secretarial work report more symptoms, perhaps due to the type of work (e.g., paper handling, working with a PC) and increased exposures (e.g. emissions from copier, fax) (Groes et al., 1996). Extrapolating present results for atopic people and office workers, it is expected that a stronger effect would be observed than the effects shown. It may be considered in future experiments to study especially selected sensitive groups of subjects.

Another drawback of the present design is that subjects were not exposed to a change in the air pollution level in their own working environment. Although every effort was made to provide a natural, typical office environment, it may still be perceived as different from the normal workplace. Further studies on this effect would be useful.

In the present study, people occupied the office for two periods lasting 5 hours each. In real life, people are repeatedly exposed to the working environment for about 8 hours a day, 5 days per week, 4 weeks per month, etc. Such a recurrent exposure may be an important factor amplifying symptom prevalence and future experiments could address this issue.

4.6 Conclusions

- Reducing the sensory pollution load on the air indoors proved to be an effective and energy-efficient measure to improve the perceived quality of air, to lower the prevalence of symptoms and to improve productivity.

- Perceived air quality upon entering the office with carpet caused 22% persons to be dissatisfied. Removal of the carpet improved the perceived air quality so that only 15% persons were dissatisfied.

- The perceived air quality evaluated upon entering the office with bioeffluents was impaired further ($p<0.08$) independently of whether the carpet was present or not. Consequently, adding sensory pollution loads of individual sources was a reasonably good approximation of the total sensory pollution load in the office, with the perceived air quality causing less than 25% persons to be dissatisfied.

- Moderate adaptation to air pollutants in the office was observed during the first hour of occupation

- Visitors' and occupants' assessments of the air quality were significantly correlated.

- Slightly higher concentrations of odorants and irritants in the office with carpet were observed.

- Improved perceived quality of air in the office without carpet was a consequence of the reduced sensory pollution load caused by the building from 0.25 olf/m^2floor in the office with carpet down to 0.14 olf/m^2floor in the office without carpet.

- Occupants of the office without carpet suffered significantly less from headaches during typing than occupants of the office with carpet ($p<0.04$).

- Headache due to polluted air was more pronounced during tasks requiring concentration.

- Occupants typed significantly less text in the office with carpet ($p<0.003$). Different psychological tests also suggested decreased performance in the office with carpet. The small difference between the office with and without carpet in the quality of air perceived by occupants (12 vs. 10% of persons dissatisfied), makes the comparison in terms of performance one that is almost a blind comparison.

- The effect of the reduced air quality due to carpet was to cause subjects to exert less effort ($p<0.02$).

- Individual control of air quality has been suggested in order to provide acceptable air quality for sensitive people.

- People regarding themselves as more sensitive to poor air quality were also more dissatisfied with the perceived air quality.

- The presence of carpet, a high workload and people reporting to be sensitive to poor air quality were found to be possible risk factors for SBS.

- Text typing proved to be a successful method for simulating office work that is sensitive to poor indoor air quality, showing that simulated work of a long duration is more sensitive to environmental effects than diagnostic tests of short duration.

- An exposure time of 4.4 hours in the office seems to be a reasonable duration of occupation, resulting in increased fatigue, sleepiness and severity of other general SBS-symptoms.

- The application of four tests from the performance battery, in a longer version than used in this study, is recommended. These tests include: logical reasoning, stroop and serial addition. Also addition of numbers can be used in future studies.

- Suggestions for future experiments are provided. They include the use of slightly stronger sources (perhaps using the ozone sources in the office), the investigation of the association between the prevalence of SBS-symptoms and the levels of dust and microorganisms contained in carpets, elimination of sorption effects, the control of temperature and illumination, the use of other subpopulations of subjects stratified for age, sensitivity and type of work, as well as the use of the independent measures design and of exposures that are regularly repeated during a working week.

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APPENDIX 1

Complete List of Studies Reviewed during the Literature Survey

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APPENDIX 2

Data on Volatile Organic Compounds Collected through a Literature Survey of Measurements of the Chemical Composition of Indoor Air in Offices

Data on VOCs Collected through a Literature Survey of Measurements of the Chemical Composition of Indoor Air in Offices

Compound	Odour threshold[1] (mg/m^3)	Description of odour[2]	Irritation threshold[3,4] (mg/m^3)	General information				Measured concentrations ($\mu g/m^3$)					Odour index
	OT			No. studies	No. buildings	No. spaces	No. measure ments	MWC[5]	Min.	50PC[6]	90PC[7]	Max.	MWC/OT
acetalaldehyde	0.34	green-sweety-fruity, pungent, ethereal, nauseating, in high conc. reminiscent of coffee and wine	90	1	10	83	83	9.0	9.0	9.0	9.0	9.0	0.027
acetic acid	0.36	sour-vinegar like, pungent, stinging, unpleasant when concentrated	25	2	21	21	21	17.3	6.0	125.0	220.2	244.0	0.048
acetone	34.67	minty chemical-sweet, light, ethereal, nauseating, powerful odor, of very poor tenacity, irritant at high conc., rather pleasant in dilution	283681.7 476.7	3	65	85	92	16.0	10.2	19.0	19.8	20.0	0.000
amylalcohol, (i-)	1.70	choking, disagreeable, cough provoking, alcoholic, pleasant in high dilution, fruity, winey		1	5	61	73	1.2	1.2	1.2	1.2	1.2	0.001
benzaldehyde	0.19	pleasant-bitter, powerful, sweet, reminiscent of freshly crushed bitter almonds, burning but sweet taste in proper dilution	20.01	5	52	145	171	2.6	0.1	4.0	9.2	12.4	0.014
benzene	12.02	sweet-solventy	9000	14	57	252	402	5.5	1.0	6.4	28.3	105.0	0.000
benzylalcohol		faint, nondescript, rather sweet		1	5	61	73	0.3	0.3	0.3	0.3	0.3	
bromodichloromethane				1	20	58	58	0.1	0.1	0.1	0.1	0.1	
butanol, (1-)	1.51	sweet, mild, fusel-like, more volatile and more choking than fusel itself, winey in character, non-descriptive, chemical	3334.6 75	3	78	134	146	68.1	0.1	5.0	121.0	150.0	0.045
butanone, (2-)	23.44	sweet-acetone like, ethereal, slightly nauseating, not exactly pleasant	590	1	14	14	14	50.0	50.0	50.0	50.0	50.0	0.002
butoxyethanol, (2-)	1.66			5	21	113	139	5.9	0.1	7.7	16.0	17.7	0.004
butoxyethoxyethylacetate				1	1	1	1	6.0					

