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The Role of Volatile Organic Compounds in the Assessment of Indoor Air Quality

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ABSTRACT

The main aim of this thesis is to assess and evaluate the relevance of air pollutants, especially volatile organic compounds (VOC), for indoor air quality (IAQ) in nonindustrial environments. Another attempt is to find out whether indoor-air VOC may be linked to human health and sensory effects. *The experiments* included the development of a method to sample and analyze VOC in indoor air (adsorptive sampling/ gas chromatographic separation/mass spectrometric identification) as well as the application of this method in studies of adsorption/desorption of VOC in building materials and ventilation systems, and the occurrence and behavior of VOC in healthy and sick buildings. The method developed is well suited for indoor air VOC analysis, especially for the fine division in temporal intervals needed for the assessment of VOC in occupied rooms. *The empirical results* show that there is a continuous interplay, regarding VOC and semivolatile organic compounds (SVOC), between indoor materials and indoor air, between ventilation components and supply air, as well as among indoor materials. The results also show that there is an accumulation indoors of outdoor compounds, that are brought indoors by ventilation supply or by materials, such as clothes. Comparatively new *statistical pattern analyses* were applied to data obtained from indoor air VOC analyses in different locations in a sick and a healthy preschool. The results, indicate that this approach may offer an opportunity to distinguish among different buildings and among different locations within buildings with regard to the indoor air composition of VOC. Although promising, further studies of the link between chemical pattern and sensory effects are needed. In a *psychophysical experiment*, it was shown that formaldehyde at the very low concentrations typical for indoor-air VOC could reliably be scaled with regard to perceived intensity and sensory detection thresholds be determined. Two methods of formaldehyde generation were validated by comparing exposure concentrations measured by two independent chemical analytical methods. Comprehensive *critical reviews* of the existing literature on VOC, supplemented the experiments, focusing on adsorption/desorption in indoor materials, methods of measurement, occurrence in the indoor air, as well as on human health-related sensory effects of VOC in indoor environments. In all, *34 compounds*, frequently detected in indoor air, were distinguished as potent for causing human sensory effects. Of these, 13 were recommended for further investigation in human sensory exposure studies, with regard to postulated criteria for non-adverse health effects and possibility of well-controlled quantitative generation. Taken together, it is *concluded* from the experiments and the literature reviews that present techniques/methods to assess IAQ, presented in the scientific literature, do not show any certain proof of a link between indoor factors, such as VOC or total volatile organic compounds (TVOC), and human sensory or health effects (special cases such as formaldehyde excluded). Nor is there any proof that these factors are irrelevant for the encountered effects. This lack of evidence is merely due to poor study design. *Future research* on IAQ and adverse health and sensory effects should be extended to include not only the nonreactive VOC, but also, for example, reactive, polar, and SVOC. Appropriate methods of human sensory measurements should be utilized, and certain groups of people with special sensitivity should be distinguished and used in IAQ studies which are characterized by low concentrations.

Keywords: Indoor air quality, VOC, TVOC, formaldehyde, adsorption, desorption, sensory effects, odor, sensory irritation, SBS

LIST OF STUDIES

The present Doctoral Thesis is based on the following seven studies which will be referred to by their arabic numbers. With the exception of Study 4, multiple authors were agreed to be listed in alphabetical order.

- (1) Johansson, I. (1978). Determination of organic compounds in indoor air with potential reference to air quality. *Atmospheric Environment*, 12, 1371-1377.
- (2) Berglund, B., Johansson, I., & Lindvall, T. (1989). Volatile organic compounds from used building materials in a simulated chamber study. *Environment International*, 15, 383-387.
- (3) Berglund, B., Johansson, I., & Lindvall, T. (1988). Adsorption and desorption of organic compounds in indoor materials. In B. Berglund & T. Lindvall (Eds.), *Healthy Buildings '88. Vol. 3: Systems, materials and policies for healthier indoor air* (pp. 299-309). Stockholm: Swedish Council for Building Research (D21:1988).
- (4) Noma, E., Berglund, B., Berglund, U., Johansson, I., & Baird, J. C. (1988). Joint representation of physical locations and volatile organic compounds in indoor air from a healthy and a sick building. *Atmospheric Environment*, 22, 451-460.
- (5) Berglund, B., Högman, L., & Johansson, I. (1988). Reliability of odor measurements near threshold. *Reports from the Department of Psychology, The University of Stockholm*, No. 682.
- (6) Johansson, I. (1990). *Volatile organic compounds in indoor air with significance for health and comfort*. Stockholm: Institute of Environmental Medicine, Karolinska Institutet (IMM-report 6/90). (in Swedish with English summary)
- (7) Berglund, B., & Johansson, I. (1996). Health effects of volatile organic compounds in indoor air. *Archives of the Center for Sensory Research*, 3(1), 1-97. (in Swedish with English summary).

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To Anders, Jesper and Elin

INTRODUCTION

The indoor environment is important to health. The concept of *health* defined by WHO is “a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity” (Appendix I). Most of our time is spent indoors, mainly in nonindustrial buildings, such as dwellings, offices, schools and caring institutions. Human bioeffluents have, traditionally, been considered the most critical among indoor air pollutants, and in occupied spaces, the concentration of the human body effluent carbon dioxide, CO₂, has been used as an indicator for indoor air quality, IAQ (e.g., Friberg & Ronge, 1970). In practice, CO₂-concentration measurements are still utilized for the control of ventilation efficiency in occupied spaces, such as schools and assembly halls. In nonoccupied indoor environments, the outdoor air was long supposed to be the critical source for indoor air pollution. However, during the 1970s, coinciding with the energy crisis, adverse health or sensory effects were frequently reported in certain buildings, and could not easily be explained. Eventually, formaldehyde in indoor air, emitted from building materials, was shown to be one cause of the problems (Andersen, Lundqvist, & Mølhave, 1975). Subsequently, the use of formaldehyde was restricted, and indoor concentrations decreased. However, the occurrence of adverse health and sensory effects in indoor environments continued. Other volatile organic compounds (VOC), with similar effects, then came into focus. The concept of VOC was eventually defined by the World Health Organization (WHO, 1989a) because it was anticipated that indoor VOC were crucial for IAQ and the appearance of adverse health and sensory effects. It was soon realized that in order to investigate potential causal relationships between IAQ and adverse health or sensory effects, interdisciplinary research is needed, involving the development of physical/chemical methods as well as theory and methods in physiology, psychophysics and psychology.

The concept of *air quality* is dubious to define, as it is a common term used in ordinary language that has not yet been defined in scientific terms. It refers to the perceptions of the air one breathes, and clearly it has to be viewed as a hypothetical construct or a complex theoretical entity. That is, one can imagine that a certain air quality experienced is good because it contains the right combination of certain properties such as temperature, relative humidity, and chemical content. In order to use this concept in a meaningful way one needs a clarified structured approach on how measures of properties involved can be combined and interrelated in a quantitative mathematical model.

For practical use, international authorities have proposed various definitions of IAQ. For example, in the definition given by the European Concerted Action on “Indoor Air Quality and its Impact on Man” (ECA, 1996), all features of indoor air are regarded to have an impact on man, thus, the atmospheric environment is included, and in particular indoor air contaminants. However, admittedly, also other agents of the indoor environment may be part of an interaction, such as the thermal environment. Lindvall (1995) concludes that in general terms IAQ is the result of a balance between pollutant production, sinks, and the supply of outdoor air. The ECA (1997) concen-

trates on giving a definition of total volatile organic compounds (TVOC) as an indicator of IAQ. The American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE, 1989) defines acceptable IAQ as: “air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities, and air with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction.” Their intention is to specify minimum ventilation rates based on IAQ, that will be acceptable to human occupants and, in addition, would help avoid adverse health effects. ASHRAE also defines a contaminant as an unwanted airborne constituent that may reduce human acceptability of air. Contaminants include various gases, vapors, microorganisms, smoke, and other particulate matter. Deleterious factors include toxicity, radioactivity, potential for inducing infection or allergies, irritants, extreme thermal conditions, and objectionable odors. In the indoor air quality program of the World Health Organization Regional Office for Europe in Copenhagen (WHO/EURO), the IAQ concept includes physical (e.g., radon), chemical and biological pollutants, and relates to human health. The program work is focused on health aspects related to indoor air contaminants like organic compounds, radon, formaldehyde, biological contaminants, combustion products, and inorganic fibres (Suess, 1992). Air Quality Guidelines for Europe were developed by WHO (1987) for 28 chemical air contaminants, with no differentiation between indoor and outdoor exposure. Criteria for carcinogenicity and other toxic effects as well as sensory effects are considered relevant. The Nordic Committee on Building Regulations (NKB, 1991) focuses on human perception and health effects in their definition of IAQ. It is stated that the indoor air quality is satisfactory if the great majority of visitors perceive the air as acceptable, and no adverse health or sensory effects are caused.

Many persons report *adverse health and sensory effects* when staying in certain nonindustrial buildings. Since the mid-1970s, the problem is common in many buildings and has come to be called the Sick Building Syndrome (SBS). WHO (1983) specified a number of symptoms that are thought to typify SBS (see Appendix I). The symptoms may be observed in the general population but are more prevalent in (healthy) persons who reside or work in a certain building. Another proposed characteristic of SBS is that the symptoms decrease or disappear when the afflicted persons are away from the suspected building. Thus, a common operational measure of SBS is the number of symptoms attributable to a building as reported by an individual or a group of individuals (e.g., Raw, 1992; B. Berglund, Jaakkola, Raw, & Valbjørn, 1996).

Volatile Organic Compounds, VOC

An internationally recognized definition of volatile organic compounds, VOC, was adopted in consensus among a group of WHO experts (WHO, 1989a). It was specified that the VOC-concept should include volatile organic compounds within a defined interval of boiling points, namely, 50-100 to 240-260 °C, sampled by adsorption and analyzed by gas chromatography (GC) or liquid chromatography (LC). Outside this

interval, the groups of compounds with low boiling points, <0 to 50-100 °C, are named very volatile organic compounds, VVOC, and those with high boiling points, 240-260 to 380-400 °C, are named semi volatile organic compounds, SVOC, and, finally, compounds with boiling points exceeding 380 °C, are named particulate organic matter, POM. (See further Appendix I).

The group of VOC is often treated as one entity, and is then named TVOC, which stands for total volatile organic compounds. Most researchers agree that TVOC should be operationally defined as the sum of all compounds sampled and analyzed within the range of boiling points specified for VOC. One problem, however, is that in practice no standardized method exists for sampling and analyzing all compounds occurring within the boiling point range specified by WHO, which would, of course, also exclude all components outside it. Typically, authors define their own arbitrary limits for VOC, based on special purposes combined with the performance characteristics of their own analytical systems. However, there are some definitions of TVOC suggested for general use as, for example, the one by Seifert (1990). He proposes a definition based upon separated VOC which are grouped into chemical classes and ranked according to their measured concentrations. Mølhave (1991) presents a tentative dose-response relationship for TVOC and discomfort, where TVOC represents the sum of a selected blend of 22 VOC, frequently occurring indoors. Later, Mølhave and G. D. Nielsen (1992) use the sum of the measurable concentrations of nonreactive substances in indoor air as a more generally applicable measure of TVOC (and air quality). In a proposal of a new definition of TVOC, ECA (1997) recommends that boiling-point ranges be replaced by a definition of an “analytical window”. That is, the air sample should be analyzed in a nonpolar GC column, and the part of the chromatogram from *n*-hexane to *n*-hexadecane should be considered to “define” VOC.

Common VVOC, VOC, and SVOC that are sampled in indoor air are aliphatic hydrocarbons (C_1 - C_5 ; C_6 - C_{16} ; C_{17} - C_{20}), unsaturated aliphatic hydrocarbons (C_2 - C_5 ; C_6 - C_{16} ; C_{17} - C_{20}), aromatic hydrocarbons (e.g., benzene, toluene, C_2 - and C_3 -alkylbenzenes), terpenes (e.g., α -pinene, limonene, carene), alcohols (e.g., propanol, 1-butanol, 2-ethylhexanol), aldehydes (e.g., formaldehyde, acetaldehyde, hexanal, heptanal, nonanal, benzaldehyde), ketones (e.g., acetone, methyl-ethyl-ketone, octanones), acids (e.g., acetic acid), and esters (e.g., *n*-butylacetate). There are also halocarbons like 1,1,1-trichloroethane, tetrachloromethane, tetrachlorethene, *p*-dichlorobenzene and some freons.

No method of chemical testing, analysis or integration covers all or even the majority of the airborne compounds occurring indoors (or outdoors), and the choice of a method of measurement for VOC inevitably defines and limits the occurrence (and concentration) of reported contamination. In practice, large differences exist in sampling strategy, method of sampling, analysis, and the interpretation of results. This implies that comparison of results from different studies is dubious, because, often more factors are different than common. The literature on methods to measure VOC in indoor air, with special emphasis on the attempt to assess TVOC, is reviewed by Hodgson (1995).

VOC in the Indoor Air of Non-Industrial Buildings

VOC are always found in indoor air as well as in the ambient outdoor air. Air contains, for example, “naturally” occurring compounds, like methane, “marsh gas”, formed by fermentation of vegetable matter under anaerobic conditions, as well as human body effluents and compounds produced by human activities, like VOC emitted from industrial processes, heat combustion, or motor vehicles. Knowledge on *composition and concentrations* of VOC in indoor air gives information about the effectiveness of ventilation systems, that is, whether these remove pollutants, or if pollutants are produced within or supplied by the systems from other sources. Knowledge on *dissimilarities* in composition and concentration of VOC, between different parts of a room, or of a building, is useful for tracing pollutant sources. Knowledge on *time variations* of VOC composition over the day, over the week, or during different seasons of the year, provides information about the influence on indoor air quality, from occupants and their activities, and from climatic conditions. Furthermore, VOC are measured in indoor spaces with the ambition to find out whether one or several compounds, or a pattern of compounds with respect to composition and/or relative concentrations, could be the “cause” of adverse sensory effects, that sometimes affect the occupants (e.g., Bornehag, 1994; 1995).

The occurrence of VOC in indoor air of nonindustrial buildings, in full use as well as empty with no occupants, has repeatedly been mapped, all over the world, especially in the industrialized countries. Extensive literature reviews on indoor air investigations are, for example, Shah and Singh (1988), WHO (1989a), Otson and Fellin (1992), S. K. Brown, Sim, Abramson, and Gray (1994), and Study 7 (B. Berglund & Johansson, 1996). Generally, it may be concluded that a great number of VOC is found in indoor air, up to 50-300 in the same place, with number and concentrations indoors significantly elevated above those outdoors. In nonindustrial buildings, the concentrations of single compounds are usually below $5 \mu\text{g}/\text{m}^3$ ($0.005 \text{ mg}/\text{m}^3$), with only one, or a few, sometimes exceeding $50 \mu\text{g}/\text{m}^3$ ($0.05 \text{ mg}/\text{m}^3$), whereas in new, or newly renovated buildings much higher concentrations are found, sometimes even as much as one order of magnitude. The total amount of all compounds, TVOC, is about $1\text{-}5 \text{ mg}/\text{m}^3$, in buildings in use, normally even below $1 \text{ mg}/\text{m}^3$, and in new buildings often $>10 \text{ mg}/\text{m}^3$.

Otson and Fellin (1992) reviewed sources and occurrences of VOC in the indoor environment. They also compiled lists of commonly observed VOC in indoor air, with typical concentrations. S. K. Brown et al. (1994) have presented a list of 80 compounds, as typical for dwellings, based upon results from statistical analyses of estimated mean values of VOC measured in 50 indoor air studies found in the literature. The compounds were listed in the order of measured concentration, and the 19 compounds having mean concentrations above $5 \mu\text{g}/\text{m}^3$ were generally considered as predominant indoor compounds (see Appendix II: Table 1). ECA (1997) presents a list of 63 known VOC, assorted with respect to chemical groups, that are estimated to be of special interest for the indoor environment; ECA recommends them as the minimum

number to be included in quantitative indoor TVOC analysis (see Appendix II, Table 2). Their list consists of 12 aromatic hydrocarbons, 15 aliphatic hydrocarbons in the interval of $n\text{-C}_6$ to $n\text{-C}_{16}$, and 1 to 5 compounds from each of the groups cycloalkanes, terpenes, alcohols, glycols/glycolethers, aldehydes, ketones, halocarbons, acids, and esters. Some interesting differences exist between the two ways of listing. For example, acetone and ethanol belong to the group of predominant indoor compounds according to S. K. Brown et al. (1994), but are excluded by the ECA (1997) definition of the “analytical window” to be considered for TVOC analysis. Conversely, a group of glycols and glycolethers are only included in the ECA (1997) list.

Sources of Indoor-Air VOC

It is difficult to distinguish the origin of indoor-air VOC because there is a great number of possible sources and each single compound may emanate from more than one source, including those outdoors. For example, the commonly occurring aromatic compounds, toluene and xylenes, typically emanate from combustion (tobacco smoke, heating, motor vehicle exhaust), fuels, building materials, furnishings, and consumer products, all of which may be present in the indoor environment. Investigations on sources of indoor air pollutants, based on chamber studies for the characterization of emission from single materials, or on field studies in new or established buildings, empty or occupied, are reviewed by Otson and Fellin (1992), S. K. Brown et al. (1994), Wolkoff (1995), Study 7 (B. Berglund & Johansson, 1996), and H. Gustafsson and Lundgren (1997).

Sources of indoor-air VOC may be categorized in different ways. For example, according to the temporal pattern of emission (Seifert & Ullrich, 1987; Wolkoff, 1995), or arbitrarily according to specific groups like outdoor, tobacco smoke, and materials (Bluyssen, De Oliveira Fernandes, Groes, Clausen, Fanger, Valbjørn, Bernhard, & Roulet, 1996), or according to tobacco smoke and other combustion sources, building materials and furnishings, consumer products, and outdoor sources (Otson & Fellin, 1992).

Seifert and Ullrich (1987) propose that the time dimension should be included in the categorization of indoor-air VOC. Sources should be distinguished with respect to their emission time, like (a) continuous, with regular or irregular source strength, and (b) intermittent, with regular or irregular time-pattern, and this should be taken into account when designing sampling strategy for an indoor environment. Wolkoff (1995) categorized sources according to their time emission profiles, that is, (a) building-related emission (building materials, ventilation and soil), including emission times of weeks up to continuous, (b) human activity-related emission (household and consumer products, humans, and office equipment), including emission times of minutes to hours, and (c) outdoor-related sources (traffic and neighboring industry) with emission times of hours. For building materials, Wolkoff (1995) distinguishes between primary pollutant sources, emitting residues from the manufacturing (solvents, additives, and

unreacted monomers) and secondary pollutant sources, emitting as a result of degradation through chemical reactions or adsorption/desorption of ambient compounds.