APPENDIX 2

Compound	Odour threshold[1] (mg/m^3)	Description of odour[2]	Irritation threshold[3,4] (mg/m^3)	General information				Measured concentrations (µg/m^3)					Odour index
	OT			No. studies	No. buildings	No. spaces	No. measure ments	MWC[5]	Min.	50PC[6]	90PC[7]	Max.	MWC/OT
butylacetate, (n-)	0.93	fruity	17333.5 473.3	4	22	99	113	0.9	0.6	1.5	4 8	6.0	0.001
butylbenzene, (n-)				2	6	193	205	0.9	0.5	0.8	1.0	1.1	
camphene		mild, oily, camphoraceous, with little or no "warm-cold" feel		1	1	132	132	0.7	0.7	0.7	0.7	0.7	
carbon tetrachloride	120.23	sweet-pungent		3	28	86	202	0.9	0.5	1.0	2.3	2.6	0.000
carene, (3-)		sweet, diffusive, penetrating, reminiscent of refined Limonene		2	15	146	146	1.1	0.2	5.1	9.0	10.0	
chlorobenzene	3.55	sweet-almond like	48582.6 933.3	3	22	64	74	0.1	0.0	0.1	0.3	0.4	0.000
cumene	0.12	sharp-aromatic, pungent, slightly green-sharp, kerosene-like, poor tenacity		1	1	7	7	0.5	0.5	0.5	0.5	0.5	0.004
cyclohexane	77.62	sweet-aromatic	1050	4	25	44	58	33.1	0.4	19.2	69.6	90.0	0.000
cyclohexanone	2.88			1	2	2	2	15.0					
cyclohexene	1.23			2	1	7	7	2.4	2.4	2.4	2.4	2.4	0.002
cymene, (p-)	0.01	gassy, kerosene-like, citruisy when highly purified, reminiscent of lemon, fresh		1	1	132	132	2.3	2.3	2.3	2.3	2.3	0.187
decanal, (n-)	0.01	penetrating and very powerful, sweet, waxy, orange-peel like, in extreme dilution refreshing, citrus-peel like		2	8	12	12	8.8	3.0	8.0	12.0	13.0	1.500
decane, (n-)	4.37			12	64	312	458	13.9	0.7	8.8	38.7	279.0	0.003
decene, (n-)	5.01			1	1	132	132	38.4	38.4	38.4	38.4	38.4	0.008
dibuthylphtalate, (n-)				1	2	5	5	3.6	3.6	3.6	3.6	3.6	
dichlorobenzene, (1,4-)	0.30	mothballs	240	2	2	16	36	4.9	0.9	3.5	5.6	6.1	0.017

Data on VOCs Collected through a Literature Survey of Measurements of the Chemical Composition of Indoor Air in Offices

Compound	Odour threshold[1] (mg/m^3)	Description of odour[2]	Irritation threshold[3,4] (mg/m^3)	General information				Measured concentrations (µg/m^3)					Odour index
	OT			No. studies	No. buildings	No. spaces	No. measure ments	MWC[5]	Min.	50PC[6]	90PC[7]	Max.	MWC/OT
dichlorobenzene, (m- & p-)				3	29	81	197	2.0	1.5	2.6	13.3	16.0	
dichloroethene, (1,2-)	77.62	acrid-ethereal		1	20	58	58	0.0	0.0	0.0	0.0	0.0	0.000
dichloromethane	100.00	sweet	8280	2	20	40	40	3.3	1.4	6.2	10.0	11.0	0.000
dichloropropane, (1,2-)	3.98			2	21	190	190	1.3	0.0	0.9	1.7	1.9	0.000
diethylbenzene, (m-)				2	2	146	160	1.8	0.3	4.6	8.1	8.9	
diethylcyclohexane				1	1	14	28	26.0	26.0	26.0	26.0	26.0	
diethylphtalate		odorless when pure		1	1	2	8	0.8	0.8	0.8	0.8	0.8	
dimethyl (2,4-)ethylpentane, (3-)				1	1	1	2	5.0	5.0	5.0	5.0	5.0	
dimethylcyclohexane				1	1	1	2	4.0	4.0	4.0	4.0	4.0	
dimethylethylbenzene, (2,5-)				1	1	14	28	9.4	9.4	9.4	9.4	9.4	
dimethylpentane, (2,4-)	363.08			1	1	14	28	14.9	14.9	14.9	14.9	14.9	0.000
dimethylphtalate		very faint, ethereal, odor of methanol		2	2	6	16	0.5	0.3	0.5	0.7	0.7	
dioxane, (1,4-)	20.42	ether like, sweet, mild ethereal	792	2	2	17	17	23.8	11.1	26.5	38.9	42.0	0.001
dodecane, (n-)	14.45			11	48	283	421	17.7	0.2	4.3	14.0	430.0	0.001
epoxy, (2,3-), methylpentane, (4-)				1	1	1	1	97.0	97.0	97.0	97.0	97.0	
ethanol	54.95	sweet-alcoholic, ethereal, mild, diffusive	16969 9500	6	47	89	110	112.4	11.1	29.8	374.0	680.0	0.002
ethoxyethanol, (2-)	4.57			1	1	1	1	21.0	21.0	21.0	21.0	21.0	0.005
ethoxyethylacetate, (2-)	1.00			2	5	6	6	9 7	1.7	25.8	45.2	50.0	0.010
ethylacetate	9.77	fruity-pleasant, ethereal, Brandy-like, nauseating in high concentrations	242398.3 350	5	35	120	132	3.2	0.0	1 2	17.2	20.0	0.000

APPENDIX 2

Compound	Odour threshold[1] (mg/m³)	Description of odour[2]	Irritation threshold[3,4] (mg/m³)	General information				Measured concentrations (µg/m³)					Odour index
	OT			No. studies	No. buildings	No. spaces	No. measure ments	MWC[5]	Min.	50PC[6]	90PC[7]	Max.	MWC/OT
ethylbenzene	0.01	aromatic, sweet but somewhat gassy, hyacinth-type	43857.5 870	13	51	309	461	16.3	0.3	5.7	28.5	42.0	1.267
ethylhexanol, (2,1-)	1.32	musty, mild, oily, sweet, slightly floral, rosy		1	5	61	73	3.0	3.0	3.0	3.0	3.0	0.002
ethylmethylbenzene, (1,2-)				1	1	10	10	0.0	0.0	0.0	0.0	0.0	
ethyltoluene				2	19	53	169	5.2	3.7	4.6	5.3	5.5	
ethyltoluene, (2-)				2	13	164	164	1.4	1.1	1.8	2.3	2.4	
ethyltoluene, (4-)				1	1	132	132	12.4	12.4	12.4	12.4	12.4	
ethyltoluene, (m-)				2	5	137	137	18.3	4.3	11.6	17.4	18.8	
furfuryl alcohol		very mild, warm oily, burnt odor, virtually odorless when pure		1	5	61	73	3.5	3.5	3.5	3.5	3.5	
heptadecane				2	3	9	13	30.1	0.5	38.9	69.7	77.4	
heptanal, (n-)	0.02	very powerful and diffusive, oily-fatty, "rancid", penetrating and pungent at high conc., almost fruity, *fermented fruity like in extreme* dilution		1	3	7	7	1.0	1.0	1.0	1.0	1.0	0.044
heptane, (n-)	40.74	gasoline like, sweet, ethereal, diffusive, poor tenacity, sulfuraceous, tarry, phenolic, "gassy", styrene-like, not pleasant when pure		9	61	369	396	5.2	1.0	3.0	21.6	30.0	0.000
heptene, (1-)				1	1	132	132	9.4	9.4	9.4	9.4	9.4	
hexadecane, (n-)				4	5	148	152	5.8	0.4	1.9	93.9	133.1	