The outdoor air is an important source of indoor air pollution and the composition of outdoor-air VOC is usually reflected indoors. However, the number and concentrations of VOC indoors are usually elevated above those outdoors, indicating that there are also sources indoors that influence air quality (e.g., S. K. Brown et al., 1994; Wolkoff, 1995). Based on the results of two field investigations (Seifert, Mailahn, Schultz, & Ullrich, 1989; Wolkoff, Clausen, P. A. Nielsen, & Mølhave, 1991), Wolkoff (1995) states that the major sources of indoor VOC are building materials and human activities, approximately in a 1:1 ratio in established buildings. For new buildings, or newly renovated buildings, the VOC concentrations are considerably higher than those encountered in established buildings, with building materials, including paints, glues, wall paper and carpets, as the dominant sources. Usually VOC concentrations decrease down to “normal” levels within weeks or months and a higher ventilation rate is recommended during the first half year after building completion (e.g., B. Berglund, Johansson, & Lindvall, 1982b; Seifert et al., 1989). However, more recently it has been pointed out that building materials of a new kind have been introduced, in which traditional synthetic low-boiling solvents are substituted with natural compounds and high-boiling synthetic chemicals. This may give a low initial TVOC emission, but on the other hand, there is an additional, delayed, emission of less volatile compounds which may stay at elevated concentrations during several months (Reitzig, Mohr, Heinzow, & Knöppel, 1998). Earlier, Ku, Andersson, B. Andersson, C. A. Nilsson, and Sandström (1996a, 1996b) reported on a delayed emission process when using ecological water-based paints containing linseed oil.

The contribution from body effluents, as a source of air pollution, is often neglected in indoor investigations or reported to be very low. However, this may be due to the fact that characteristic human VOC consist of very volatile compounds that may not be comprised by the air sampling methods (Tenax adsorbent), and strongly polar compounds, like organic acids, that are not eluted in the chromatographic analysis.

Chemical and Physical Processes of VOC in Indoor Air

VOC in indoor air originates from primary sources indoors and from chemical and physical interactions among sources and between sources and the environment. The primary emission of VOC is from different indoor sources (humans, activities, materials) and from a transfer of VOC into the indoor environment from sources outside the building envelope. The secondary emission of VOC, is either due to adsorption/desorption processes on materials, or chemical reactions on material surfaces or within materials. Finally, chemical reactions may occur in the indoor air, between different VOC, or between VOC and inorganic gases like O_3 or NO_x , reactions sometimes influenced by relative humidity and temperature.

The phenomena of adsorption and desorption has been the subject of several investigations, as reviewed in Study 3 (B. Berglund, Johansson, & Lindvall, 1988) and

Study 7 (B. Berglund, & Johansson, 1996). For example, there is a “sink effect” in any indoor (enclosed) space, that is, pollutants may be removed, temporarily or permanently, from the indoor air through adsorption on material surfaces. Also, a delayed emission may occur, that is, compounds emanating from activities or newly installed materials are adsorbed onto other materials, from which they are subsequently emitted at a much lower rate than from the original material. Odorous and nonodorous pollutants originating from a material may be detected in the indoor air a long time after the material itself has been removed. A well-known example of delayed emission is the odor of environmental tobacco smoke, ETS, that may be perceived in room air several months after smoking was terminated.

It has recently been pointed out that chemical reactions between certain, unsaturated VOC, or SVOC, and oxidants, such as O_3 or NO_2 , may take place in indoor air under certain circumstances, yielding new compounds with potential sensory irritation effects. It is hypothesized that, through these reactions, very polar compounds such as aldehydes, ketones and carboxylic acids are formed. Also, short-living chemical radicals and other possible reaction products, such as alkyl nitrates and peroxyacyl nitrates may be formed, which are not detected by the conventional indoor air analyzers. Several laboratory studies support these theories. For example, Weschler, Hodgson and Wooley (1992) exposed a new carpet to O_3 , and found that formaldehyde, acetaldehyde, higher aldehydes (C_5 to C_{10}) as well as benzaldehyde were formed. In addition, an increase was observed in the concentration of TVOC. It is assumed that through chemical reactions in the outer layers of the carpets, volatile compounds are formed from nonvolatile compounds. Zhang, Wilson and Liou (1994) studied the reaction between O_3 (ca. 50-350 $\mu g/m^3$) and unsaturated VOC. Formaldehyde and formic acid were formed in the reaction between O_3 and styrene, and benzaldehyde and acetic acid were formed from the mixture of limonene, O_3 and air. In a simulated ventilation equipment, B. Andersson, Ku. Andersson, C. A. Nilsson, Sandström, Stjernberg, and Sundell (1996) studied the chemical reactions between styrene and O_3 and also found formaldehyde and benzaldehyde to be major products.

Sampling Methods for VOC in Indoor Air

Available techniques for the sampling of VOC are *direct-reading continuous analysis*, *grab sampling*, *cryogenic sampling*, and *adsorptive sampling* on solid or liquid media. The last mentioned type of sampling, adsorptive sampling, may either be *active (pumped)*, i.e., the sample is sucked through the sorbent by a pump, or *passive (diffusive)*, i.e., the sample is diffused through a static air layer or permeated through a membrane into the sorbent. No single method of sampling exists that may be used for the whole spectrum of VOC in indoor air. Therefore, a method must be chosen with respect to the aims of investigation. Several aspects should be regarded, such as, what spectrum of compounds and what concentrations are to be expected. Also, variations over time of composition and concentration are essential, and whether the interest

is to observe short-time (minutes) concentration peaks or long-time (hourly, weekly or monthly) averages of concentrations.

The *direct-reading continuous analysis* involves momentary sampling and analysis and may be used if the concentrations are high enough to be detectable, or specific VOC need not be identified. Detectors used in continuous flow analytical instruments are Flame Ionization Detector (FID), Photo Ionization Detector (PID) (e.g., Wolkoff et al., 1991), and Photoacoustic Spectrometry (PAS) also named photoacoustic infrared (IR), (Brüel & Kjær, Denmark; Krüger, Kraenzmer, & Strindehag, 1995). The responses from all three methods are equivalent to the sum of all detected VOC. A limited review and comparison of direct on-site analysis techniques is presented by Hodgson (1995). Several recently developed so-called “electronic noses” are also direct reading instruments. The detection principles are based on a change in electrical resistance of semiconducting sensors made of metal oxide or conducting polymers (ECA, 1999). The use of a combination of several different sensors may give a semi-qualitative response for different compounds, but none of the available instruments has been proven to have a satisfactory validity, that is, to be able to substitute human observers in measuring odor (e.g., Wenger, Quistgaard, & Miller, 1995). Generally, all mentioned direct-reading instruments have the disadvantage that the response is nonselective, and, more importantly, they are only capable of measuring total concentrations that are higher (≥ 1 mg/m³) than those usually pertaining to indoor environments.

For formaldehyde, there are some automated analytical instruments available which may be used for continuous analysis of concentrations below 1 mg/m³. One instrument applicable for indoor air is based on flow analysis with UV-detection, utilizing the reaction between acetylacetone and ammonium acetate (cf. Skalar 9400, Skalar Analytical, EZ Breda, The Netherlands), and another is based on wet-chemical analysis (cf. CEA Instruments, Inc., Model 555) utilizing the formaldehyde selective pararosaniline colorimetric analysis method (Lyles, Dowling, & Blanchard, 1965; Matthews, Hawthorne, Howell, Metcalfe, & Gammage, 1982).

In *grab sampling*, the whole-air sample is taken into evacuated stainless steel canisters or sucked into plastic bags by a pump (Wallace, 1991; Knöppel, 1992). The vessels are intended for keeping the air volume and pollutant concentration constant during sampling and subsequent transport. In the laboratory, either the whole sample is recovered by cryogenic focusing, or only a small fraction is taken out, and analyzed. The low sample volumes, regarded as possible to handle in field studies, about 1 L to 6 L, are usually insufficient for available methods of chemical analysis, especially for available methods of identification. Furthermore, wall effects in the sample pump, fittings, and the sample container, like adsorption or degradation, may cause loss of sample during transport.

In *cryogenic sampling*, the air sample is sucked through a low volume trap, immersed in a cooling medium like liquid nitrogen or solid carbon dioxide, by which VOC are condensed (Perry & Young, 1977; Jonsson & Berg, 1983). The compounds sampled are then heat desorbed and transferred by carrier gas into an analytical instru-

ment, usually a gas chromatograph. This procedure is rather complicated in field applications, and the water content of the air, several g/m^3 , will also be trapped and may then disturb or even preclude the subsequent analysis.

Adsorptive Sampling of VOC in Indoor Air

Normally, in indoor air investigations, the target compounds must be enriched before analysis, and the most suitable and common method for this is *adsorptive sampling*, either by *actively sucking* the air through an adsorption trap, or by *passive diffusion* onto the trap. The compounds sampled are then recovered by either solvent extraction or thermal desorption. The solvent extraction leads to a dilution of the compounds sampled and only a small fraction of the extract may be injected into the analytical system. In thermal desorption, the whole sample is recovered but diluted by the carrier gas, although, in this case it may easily be reconcentrated into a smaller volume by a second step of cryofocusing. Finally, the sample is injected into an analytical instrument for separation, quantitation and identification, usually a gas chromatograph connected to a mass spectrometer.

Active sampling is accomplished by drawing the air through the sorbent trap by a (battery driven) sampling pump. To avoid condensation of water, the trap is usually kept at ambient temperature. For indoor air, with sample volumes of about 10 to 15 L, the detection limits are about $0.1 \mu\text{g/m}^3$ for quantitative analysis.

Passive sampling is controlled by a physical process, such as diffusion through a static air layer or permeation through a membrane. The theoretical basis for these processes can be described by Fick's first law of diffusion (see e.g., Daniels & Alberty, 1961). It involves mathematical expressions relating the mass uptake to the concentration gradient, the time of exposure, and the sampler area exposed to the pollutant atmosphere. In field investigations, special factors have to be taken into account, for instance nonsteady-state sampling, the effects of fluctuating concentrations, sorbent saturation, temperature, and pressure (R. H. Brown, 1993). The sampling rate is relatively low and, for indoor air applications, it may be necessary to expose the samplers for several days, or weeks, in order to collect sufficient material for accurate analysis. Typically, the sensitivity of the procedure for one week of exposure may be about $1 \mu\text{g/m}^3$ (De Bortoli, Knöppel, Pecchio, Schauenburg, & Vissers, 1992). The mass uptake rates decrease as the exposure time increases (e.g., Bradshaw & Ballantine, 1995), especially at high concentrations (ppm-levels) and when the adsorbent/adsorbate pairing is nonideal (e.g., Bradshaw & Ballantine, 1995).

When an adsorptive air sampling method is designed, it has to be considered that the *water content* of indoor air, especially in the presence of occupants, may be large (ca. $3,000\text{--}7,000 \text{ mg/m}^3$), as compared to the VOC content ($< 1 \text{ mg/m}^3$). This implies that the target compounds have to be extracted, not only from the air, but also from the great water content. This is usually accomplished during the concentration step by using a sorbent with low affinity to water or, which is less common, during the subse-

quent analysis by using a selective separation column or a detector that discriminates water.

Selection of suitable *sorbent media* depends on type of sample, on whether a broad spectrum of different compounds or only some selected target compounds are looked for, and on the chemical and physical properties of the individual compounds. Influential properties are volatility, polarity, reactivity, chemical structure, and molecular size. Many investigations and reviews have had as their aim to characterize sorbents suitable for ambient air sampling, for example, Sheldon, Sparacino, and Pellizzari (1985), Namiesnik (1988), Rothweiler, Wäger, and Schlatter (1991), De Bortoli et al. (1992), Quintana, Uribe, and Lopez Arbeloa (1992), Tirkkonen, Mroueh, and Orko (1995), Wolkoff (1995), and R. H. Brown (1996). Applicable media are *inorganic materials*, like silica gel, molecular sieves (usually made from aluminosilicates, named zeolites), *porous polymers* (polymeric resins), and *carbon based products*. Of these, the *inorganic materials* are normally not used for VOC since they are thermally unstable and have a high affinity for water, whereas the other sorbents are frequently used, either alone or combined in so-called multisorbent traps. The properties of the sorbents may be modified by impregnation with stationary phases of chromatography, or selectively reactive chemicals, as, for example, the use of diphenylhydrazine impregnated on glass filters for trapping aldehydes (Levin, Ku. Andersson, Lindahl, & C. A. Nilsson, 1985).

The *carbon based products*, also called *charcoal*, are activated carbon and carbon black which are used either as they are, or graphitized, or modified with a stationary phase. Activated carbon consists of charcoal, treated at high temperature with steam, air, or CO₂. Charcoal is in turn produced by stove combustion of wood in an oxygen deficient atmosphere, giving a low-order graphitic structure. The type of wood, for example, different types of nut shell, is essential for the properties of the final product. On the other hand, carbon black is obtained by the incomplete combustion of natural gas or liquid hydrocarbons. Commercially available products of graphitized carbon blacks are, for example, Carbotrap and Carbograph.

Examples of *porous polymers* used in air sampling are 2,6-diphenyl-*p*-phenyleneoxide (e.g., Tenax, Chrompack), styrene-divinylbenzene (e.g., Chromosorb 102 or 106; Porapak Q), and divinylbenzene (e.g., HaySep Q). Tenax (e.g., Tenax GC, Tenax TA) is the most extensively used sorbent for indoor air sampling. It is also the most investigated material with respect to adsorption and desorption efficiency for a wide range of organic compounds found in indoor and outdoor air, and to background emission and formation of artifacts depending on sampling, desorption and storage conditions (Rothweiler, Wäger, & Schlatter, 1991; De Bortoli et al., 1992; Tirkkonen, Mroueh, & Orko, 1995; R. H. Brown, 1996). One disadvantage, however, that has to be considered in indoor air studies, is that the adsorption capacity for compounds of molecular weight <C₆ is deficient for Tenax (Rothweiler, Wäger, & Schlatter, 1991; V. M. Brown, Crump, & Gardiner, 1992; Bayer, 1994).

Several authors report the use of *multisorbent traps*, that is, traps that are packed with several sorbents in a series. For example, Bayer, Black, and Galloway (1988)

used Ambersorb XE 340 (Polyscience), Tenax RGC 60/80 m (Alltech Associates), and glass beads (Alltech Associates), separated by glass wool plugs; Bianchi and Varney (1992) used triple-packed adsorbent tubes with a combination of carbon black and molecular sieve sorbents (Carbotrap B, C, and Carbosieve SIII); and Bishop and Valis (1990) used a multisorbent trap containing Tenax-Ambersorb-charcoal. Multisorbent traps may be useful for sampling a wide spectrum of compounds at the same time, but a drawback is that they may also produce more complex background.

The adsorption capacity of a sorbent can be determined as the *break through volume* (BTV), that is, the volume of air that may be sampled before the target compounds appear as an effluent of the sorbent trap. According to the American organizations, National Institute of Occupational Safety and Health (NIOSH, 1977) and Occupational Safety and Health Administration (OSHA, 1985), the BTV for occupational investigations is to be determined for pumped samples in a standard atmosphere of twice the permissible exposure limit (PEL) concentration and at 80 % relative humidity. Break through is defined to occur when the effluent concentration reaches 5% of the inlet concentration. The safe sample volume is set at two-thirds of the 5% break through volume. The BTV may be determined by analyzing a similar adsorbent tube connected in series with the original, or by continuous direct analysis of the effluent in a FID (R. H. Brown & Purnell, 1979; Bertoni, Bruner, Liberti, & Perrino, 1981; M. Harper, 1993). Important influential factors to be considered are flow-rate, temperature and relative humidity during sampling, as well as the concentration of the organic compounds, their mutual interference, and their boiling points. An alternative method is to determine chromatographic retention volumes in a separation column packed with the sorbent (R. H. Brown & Purnell, 1979). However, with this method, factors like sample concentrations, variations in temperature, relative humidity during sampling, and the presence of other compounds in the sample are not taken into account.

Artifacts and background. Cleaning of sorbents before use is accomplished either by solvent extraction or, more usually, by thermal elution at slightly higher temperatures than used for sample elution. An unused, newly cleaned sorbent may have a very low, or almost no background, but after sampling, artifacts may become apparent. For Tenax, which is the most investigated sorbent, typically, the background contains oxidation products like benzaldehyde, acetophenone, 1-phenylethanone, benzoic acid (Atlas, Sullivan, & Giam, 1985; Walling, Bumgarner, Driscoll, Morris, Riley, & Wright, 1986), especially when exposed to low ozone concentrations (Cao & Hewitt, 1994a). In addition, a significant background of benzene and toluene has been found for Tenax (De Bortoli et al., 1992).

Long-time *storage* of conditioned, or sampled, adsorbent traps may result in enhanced background levels and losses of sampled compounds of low volatility (Cao & Hewitt 1994b; Bishop & Valis, 1990). De Bortoli et al. (1992) conclude that, for Tenax and Carbotrap, storage at room temperature will increase all background values significantly, compared to storage at -15°C for several weeks with no resulting increase in background level.

In indoor air studies, there are few reports on *sample decomposition on sorbent*. Calogirou, Richter Larsen, Brussol, Duane, and Kotzias (1996) found that, in the presence of low concentrations (8-150 ppbv) of ozone during active sampling on Tenax, terpenes and terpenoids containing C-C double bonds are significantly decomposed (i.a., *b*-pinene < *a*-pinene < *d*-limonene).

Analysis of VOC in Indoor Air

For analysis, the sampled VOC are normally injected into a gas chromatograph, which is coupled to either a general detector for quantitation or to a mass spectrometer for identification and quantitation of the separated compounds. In contrast to the vast literature available on development and comparison of sampling methods for airborne VOC, and on properties of different sorbent materials, the analytical procedures of separation, detection, quantitation, and identification of sampled compounds are usually listed in indoor air studies without any critical comments or discussions.

The injection of sample is mainly a two stage process. First, the sorbent trap is extracted through *thermal desorption* and the desorbed VOC are brought by the carrier gas into a low volume cold trap for preconcentration. Secondly, the cold trap is flash heated and the vaporized compounds are injected into the separation column. In order to attain a complete recovery of sampled components from sorbents like Tenax or graphitized carbon black, high desorption temperatures are needed, 250-300 °C. For Porapak Q, a desorption temperature of 150 °C is sufficient. Using high temperatures entail a risk of degradation of sampled compounds, and the analytical result will not be representative of the sampled air. Unfortunately, this problem is often neglected in indoor air studies. A less common method of sample injection today is the use of *solvent extraction* of the sorbent trap followed by injection of an aliquot of the extract into the GC column.

For *gas chromatographic separation* capillary columns are used, made of fused silica or glass, at 25-50 m length, with low inner diameter (0.2-0.3 mm) and the inner surface coated with a thin film (0.2-1.0 µm) of stationary phase. Indoor air contains a wide range of VOC with respect to boiling points, volatility, and polarity, and, therefore, stationary phases for general purpose (low or moderate polarity) are used for the separation. Common phases are silicones (polyorganosiloxanes) like 100% dimethylpolysiloxane (e.g., SE-30, OV-1, OV-101, DB-1, HP-1, BP-1, Ultra-1), 5% phenylpolysiloxane-95% dimethylpolysiloxane (e.g., SE-54, DB-5, Ultra-2), or 14% cyanopropylphenylpolysiloxane-86% methylpolysiloxane (e.g., OV-1701, CP Sil 19CB). The polarity increases with increasing proportion of aromatic substitutes or double bonds, in the polymer. When highly polar compounds like organic acids or low molecular alcohols are present, still more polar stationary phases may be needed, like modifications of polyethyleneglycol (e.g., DB-Wax, Supelcowax 10, Carbowax), polypropyleneglycol (e.g., UCON HB 5100, UCON LB 550), or polyoxyethylated fatty alcohol (e.g., Emulphor ON 870). In some early publications, support-coated open tubular (SCOT) columns (Pellizzari, Bunch, Berkley, & McRae, 1976b; Jarke,

Dravnieks, & Gordon, 1981), or even packed columns (Wang, 1975; Norbäck, Rand, Michel, & Amcoff, 1989) were used, however, today fused silica capillary columns are predominating. For example, ECA (1997) recommends the use of a capillary column with well deactivated nonpolar stationary phase, like pure methylpolysiloxane or methylpolysiloxane with the addition of not more than 8% of phenyl-polysiloxane. This recommendation is intended for the determination of TVOC according to ECA (1997) definition.

Temperature conditions during chromatography involves an isothermal start temperature, varying from -80 to 70 °C (usually about 0 to 40 °C) followed by a temperature increase at one constant rate, or stepwise at two or three different rates, and then the procedure is ended with an isothermal period within an interval of 150 to 300 °C. The choice of temperature conditions depends on what type of sampling adsorbent that has been used. For example, with Tenax, which insufficiently retains low molecular compounds ($<C_6$), a high start temperature is preferred in order to decrease the retention volumes for the early eluting compounds, and a fairly high end temperature, 250-300°C, thus favoring the elution and resolution of high molecular compounds ($>C_{16}$). With Porapak, which has a high adsorption capacity for low molecular compounds (C_3 - C_6), a low initial temperature, 0-20 °C, will permit proper resolution of these compounds, whereas a final temperature $<200^\circ\text{C}$ is satisfactory for the elution of compounds $<C_{16}$, which is an upper limit for accurate sampling by this sorbent.

For the *detection and quantitation* of separated compounds, the column effluent is fed into a FID, or when *identification* is wanted the column is interfaced with the ionization chamber of a mass spectrometer, MS. The column effluent may also be split between the two detectors and analyzed in parallel. FID has a high sensitivity to organic compounds (especially hydrocarbons), a wide range of linearity (0 to 10^6 , or to 10^7), and a low dead volume. However, a well-known disadvantage with FID is the decreased sensitivity for compounds substituted with functional groups (e.g., low molecular aldehydes, alcohols and acids), or other heteroatoms, like chlorine (Hodgson, 1995). For example, 1,1,2,2-tetrachloroethane which, like the common indoor air pollutant tetrachloroethylene, is a short chain hydrocarbon substituted with 4 chlorine atoms, may have a relative FID-response factor of about 0.2 as compared to the response factor of decane of 1.0 (e.g., Yieru, Qingyu, & Weile, 1990).

The common method of VOC identification is mass spectrometry, with electron impact (EI) ion source, and either electromagnetic or quadrupole analysis of mass fragments (Skoog, Holler, & Nieman, 1998). Finally, a transducer converts the ions into electrical signals by an electron multiplier. The result is processed and stored in a computer, and compound identifications are based on comparison with spectra of authentic standards or with a spectra library (e.g., The National Institute of Standards and Technology; Wiley Libraries; National Bureau of Standards). There are also reports on the use of compact and less expensive ion trap detectors (ITD), in which both ionization of separated compounds and scanning of mass fragments is performed in the same space. Mass spectrometers ordinarily have several display modes like total ion current chromatogram (TIC, a plot of the sum of all ion currents as a function of

time), selected ion current chromatograms (a plot of ion currents for one or a few ions as a function of time), and mass spectra of various peaks. For detection and quantitation, the TIC is normally preferred in indoor air studies, whereas the more sensitive technique of selected ion measurement is seldom used even though it is available in most instruments. The TIC-response varies with type of compounds, displaying the highest sensitivity for alkanes and the lowest for chlorinated hydrocarbons and oxidized compounds (Hodgson, 1995).

Odor and Sensory Irritation Relevant for Indoor Air

The human perception of air quality is related mainly to the perception of odor and thermal sensations. Other relevant sensations are irritation in the eyes, nose and throat. Some researchers have proposed, that human perception of odor and irritation should be used as a measuring instrument for assessing indoor air quality in parallel with, or even instead of, chemical and physical measurements. Even though international research is in progress within this area, it is important to realize that a complete understanding of the functioning of the human sensory systems involved in olfaction and irritation, is still not available. However, in order to measure odor, irritation, and sensory functions, such complete and detailed knowledge is not always necessary. Perceptual or sensory measurements can be accomplished in a reliable and valid way by using available psychophysical methods (see e.g., Lindvall, 1974; Cain & Moskowitz, 1974; Baird & Noma, 1978; B. Berglund, 1991; B. Berglund & Lindvall, 1992b; ECA, 1999).

Olfaction and Odorous Compounds

Olfactory system. The olfactory system consists of the olfactory epithelium located in the superior region of the nose, the olfactory bulb which is an extension of the forebrain, and the piriform cortex in the lower part of the brain (MacLeod, 1971; B. Berglund & Lindvall, 1982; Doty, 1995a). The human olfactory epithelium, containing the receptor neurons, has an area of 100 mm² in each nostril (Lovell, Jafek, Moran, & Rowley III, 1982; Moran, Rowley, Jafek, & Lovell, 1982) and is reached by about 2-5% of the inhaled air. The olfactory receptor neurons and the system of glomerulus in the olfactory bulb appear to respond to odorous compounds divided in broad categories, based on similarities in molecular structure, chemical functional groups, and odor quality as perceived by humans. (For a detailed description of the olfactory system and its physiological functions, see Appendix III).

Perceptual functions. The perceptual functions of *olfaction* include detection and recognition (threshold level), and intensity, quality, and hedonics (suprathreshold level) (e.g., B. Berglund & Lindvall, 1982). The *absolute odor threshold* for a chemical compound is usually defined as the concentration at which a representative group of observers can detect an odor in 50% of the presentations from a series of concentrations (e.g., Engen, 1971a, 1971b). This detection threshold refers to the mere

presence of an odor (smelling) whereas the *recognition threshold* refers to the recognition or identification of a specific odor (Shams Esfandabad, 1993b; Doty & Kobal, 1995; B. Berglund & Zheng, 1999). It is important to know that a threshold value cannot be used as an indicator or measure of perceived intensity (or of quality) for exposures above threshold levels (e.g., Lindvall, 1974; B. Berglund & Lindvall, 1982; Högman, 1988). Today, there is an agreement among researchers that *perceived odor intensity* increases as a power function of stimulus concentration; although historically, several equations have been suggested to represent this function (see e.g., S. S. Stevens, 1975). One of the original and simplest, and also empirically verified psychophysical functions is the power function presented by S. S. Stevens (1957):

$$I = k * C^n$$

where I stands for perceived odor intensity, C for the concentration of odorous compound, k is a multiplicative constant that adjusts for differences in unit of measurement, and n is the exponent. For odor intensity, the exponent has typically been found to be less than one, generally down to 0.1 (see e.g., B. Berglund, U. Berglund, Ekman, & Engen, 1971; Engen, 1982, p. 57). This means that the perceived odor intensity will be more attenuated at higher concentrations. Exceptions of exponents larger than one exist occasionally (e.g., Laing, Panhuber, & Baxter, 1978). *Perceived odor quality* of odorous compounds is, for example, assessed by classification (sorting in groups) or by similarity judgements (pairwise comparisons) followed by multidimensional scaling (R. Harper, Bate-Smith, & Land, 1968; Engen, 1982). Large interindividual differences exist in similarity judgments (B. Berglund, U. Berglund, Engen, & Ekman, 1973) and, therefore, no agreement has been reached about a common space of (perceived) odor quality. In psychology, the concept of *hedonics* refer to the study of pleasurable and painful states of consciousness; in olfactory research, typically, hedonics include the quantification of pleasantness or unpleasantness or the classification of different odors (or odorous substances) with regard to these or related attributes (see e.g., Engen, 1982, pp. 125-144).

Odorous Compounds. Typical odorants are organic compounds with molecular weights less than 350, usually less than 150, and at certain concentration ranges (human sensitivity varies widely among odorous substances). Odor perception depends on the chemical and physical properties of the odorous compounds as well as on properties of components in the olfactory system (Appendix III). Significant properties of odorous compounds are their volatility, polarity, water solubility, and molecular structure (e.g., Schiffman, 1974; Laffort, Patte, & Etcheto, 1974). However, as pointed out by Engen (1963), no single physical dimension such as, for example, carbon chain length is likely to give any simple explanation for odor. Cometto-Muñiz and Cain (1990; 1994) have shown that for homologous series of organic compounds (C_1 to C_{10}), the odor and nasal pungency thresholds are decreasing with increasing carbon number, and also with increasing polarity of substituent groups. However, if thresholds are expressed as percentages of saturated vapor, which may account for differ-

ences in solubility and in phase distribution in the mucosa among the various odorous compounds, odor and pungency thresholds both remain almost constant within the homologues series. Ranson and Belitz (1992) showed that the introduction of one double C-C bond in, for example, *n*-hexanal or *n*-heptanal will result in *either* an increased *or* a decreased odor threshold. The outcome depends on the position of the double bond in the carbon chain, and whether the double bond involves a *cis*- or *trans*-configuration.

Trigeminal System and Chemical Irritants

Trigeminal System. The trigeminal nerve (cranial nerve V) innervates the entire facial and forehead skin and the mucous membranes of the eyes, nose, and mouth. It responds to mechanical, thermal, nociceptive and proprioceptive stimuli; and in addition, the free nerve endings distributed in the nasal cavity, the oral cavity, and the eye are sensitive to chemical stimuli (e.g., Silver & Finger, 1991). The chemical sensitivity of the trigeminal system is referred to as somesthesia, chemesthesia, or the 'common chemical sense' (e.g., B. C. Green, Mason, & Kare, 1990). The last term is by some researchers considered dubious, since it also refers to a system of chemoreceptors distributed over the whole body, only found in aquatic vertebrates. Conversely, it may be noted that nociceptors that react to chemical stimulation are present as open nerve endings in human skin and mucosa (e.g., B. Berglund & Lindvall, 1986). In humans, the trigeminal system has no specific receptor structures, such as the different specific transmembrane proteins in the olfactory receptor neurons (Appendix III). The chemical sensations in the nose, include, for example, stinging, prickliness, tingling, irritation, burning, piquancy, and freshness (Kobal & Hummel, 1991; Cometto-Muñiz & Cain, 1996). In olfactory research the term *nasal pungency* is often used to represent this group of sensations. Similar perceptual qualities are also involved in the trigeminal response of the eye, named *eye irritation*. Collective terms used for all these sensations in indoor air quality research are *mucosal irritation* or simply *sensory irritation*.

Perceptual functions. The perceptual functions of the trigeminal system include detection, recognition, intensity, quality, and as adverse perceptions, obviously, also hedonics. Most VOC will affect both the trigeminal and the olfactory receptors, however, the detection thresholds for irritation are usually higher than those for odor (Cometto-Muñiz & Cain, 1991; Shams Esfandabad, 1993b), and for formaldehyde the *recognition* thresholds are somewhere in-between the odor and sensory irritation detection thresholds (B. Berglund & Zheng, 1999). In contrast to odor, the exponent of the psychophysical power function for sensory irritation (and pain) is larger than one, that is, the *perceived intensity* will accelerate with increasing stimulus concentration. In an experiment with high concentrations of 47 nasally-inhaled chemicals, Doty, Brugger, Jurs, Orndorff, Snyder, and Lowry (1978) report trigeminal sensations for each of *qualitatively* different variables (intensity, pleasantness, coolness, warmth, and presumptive safety). Perceptual measurement of irritation intensity was shown

possible in the presence of odor, and similar profiles of the variables were reported for subjects lacking the ability to perceive odor and normal subjects (i.e., anosmics and normosmics, respectively).

Chemical Irritants. Several attempts have been made to characterize sensory irritants as reviewed by, for example, Silver and Finger (1991). Alarie (1973) proposed mechanisms, in which, affinity for reacting with thioalcohol (-SH) groups on (receptor-) proteins, the ability to cleave sulfur (S-S) bonds in proteins, and lipid solubility are important factors. A model for the physical and chemical interactions of sensory irritants with receptor proteins is presented by G. D. Nielsen and Alarie (1982). However, many irritants do not fit into these mechanisms, such as the relatively nonreactive *n*-alcohols and *n*-acetates with carbon chain lengths of 1 to 8 (e.g., Cometto-Muñiz & Cain, 1996). Among indoor air compounds, only formaldehyde has been systematically researched with regard to sensory irritation effects (Engen, 1986; WHO, 1989b; Shams Esfandabad, 1993a). However, there is a growing body of human psychophysical research on sensory irritation to various gases and vapors and their mixtures performed mainly in the USA and in Sweden. In Study 6 (Johansson, 1990) several compounds with potential irritating effects that may occur due to indoor air, are reviewed.

Methods for Measuring Odor and Sensory Irritation

The measurement of odor and sensory irritation is interdisciplinary, including primarily physiology and psychology (e.g., Engen, 1982; Doty & Kobl, 1995; B. Berglund & Johansson, 1996). Methods for the quantitative study of the relationship between physical or chemical stimuli (e.g., sound, light, or chemicals) and psychological responses are taken from *psychophysics*, a subdiscipline of psychology.

Physiological Methods. The (usually negative) potential in the surface of olfactory mucosa, evoked by inhaled odorants, is recorded by micro-electrodes resulting in a human electro-olfactogram, EOG, (Ottoson, 1956). Trigeminal reactivity may be recorded as the negative mucosal potential, NMP, from the surface of the respiratory epithelium (surrounding the olfactory epithelium). Kobl (1985) tentatively called this potential an electrotrigeminogram (ETG). Human electroencephalogram, EEG, consists of changes in electrical fields generated by large populations of neurons, and these are recorded by electrodes placed on the surface of the skull. Typical EEG recordings in the sensory area are olfactory event-related potentials, OERP, and chematosensory (trigeminal) event-related potentials, CSERP (Doty & Kobl, 1995). So far, little evidence is available whether EEG measures are specifically related to activities in the olfactory system and/or to cortical activity.

Several physiological methods for the measurement of sensory effects occurring in the indoor environment have been proposed. Most of them concern trigeminal effects in the eyes, rather than trigeminal effects in the nasal mucosa or effects on the olfactory system. For example, eye redness, decreased tear film stability, foam formation in the eye, epithelium damage and conjunctival cytology are suggested to be measurable

effects of irritation of the eyes and their mucous membranes (e.g., Kjærgaard, 1992; Winneke, 1992; Skov, Petersen, & Wolkoff, 1999). Two methods have been developed to measure physiological changes in the mucous membrane of the nose in terms of its volume, namely acoustic rhinometry (Hilberg, Jackson, Swift & Pedersen, 1989) and rhinostereometry (Ohm, Juto, & Kj. Andersson, 1993; Falk, Juto, Stridh, & Bylin, 1994).

Physiological Measurements. Sensory effects that occur in indoor environments are subtle, and traditional health-related physiological measurements are generally not sensitive enough to be used as correlates or indicators for health effects. For example, in order to obtain detectable potentials in the respiratory epithelium for an ETG, concentrations of several thousand ppm of the irritating compound are needed (Kobal, 1985). Perceived eye irritation (questionnaire study) and physiologically assessed eye effects (eye redness, tear film stability, epithelial damage on conjunctiva) have been found in occupants of a sick building, however, a strong relationship between these effects and a confounder, the use of eye make-up, could not be ruled out (Kjærgaard, B. Berglund, & Lundin, 1993). For four office buildings with different SBS prevalences in the occupants, Franck, Bach, and Skov (1993) obtained correlations between perceived eye irritation and objective eye manifestations (e.g., absence of foam and damage of conjunctival epithelium). The prevalence of objective eye manifestations was also elevated in the occupants, as compared to the general population. The application of the methods for measuring changes in nasal volume is limited to two rhinometry studies (Ohm, Juto, & Kj. Andersson, 1992; Falk et al., 1994); and there is an urgent need for more general normative information from healthy individuals.

Psychophysical Methods. Even though potential physiological correlates of perceptions of odor, or sensory irritation, may be found, they must always be validated against perceptual scales. It follows that physiological correlates cannot be more valid measures than the perceptual measures used to validate the correlates. To find out how humans perceive and evaluate odor and irritation, psychophysical methods must be used. These methods include threshold measurements (detection, recognition, discrimination) and suprathreshold scaling (intensity, quality, hedonics), (Engen, 1971a, 1971b, 1971c; Baird & Noma, 1978; Engen, 1982; Coren, Ward, & Enns, 1994). Judgments of odor intensity and quality are always relative, influenced by personal predisposition and contextual factors such as background odor. A discussion of problems and possibilities as well as quality assurance in the use of psychophysical methods for measuring environmental perceptions is presented by B. Berglund (1991).

Psychophysical Measurements. The measurement of human perception of odor and irritation is intricate because interindividual differences cannot simply be accounted for as error of measurement. Rather all perceptual measures will naturally be influenced by study contexts (individual factors and experimental design). Individually, the sensitivity in the physiological sensory process varies from time to time and there is always an internal noise present, generated by the individuals' own sensory system. There is also an external noise present, generated by other odorous or irritating compounds, variations in air flow over the mucosa of the olfactory and respiratory epithe-

lia, or variations in air temperature. However, in spite of all contextual problems, it has been found that the human observer has a good ability to match numbers to his or her perceptions and they may serve as a measuring instrument for environmental exposures, such as, odor, sensory irritation, and air quality (ECA, 1999).