Data on VOCs Collected through a Literature Survey of Measurements of the Chemical Composition of Indoor Air in Offices

Compound	Odour threshold[1] (mg/m³)	Description of odour[2]	Irritation threshold[3,4] (mg/m³)	General information				Measured concentrations (µg/m³)					Odour index
	OT			No. studies	No. buildings	No. spaces	No. measurements	MWC[5]	Min.	50PC[6]	90PC[7]	Max.	MWC/OT
hexanal, (n-)	0.06	very powerful, penetrating fatty-green, grassy, sweet-like, in extreme dilution reminiscent of freshly cut grass and unripe fruits (apple, plum)		3	20	100	112	5.3	1.9	4.3	6.4	6.9	0.092
hexane, (n-)	79.43		1800	8	72	243	269	16.6	0.1	17.9	78.1	100.0	0.000
hexanol	0.19	sweet-alcohol, "chemical", winey, slightly fatty, and fruity, weaker than Amyl alcohol	1672	2	3	19	33	25.2	20.9	23.5	25.5	26.0	0.135
isoprene				1	22	22	22	8.0					
limonene	2.45	fresh, light, sweet, citrusy, strong resemblance to orange peel oil, poor tenacity		6	48	221	235	34.7	5.8	28.8	45.6	49.0	0.014
methyl, (4-), pentanol, (1-)				1	1	10	10	0.0	0.0	0.0	0.0	0.0	
methyl, (4-)-pentanone, (1-)				1	1	10	10	1.9	1.9	1.9	1.9	1.9	
methyl, (4-)-Pentanone, (2-)	2.29	sweet-sharp	410	2	2	8	8	2.7	2.4	3.7	4.7	5.0	0.001
methylalkylcyclohexane				1	1	1	2	2.5	2.5	2.5	2.5	2.5	
methylbutane, (2-)				2	14	23	23	10.9	6.9	10.5	13.3	14.0	
methylcyclohexane		faint-benzene like		7	50	98	113	17.3	0.0	3.5	36.8	50.0	
methylcyclopentane				3	23	52	52	10.9	0.0	1.5	41.9	52.0	
methyldecane, (5-)				1	1	14	28	16.0	16.0	16.0	16.0	16.0	
methylethylbenzene, (o-)				1	1	14	28	14.0	14.0	14.0	14.0	14.0	
methylhexane, (3-)				2	13	33	34	1.8	1.4	4.7	7.3	8.0	
methylmethacrylate	1.48			1	6	6	6	11.0					
methylnonane, (2-)				1	1	1	2	8.5	8.5	8.5	8.5	8.5	
methylpentane, (2-)				1	37	37	37	16.0	16.0	16.0	16.0	16.0	

Compound	Odour threshold[1] (mg/m³)	Description of odour[2]	Irritation threshold[3,4] (mg/m³)	General information				Measured concentrations (μg/m³)					Odour index
	OT			No. studies	No. buildings	No. spaces	No. measure ments	MWC[5]	Min.	50PC[6]	90PC[7]	Max	MWC/OT
methylpentane, (3-)				2	15	24	24	27.3	19.2	26.1	31.6	33.0	
methylpropylbenzene, (o-)				1	1	14	28	8.6	8.6	8.6	8.6	8.6	
methylstyrene, (alpha-)	0.76	sweet-aromatic	960	1	1	7	7	0.5	0.5	0.5	0.5	0.5	0.001
nitrobenzene	0.22	shoe polish-pungent, harsh, offensive, bitter almond type, poor tenacity, irritating to eyes and human mucous membranes	230	1	5	61	73	0.6	0.6	0.6	0.6	0.6	0.003
nonanal, (n-)	0.01	very powerful and diffusive, fatty, floral, waxy, moderate tenacity, in proper dilution becomes more pleasant, floral-waxy, more rosy sweet and fresh		4	19	92	118	3.4	0.1	6.0	9.9	10.7	0.253
nonane, (n-)	6.76			12	41	275	319	13.5	0.2	5.4	82.4	139.0	0.002
nonene, (n-)				2	2	139	139	0.1	0.1	0.3	0.5	0.5	
octadecane				1	2	5	5	24.6	24.6	24.6	24.6	24.6	
octanal, (n-)	0.01	powerful when not diluted, harsh, fatty, penetrating, in extreme dilution sweet, orange like, slightly fatty, honey like, moderate to poor tenacity		2	4	21	35	10.0	10.0	10.0	10.0	10.0	1.380
octane, (iso-)				2	15	28	42	17.2	15.9	17.9	19.6	20.0	
octane, (n-)	27.54	gasoline like	1450	9	38	256	278	17.1	0.0	2.1	74.4	300.0	0.001
octanol, (1-)	0.03	powerful, fresh, orange-rose like, waxy, sweet, poor tenacity, balsamic-herbal undertones oily-fruity, sweet and slightly herbaceous	3727.6	2	1	132	132	1.8	1.1	1.2	1.2	1.2	0.056
pentadecane, (n-)				5	6	31	49	15.8	0.2	5.2	52.9	80.3	

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Compound	Odour threshold[1] (mg/m³)	Description of odour[2]	Irritation threshold[3,4] (mg/m³)	General information				Measured concentrations (µg/m³)					Odour index
	OT			No. studies	No. buildings	No. spaces	No. measure ments	MWC[5]	Min.	50PC[6]	90PC[7]	Max.	MWC/OT
pentamethylheptane, (2,2,4,6,6-)				1	1	14	28	12.9	12.9	12.9	12.9	12.9	
pentanal	0.02	very powerful and diffusive, penetrating, acrid, pungent, choking when concentrated, cough-provoking, in extreme dilution dry-fruity, musty, nut like		2	17	93	105	0.3	0.1	0.4	0.6	0.6	0.012
pentanal, (n- & i-)		"i-": very powerful, penetrating, acrid pungent, causing cough reflexes unless highly diluted, in high dilution heavy fruity, rather pleasant, peach like		1	3	7	7	11.0	11.0	11.0	11.0	11.0	
pentane, (n-)	95.50	gasoline like		2	18	38	38	14.0	7.4	28.2	44.8	49.0	0.000
phenol	0.43	medicinal-sweet	182.4	1	66	66	66	1.0	1.0	1.0	1.0	1.0	0.002
phenoxy-2-ethanol				1	1	1	1	21.0					
phenylcyclohexene, (4-)				1	1	7	7	3.5	3.5	3.5	3.5	3.5	
pinene, (alpha-)	3.89	warm, resinous, refreshing, pine like, "turpentine" like, raisin like, herbaceous, aromatic		8	38	244	372	5.7	1.9	7.5	61.0	110.0	0.001
pinene, (beta-)		dry, woody, resinous, piney, poor tenacity		2	3	137	137	0.9	0.7	3.7	6.1	6.7	
propanol, (2-)	25.70	alcoholic, ethereal, acetone-like	44577.2 13750	3	27	56	56	18.7	2.3	5.7	49.1	60.0	0.001
propylbenzene, (i- & n-)				1	7	21	137	1.5	1.5	1.5	1.5	1.5	
propylbenzene, (n-)			7310.3	4	8	209	241	2.9	0.9	1.6	9.8	13.2	
styrene	0.63	solventy-rubbery, extremely diffusive, sweet, gassy, in dilution balsamic and almost floral, poor tenacity, chemical odor that of hydrocarbon	4300	7	94	194	328	63.5	0.5	1.7	128.0	310.0	0.101

Compound	Odour threshold[1] (mg/m³)	Description of odour[2]	Irritation threshold[3,4] (mg/m³)	General information				Measured concentrations (µg/m³)					Odour index
	OT			No. studies	No. buildings	No. spaces	No. measure ments	MWC[5]	Min.	50PC[6]	90PC[7]	Max	MWC/OT
terpinene, (alpha-)		refreshing, lemony, citrusy, poor tenacity		1	1	132	132	0.5	0.5	0.5	0.5	0.5	
terpinene, (gamma-)		refreshing, herbaceous, citrusy, less lemony than alpha isomer, warmer, poor tenacity		1	1	132	132	0.3	0.3	0.3	0.3	0.3	
tetrachloroethene	42.66	chlorinated solvent	710.2	10	62	229	355	3.4	0.1	3.3	5.3	11.2	0.000
tetradecane, (n-)				6	12	80	96	2.5	0.1	3.8	19.7	25.4	
tetramethylbenzene, (1,2,3,5-)				1	1	132	132	0.9	0.9	0.9	0.9	0.9	
tetramethylbenzene, (1,2,4,5-)	0.15			1	1	132	132	1.6	1.6	1.6	1.6	1.6	0.010
texanol				1	2	5	5	20.2	20.2	20.2	20.2	20.2	
texanol di-iso-butyrate				1	2	5	5	31.5	31.5	31.5	31.5	31.5	
toluene	5.89	rubbery-mothball-pungent, sweet, gassy, milder than that of Benzene, less toxic than Benzene	111449.8 750	18	177	497	541	42.8	0.8	21.9	83.3	610.0	0.007
trichloroethane, (1,1,1-)	125.89			14	89	268	404	39.1	0.8	22.3	280.3	565.0	0.000
trichloroethene	26.92	solventy	864	10	60	151	268	15.2	0.9	8.4	205.9	349.0	0.001
trichlorofluoromethane		sweet		2	13	46	60	7.4	4.2	7.6	10.3	11.0	
trichloromethane	58.88	diffusive, heavy, sweet, ethereal, considerable anesthetic effect	20480	1	20	58	58	3.8	3.8	3.8	3.8	3.8	0.000
tridecane, (n-)	16.60			5	10	79	101	1.8	0.4	1.3	9.1	13.9	0.000
trimethyl, (2,4,4-)-pentene, (2-)				1	1	14	28	17.1	17.1	17.1	17.1	17.1	
trimethylbenzene				1	7	21	137	7.5	7.5	7.5	7.5	7.5	
trimethylbenzene, (1,2,3-)				5	20	249	275	19.2	0.0	2.7	26.2	35.6	
trimethylbenzene, (1,2,4-)	0.78			10	42	271	307	17.5	0.5	4.4	40.0	105.5	0.023
trimethylbenzene, (1,3,5-)	1.15			6	21	250	280	5.1	0.5	1.8	10.2	13.4	0.004

Data on VOCs Collected through a Literature Survey of Measurements of the Chemical Composition of Indoor Air in Offices

Compound	Odour threshold[1] (mg/m³)	Description of odour[2]	Irritation threshold[3,4] (mg/m³)	General information				Measured concentrations (μg/m³)					Odour index
	OT			No. studies	No. buildings	No. spaces	No. measurements	MWC[5]	Min.	50PC[6]	90PC[7]	Max.	MWC/OT
trimethyldecane, (3,3,4-)				1	1	14	28	11.8	11.8	11.8	11.8	11.8	
trimethylhexane, (2,2,5-)				1	12	32	32	0.7	0.7	0.7	0.7	0.7	
trimethyloctane, (2,5,6-)				1	1	14	28	30.3	30.3	30.3	30.3	30.3	
undecane, (n-)	7.76			12	61	296	435	7.7	0.5	6.1	90.4	100.0	0.001
undecene, (n-)				1	1	132	132	0.4	0.4	0.4	0.4	0.4	
xylene		sweet, pungent, "gassy", kerosene like, not as powerful as Toluene, not as nauseating as Benzene, sweeter, milder than the two	435	4	75	102	239	33.8	12.0	19.4	55.3	70.0	
xylene, (m- & p-)				8	33	321	343	8.4	0.5	7.0	29.2	66.5	
xylene, (m-)	1.41			2	61	61	61	18.5	18.0	19.0	19.8	20.0	0.013
xylene, (o-)	3.80			10	62	291	313	12.7	0.4	4.2	23.0	30.0	0.003
xylene, (p-)	2.14			2	17	23	23	10.5	9.3	10.1	10.8	11.0	0.005

Legend:

1 from Devos et al. (1990)
2 from Arctander (1969)
3 from Cometto-Muñiz and Cain (1990)
4 from Ruth (1986)
5 mean weighted concentration (weighing factor - number of measurements)
6 50th percentile concentration (median)
7 90th percentile concentration

APPENDIX 3

Parameters of the VOC-Generation System Documented during Sensory Evaluations

Table A3.1 Parameters of the VOC-generator and VOC-polluted air documented during sensory evaluations of air polluted by n-butanol

Liquid injected: *n-butanol* (density, ρ = 0.81 kg/L, molecular weight =74.1 g/mol)	**Untrained panel** (N=38)	**Trained panel** (N=15)
Parameters of the VOC-generator producing the air polluted with VOCs:		
• temperature of the injection block (°C)	140	140
• temperature of the oven (°C)	100	100
• flow rate of diluting air and nitrogen, Q_{a+cg} (L/min)	14.6	14.6
• flow rate of the liquid injected, I (ml/h)	0.1	0.1
Concentration of the polluted air presented for sensory evaluations through diffuser:		
• GC/MS analysis		
– at flow proportion of n=31.5 (mg/m^3)	2.142	2.142
• PAS measurements (TVOC toluene-equivalent)		
– at flow proportion of n=0, background air (mg/m^3)	3.91	3.91
– at flow proportion of n=20 (mg/m^3)	11.01	11.01

Table A3.2 Parameters of the VOC-generator and VOC-polluted air documented during sensory evaluations of air polluted by n-decane

Liquid injected: *n-decane* (density, ρ = 0.73 kg/L, molecular weight =142.3 g/mol)	**Untrained panel** (N=42)	**Trained panel** (N=14)
Parameters of the VOC-generator producing the air polluted with VOCs:		
• temperature of the injection block (°C)	180	180
• temperature of the oven (°C)	140	140
• flow rate of diluting air and nitrogen, Q_{a+cg} (L/min)	14.3	14.3
• flow rate of the liquid injected, I (ml/h)	2.0	2.0
Concentration of the polluted air presented for sensory evaluations through diffuser:		
• GC/MS analysis		
– at flow proportion of n=31.5 (mg/m^3)	42.4	42.4
• PAS measurements (TVOC toluene-equivalent)		
– at flow proportion of n=0, background air (mg/m^3)	9.8	9.8
– at flow proportion of n=20 (mg/m^3)	182.4	182.4

Table A3.3 Parameters of the VOC-generator and VOC-polluted air documented during sensory evaluations of air polluted by ethylbenzene

Liquid injected: *ethylbenzene* (density, ρ = 0.87 kg/L, molecular weight =106.2 g/mol)	**Untrained panel** (N=41)	**Trained panel** (N=15)
Parameters of the VOC-generator producing the air polluted with VOCs:		
• temperature of the injection block (°C)	150	150
• temperature of the oven (°C)	100	100
• flow rate of diluting air and nitrogen, Q_{a+cg} (L/min)	14.5	14.5
• flow rate of the liquid injected, I (ml/h)	0.1	0.1
Concentration of the polluted air presented for sensory evaluations through diffuser:		
• GC/MS analysis		
– at flow proportion of n=31.5 (mg/m^3)	2.636	2.636
• PAS measurements (TVOC toluene-equivalent)		
– at flow proportion of n=0, background air (mg/m^3)	3.6	3.3
– at flow proportion of n=20 (mg/m^3)	7.0	6.6

Table A3.4 Parameters of the VOC-generator and VOC-polluted air documented during sensory evaluations of air polluted by n-hexane

Liquid injected: *n-hexane* (density, ρ = 0.66 kg/L, molecular weight =86.2 g/mol)	**Untrained panel** (N=41)	**Trained panel** (N=14)
Parameters of the VOC-generator producing the air polluted with VOCs:		
• temperature of the injection block (°C)	70	70
• temperature of the oven (°C)	70	70
• flow rate of diluting air and nitrogen, Q_{a+cg} (L/min)	14.4	14.4
• flow rate of the liquid injected, I (ml/h)	2.5	2.5
Concentration of the polluted air presented for sensory evaluations through diffuser:		
• GC/MS analysis		
– at flow proportion of n=31.5 (mg/m^3)	50.267	50.267
• PAS measurements (TVOC toluene-equivalent)		
– at flow proportion of n=0, background air (mg/m^3)	6.9	5.7
– at flow proportion of n=20 (mg/m^3)	193.8	210.4

Table A3.5 Parameters of the VOC-generator and VOC-polluted air documented during sensory evaluations of air polluted by toluene

Liquid injected: *toluene* (density, ρ = 0.87 kg/L, molecular weight =92.2 g/mol)	**Untrained panel** (N=42)	**Trained panel** (N=15)
Parameters of the VOC-generator producing the air polluted with VOCs:		
• temperature of the injection block (°C)	100	100
• temperature of the oven (°C)	100	100
• flow rate of diluting air and nitrogen, Q_{a+cg} (L/min)	14.7	14.7
• flow rate of the liquid injected, I (ml/h)	0.5	0.5
Concentration of the polluted air presented for sensory evaluations through diffuser:		
• GC/MS analysis		
– at flow proportion of n=31.5 (mg/m^3)	11.9	11.9
• PAS measurements (TVOC toluene-equivalent)		
– at flow proportion of n=0, background air (mg/m^3)	3.85	3.85
– at flow proportion of n=20 (mg/m^3)	11.55	11.55

Table A3.6 Parameters of the VOC-generator and VOC-polluted air documented during sensory evaluations of air polluted by 1,2,4-trimethylbenzene

Liquid injected: *1,2,4-trimethylbenzene* (density, ρ = 0.88 kg/L, molecular weight =120.2 g/mol)	**Untrained panel** (N=39)	**Trained panel** (N=15)
Parameters of the VOC-generator producing the air polluted with VOCs:		
• temperature of the injection block (°C)	130	130
• temperature of the oven (°C)	100	100
• flow rate of diluting air and nitrogen, Q_{a+cg} (L/min)	14.5	14.5
• flow rate of the liquid injected, I (ml/h)	0.1	0.1
Concentration of the polluted air presented for sensory evaluations through diffuser:		
• GC/MS analysis		
– at flow proportion of n=31.5 (mg/m^3)	2.71	2.71
• PAS measurements (TVOC toluene-equivalent)		
– at flow proportion of n=0, background air (mg/m^3)	4.42	4.42
– at flow proportion of n=20 (mg/m^3)	9.03	9.03

Table A3.7 Parameters of the VOC-generator and VOC-polluted air documented during sensory evaluations of air polluted by m-xylene