In *threshold experiments*, the presentation order of stimuli, that is, ascending, descending, or randomized orders of concentrations, including a number of clean air presentations (blanks), is important for the final result. The time of exposure is crucial, since it must be long enough to let the subject detect and perceive the stimulus and give an answer, but short enough in order to avoid adaptation or habituation effects. The use of a payoff matrix in a design according to the signal detection theory, that is, a set of rewards and penalties given to the observer according to right and wrong answers to a stimulus, will also have an impact on the results (Engen, 1971b). Considering all these variables, it is easy to understand that reported thresholds and psychophysical functions vary substantially especially for experiments with small groups of persons using various methods (see e.g., Engen, 1982; Devos, Patte, Rouault, Laffort, & Van Gemert, 1990). It may even be assumed that there is no generally fixed sensory threshold, because according to signal detection theory (D. M. Green & Swets, 1966) the response criteria for detecting the stimulus will vary among the test subjects (cf., Lindvall, 1974; Baird & Högman, 1988). Accordingly, absolute perception thresholds and psychophysical functions may be determined statistically, based on data from several psychophysical experiments including large groups of subjects.

The main problem in the measurement of *perceived intensity* is to develop and use proper scales. Depending on purpose of measurement, different types of scales are applied, such as, nominal (non-quantitative classification, yes/no category), ordinal (rank order), interval (constant distance relative to a reference zero point), or ratio (constant ratios, absolute zero point), (Engen, 1971c). Especially for environmental evaluations, it is important that sensory scales, if possible, can be related to some physical scale, such as concentration of stimulus or dilution factors (ECA, 1999).

Detection threshold. Psychophysical methods used for determining the absolute threshold of perception in environmental studies are the *method of limits*, the *method of constant stimuli (MCS)*, and the *method of adjustment* (e.g., Engen, 1971b; ECA, 1999). In the method of limits, the stimuli are presented in alternating ascending and descending series of concentrations until a change in a subject's response occurs (detection/nondetection). In the MCS, each of a number of stimuli, above and below the assumed threshold, are presented in random order and, thus, judged repeatedly (detection/nondetection). A basic assumption in MCS is that the momentary individual threshold value varies from time to time and that this variation has a normal distribution (Lindvall, 1974). Usually the MCS is combined with methods based on the *theory of signal detection* (e.g., D. M. Green & Swets, 1966; Engen, 1971b; Baird & Högman, 1988). That is, the stimulus presentation is combined with random presentations of clean-air (so-called blanks) in order to be able to separate false positive responses (false alarms) from correct positive responses (hits). Advantages of the MCS are, for example, that it gives a psychometric function relating detection percentage to

concentration, and it includes estimation of the magnitude of response error (false alarm). The method of limits only provides one-point assessment of the threshold (a mean and a measure of variability). In addition, in MCS the risk of adaptation and anticipation is minimized as compared to the method of limits (Lindvall, 1970). In Study 5 (B. Berglund, Högman, & Johansson, 1988), the odor threshold of formaldehyde was determined by MCS. The method also included blank presentations and pyridine was used as a reference substance for interstudy comparisons.

Perceived intensity. For the quantitative evaluation of perceived intensity of odor, or sensory irritation, the most common methods are category or magnitude scaling. In the method of *magnitude estimation*, the subjects are asked to match their subjective impressions of magnitude of numbers to their subjective impressions of sensory stimuli. Different versions of magnitude estimation are with memory references and with physical references (one reference or several references) and master scaling (e.g., ECA, 1999). In Study 5 (B. Berglund, Högman, & Johansson, 1988), the method of *free number magnitude estimation* was preferred for determining the psychophysical function of formaldehyde (e.g., B. Berglund, 1991; Nordin, 1992). In order to compare the results between different environmental studies, the perceived intensity of individual scales has to be calibrated to, for example, equal intercepts or to a reference scale. To fully account for the subject differences, a *master scale* with independent references may be used for this calibration (e.g., B. Berglund, 1991): Five or more concentrations of a reference chemical are jointly scaled with the target stimuli during the whole investigation. The set of target sensory data is then transformed with factors necessary for transforming the individual psychophysical functions of these reference functions to the group function for the references (Master scale).

Olfactometers

In order to test and measure sensory thresholds and perceived intensities of odor and irritation, the technique of olfactometry is used. The technical device, called an olfactometer, is used to generate and deliver a chemical stimulation, or a mixture of chemical stimulations, to the olfactory and trigeminal systems of subjects. The human response to various stimuli is measured “outside” the olfactometer, with the use of physiological, electrophysiological, or psychophysical methods. Human chemoreception is very sensitive to selected compounds, usually much more sensitive than most chemical or physical detectors (Devos, et al., 1990). This entails that in sensory threshold measurements very low concentrations of stimuli must be handled, usually at ppb levels.

An olfactometric exposure system may, in principle, be either *static* or *dynamic* (B. Berglund, U. Berglund & Lindvall, 1986; Doty & Kobal, 1995; Prah, Sears, & Walker, 1995). In a *static exposure* system, concentrations of chemical compounds are presented to subjects, for example, from closed vessels or different types of sniff bottles in which the headspace of the chemical compound is sniffed (e.g., plastic squeeze bottles), microencapsulated odorants, that is, the odorants/irritants (chemical compounds), are embedded in 10-50 mm plastic capsules which are scratched and sniffed

by the subjects (e.g., UPSIT, the University of Pennsylvania Smell Identification Test: Doty, Shaman, & Dann, 1984), glass rods or wooden sticks dipped in solutions of stimuli, or bottles from which blasts of odorant/irritant are injected into the nose (Engen, 1982, pp. 36-42; Doty & Kobal, 1995). These systems are rather simple and easy to handle, however, it cannot be assured that the concentrations are constant because there is no control of the amount of ambient air diluting the sample.

A *dynamic exposure* system should be used for obtaining a high degree of control over chemical concentration, needed for determining psychophysical functions and absolute odor thresholds as well as in environmental implementation studies. Quantitatively well-controlled exposure concentrations in a continuous air-flow without unwanted dilution from background air are presented to a subject either in a hood, where only the face or the head is exposed, or in a whole-body exposure chamber. Important principles are the accurate regulation and control of dilution flows to reach exact concentrations, and control of all concentrations, including the finite exposure concentration, with the aid of chemical analyses as, for example, in Study 5 (B. Berglund, Högman, & Johansson, 1988). In human exposure, it is important to use a high flow of the diluted stimuli in order to avoid changes in flow rate and concentration due to the breathing pattern of subjects. Enough air volume for inhalation must be provided in order not to disturb the concentration in the air flow. A minimum air flow is 60 L/min, but a flow of 100 L/min is recommended. Furthermore, in order to pre-condition the upper airways, the subject should always stay at least 15 min in a clean air environment before any exposure takes place (Lindvall, 1970; B. Berglund, U. Berglund, Johansson, & Lindvall, 1986).

Well-known psychophysical methods, for threshold measurements and suprathreshold scaling, are seldom used for *measuring sensory effects encountered indoors*. Such field investigations are probably considered difficult and laborious to perform. Transport of indoor air samples to a stationary exposure laboratory involves risks for sample loss and contamination and presents problems in collecting and transporting required air volumes. Instead, in-situ analysis would be preferred in which subjects and laboratory equipment are transported to the object of investigation. Unfortunately, this is a complicated and expensive solution, and there are only few reports on such indoor air studies. For example, B. Berglund, T. Lindvall, and co-workers have developed a mobile unit containing an olfactometer, an exposure chamber, analytical instruments, and a waiting room supplied with clean air for subjects (B. Berglund et al., 1986). The equipment was used in an investigation of the interaction effects of formaldehyde and indoor air of a "sick building" (a detached preschool), (Ahlström, B. Berglund, U. Berglund, & Lindvall, 1986). An earlier version of the mobile equipment for sensory studies was used by B. Berglund and Lindvall (1979) for the application of a signal-detection approach to IAQ in building investigations. The technique of using mobile odor laboratories has been used in investigating the odor of exhausts from pulp mills (Lindvall, 1970), traffic (Lindvall, 1973), agricultural areas (B. Berglund, U. Berglund, & Lindvall, 1974), pigfarms, and composting plants (B. Berglund, U. Berglund, & Lundin, 1988).

Sensory Effects of Indoor-Air VOC

The majority of indoor-air VOC are odorous (e.g., B. Berglund, U. Berglund, Lindvall, & Nicander Bredberg, 1982), and many of them are also irritating (Study 6: Johansson, 1990), however, usually their concentrations are below sensory detection thresholds. Still, odor, and often also sensory irritation, are perceived in common indoor air environments and may, thus, contribute to the IAQ. So far, odor or other sensory effects cannot be predicted from the chemical composition of the air and, therefore, in order to evaluate IAQ, sensory analysis is needed. During exposure to a complex mixture of compounds, such as indoor air, interactions and temporal sensory processes will take place, such as *adaptation* (decrease in sensitivity with time of constant exposure), *cross-adaptation* (decrease in sensitivity to one odor substance caused by adaptation to another), *facilitation* (the inhalation of one odor may increase the perceived intensity of another particularly at near-threshold levels), and *hypoaddition* (decrease in perceived intensity of a mixture relative to the arithmetic sum of its singly presented compounds), (e.g., B. Berglund & Lindvall, 1982; Fang, Wargocki, Witterseh, Clausen, & Fanger, 1999).

Generally, the perceived intensity of a mixture is less than the sum of the perceived intensities of the compounds mixed, when presented alone (B. Berglund, U. Berglund, Lindvall, & Svensson, 1973; B. Berglund, & Olsson, 1993a, 1993b; Olsson, 1993). For example, for a mixture of two equally strong components, the perceived odor intensity is approximately 1.3 times that of the single components, while the odor intensity of mixtures of three, four and five compounds are approximately only as strong as the intensity of the strongest compound (B. Berglund, 1974). However, for detection thresholds of mixtures, less firm data is available than for perceived intensities. Also for thresholds, it is reasonable to expect an *additive effect* from exposure to mixtures of several compounds because the likelihood of detection of odor or irritation would increase statistically with the number of compounds present in the air (B. Berglund, 1990). For indoor air, this would mean that the air could be perceived odorous or irritating even if no single compound is present in the concentration required for its detection threshold when presented alone. This has recently been shown for a mixture of three (Patterson, J. C. Stevens, Cain, & Cometto-Muñiz, 1993) and of nine compounds (Cometto-Muñiz, Cain, & Hudnell, 1997): In both studies the mixtures were perceived as odorous even though all constituent compounds were at concentrations below their individual thresholds. However, the concentrations investigated were decidedly higher than those common for various VOC in indoor air in non-industrial environments and, therefore, the results may turn out to be different for larger patterns of compounds (B. Berglund & Lindvall, 1992a). For example, for indoor-air samples which contain 28 identified critical odorous compounds, at least 10 of these compounds must be present and judged to be relatively “strong” for the air sample to be odorous (B. Berglund et al., 1982).

Adaptation to odor of indoor air will occur already within some minutes, and what is perceived as odorless by occupants staying in a room will be odorous to visi-

tors just entering the room (cf. Yaglou, Riley, & Coggins, 1936). However, it has been shown that mixtures exhibit less adaptation than expected from their single compounds when presented alone (Schiet & Cain, 1990; B. Berglund & Engen, 1993). Furthermore, low concentration exposure over longer periods of time facilitates the irritation outcome and substances with high irritation potency seem to counteract olfactory adaptation (B. Berglund, U. Berglund, & Lindvall, 1978; Cain & Murphy, 1980; B. Berglund & Lindvall, 1992a; B. Berglund & Johansson, 1996). Thus, several adaptation experiments have shown that combinations of odorous substances, which at high concentration show *cross-adaptation*, can show *cross-facilitation* at weak concentrations (e.g., B. Berglund & Engen, 1993). Olfactory adaptation primarily affects sensitivity to the stimuli to which one has been exposed, whereas exposure to other odorants plays a minor role. Thus, any new odorant introduced into an indoor air mixture to which persons are adapted will, with a high probability, be facilitated. This means that we have the ecological ability to comprehend a new “warning” compound in a mixture even at low concentration (B. Berglund & Engen, 1993).

An example showing the *difficulties in predicting and interpreting* odor and sensory effects arising in multicomponent mixtures is reported by Lindvall (1977). Perceived odor intensity of some organic sulphur compounds from pulp mills were studied and the results showed a potential effect of a subthreshold odorous gas on the perceived odor of another gas. Investigated compounds were carbonyl sulfide (COS) alone, COS plus nitrogen oxide (NO), and COS plus O₃. Perceived odor intensity of the sulfide was unaffected by O₃, but enhanced by NO. As both NO and O₃ were presented at subthreshold levels (adapted sense), perceptual interaction is not likely to have taken place. In addition, the reinforcing effect of NO on the sulfide odor was most evident at low intensities. As a tentative explanation, Lindvall (1977) suggests that NO may stimulate the trigeminal nerve, but not enough to create a sensation by itself, or that NO may affect the nasal mucosa or the mucus, hence making the sulfide a more powerful receptor stimulation. Although only a few substances have been studied with regard to near-threshold odor facilitation, the phenomenon must be considered when interpreting how components of complex chemical mixtures are perceived in indoor environments. Recent studies show that NO is endogenously produced within the human body and that NO is important for the signal transduction processes in the olfactory neurons (e.g., L. E. Gustafsson, Leone, Persson, Wiklund, & Moncada, 1991; Broillet & Firestein, 1996; Firestein, 1996). These more recent results may form the base for other explanations of the above-mentioned phenomenon of near-threshold odor facilitation. For example, the presence of NO may strengthen (amplify) the odor receptor signal.

AIM OF THE THESIS

The aim of this thesis is to investigate air pollutants relevant for the air quality in nonindustrial indoor environments and to attempt to find out whether there is a link between VOC in indoor air and human health-related sensory effects. The experimental works include the development of a method to sample and analyze VOC in indoor air, as well as the application of this method in studies of adsorption/desorption of VOC in building materials and ventilation systems, and of VOC in healthy and sick buildings. The experimental works also include an in-depth study of near-threshold odor measurements of formaldehyde, which is a common indoor air pollutant. Comprehensive critical reviews of the existing literature have also been conducted with a focus on adsorption/desorption in indoor materials, and on human health-related sensory effects.

SUMMARY OF STUDIES

The research started with the development of a method for sampling, quantitation, and identification, of indoor-air VOC. Very short sampling periods (10 min) were used because the first application was to map temporal VOC-variations during class meetings in two different schools. The relative concentrations of VOC indoors and outdoors, and the influence on indoor VOC composition due to occupants was studied (*Study 1*). The next step of research was to find out whether old used building materials still have an emission that may deteriorate indoor air quality. The emission of building materials from a 7-year-old sick preschool building were measured in a climate chamber. The results showed not only that used building materials may still have VOC emission after several years, but also that there is an exchange of contaminants between surfaces of indoor sources and the indoor air (*Study 2*). The next step of research was a literature review on VOC in indoor air with special focus on adsorption/desorption effects, followed by a field study of adsorption/desorption effects of VOC in a ventilation system of a building. The field study showed that a rotating wheel heat exchanger, after some time of use, may transfer VOC from exhaust air to supply air (*Study 3*). The next step of research concerned indoor air differences between a healthy and a sick preschool. Correspondence analysis and other statistical techniques were used to describe the relationship between airborne VOC and location in the two buildings. The VOC-pattern analyses clearly distinguished among the buildings and among locations within each building, including whether the sample was collected outdoors or indoors (*Study 4*). Since VOC is present in indoor air at very low concentration, the next step of research concerned an investigation of the reliability of odor measurements near threshold for formaldehyde and pyridine. Two methods of formaldehyde generation were compared and the exposure concentrations were measured by two independent chemical analytical methods. The results showed that the subjects were indeed able to reliably detect formaldehyde at low concentration (*Study 5*). Two comprehensive reviews on indoor air contaminants relevant for sensory ef-

fects and on health related effects of indoor VOC, constitute the last step of research for this thesis. The first review was restricted to sensory effects, that is, odor and irritation, and focused on an evaluation of chemical compounds that may be considered important for sensory studies (*Study 6*). The second critical literature review concerned potential health effects of indoor VOC, and the measurement of these effects in local (body) exposure, chamber, and field studies. The review also includes methods of chemical measurement of VOC, the occurrence of VOC, and chemical and physical processes in nonindustrial indoor air (*Study 7*).

Determination of Organic Compounds in Indoor Air with Potential Reference to Air Quality (*Study 1*)

Background and Problem

At the time the results of Study 1 were published, the presence of persons indoors was assumed to be the most important factor affecting indoor air quality. Consequently, the concentration of carbon dioxide, CO₂, from human expired air was used as the only indicator of indoor air quality (e.g., Friberg & Ronge, 1970). The remaining chemical content of indoor air was expected to be almost the same as for outdoor air. Possible pollutants from humans were volatile organic compounds like methane, isoprene, ethanol, butyric acid, acetic acid, and ethyl acetate (Jansson & Larsson, 1969; Wang, 1975). However, they were almost never investigated in indoor air. It was suggested that a new indoor air quality index should be developed, based on the amount and composition of VOC and their sensory effects on humans, rather than based on the concentration of the nonodorous CO₂. The index would be used as a more adequate descriptor for indoor air quality than CO₂.

The composition of indoor-air VOC was not completely mapped (Ryd, 1967; Dravnieks & Whitfield, 1971). However, the amounts of VOC, especially body effluents, were assumed to be less than the detection threshold of most analytical instruments. The ambient air, on the other hand, was already the subject of many investigations and the contents of organic compounds of different outdoor environments had been listed (e.g., K. Grob & G. Grob, 1971). The outdoor air concentrations were also below detection limits of available direct reading instruments and, therefore, several analytical systems had been developed, preferably those involving enrichment of the compounds on sorbent media followed by desorption and subsequent separation by gas chromatography (K. Grob & G. Grob, 1971; Lonneman, Kopczynski, Darley, & Sutterfield, 1974; Raymond & Guiochon, 1974; Versino, de Groot, & Geiss, 1974; Russel, 1975; Pellizzari, Bunch, Berkley, & McRae, 1976a, 1976b).

The aim of the present study was to develop a suitable method for sampling, identifying, and quantifying VOC that are characteristic of indoor air, as compared to outdoor air, and to test this method under field conditions. The air of class rooms in two different schools was selected as study object and a number of different conditions were varied.

Method

It is important to realize that the air concentration of water, especially indoors in the presence of humans, is much higher than the concentrations of any single organic compound in air, often two or three powers of 10. In order to detect selectively indoor air VOC, the water has to be eliminated either during the concentration step and/or during the subsequent analysis. Therefore, it was decided to concentrate the sampled air on sorbent media, characterized by low retention volume for water, and to use a flame ionization detector which has a very low water sensitivity, in the subsequent gas chromatographic analysis.

An investigation of adsorption and desorption efficiency was performed for some common stationary phases for gas chromatography—PEG 400 (polyethyleneglycols), Apiezon, and triethanolamines—loaded on the chromatography support material Chromosorb W. The procedure and results of this investigation was not reported in the original publication but will shortly be described here. The stationary phases were tested either one at time or two or three combined in a series. Also inorganic particulate materials, with large surface area, like activated carbon black, aluminum oxide, and molecular sieve, were used as well as the porous polymers Porapak Q and Tenax GC. The sorbents were tested with a vapor gas mixture, consisting of methanol, ethanol, acetic aldehyde, acetone, and isoprene which all are characteristic compounds of human expired air. The mixture was prepared by injecting the pure standard compounds into a 7-L gas cylinder which was then filled with nitrogen at a pressure of about 20 kg/cm². The resulting concentrations at ambient pressure were about 10 ppm, that is, 5-10 times higher than normal expired air concentrations. Samples were taken from the cylinder either by gas tight syringes or just by direct flow through the adsorbent tubes.

The methodological study showed that Porapak Q was the most suitable sorbent for indoor air samples because of its ability to retain all the VVOC and VOC of the standard mixture and because of its relatively low retention volume for water. Porapak Q is a porous polymer composed of ethylvinylbenzene, cross-linked with divinylbenzene, to form a uniform structure of a distinct pore size. It had first been applied as a column material in gas chromatography by Hollis (1966), where, for example, its rapid elution of water makes it useful for the determination of trace amounts of water in solutions of organic compounds (Hollis & Hayes, 1966). Tenax GC showed insufficient adsorption of the VVOC but provided better adsorption and recovery of the VOC and was, therefore, proposed as a useful complement to Porapak.

In order to depict time variations of VOC due to occupants in assembly rooms, effective sampling within a short time is needed. A sampling length of 10 min is suitable for repeated sampling during a class meeting of 45 min. Sampling tubes were designed to contain a large quantity of adsorbent (0.8 mg) within a short length and a big inner diameter, allowing for high flow and low pressure drop suitable for the field pump capacity (battery operated diaphragm pump, Mine Safety Appliances, MSA, Pittsburgh, Pa, USA). The aim was to map time variations of VOC, as compared to CO₂, which was normally used for controlling ventilation efficiency.

Air sampling in the field was performed at a flow rate of 1.5 L/min through the trap that was kept at room temperature in order to avoid water condensation. The sample volumes were 15 L for FID-analyses and 100-300 L for MS identification. In the laboratory, the compounds were desorbed by heat (140 °C) and purged with carrier gas onto the first part of a wall-coated open tubular steel capillary column (0.75 mm id x 145 m, coated with polypropyleneglycol, UCON 50HB 5100) which was immersed in liquid nitrogen. Finally, the sample was injected into the gas chromatograph by heating the cooled part of the column to 140 °C. For selected samples the column was connected to the first stage of the jet-separator of a single focusing magnetic field mass spectrometer to accomplish identification of the separated compounds.

Two class rooms, A and B, situated in two different school buildings in different residential city areas of Stockholm, were selected as study objects. Room A was ventilated by a self draughting system and Room B by an overflow system with exhaust valves inside the room. The measured air exchange rates were in Room A 0.7, corresponding to $6 \text{ m}^3\text{p}^{-1}\text{h}^{-1}$, and in Room B 1.8, corresponding to $15 \text{ m}^3\text{p}^{-1}\text{h}^{-1}$ (p = person). In Room B temperature and relative humidity were recorded continuously and CO_2 was measured every 5 min during the investigation. Air samples for VOC analysis were taken during 10-min periods at the beginning and at the end of a 45-min period, either during a class session or in the unoccupied room, with fresh air supplied from the ventilation system only. For comparison also the outdoor air was analyzed at each indoor sampling occasion.

Results and Conclusion

A method for sampling, quantitation, and identification, of indoor air VOC was developed. It involves very short sampling periods (10 min) which, in contrast to current methods, makes it possible to map temporal VOC variations during less than one hour. The detection limit for quantitation is at least $0.1 \text{ }\mu\text{g}/\text{m}^3$ and for identification about $0.3 \text{ }\mu\text{g}/\text{m}^3$.

The method was applied in an investigation of the variation of VOC with time in class rooms in two different schools. The qualitative composition of the indoor and outdoor air of the school rooms was found to be about the same: aliphatic and aromatic hydrocarbons were predominating, though indoors the number of compounds detected was larger (104 indoors; 49 outdoors) and also the indoor concentrations were higher. In the presence of humans, both the number (161) and the concentrations increased, but only acetone and partly also ethanol could be characterized as typical body effluents, whereas the other compounds were supposed to emanate both from outdoor air and from indoor sources such as building materials. In Room A, with the lowest air exchange rate, the highest number and concentrations of VOC were found.

For Room B, the outdoor concentration of CO_2 was 300-400 ppm and the same concentration was obtained in the empty class room, even after a 45-min period with no occupants. In the occupied room, CO_2 increased during class meetings, reaching 500-1200 ppm, depending on number of occupants and the air exchange rate. Also, the indoor VOC increased during class meetings. In Figure 1, a reanalysis of the data from

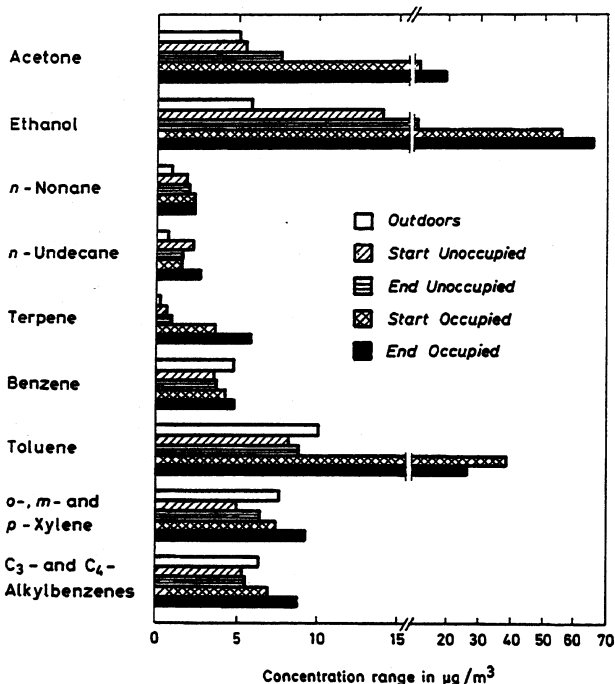


Figure 1. Concentration ranges ($\mu\text{g}/\text{m}^3$) of a selection of components in outdoor air, indoor air from the start and end of a 45-min time period in unoccupied class room, and indoor air from the start and end of a 45-min time period in occupied class room (Room B in Study 1) [Reanalysis from data, Study 1].

Room B is presented. It shows the concentration ranges ($\mu\text{g}/\text{m}^3$) of selected components in outdoor air, and indoor air from both the start and the end of a 45-min period in the unoccupied and the occupied room. Already in the unoccupied room the concentrations of several compounds, such as acetone, ethanol, and some aliphatic hydrocarbons, are elevated as compared to outdoors. During class meetings, the concentrations increase, especially for acetone and ethanol. For the aromatic compounds, such as benzene, toluene, and the lower alkylbenzenes (originating from non-human sources), the indoor concentrations in the empty room are lower than outdoors, but in the presence of occupants they increase. That is, the indoor VOC show continuous individual variation over time and location, unrelated to the CO_2 concentrations. Not even the body effluents, acetone and ethanol, follow the same pattern as CO_2 .

It was concluded that the developed method for sampling and analysis is well suited for the fine division in temporal intervals needed in studies of occupied indoor environments. It was also concluded that more studies are needed about interactions among constituents of the indoor air, and between these and the various materials in a room. For example, based on the results I would propose that there exists an accumulation indoors of the outdoor components (e.g., aromatic hydrocarbons) that are brought into the indoor air by the ventilation supply or by materials such as clothes. I would

also propose that the room may act as a “chemical reaction chamber”, for which reason the composition of the indoor air would not be exclusively defined by the composition of the inlet air and the emissions from occupants and materials in the room.

Volatile Organic Compounds from Used Building Materials in a Simulated Chamber Study (*Study 2*)

Background and Problem

In the indoor environment, building materials are regarded as potential sources of chemical emissions, in addition to outdoor air and occupants. Moreover, it is well known that new building materials often emit VOC that are known to be odorous and sensory irritating. Many scientific reports present lists of emitted compounds from indoor materials, as well as emission rates and emission factors (e.g., Mølhave, 1982; Girman, A. T. Hodgson, Newton, & Winkes, 1986; Sanchez, Mason, & Norris, 1987; Wallace, Pellizzari, Leaderer, Zelon, & Sheldon, 1987). Mathematical models have been proposed that estimate the gaseous emission from materials indoors and that predict room concentrations when the emission rates of individual materials are known (e.g., Mølhave, Bisgaard, & Dueholm, 1983). However, most chemical surveys that have been published on building materials comprise new materials or newly applied wet products like paints and glues, and only a few reports have considered the aging of materials which of course also is of utmost importance for emissions in buildings.

The aim was to find out whether old, used building materials still have an emission great enough to affect specifically the indoor air quality. A study was performed in which the emission of VOC from materials collected from a 7-year-old building was studied in a climate chamber.

Method

Samples of building materials (floor, wall, and ceiling) were removed from a room in a 7-year-old preschool that was classified as a sick building and had been closed since 3 years (subsequently this building was torn down because it was considered unusable). The sample materials were transported to an experimental climate chamber, made of stainless steel and ventilated with filtered air at an exchange rate of 0.5 ach. The VOC in the original room was analyzed just before removal of the materials, and the chamber exhaust was analyzed once after one day of equilibration with the materials in the chamber and, thereafter, an additional 12 times distributed over a period of 41 days. The method of sampling and analysis described in Study 1 was used, with some modifications. For example, for the gas chromatographic analysis the heat desorbed sample was preconcentrated in a cold trap (a glass lined steel capillary containing glass beads, emerged in liquid nitrogen) and then heat injected (150°C) into the GC. The separation column was changed from steel capillary with large inner diameter (0.75 mm) to a newly available fused silica capillary (60 m x 0.322 mm) coated

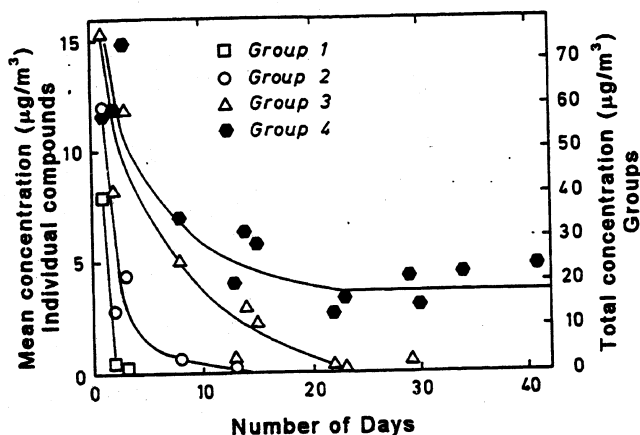


Figure 2. Concentrations for 4 groups of VOC classified according to the number of days they were present in the chamber air. Mean concentration for individual compounds in each group (left y-axis), total concentration of each group (right y-axis). [From Study 2. For list of compounds in each group, see Study 2]

with DB-5 (5% phenylpolysiloxane & 95% dimethylpolysiloxane). A single-focusing quadrupole mass spectrometer was used for identification of separated compounds.

Results and Conclusion

The method of analysis developed in Study 1 was improved. That is, the separation efficiency was refined through the cold trap preconcentration, which decreased the volume of injected sample. Also, the introduction of the glass capillary column resulted in less tailing of peaks and higher resolution than for the steel column.

Surprisingly, the first days in the chamber, the composition of VOC in the air was almost the same as in the preschool room. Then the concentrations and the number of compounds decreased during a period of almost 3 weeks at different rates for different compounds, as shown in Figure 2.

It was concluded that most of these compounds had been adsorbed earlier from the polluted preschool air, onto the material surfaces, and now they were desorbed again in the clean chamber air. The compounds were classified into four groups, according to increasing decay time in the chamber. Groups No 1, 2, 3, and 4 contained 8, 9, 11 and 17 compounds, respectively. The types of compounds were common and rather similar chemically in all groups (aliphatic and aromatic hydrocarbons, terpenes). During the last 10 days of the experiment, the compounds in Group 4 remained at constant concentrations, implying that only these compounds were representative for the original emission of the building materials. The 17 compounds of Group 4 were aldehydes C_4-C_9 , ethylhexanol and aromatic hydrocarbons like toluene, and xylenes.

The results showed that used building materials may still have an emission of VOC after several years, but also that there is an exchange of contaminants between surfaces of indoor sources and the indoor air. This means that emitted compounds from one source may be adsorbed to another and then later, when conditions have changed, they may be desorbed again and join other VOC in the air.

Adsorption and Desorption of Organic Compounds in Indoor Materials (*Study 3*)

Background and Problem

Indoor sources of air pollutants may be classified in two main categories with respect to generation pattern of pollution as a function of time: continuous (as for building materials) and intermittent (as for occupants and their activities), (Seifert & Ulrich, 1987). However, according to the results in Study 2, it is not possible to predict the amount or composition of air pollutants in a building solely from emission data of single sources, because there is also an interaction between sources that has to be taken in account. Influential factors are temperature, relative air humidity and chemical and physical properties of the material surfaces. A literature survey was, therefore, undertaken that focused on emission, adsorption and desorption of indoor air pollutants.

Important surfaces in a building, identified in the literature survey, are the ventilation air ducts and accumulated particulate matter in them which may interact with airborne volatile compounds. For this reason, sometimes mechanical cleaning of the ventilation system is conducted as a measure to solve problems with complaints about bad indoor air quality in buildings. The aim was to investigate the effect of such cleaning, and an intervention study was undertaken in which the supply air was analyzed for VOC before and after cleaning of a ventilation system.

Method

As a first step a search of the literature on adsorption and desorption of organic compounds was performed with special interest in: (a) Sources and characterization of indoor organic compounds; (b) Aging of materials and aging of buildings; (c) Importance of indoor climate variables and building factors; (d) Semivolatile organic compounds; and (e) Odor as an additional criterion in defining indoor air quality.

As a second step a field study was performed in a large office building where complaints about bad indoor air had been reported, especially from a printing office. In the ventilation system, only serving the printing office, the ventilation fans, the rotating-wheel heat exchanger, and the supply air ducts were cleaned by mechanical brushing and vacuum cleaning. All air filters in the system were also changed. The ventilation air was analyzed before the cleaning procedure and then at 1, 5, 12 and 19 months after the cleaning. Air sampling locations were selected in the supply air duct on both sides of the heat exchanger, at the end of the supply air ducts in the printing office, and in the outdoor air. After the cleaning, the air was sampled in the same locations along with two locations in the exhaust air duct on both sides of the heat

exchanger. VOC were sampled and analyzed by the method described in Study 2. Although the sampling occasions at 12 and 19 months were performed after the publication of Study 3, the results will be included in the presentation below.

Results and Conclusion

The *literature survey* showed that the emission of building materials as well as of household products has been measured and reported in several studies, but only a few of these pay attention to the fact that also adsorption of compounds on indoor materials, “wall effects”, and “sink effect” have to be taken into consideration when evaluating the results (e.g., Tichenor, 1987; Dunn & Tichenor, 1988). The expression “sink” and “sink effect” is used to describe the reduction of airborne contaminants achieved because of the presence of solid materials and other things influencing the concentration of the contamination through adsorption, chemical reaction, or simple leakage out of the space. Most surveys of indoor air pollution sources comprise new materials, newly applied surface treatment products or new buildings. However, there are some exceptions. For example, P. A. Nielsen (1985) studied longitudinally (months) the aging of new building materials in a climate chamber and found initial half-life periods of several weeks, and Mølhave, Lundqvist and Andersen (1985) studied the emission from building materials over one year in new but unoccupied buildings. Several studies (e.g., Gebefügi & Korte, 1988; Gebefügi & Kettrup, 1995) conclude that SVOC may be much more important to the indoor environment than VOC, since there is a high degree of accumulation of semi-volatile compounds on indoor surfaces and then, due to the subsequent desorption, they may remain above “normal” indoor levels for a long time. Only a few systematic studies concerned the question whether indoor environmental factors may cause adverse health effects in humans. In a survey of 14 office buildings in Denmark, Skov, Valbjørn, and Pedersen (1989, 1990) concluded that the prevalence of mucosal irritation and other general symptoms, considered to be typical of the SBS, are strongly associated with building factors like great areas of textiles and open shelves. The explanation is that materials are capable of depositing/adsorbing/accumulating pollutants, greatly affecting indoor air quality. Since odor has an obvious relationship to human discomfort, some reports point out odor as a useful criterion, in addition to physical and chemical analysis, in defining indoor air quality (Fanger, 1988; Fanger, Lauridsen, Bluyssen, & Clausen, 1988).