Liquid injected: *m-xylene* (density, ρ = 0.86 kg/L, molecular weight =106.2 g/mol)	**Untrained panel** (N=37)	**Trained panel** (N=14)
Parameters of the VOC-generator producing the air polluted with VOCs:		
• temperature of the injection block (°C)	150	150
• temperature of the oven (°C)	110	110
• flow rate of diluting air and nitrogen, Q_{a+cg} (L/min.)	14.5	14.5
• flow rate of the liquid injected, I (ml/hr)	0.4	0.4
Concentration of the polluted air presented for sensory evaluations through diffuser:		
• GC/MS analysis		
– at flow proportion of n=31.5 (mg/m^3)	9.96	9.96
• PAS measurements (TVOC Toluene-equivalent)		
– at flow proportion of n=0, background air (mg/m^3)	4.24	4.24
– at flow proportion of n=20 (mg/m^3)	16.04	16.04

Table A3.8 Parameters of the VOC-generator and VOC-polluted air documented during sensory evaluations of air polluted by m8-mixture

Liquid injected: *m8-mixture* (density, ρ = 0.72 kg/L, molecular weight = 121.8 g/mol)	**Untrained panel** (N=33)	**Trained panel-1** (N=14)	**Trained panel-2** (N=9)
Parameters of the VOC-generator producing the air polluted with VOCs:			
• temperature of the injection block (°C)	108	108	108
• temperature of the oven (°C)	120	120	120
• flow rate of diluting air and nitrogen, Q_{a+cg} (L/min)	15.0	9.6	9.7
• flow rate of the liquid injected, I (ml/h)	0.5	0.2	0.1
Concentration of the polluted air presented for sensory evaluations through diffuser:			
• GC/MS analysis			
– at flow proportion of n=31.5 (mg/m^3)	-	-	-
• PAS measurements (TVOC toluene-equivalent)			
– at flow proportion of n=0, background air (mg/m^3)	4.7	3.8	3.2
– at flow proportion of n=20 (mg/m^3)	46.5	30.0	16.4

Table A3.9 Parameters of the VOC-generator and VOC-polluted air documented during sensory evaluations of air polluted by m19-mixture

Liquid injected: *m19-mixture* (density, ρ = 0.79 kg/L, molecular weight =100.8 g/mol)	**Untrained panel** (N=59)	**Trained panel** (N=11)
Parameters of the VOC-generator producing the air polluted with VOCs:		
• temperature of the injection block (°C)	108	108
• temperature of the oven (°C)	120	120
• flow rate of diluting air and nitrogen, Q_{a+cg} (L/min)	14.0	14.1
• flow rate of the liquid injected, I (ml/h)	0.2	0.1
Concentration of the polluted air presented for sensory evaluations through diffuser:		
• GC/MS analysis		
– at flow proportion of n=31.5 (mg/m^3)	-	-
• PAS measurements (TVOC toluene-equivalent)		
– at flow proportion of n=0, background air (mg/m^3)	4.0	3.1
– at flow proportion of n=20 (mg/m^3)	17.5	9.83

Table A3.10a Parameters of the VOC-generator and VOC-polluted air documented during sensory evaluations of air polluted by m22-mixture

Liquid injected: *m22-mixture* (density, ρ = 0.86 kg/L, molecular weight =110.4 g/mol)	**Untrained panel-1** (N=33)	**Untrained panel-2** (N=36)	**Untrained panel-3** (N=43)
Parameters of the VOC-generator producing the air polluted with VOCs:			
• temperature of the injection block (°C)	108	108	108
• temperature of the oven (°C)	120	120	120
• flow rate of diluting air and nitrogen, Q_{a+cg} (L/min)	15.0	10.2	15.4
• flow rate of the liquid injected, I (ml/h)	0.2	0.1	0.1
Concentration of the polluted air presented for sensory evaluations through diffuser:			
• GC/MS analysis			
– at flow proportion of n=31.5 (mg/m^3)	-	-	-
• PAS measurements (TVOC toluene-equivalent)			
– at flow proportion of n=0, background air (mg/m^3)	3.58	4.0	2.0
– at flow proportion of n=20 (mg/m^3)	12.99	10.75	6.18

Table A3.10b Parameters of the VOC-generator and VOC-polluted air documented during sensory evaluations of air polluted by m22-mixture

Liquid injected: *m22-mixture* (density, ρ = 0.86 kg/L, molecular weight =110.4 g/mol)	**Trained panel-1** (N=14)	**Trained panel-2** (N=14)
Parameters of the VOC-generator producing the air polluted with VOCs:		
• temperature of the injection block (°C)	108	108
• temperature of the oven (°C)	120	120
• flow rate of diluting air and nitrogen, Q_{a+cg} (L/min)	10.2	10.2
• flow rate of the liquid injected, I (ml/h)	0.1	0.1
Concentration of the polluted air presented for sensory evaluations through diffuser:		
• GC/MS analysis		
– at flow proportion of n=31.5 (mg/m^3)	-	-
• PAS measurements (TVOC toluene-equivalent)		
– at flow proportion of n=0, background air (mg/m^3)	4.17	3.97
– at flow proportion of n=20 (mg/m^3)	10.92	10.95

Table A3.10c Parameters of the VOC-generator and VOC-polluted air documented during sensory evaluations of air polluted by m22-mixture

Liquid injected: *m22-mixture* (density, ρ = 0.86 kg/L, molecular weight =110.4 g/mol)	**Trained panel-3** (N=9)	**Trained panel-4** (N=8)
Parameters of the VOC-generator producing the air polluted with VOCs:		
• temperature of the injection block (°C)	108	108
• temperature of the oven (°C)	120	120
• flow rate of diluting air and nitrogen, Q_{a+cg} (L/min)	19.0	15.4
• flow rate of the liquid injected, I (ml/h)	0.1	0.1
Concentration of the polluted air presented for sensory evaluations through diffuser:		
• GC/MS analysis		
– at flow proportion of n=31.5 (mg/m^3)	-	-
• PAS measurements (TVOC toluene-equivalent)		
– at flow proportion of n=0, background air (mg/m^3)	3.35	2.24
– at flow proportion of n=20 (mg/m^3)	7.15	6.44