The results of the *field study* showed effects of adsorption and desorption of VOC in the rotating wheel of the heat exchanger. A reanalysis of data, from the sampling before cleaning and at 1 and 19 months after the cleaning, is given in Figure 3. It shows the concentrations in intake air and in supply air, right before and right after the rotating wheel. Before cleaning, supply air passing through the heat exchanger was contaminated by hydrocarbons C_8 to C_{12} (upper diagram). Headspace analyses of solvents frequently used in the printing office showed a great amount of hydrocarbons C_8 to C_{12} , and it was assumed that these compounds, when occurring in the room, are transferred from the exhaust air to the supply air by the rotating wheel heat exchanger. The emission of the solvents also contained 1,1,1-trichloroethane and one other VVOC,

Cleaning of Rotating Wheel Heat Exchanger

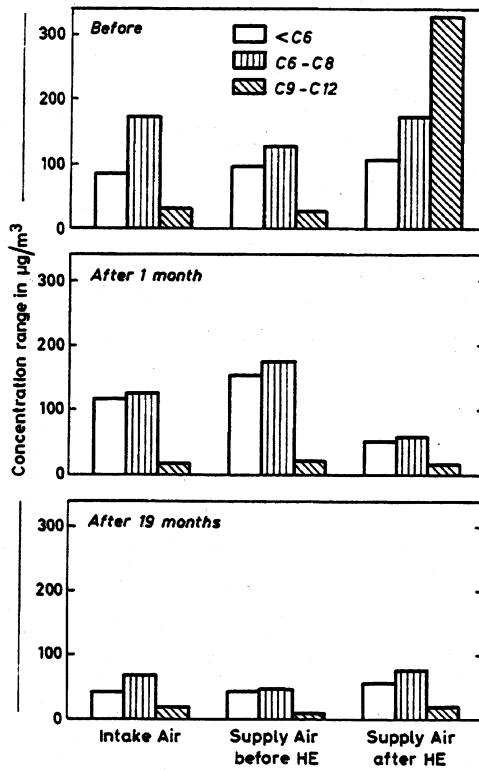


Figure 3. Concentration ranges ($\mu\text{g}/\text{m}^3$) of VOC in intake air, and in supply air right before and right after a rotating wheel heat exchanger. The diagrams represent three sampling times: before cleaning the rotating wheel (upper diagram), 1 month after cleaning (middle diagram), and 19 month after cleaning (lower diagram). The three bars represent the sum of VOC in three retention time periods of the chromatograms, corresponding to $<C_6$, C_6-C_8 , and C_9-C_{12} , respectively. [Reanalysis of data from Study 3]

probably some type of freon, but none of these was present in the supply air. At 1 and 5 months after the ventilation system was cleaned, no contamination was found in the supply air after the passage through the heat exchanger (middle diagram). However, it is interesting to note, that the newly cleaned wheel seems to adsorb the pollutants in intake air, and thus act as a supply air cleaner. At 12 and 19 months after cleaning, the supply air after the exchanger is slightly contaminated again by the hydrocarbons, C_8 to C_{12} (lower diagram). This time, also the exhaust air from the printing office was analyzed and a great amount of C_8-C_{12} hydrocarbons, was found as well as 1,1,1-trichloroethane and the freon. However, in the supply air, only the C_8-C_{12} hydrocarbons were found while the freon or halocarbon were neither detected before nor after the heat exchanger.

From the results of Study 3, it is concluded that this rotating wheel heat exchanger (large specific area), that every day is passed by very polluted exhaust air, will after some time (12 to 19 months) transfer pollutants from exhaust air to supply air. VOC, especially those with boiling points $>150^{\circ}\text{C}$, are adsorbed on the porous surface of the heat exchanger and then when the exchanger surface is saturated with pollutants they are desorbed again when the wheel rotates into the clean supply air. The two VVOC, 1,1,1-trichloroethane and the unidentified freon, which are too volatile and non-reactive to be adsorbed on the wheel, are not at all present in the supply air. This indicates that there is no air leakage between the supply and exhaust air linings, and evidently the only possible transfer of contaminants between the two air streams is through adsorption and desorption in the rotating exchanger wheel.

From the *literature survey* it was concluded that compounds are adsorbed from room air to indoor materials and then desorbed again when the materials are ventilated. Moreover, from the *field study* it is concluded that a rotating wheel heat exchanger may be an active component in a ventilation system that continuously, through adsorption and desorption, transfers organic compounds from exhaust to supply air.

Joint Representation of Physical Locations and Volatile Organic Compounds in Indoor Air from a Healthy and a Sick Building (Study 4)

Background and Problem

Previous investigations and literature surveys indicate that there is no obvious difference between healthy and sick buildings with respect to single VOC or groups of VOC. This implies that a different approach to the problem must be adopted. It is suggested that instead of seeking a single chemical, or cataloguing all chemicals in the indoor locations, one should seek an explanation in terms of differences in subpatterns of many chemicals across different locations within and between buildings (B. Berglund & Lindvall, 1990). The central idea is that joint presence or interactions among pollutants may cause the sick building symptoms, and the absolute concentrations of pollutants may be less important than location-to-location differences in pollutant concentrations within a building. A methodology is introduced to identify chemical gradients within a building and then suggest how these gradients can further the understanding of why people become sick in some buildings more than in others.

Method

Air samples were taken from locations (17 locations; 170 samples) inside and outside two Stockholm preschools, one considered healthy, the other, sick. The particular locations were chosen in order to cover the major, distinct volumes of air within the buildings, with special emphasis placed on regions associated with the heating and exhaust systems. VOC were sampled and analyzed using the method reported in Study 2. Both the chemical differences between sick and healthy buildings, and among selected locations within these buildings, were examined. The data were subjected to a

correspondence analysis which simultaneously represents both chemicals and building locations as points in a geometric space. A discriminant analysis was subsequently used to create a decision rule for classifying each sample into one of the locations. To cluster the chemicals, a principal component analysis was conducted of the peak heights of the chemicals as measured in each of the 170 air samples.

Results and Conclusion

Across all 170 chromatograms, 158 peaks could be differentiated from the base level of the FID-response. Thirty-three of these could be positively identified by MS as one (or in some cases two) specific chemical compound and were quantified by GC peak heights. The 170 gas chromatograms (coded by building location) and the 33 chemical concentrations (peak heights of identified compounds) were then subjected to statistical analysis.

Fifteen chemicals had been identified as either typical “indoor substances” or typical “outdoor substances” (B. Berglund, Johansson, & Lindvall, 1982a). The correspondence analysis shows that different locations contain partly different chemicals and that indoor chemicals increase in concentration with distance from air intake. For outdoor chemicals, however concentration increases with distance from the air intake in the sick building, but not in the healthy one. This suggests that pattern differences may distinguish sick and healthy buildings. The discriminant analysis demonstrates how the locations may be grouped into chemically distinguishable clumps. For example, the location groups may be differentiated as people-present vs. people-absent, the sick building with people present vs. all others, and outdoor air near the sick building vs. all others. When clustering the chemicals with a principal component analysis it was found that the factors do not show groupings of chemicals by chemical class. This means that the chemicals in, for example, the terpene class are not a unified entity which either occurs or does not occur in an air sample. The results indicate that no single chemical class differentiates sick from healthy buildings, and chemicals in the same class do not have common origins or circulation patterns within buildings. Within the sick preschool, concentrations of light aromatic hydrocarbons increased with distance from the air supply, but there was no similar gradient in the healthy preschool. The link between these findings and the health problems reported in one of the buildings was never studied.

Through further cluster analysis of the same data, based on the pattern of presence and absence of chemicals, locations within and between the healthy and sick building were separated (Baird, B. Berglund, U. Berglund, Nicander-Bredberg, & Noma, 1987). Ten chemicals were present that distinguished absolutely between the two buildings. Six of these were identified as: tetrachloroethene, β -pinene, 1,1,1-trichloroethane, butylacetate, *n*-dodecane, *n*-tridecane. The remaining 4 chemicals appeared at too low concentrations to be identified by the MS analysis.

The relationship between chemicals and locations in the two preschools was represented spatially by correspondence analysis and other statistical techniques. The analyses clearly distinguished among the buildings and among locations within each building,

including whether the sample was collected outdoors or indoors. The results obtained by the comparatively new method of correspondence analysis are supported further by the discriminant analysis and the principal component analysis.

Reliability of Odor Measurements Near Threshold (*Study 5*)

Background and Problem

WHO (1987) established that although objectional odors or odor annoyance cannot be regarded as an adverse health effect in a strict sense, it affects the quality of life. Therefore, odor threshold levels for chemicals that have malodorous or irritating properties at concentrations below those at which toxic effects occur, should be given separate guidelines for air quality. The psychophysical measurement of weak odors is important for learning more about the (adverse) sensory effects of low concentration compounds in indoor and ambient air. However, there is a great variation in literature data on sensory detectability and perceived intensity, depending on what type of methods were used for threshold definition, panel selection, stimulus presentation, purity of chemicals, and data treatment and interpretation. Furthermore, the olfactometric technique and the chemical analytical control of actual concentrations varies a lot between different investigations. This implies that if sensory measurements are to be successfully applied in environmental settings, more knowledge is needed about construct validity, reliability and the quality assurance of sensory measures for near-threshold weak concentrations. Since odor threshold levels usually are at concentration levels well below detection limits of chemical analytical instruments, the concentrations to which observers are exposed, usually, are expressed solely as dilution factors, or as predicted concentration levels when chemical analyses actually have taken place at a preceding higher concentration step in the dosage system. Since losses due to wall adsorption or chemical alteration may occur, the validity of the dilution calculations in olfactometers must always be proven.

Formaldehyde, which has a characteristic pungent odor, is one of the first indoor air organic components that was reported as a possible cause of indoor health problems (Andersen, Lundqvist, & Mølhave, 1975). Problems appeared, and are in some cases still remaining, in dwellings where chipboard was used as a construction material or urea formaldehyde foam was used as an isolation material. A reasonable amount of research have been devoted to studying the health effects of formaldehyde, including odor and irritation thresholds, as well as to surveying indoor concentrations in buildings.

For sensory studies, formaldehyde is often generated by dilution of the headspace of paraformaldehyde with temperature-controlled clean air. Paraformaldehyde is a solid, white, low molecular condensate of polyoxymethylene glycols containing from 8 to 100 formaldehyde units per molecule which, at ordinary temperatures, gradually vaporizes into its monomer. However, the vapors may also contain water, formic acid, methanol, methylal, and probably also the dimer and the trimer of formaldehyde. It

should be noted that the cyclic trimer, trioxane (CH_2O)₃, is not irritating but has a pleasant chloroform-like odor (Walker, 1964).

To avoid these impurities, a new method was applied (Mølhav, 1984), where stimulus is generated from a stabilized sodium hydroxide solution of formaldehyde, which is supposed to emit only the pure monomer. Furthermore, in order to assess exposure concentrations, the headspace concentration of the solution, and the diluted concentrations of stimulus presented to subjects, were each measured with two independent methods. To find out whether the method of stimulus generation may influence odor detectability or perceived odor intensity, the results from an experiment performed with the new method were compared with the results from an earlier experiment, in which paraformaldehyde headspace generation was used (U. Berglund & Högman, 1988).

The purpose of the sensory experiments was to determine the test-retest reliability of odor detection as well as of perceived odor intensity scales obtained for near threshold concentrations of formaldehyde. A further purpose was to investigate the relationship between the effective threshold obtained with the method of constant stimuli and the threshold extrapolated from the psychophysical power function, both thresholds being possible to determine with the aid of data on detections of clean air presentations (blanks). The aim was also to provide quality assured measures of odor detection and perceived odor intensity of formaldehyde so that guidelines can be formulated based on adverse sensory effects relevant for the near-threshold concentrations present in indoor air.

Method

In the present study (Study 5), two types of odor thresholds were determined for formaldehyde, using two different methods of assessment. One experiment utilized the method of constant stimuli and the other the method of free-number magnitude estimation. In both experiments the identical 18 formaldehyde concentrations (range 20-794 ppb in 0.125 log steps) and the same number of blanks were used as stimuli.

Formaldehyde gas is very reactive and it is difficult to make reproducible stimulus generation in the olfactometer because of adsorption and polymerization on wall surfaces. On the other hand, for sampling and analysis of formaldehyde the reactivity may be utilized. Accordingly, formaldehyde in air is often sampled through quantitative chemical reaction resulting in a stable reactant which may be analyzed by, for example, spectrometry or liquid chromatography. Usually long sampling periods (15 min to 1 h) are needed in order to collect enough amount of sample to reach the detection threshold of the chemical analysis. This in turn prevents continuous monitoring of the low odor threshold concentrations during exposure. In this case an automated analytical equipment is preferred, such as the flow analysis instrument for formaldehyde from Skalar Analytical (Skalar 9400, EZ Breda, The Netherlands). The air sample is led through a water solution of acetylacetone and ammonium acetate, a yellow colored complex is formed which is analyzed by a UV-detector. The instrument may be used for continuous analysis of concentrations from 0 to 1 ppm.

The experiments were performed in an air quality laboratory. A dynamic olfactometer was used which allowed rapid changes of well-controlled concentrations (Lindvall, 1970; B. Berglund et al., 1986). The exposure is given in a hood with an opening for the observer's nose and mouth. For the preparation of formaldehyde solution, paraformaldehyde (Merck, extra pure) was pretreated by heat (105-110 °C, 3 h) in order to decrease the molecular sizes of the polymer, and dissolved in 0.01 N sodium hydroxide. From this solution, a base concentration of 100 ppm formaldehyde was generated in the dynamic air flow system containing combinations of steel capillaries of varying length and diameter. By means of magnetic valves, the gas flow from the capillaries were injected into a continuous 100 L/min air flow through the exposure hood.

The basic concentration in air was continuously measured and registered by an IR-instrument (Miran 80, Foxboro Analytical, Buckinghamshire, England) which in turn was calibrated with the method of sodium bisulfite (Skare & Dahlner, 1973). The latter is based on the quantitative formation of a formaldehyde-bisulfite addition product when formaldehyde is passed through a sodium bisulfite solution. The excess sodium bisulfite is eliminated with iodine, then the addition product is decomposed by alkali, and the resulting sodium bisulfite is determined quantitatively with iodine. To control the actual concentrations in the exposure hood, each concentration was measured every experimental day with the formaldehyde monitor (Skalar SA 9400).

As an extra quality assurance, the hood concentrations were also measured by an independent external laboratory using a chemisorption method with sampling on glass fiber filter impregnated with 2,4-dinitrophenylhydrazine and phosphoric acid. The formaldehyde hydrazone, formed during sampling, is then desorbed with acetonitrile and determined by high-performance liquid chromatography (Levin et al., 1985).

Results and Conclusion

The two methods for determining hood concentrations, prediction from IR-measurement before dilution and continuous measurement in the hood, show a near to perfect agreement which was also confirmed by the analyses of the hood samples performed by the external independent laboratory. The formaldehyde concentration before dilution was on average 100.1 ppm (SD = 6.79; N = 200) as measured by the IR analysis. When the formaldehyde concentrations measured directly in the hood are plotted against the calculated hood concentrations (based on the concentrations before dilution and from the capillary flows) they show a close to perfect agreement. The data points coincide well with the principal diagonal ($Y = -0.13 + 1.05X$; $R = 0.997$; $N = 18$). In the former experiment with formaldehyde generation from headspace of solid paraformaldehyde (U. Berglund, & Högman, 1988) there were also a good agreement between the continuously measured hood concentrations and the volumetric predicted concentrations ($Y = 0.06 + 0.97X$; $R = 0.998$ $N = 12$).

Two new threshold concepts are introduced. The effective threshold (odor detection data) was defined as the highest concentration where the probability of hits equals the probability of false alarms. The extrapolated threshold (perceived odor intensity data) was derived from the psychophysical power function, representing the highest

formaldehyde concentration at which the perceived intensity equals the perceived intensity of the clean air presentations (blanks). The threshold and perceived-intensity assessments of threshold agree well over subjects, the median is 47.9 and 27.9 ppb, respectively. From the results of these experiments, it is recommended that formaldehyde concentrations are to be kept below 100 ppb in indoor air of nonindustrial buildings.

In conclusion, the main source of the great variability in published detection thresholds (or parameters of the power function for odor intensity) is probably not methods of formaldehyde generation, purity of chemicals or reproducibility of stimulus concentrations, specific groups of normal observers, or intra- or inter-individual differences in odor sensation over time. It is probably a result of a variation in the quality of olfactometric or psychophysical measurement procedures between international research laboratories.

Volatile Organic Compounds in Indoor Air with Significance for Health and Comfort (*Study 6*)

Background and Problem

Sensory effects, like odor and irritation of mucous membranes, are of central importance when assessing indoor air quality, with respect to health and comfort, in nonindustrial environments. Research is needed on human sensory effects of typical indoor air compounds, like for example, compounds that are susceptible to influence perceived air quality or that are documented as odorous or irritating at low concentrations. However, a compound that is intended to be used in human sensory studies must not be carcinogenic, mutagenic, toxic or in any other way contribute to allergic reactions in the low concentrations that are of concern indoors. As a consequence, the threshold limit values (TLV) must be much higher than exposure concentrations. Also, the odor and irritation thresholds should be lower than typical indoor concentrations in order to be perceptually detected. Furthermore, the chemical and physical properties, like reactivity and volatility, of the compound must permit quantitative generation and dilution in an olfactometer. A literature study was performed to provide a basis for the selection of suitable compounds characteristic of indoor air pollutants, to be investigated in further studies of human sensory reactions.

Method

In the literature review the interest was focused on: (a) Compounds that have been used earlier in human exposure studies; (b) Compounds generally found in the indoor environment; (c) Compounds that, according to the literature, are believed to be important to indoor air quality; (d) Special indoor compounds that have been observed in sick buildings; (e) Compounds found in indoor air that are known to be sensory irritating; and (f) Compounds found in indoor air that are known to be odorous. As a bases for the selection of compounds that may be studied, medical and sensory properties of

compounds were considered, like: general toxicity, genotoxicity, allergen effects, odor, and irritating effects on mucous membranes and skin.

Results and Conclusion

The review comprises a survey of indoor air compounds found in field studies. Several hundreds of VOC may occur at the same time, but usually only 10-20 of them are chemically dominating. The review also includes descriptions of some special compounds (e.g., low molecular aldehydes, butylphthalates, isocyanates, epoxy products, and acrylates), and results from human dose-effect studies with special component mixtures referring to the indoor environment.

Based upon literature data, a list is presented containing 34 compounds (3 VVOC, 29 VOC, 1 SVOC, and the inorganic gas NO₂), considered urgent to investigate for human sensory effects. As far as literature data was available, also molecular weights, boiling points, vapor pressure, odor thresholds, and TLV/MAK (Maximale Arbeitsplatz-Konzentrationen) values are listed. However, with regard to the postulated criteria about not too adverse health effects and possibility for quantitative generation in exposure studies, most of the compounds have to be excluded, even though they may be able to cause so-called sick building symptoms. Finally, 13 compounds (12 VOC and NO₂) were selected to be of interest and recommended for investigation in further human sensory studies focusing on indoor air problems.

Health Effects of Volatile Organic Compounds in Indoor Air (Study 7)

Background and Problem

Single volatile organic compounds (VOC), total volatile organic compounds (TVOC) and concentration patterns of VOC are all partial descriptions of the chemical composition of indoor air that have been used as indicators of air quality and potential health and comfort effects. The question is whether this is a relevant way to describe the complex air quality and its potential relation with adverse effects in indoor environments.

In order to investigate the relationship between health and sensory effects and the indoor air, it is necessary to characterize pertinent health effects as well as physical-chemical characteristics of the air. So far, there are presently no consistent assessments of, or consensus on, either of them. A critical analysis of the literature is needed concerning indicators, such as TVOC, and various indices of the health and sensory effects associated with the chemical measures. Special interest should be given to the importance of human sensitivity to odor and sensory irritation as well as discomfort.

Method

A literature search was performed focused on methods of chemical and sensory analysis, as well as field studies of air quality and sensory effects in indoor environments. For the *chemical characterization of VOC* in indoor air, the following topics were

surveyed: chemical methods of measurement of low concentrations of VOC (including both methods of air sampling and of chemical analysis); the occurrence of VOC in indoor air of nonindustrial rooms; sources of VOC in indoor air; variations of VOC composition over time; and chemical and physical processes (e.g., adsorption/desorption and chemical reactions among chemical compounds) in the indoor environment. The possibility to use single compounds, TVOC, or patterns of VOC detected in indoor air, as indicators of IAQ is analyzed.

For the *characterization of sensory effects from VOC* in indoor air, methods of measurement of sensory detection thresholds, quantitative scaling, and qualitative characterization of perception were surveyed. Also an evaluation of physiological methods, for the measurement of effects like eye irritation, irritation in the mucous membrane of the nose, and in the upper and lower air passages, were included. For the perception of discomfort, health related effects, odor and sensory reactions, the interest was focused on effects associated with either individual VOC, or complex mixtures of VOC, at low indoor-air concentrations. Studies of effects on humans exposed in chambers to special VOC or to mixtures of VOC as well as field studies of odor quality indoors, were also included. The possibility of using single compounds, TVOC, or pattern of VOC as indicator of health effects is analyzed. Finally a summary of the assessments and recommendations is presented, and the use of TVOC as indicator of air quality and health effects is evaluated.

Results and Conclusion

Single VOC in indoor air are typically detected at very low concentrations, often 100 to 1,000 times below the occupational TLV. There are presently no *field studies* that with certainty can point out measured VOC as “causes” of problems in the nonindustrial indoor environment. Neither are there any studies that with certainty can reject them. General criticism is, for example, that the differences in VOC concentrations between investigated sick and healthy buildings are so small that no differentiation regarding effects could be expected, or that the measurements of VOC are not made at the same time as the measurements of SBS-symptoms or other health or sensory effects. The basis for the evaluation of health effects is sometimes not firm enough because of response loss (from occupants), or it is uncertain whether an assumed sick building really is sick. Also, regarding the assessment of VOC content in air, there are too few samples for the analysis of VOC to enable generalization, or there are no comparative measurements in other rooms or buildings with no problems, or in the outdoor air. In some cases, the method of VOC analysis is not sensitive enough (ppm-levels) or there are too few data collected for being considered representative for longer time periods.

Chamber studies have shown correlations between VOC and effects such as perceived odor, sensory irritation, and perceived deterioration of air quality, but they are not able to demonstrate clear relationships to health effects. Typically, higher chamber concentrations than those normally observed in indoor air of rooms have been used, and therefore, the reliability of the investigations can be questioned. Often, also the

background chamber concentrations of VOC are higher than those found in normal indoor environments. Chamber studies are for practical reasons restricted to very short periods of exposure (an hour or a few hours). Long-term habituation to air quality can, therefore, not be studied, certain symptoms or discomfort may not emerge, and possible accentuation of symptoms in time will not at all be registered. Furthermore, the artificial laboratory environment may have a negative influence on the relatively subtle effects in question. However, the advantage of chamber studies is the possibility to keep full control of variables such as thermal climate, air exchange, and pollutant concentration as well as activities within the room. Experimental conditions may be repeated frequently, for the same set of subjects or for several different subjects at different occasions.

In many epidemiological field studies, it has been proposed that the occurrence of SBS symptoms are caused by other compounds than the measured VOC, formed by *chemical reactions in the indoor air*. For example, through reactions between O_3 and certain VOC, short-lived chemical radicals or oxidized compounds may be formed. However, there is not yet any positive evidence that such compounds have been produced in amounts enough to explain human adverse health or sensory effects.

From the critical review, it was concluded that TVOC can not possibly be used as an *indicator* of health and sensory effects, because potential effects probably are related to the chemical composition of VOC rather than to the total concentration of VOC. It can neither be used as a *measure* of IAQ or VOC because the TVOC scale is not unidimensional. Rather it is a combined measure whereby the same TVOC values can come about through many different combinations and concentrations of the included VOC (different buildings have different patterns of VOC). Finally, the review indicates that most VOC in indoor air actually are *odorous irritants* and, therefore, it is recommended, regarding effects on humans, that future resources and research efforts should be devoted to basic scientific studies of the effects on humans specifically including the highly sensitive modalities of odor and sensory irritation.

GENERAL DISCUSSION

The aim of this thesis is to investigate air pollutants, especially volatile organic compounds (VOC), relevant for indoor air quality (IAQ) in nonindustrial environments. There is also an attempt to find out whether or not there is a link between indoor air VOC and human health and sensory effects. In the following, the definition, assessment, and improvement of IAQ, with regard to indoor air pollutants and their effects on humans are discussed.

Indoor Air Quality and VOC

The concept of IAQ is still ambiguous and will probably remain so. However, for practical use of the concept some principles may be agreed upon. For example, the definition and assessment of IAQ must be based on both environmental factors and human individual effects. That is, chemical and physical properties of indoor air, as well as human health, physiological and sensory effects must be taken into account. The weight of each variable is dependent on what is assumed to be influenced by the IAQ. Here the focus of interest is on potential influences on human health and sensory effects. The thesis is devoted to the role of airborne organic compounds, not necessarily restricted to VOC as defined by WHO (1989a).

Definition of IAQ

Chemical, physical and sensory definitions of IAQ are summarized in Figure 4. Chemically, the IAQ is defined by the indoor air content of inorganic gases (e.g., CO, CO₂, O₃, and NO_x) and volatile organic compounds (e.g., VVOC, VOC, SVOC, and TVOC) as related to published TLVs or guideline values. For a physical definition, temperature and relative humidity are predominating factors, although, particles and air ions as well as light and noise are not the less important. The sensory definition includes perceived odor, sensory irritation, and the perception of air quality. According to WHO (1987; 1989a) odors and sensory irritants are potential causes of adverse health effects, and in the WHO Air Quality Guidelines for Europe (WHO, 1987) guideline values based on odor are given for eight substances, including formaldehyde.

For IAQ, the basic rule adopted by WHO (1989a) is that unwanted odorous compounds should not be present in concentrations exceeding the 50% probability of odor detection when presented alone and tested in a representative sample of the general population. For sensory irritation, the corresponding criterion adopted is 10% probability of irritation detection. For health, typical symptoms characteristic of problem buildings are defined by WHO (1983), (Appendix I). However, it is still not confirmed that the variables of odor, sensory irritation, and symptoms are relevant, or properly evaluated, for supporting the definition of IAQ.

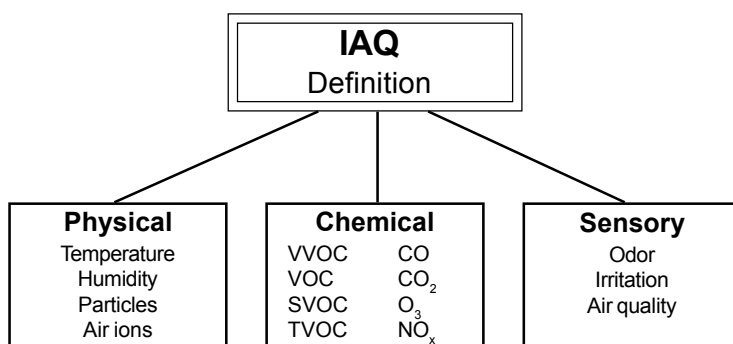


Figure 4. Block diagram of a basis for definition of indoor air quality, IAQ. Examples of potential variables.

Assessment of IAQ

A basis for the assessment of IAQ is presented in the block diagram of Figure 5. The assessment of IAQ, must be based on simultaneous measurements of chemical compounds, physical variables, symptoms, and other sensory effects, and perception of the total air environment. Measures of TVOC or CO₂ can neither be used as indicators of IAQ, nor as a basis for the assessment of IAQ (Study 1, Study 6, Study 7). To obtain a proper basis for measured variables, the *study design* including the *sampling strategy* is critical. Examples of important considerations for chemical and physical measurements are the choice of exact within-building location as well as outdoor location, time for sampling, and duration of sampling. Also for the sensory measurements, the time frame for the reports (instantaneous or retrospective) is critical. The individual differences in susceptibility, sensitivity, and personality, are decisive for the appearance of symptoms and other sensory perceptions. In indoor air studies, sensitive individuals as compared to normal, should be particularly considered.

For inorganic gases portable direct-reading instruments are available, which may deliver both instantaneous and time integrated values. For VOC, the situation is more complicated since momentary monitoring is impossible, and the sampling and analysis of air samples is tedious and expensive. The sampling is always an integration over time, the duration depending on type of sampling method. That is, for VOC measurements, there are severe restrictions as to the number of samples and sampling occasions. This, in turn, puts a stress on the design of sampling strategy for VOC, in order to cover all possible situations and variations in composition and concentrations (see e.g., ECA, 1994).

Parallel sampling of several *locations* must be performed in order to obtain adequate information about pollutant sources and the interactive transport of pollutants between within-building locations. For example, through parallel sampling indoors and outdoors in Study 1, it was found that the outdoor air was indeed an important source of indoor air pollution. Another case of parallel indoor/outdoor sampling showed

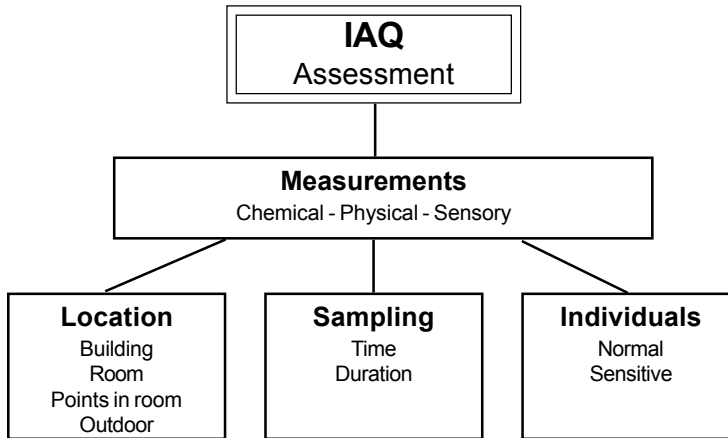


Figure 5. Block diagram of a basis for the assessment of indoor air quality, IAQ. Factors to be included in the design of sampling strategy.

that the investigated building helped to protect against high concentrations of outdoor pollutants, because the location of the air intake was in a clean area (B. Berglund, Johansson, & Lindvall, 1982a). The careful sampling strategy used in Study 4, with sampling locations outdoors, indoors in several rooms, and in supply and exhaust air, provided a basis for an important set of conclusions about the origin and accumulation of different groups of VOC.

Several sampling occasions, *time of sampling*, are needed to reflect fluctuations with time of pollutant composition. Occasional measurements, short time (10 min - 1 hour) or long time (8 hours - weeks), are not representative, or are even deceptive, for the characterization of the indoor air VOC composition. Typically, in urban areas great seasonal variations in outdoor VOC, will depend on emissions from motor vehicles and heating, with the largest amounts occurring during the cold seasons (fall and winter). Furthermore, the formation of O₃ outdoors, which may influence the VOC composition outdoors as well as indoors, is favored by UV-light and, consequently, the concentrations are highest during summer (WHO, 1987). There is also a diurnal variation in outdoor VOC, depending on meteorological and traffic variations, with peak concentrations appearing morning and afternoon during weekdays (e.g., B. Berglund, Johansson, & Lindvall, 1982a, 1993).

In addition to the influence of outdoor air variations, the indoor time variations in air pollutant composition due to sources, occupants, and activities, must be considered. Only few indoor air studies used sampling strategies that try to cover seasonal or diurnal variations (e.g., Seifert et al., 1989; B. Berglund, Johansson, Lindvall, & Lundin, 1990a; B. Berglund, Johansson, & Lindvall, 1993).

The possible *duration of sampling* for VOC depends on sampling method. Active sampling takes 10 min up to 8 hours whereas passive sampling requires 1 or 2 weeks. Diurnal variations are best determined by consecutive short-duration samplings

(10 min - 1 hour) over several days such that a detailed information on variations in composition and peak concentrations will be obtained. However, at the same time, information about sudden concentration peaks or decreases may be lost, and consequently predicted average daily concentrations will be incomplete. Therefore, for the assessment of average dose or exposure, long-time integrated sampling, over several hours or days should be used.

The method of air sampling developed in Study 1 was aimed at the study of temporal variations of VOC within one hour, to be used as a basis for ventilation requirements for occupied indoor spaces (class rooms). The original idea was to obtain a more detailed and better covering measure of IAQ than CO₂, a measure that would be involved in human sensory perception, which CO₂ is not. That is, a valid chemical method was sought for measuring odorous human body emission in occupied rooms. Short sampling periods of 10-15 min were well suited for this purpose and superior to other methods used at that time which required several hours per sample (e.g., Raymond, & Guiochon, 1974; Pellizzari, Bunch, Berkley, & McRae, 1976b). However, the patterns of VOC obtained in Study 1 were complex and the concentration of single compounds never reached odor or irritation threshold levels, and consequently, the results could not be referred to human sensory perceptions of IAQ. On the other hand, through the short sampling duration, detailed information on the influence of the presence of occupants was obtained on indoor-air composition of VOC and on ventilation efficiency.

The ambition to map the VOC content in all locations and through all concentration variations with time will result in an immense amount of data which is difficult and tedious to interpret. Therefore, a fruitful approach to assessing IAQ, would be to integrate, comparatively, data from chemical/physical and human health and sensory measurements by *pattern analyses* (cf. Study 4; Bornehag, 1994). Variables to be included are: (a) *chemical/physical data*, e.g., TVOC, VOC, indoor-related VOC, SVOC, odorants, irritants, O₃, CO₂, temperature, relative humidity, and particles, (b) *sensory data*, e.g., odor and irritation intensity, and perceived air quality, (c) *locations*, e.g., buildings, rooms in buildings, and outdoor environment, (d) *time* variations over day, week, or season, (e) groups of *individuals*, selected according to hypersensitivity or other person-related factors, and/or (f) type, frequency, and severity of *symptoms*. However, for each set of variables, there is obviously a great uncertainty about appropriate methods of measurement and of analysis as well as about how to evaluate results of measurements. In addition, it may be questioned whether current methods are sensitive enough or whether they focus on relevant variables. Opinions differ and the choice of analyses and interpretation of results is not always agreed upon among researchers.

Improvement of IAQ

For a possible success in improving IAQ in problem buildings, measures must be based on both chemical/physical and health/sensory measurements. That is, health and sensory effects must be related to chemical or physical factors, that are possible to

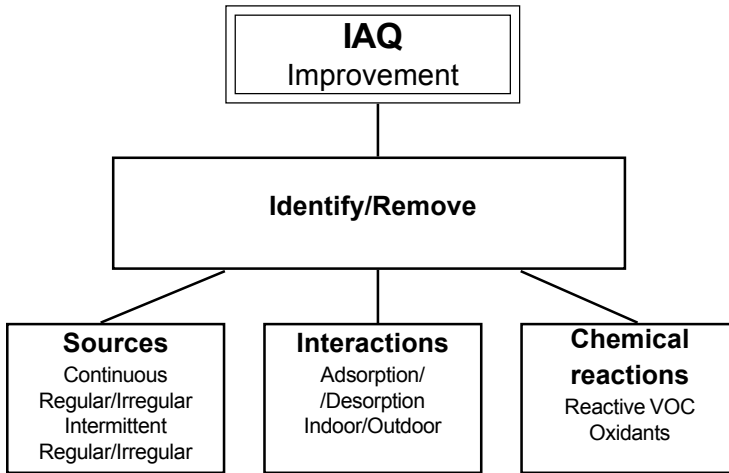


Figure 6. Block diagram of the basis for improving indoor air quality, IAQ. Examples of factors to be considered.

measure and, most importantly, physical factors that are possible to rectify. In order to obtain data that are really representative of time intervals and locations of concern, the sampling strategies for indoor air investigations should include parallel assessments of all influencing factors. Factors to be considered for improving IAQ are presented in Figure 6.

For improving IAQ, *sources* indicated as potential causes of problems must be verified and removed. Then it must be considered that the temporal emission pattern from pollutant sources, may be continuous or intermittent, in either case with a regular or irregular character (Seifert & Ulrich, 1987).

A continuous interplay of pollutants takes place due to *adsorption* and *desorption*, between indoor materials and indoor air, among the indoor materials themselves, and between ventilation components and supply air. This will provide difficulties when one attempts to trace and remove the origin of specific contaminants in problem buildings. Study 2 showed that old, used building materials, had an “imprint” of organic pollutants, probably originating from other materials and activities in the room, and from the room supply air. Several weeks of fresh air ventilation were needed to desorb fully these compounds and to discern compounds originating from the materials themselves. In Study 3, it was shown that a rotating wheel heat exchanger was saturated with (had an “imprint” of) certain exhaust air pollutants, that two years later started to desorb again and, thus, polluting the supply air. Similar results were obtained in an early study of four preschools, where high VOC concentrations were found in the supply air of the only building equipped with a rotating wheel heat exchanger (Johansson, Pettersson, & Rehn, 1978; 1979). It was hypothesized that the pollutants were transferred by the rotating wheel through adsorption/desorption effects, however, at that time it could not be fully proved, since no samples were collected within the air ducts

right before and after the wheel (cf. Study 3). Adsorption/desorption effects in buildings were also observed in, for example, the Danish Town Hall study by P. A. Nielsen (1987). He found a correlation between certain indoor factors, such as great total area of textiles and of open shelves (“fleece index” and “shelf index”) and symptoms characteristic of SBS. Some later studies have not been able to confirm this relationship (e.g., Sundell, Lindvall, Stenberg, & Wall, 1994).

In Study 1, it was claimed that the explanation of the high VOC concentrations obtained in an occupied class room was that VOC were brought indoors adsorbed on occupants clothes. In the warm and poorly ventilated room, VOC were desorbed again and accumulated in room air, thus, contributing to the indoor air pollution. No other studies were found, confirming this hypothesis about clothing as a possible secondary source of contaminants. However, more recently, Gebefügi and Korte (1988) and Gebefügi and Kettrup (1995) present chamber studies, showing that adsorption on textiles may delay the decrease in concentration of momentary injected SVOC in room air with several hours or days.

The degree of adsorption and desorption is increasing with decreasing volatility of compounds (SVOC) and increasing polarity and number of unsaturations in organic compounds. For inorganic nonreactive gases the sorption effects are negligible which will explain why CO₂ is easily ventilated from an occupied room whereas most VOC are delayed for several hours (e.g., B. Berglund, Johansson, & Lindvall, 1993).