APPENDIX 4

Results of PAS Measurements of the Air Polluted with VOCs

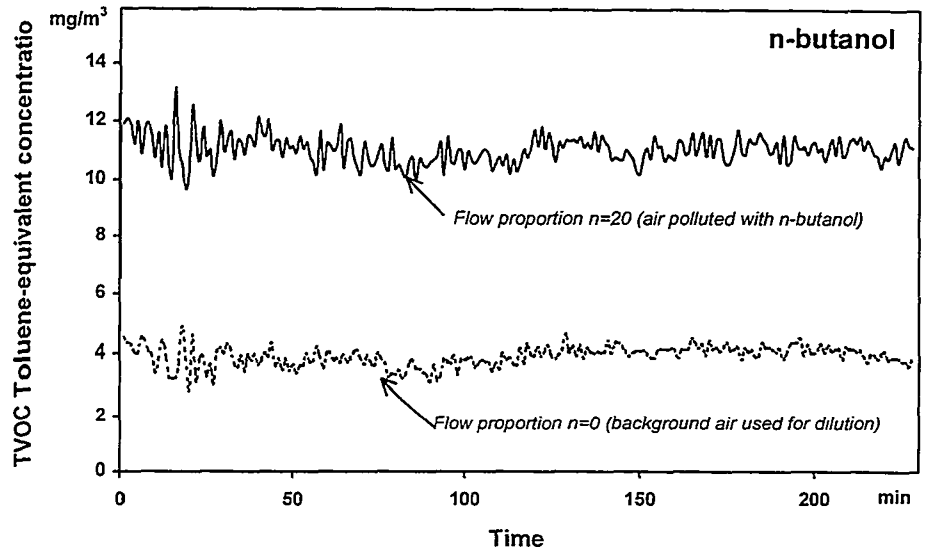

Figure A4.1 PAS measurements of TVOC toluene-equivalent concentration of the air polluted with n-butanol and of the air used for dilution (background air) carried out concurrently with the sensory evaluations made by untrained and trained panels

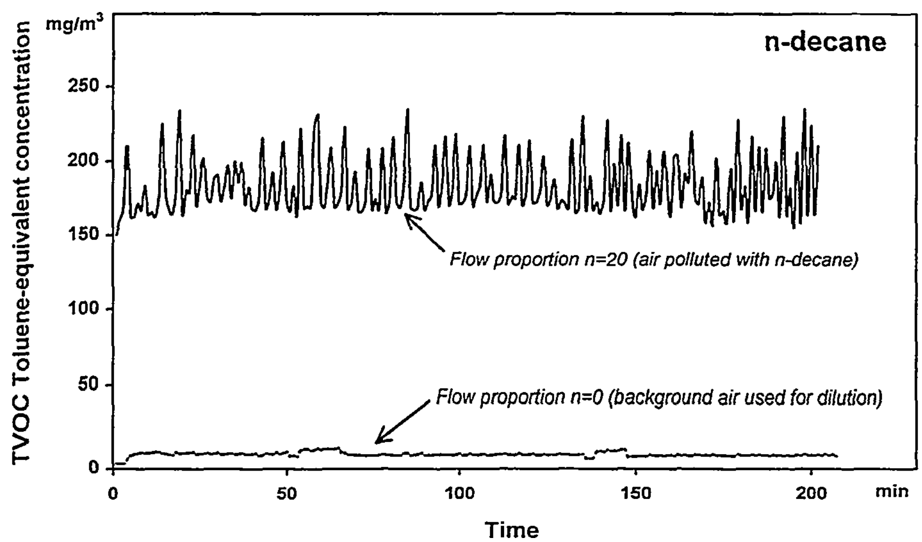

Figure A4.2 PAS measurements of TVOC toluene-equivalent concentration of the air polluted with n-decane and of the air used for dilution (background air) carried out concurrently with the sensory evaluations made by untrained and trained panels

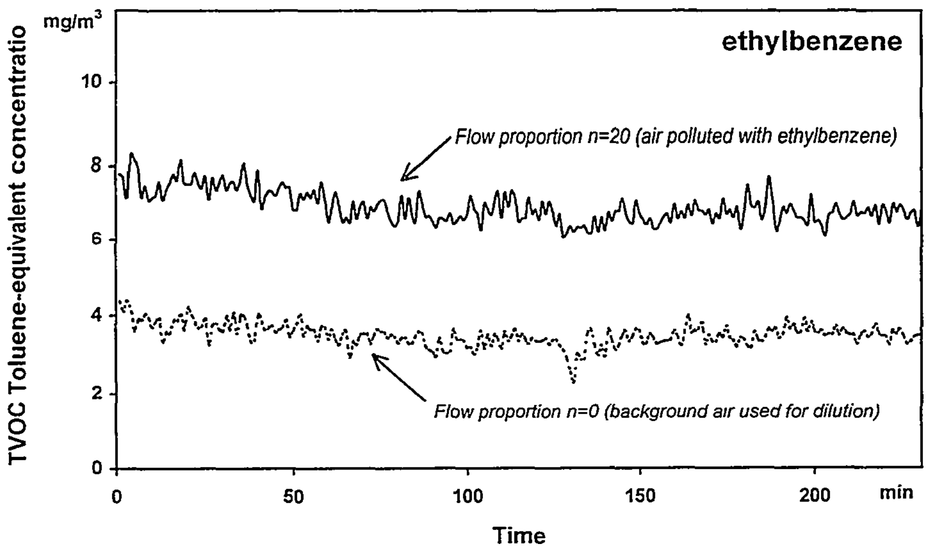

Figure A4.3 PAS measurements of TVOC toluene-equivalent concentration of the air polluted with ethylbenzene and of the air used for dilution (background air) carried out concurrently with the sensory evaluations made by untrained and trained panels

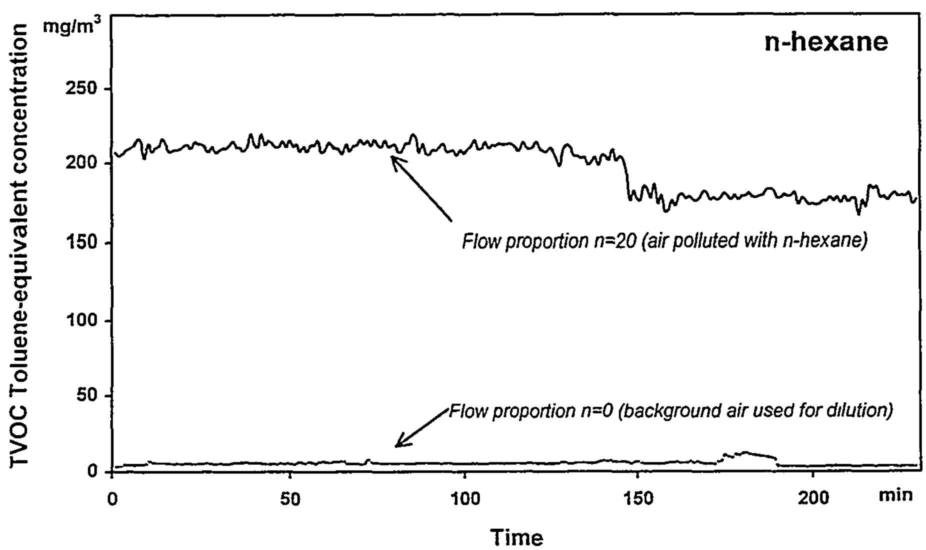

Figure A4.4 PAS measurements of TVOC toluene-equivalent concentration of the air polluted with n-hexane and of the air used for dilution (background air) carried out concurrently with the sensory evaluations made by untrained and trained panels

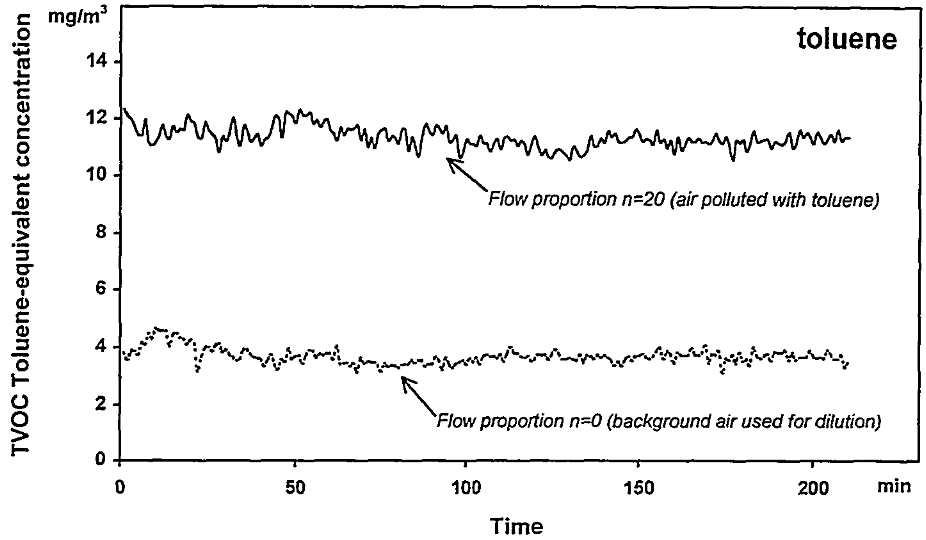

Figure A4.5 PAS measurements of TVOC toluene-equivalent concentration of the air polluted with toluene and of the air used for dilution (background air) carried out concurrently with the sensory evaluations made by untrained and trained panels

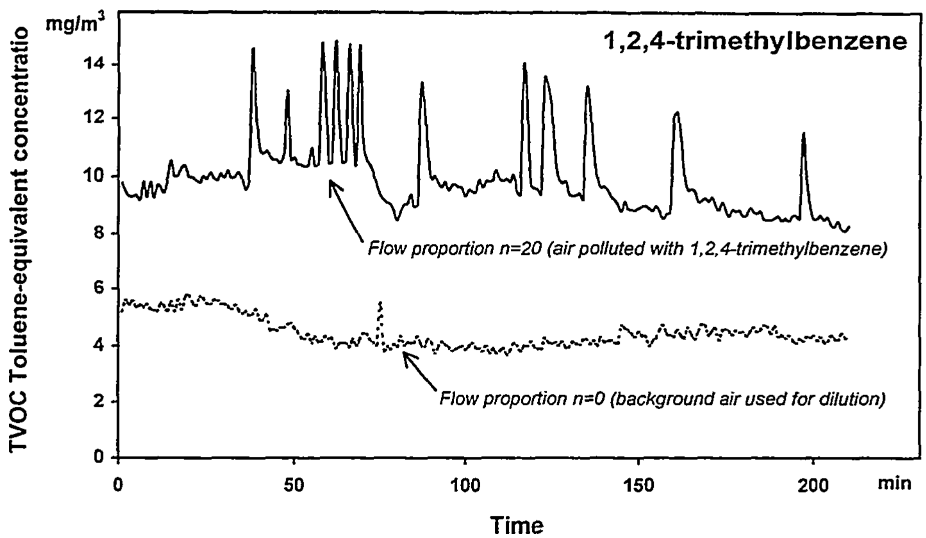

Figure A4.6 PAS measurements of TVOC toluene-equivalent concentration of the air polluted with 1,2,4-trimethylbenzene and of the air used for dilution (background air) carried out concurrently with the sensory evaluations made by untrained and trained panels

Table A5.1 Randomization of the order of presentation of performance tasks to subjects during occupation of the office with and without carpet

Group of subjects	Subject	Order of presentation*			
		Office w/o carpet		Office with carpet	
		try-1†	try-2‡	try-1†	try-2‡
A	1	1	2	3	4
	2	1	2	3	4
	3	1	2	3	4
	4	2	1	4	3
	5	2	1	4	3
	6	2	1	4	3
B	7	2	3	4	1
	8	2	3	4	1
	9	2	3	4	1
	10	3	2	1	4
	11	3	2	1	4
	12	3	2	1	4
C	13	3	4	1	2
	14	3	4	1	2
	15	3	4	1	2
	16	4	3	2	1
	17	4	3	2	1
	18	4	3	2	1
D	19	4	1	2	3
	20	4	1	2	3
	21	4	1	2	3
	22	1	4	3	2
	23	1	4	3	2
	24	1	4	3	2
E	25	1	2	3	4
	26	2	1	4	3
	27	2	3	4	1
	28	3	2	1	4
	29	3	4	1	2
	30	4	3	2	1

* numbers 1, 2, 3 and 4 correspond to the order of presentation of tasks from the performance assessment battery - PAB (PAB-1, PAB-2, PAB-3 & PAB-4, respectively), creative thinking tasks (CT-1, CT-2, CT-3 & CT-4, respectively), addition tasks (A-1, A-2, A-3 &A-4, respectively) and text tasks (T-1, T-2, T-3 & T-4, respectively);

† try-1 took place: for PAB tasks between ca. 5and 25 min of occupation, for addition task between ca. 50 and 80 min of occupation and for the typing text between ca. 80 and 125 min of occupation;

‡ try-2 took place: for PAB tasks between ca. 245 and 265 min of occupation, for addition task between 190 and 215 min of occupation and for text typing between 140 and 190 min of occupation

Table A5.2 Randomization of the exposure conditions in the office (office with and without carpet) among 5 groups of subjects

Group of subjects	Day of a week	Week 1 (day-1)	Week 2 (day-2)
A	Tuesday	w/o carpet	with carpet
B	Wednesday	with carpet	w/o carpet
C	Thursday	w/o carpet	with carpet
D	Friday	with carpet	w/o carpet
E	Monday	w/o carpet	with carpet