The role of *chemical reactions* in indoor air is still not fully known. However, for the improvement of IAQ, possible reagents such as O₃, NO_x and unsaturated VOC should be kept at low concentrations. It should also be realized that the origin of certain air pollutants, such as aldehydes or acids, could be either indoor materials or a result of chemical reactions.

Indoor-Air VOC and Health and Sensory Effects

A linkage between adverse health and sensory effects, including SBS symptoms, and certain indoor environments is generally accepted among researchers (Sundell, 1994; Study 7; Ku. Andersson, Bakke, Bjørseth, Bornehag, Clausen, Hongslo, Kjellman, Kjærgaard, Levy, Mølhave, Skerfving, & Sundell, 1997). For example, in a longitudinal study of an assumed sick building, B. Berglund and co-workers found relationships between symptoms and building factors, and also time-related variations of symptom over the day (B. Berglund, Johansson, Lindvall, & Lundin, 1990b). However, the relationship between adverse health and sensory effects and chemical composition of the indoor air is still debated. In Study 7, we lack evidence that the common nonreactive VOC, measured in indoor air, have adverse health or sensory effects on humans. On the other hand, we also lack evidence that these compounds, or these compounds in interaction with other indoor factors, are *not* “causing” adverse health and sensory effects. An explanation to this lack of evidence is that the questions presented below were not considered or not fully answered in any study:

Are measured symptoms or sensory effects *persistent* over time? That is, do persons have symptoms or perceive adverse sensory effects all the time they stay in a special environment. If so, the measured VOC in this environment surely cannot be the cause to the problems, because the composition and concentrations of VOC are never persistent over time. Rather, there is a large variability, diurnal and weakly, as well as seasonal, of composition and concentrations of VOC. This is also valid for many other indoor air factors.

Are the prevalence and intensity of symptoms or sensory effects *variable* over time? Then indoor pollutants, such as VOC, TVOC, and CO₂, could be a possible “cause”. However, in order to prove any relationships, these pollutants must be measured in parallel with the measurement of symptoms and sensory effects. With one known exception (the Swedish Library Study, B. Berglund et al., 1990a, 1990b), this has not been done in a proper way and, thus, no evidence has been obtained.

Are symptoms or sensory effects occurring only within a special *location*? Then, it must be proved that the presumed “causing” factors, or combination of factors, are unique to this location. That is, they must be measured within this location as well as in the surrounding areas, including the outdoor environment, in order to prove that the composition is unique to this special location. Such comparative assessments are usually neglected in the study design and sampling strategies for investigations of problem buildings.

However, even in regarding all these factors, the results of field IAQ investigations may still be obscure. For example, the carefully designed and well-documented Swedish Library Study by B. Berglund and co-workers (Berglund, Johansson, Lindvall, & Lundin, 1989) showed that, even though sensory measurements (questionnaires) and chemical/physical measurements (VOC, CO₂, temperature, relative humidity) were performed simultaneously, at many occasions throughout 33 weeks, the results did not contribute to a confirmation, or a rejection, of a causal relationship between indoor-air VOC and sensory effects. However, there was a linear relationship between the change over a day of 8 SBS symptoms and the mean concentration of 34 VOC in exhaust air.

A general conclusion is that probably *no single “cause”* of health and sensory effects will be identified in problem buildings, rather it seems most likely that different “causes” occur in different indoor environments. Many researchers are still convinced that indoor-air VOC surely is one important, however, not the only factor “causing” indoor air problems (Study 7).

Future Research on Indoor Air Quality and Health and Sensory Effects

The cause, or causes, of adverse health and sensory effects in indoor environments are still not clarified, therefore, new research approaches should be found. For example, basic investigations of *chemical and physical reactions and interactions* are needed to support or reject the hypotheses of chemical reaction products as adversely influencing factors. Considerations about chemical reactions in indoor air are quite

recent and based on a limited amount of quantitative data. It is, therefore, difficult to draw any general conclusions about their significance for the indoor environment. Nevertheless, chemical reactions in indoor air are interesting phenomena that should be investigated in future research (e.g., Wolkoff, Clausen, Jensen, G. D. Nielsen, & Wilkins, 1997). Suggested approaches are, for example, laboratory experiments with model substances, such as, typical oxidants and reactive VOC or SVOC (e.g., B. Andersson et al., 1996). It may also be possible, in field studies, to analyze the decrease or increase of compounds supposed to be involved in the chemical reactions. For example, the decrease (consumption) of O_3 , or increase of reaction products, such as aldehydes or acids, over time.

Another important factor to be considered in future research on IAQ and sensory effects is the role of air-borne *particles*. It is well known that they may cause adverse health effects as they are (e.g., Dockery & Pope, 1996), but it should be remembered that they may also function as carriers of VOC and SVOC which are adsorbed or condensed on the particles. During suitable conditions, for example, when the particles are inhaled or when they are ventilated with fresh air, the adsorbed compounds may be desorbed again. This may cause adverse sensory or health related effects and/or delayed decrease of pollutant emission.

The role of *body effluents* should be clarified. The findings in Study 1 show that acetone and ethanol may reach substantial concentrations in the presence of humans (up to an average of 24 and 55 $\mu\text{g}/\text{m}^3$, respectively). Other possible body effluents are organic acids originating from transpiration, and methane, isoprene, methanol, butyric acid, acetic acid and ethyl acetate which are emitted in measurable quantities through exhalation (Jansson & Larsson, 1969; Wang, 1975). Based on a study where VOC concentrations in the air of two class rooms and the expired air of children in these rooms were observed, Cailleux, Turcant, Premel-Cabic, and Allain (1993) even suggest that isoprene can be regarded as a measurable index of contaminants of human origin. For body effluents to be included in indoor air investigations, the methods of sampling and analysis must be modified. That is, for sampling of the very volatile compounds, either special adsorbents (e.g., molecular sieves) or cryogenic sampling is needed. For the polar compounds, liquid chromatography should be used rather than gas chromatography as a method of analysis.

Most VOC in indoor air actually are *odorous irritants* and, therefore, it is recommended that future resources and research efforts should be devoted to basic scientific studies of the effects on humans involving the highly sensitive modalities of odor and irritation. The methods of *psychophysical measurements* including detectability and perceived intensity of odor and sensory irritation should be used for the evaluation of IAQ (see e.g., Berglund, Lindvall, & Nordin, 1992). Background to and advice on methodologies for the use of sensory measurement either per se or as related to chemical and physical measurement for the evaluation of the human perception of IAQ was recently presented by ECA (1999). It is stated that a prerequisite for successful studies is that the investigators should have acquired basic laboratory skills in psychology (psychophysics), chemistry, as well as laboratory engineering.

Knowledge is still lacking on the perception of *mixtures*, that is, the interaction between compounds involved yielding adaptation, facilitation and hypoadaptation (B. Berglund, & Engen, 1993; B. Berglund & Olsson, 1993b). Furthermore, in view of new knowledge about the human olfactory system, renewed studies on the significance of *chemical structure* and the perception of odor are recommended. For example, in order to explain the changes in odor thresholds caused by the introduction and position of a double bond in the carbon chain of odorous compounds, as reported by Ranson and Belitz (1992).

For the exponents of psychophysical functions for different compounds, substantial interindividual, as well as intraindividual, variation has been shown (B. Berglund et al., 1971). The *interindividual variability* in sensory sensitivity provides interesting information and should not be considered as measurement error. Rather, there is a reason to use the individual differences, for example, when looking for “causes” of adverse health and sensory effects in indoor environments, and SBS. That is, it may be possible to use specially sensitive individuals as measuring instruments for more quantitative and qualitative data, rather than using random samples from the general population and counting frequency of perceptions or symptoms (Study 7). When searching for these individuals, sensory thresholds as well as psychophysical functions are to be considered, because, based on present perceptual research, it is still not possible to predict from a person’s threshold data for a compound, the slope of his or hers psychophysical function for that compound (cf. Högman, 1988). People with *special sensitivity* to the indoor air environment, especially those with SBS, should be identified, and used for future research (e.g., Garriga-Trillo & Bluysen, 1999).

In addition to sensory sensitivity, also other individual factors should be regarded. For example, B. Berglund and Gidlöf Gunnarsson (1997, 1999) included person-linked factors, (e.g., allergy, somatization and depression) in an SBS questionnaire, with the aim to distinguish SBS sensitives from SBS nonsensitives. Their hypothesis is that only SBS sensitives can experience SBS and, therefore, only these should be used for measuring SBS. This group of individuals should not to be regarded as “extremes”, but rather are embedded in the normal distribution of the population.

FINAL CONCLUSIONS

Conclusions based upon the empirical studies and literature reviews presented in this thesis (Studies 1-7) are:

[a] A new method of analysis for indoor air VOC has been developed. It includes adsorptive sampling, gas chromatographic separation and mass spectrometric identification. The method is well suited for the fine division of temporal intervals needed to reveal the dynamic pollutant time-course in occupied spaces.

[b] For VOC and SVOC there is a continuous interplay between indoor materials and indoor air, between ventilation components and supply air, as well as among indoor materials. At low ventilation rates, compounds are adsorbed from room air to indoor materials and due to increases in ventilation rates they may be desorbed again. An accumulation indoors of outdoor compounds, that are brought indoors by ventilation supply or by materials, such as clothes has been shown to take place.

[c] The use of statistical pattern analysis offers an opportunity to distinguish among different buildings and among different locations within buildings. However, knowledge is still lacking about what variables, relevant to IAQ and its sensory or health effects on humans, that should be put into the analysis in order to reveal sick buildings.

[d] The main source of variability in published detection thresholds (or parameters of the power function for odor intensity) of the common adverse indoor-air pollutant formaldehyde, is probably mainly a result of a variation in the quality of olfactometric or psychophysical measurement procedures. The reported methods of formaldehyde generation, specific groups of normal observers, or intra- or inter-individual differences in odor sensation over time, are of less importance for threshold variability.

[e] A list is presented containing 34 compounds (3 VVOC, 29 VOC, 1 SVOC, and NO_2), frequently detected in indoor air, considered urgent to be investigated for human sensory effects. Thirteen of these (12 VOC and NO_2) were recommended, with regard to postulated criteria about non-adverse health effects and possibility of well-controlled quantitative generation, for further investigation in human sensory exposure studies.

[f] Present techniques/methods to assess IAQ, presented in the scientific literature, do not show any certain proof of a link between indoor factors, such as VOC or TVOC, and human sensory or health effects (special cases such as formaldehyde excluded). Nor is there any proof that these factors are irrelevant for the encountered effects. Merely this lack of evidence is due to poor study design.

[g] Future research on IAQ and adverse health and sensory effects should focus on other indoor air compounds than the nonreactive VOC, for example, reactive, polar, or semivolatile compounds. Appropriate methods of human sensory measurements should be utilized, and certain groups of people with special sensitivity should be distinguished and used in SBS studies.

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APPENDIX I

ABBREVIATIONS AND DEFINITIONS

FID	Flame Ionization Detector
Health	Health is a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity (WHO definition; http://www.who.int/aboutwho/en/definition.html)
IAQ	Indoor Air Quality
MAK	Maximale Arbeitsplatz-Konzentrationen (Maximum Occupational Concentrations), according to MAK Commission, Germany
µg	Microgram, 10^{-6} g
NIOSH	National Institute of Occupational Safety and Health, USA
OSHA	Occupational Safety and Health Administration, USA. (Corresponding to the Swedish Arbetsarkyddsstyrelsen)
PPB	Parts per billion, 10^{-9}
PPBV	Parts per billion, 10^{-9} , by volume
PPM	Parts per million, 10^{-6} $\text{ppm} \times \text{molecular weight}/24.45 = \text{mg}/\text{m}^3$ (25 °C; 1 atm) $\text{ppm} \times \text{molecular weight}/0.02445 = \mu\text{g}/\text{m}^3$ (25 °C; 1 atm) $\text{ppm} = 10^3 \times \text{ppb}$
SBS	Sick Building Syndrome High frequency of symptoms and complaints reported from occupants of certain buildings. Typical symptoms according to WHO (1983) are:

<i>English</i>	<i>Swedish</i>
- eye, nose and throat irritation	- ögon-, näsa-, halsirritation
- sensation of dry mucous membranes and skin	- känsla av torrhet i slemhinnor och hud
- erythema	- hudrodnad
- mental fatigue	- mental trötthet
- headaches, high frequency of airway infections and cough	- huvudvärk, hög frekvens av luftvägsinfektioner och hosta
- hoarseness, wheezing, itching and unspecific hypersensitivity	- heshet, andfåddhet, klåda och ospecifik överkänslighet
- nausea, dizziness	- illamående, yrsel

TLV Threshold limit value, according to American Conference of Governmental Industrial Hygienists (ACGIH)

VOC Classification of indoor organic pollutants (World Health Organization, 1989).

Description	Abbreviation	Boiling point range ¹⁾ °C	Sampling methods typically used in field studies
Very volatile (gaseous) organic compounds	VVOC	<0 - 50-100	Batch sampling; adsorption on charcoal
Volatile organic compounds	VOC	50-100 - 240-260	Adsorption on Tenax, carbon molecular black or charcoal
Semivolatile organic compounds	SVOC	240-260 - 380-400	Adsorption on polyurethane foam or XAD-2
Organic compounds associated with particulate matter or particulate organic matter	POM	>380	Collection on filters

¹⁾ Polar compounds appear at the higher end of the range

TVOC The sum of all compounds sampled and analyzed within the range of boiling points specified for VOC

APPENDIX II

EXAMPLES OF VOC FOUND IN INDOOR AIR

Table 1. Summary of WAGM concentrations derived for VOCs in established dwellings. The nineteen VOCs that exhibit WAGM concentrations above 5 mg/m³ are considered to be “predominant indoor air compounds”. (WAGM = weighted average geometric mean, as estimated from results in each of 50 studies found in literature). [from Brown, Sim, Abramson, & Gray, 1994]

WAGM Concentrations in Dwellings (µg/m³)

<1	1-<5	
<i>i</i> -amyl alcohol	butanal	<i>n</i> -undecane
bromodichloromethane	2-butanone	<i>a</i> -terpinene
<i>n</i> -butanol	<i>i</i> -butanol	
<i>n</i> -butyl benzene	<i>n</i> -butyl acetate	5-<10
chlorobenzene	carbon tetrachloride	benzene
<i>o</i> -dichlorobenzene	chloroform	<i>n</i> -decane
<i>m</i> -dichlorobenzene	cyclohexane	<i>p</i> -dichlorobenzene
1,2-dichloroethane	1,1-dichloroethylene	ethyl acetate
1,2-dichloropropane	<i>n</i> -dodecane	ethylbenzene
diethyl ether	ethylene dibromide	nonanal
dimethylcyclopentane	2-ethyl-1-hexanol	tetrachloroethylene
1,4-dioxane	<i>n</i> -heptane	1,2,4-trimethylbenzene
<i>n</i> -hexadecane	hexanal	<i>o</i> -xylene
1-methyl naphthalene	<i>n</i> -hexane	
<i>p</i> -methyl- <i>i</i> -propylbenz	methylcyclohexane	10-<20
naphthalene	methyl cyclopentane	camphene
N-nitrosodiethylamine	<i>o</i> & <i>m</i> & <i>p</i> -methyl ethyl	1,2-dichloroethylene
N-nitrosodimethylamine	benzene	dichloromethane
N-nitrosopyrrolidine	2 & 3-methyl hexane	<i>m</i> & <i>p</i> -xylene
<i>b</i> -pinene	3-methyl pentane	(<i>o</i> & <i>m</i> & <i>p</i> -xylene)
1,2,3,5-tetramethylbenz	<i>n</i> -nonane	
1,2,4,5-tetramethylbenz	<i>n</i> -octane	20-<50
1,2,3-trichlorobenzene	<i>n</i> -pentadecane	acetone
1,2,4-trichlorobenzene	<i>a</i> -pinene	limonene
1,3,5-trichlorobenzene	<i>n</i> & <i>i</i> -propylbenzene	toluene
1,2,3-trimethylbenzene	styrene	1,1,1-trichloroethane
4-methyl-2-pentanone	tetradecane	
	trichloroethylene	>50
	1,3,5-trimethylbenzene	ethanol

Table 2. Minimum number of compounds to be included in TVOC analysis [ECA, 1997]

<i>Aromatic hydrocarbons</i>	<i>Cycloalkanes</i>	<i>Ketones</i>
benzene	methylcyclopentane	methylethylketone
toluene	cyclohexane	methylisobutylketone
<i>m/p</i> -xylene	methylcyclohexane	cyclohexanone
<i>o</i> -xylene		acetophenone
<i>n</i> -propylbenzene	<i>Terpenes</i>	
1,2,4-trimethylbenzene	3-carene	<i>Halocarbons</i>
1,3,5-trimethylbenzene	α -pinene	trichloroethene
2-ethyltoluene	β -pinene	tetrachlorethene
styrene	limonene	1,1,1-trichloroethane
naphtalene		1,4-dichlorobenzene
4-phenylcyclohexene	<i>Alcohols</i>	
	2-propanol	<i>Acids</i>
<i>Aliphatic hydrocarbons</i>	1-butanol	hexanoic acid
<i>n</i> -C ₆ to <i>n</i> -C ₁₆	2-ethyl-1-hexanol	
<i>n</i> -hexane		<i>Esters</i>
<i>n</i> -heptane	<i>Glycols/Glycolethers</i>	ethylacetate
<i>n</i> -octane	2-methoxyethanol	butylacetate
<i>n</i> -nonane	2-ethoxyethanol	isopropylacetate
<i>n</i> -decane	2-butoxyethanol	2-ethoxyethylacetate
<i>n</i> -undecane	1-methoxy-2-propanol	TXIB (Texanolisobutyrate)
<i>n</i> -dodecane	2-butoxyethoxyethanol	
<i>n</i> -tridecane		<i>Other</i>
<i>n</i> -tetradecane	<i>Aldehydes</i>	2-pentylfuran
<i>n</i> -pentadecane	butanal	THF (tetrahydrofuran)
<i>n</i> -hexadecane	pentanal	
2-methylpentane	hexanal	
3-methylpentane	nonanal	
1-octene	benzaldehyde	
1-decene		

APPENDIX III

THE OLFACTORY SYSTEM AND ITS
PHYSIOLOGICAL FUNCTIONS

Introduction. Information about the morphology and functions of the olfactory and trigeminal systems is received from experimental studies with, for example, neuronal culture techniques, histological procedures, molecular biology, scanning electron microscopy (Doty, 1995b), electrophysiological recording, electroencephalography (EEG), and from new neuroscience techniques, like positron emission tomography (PET). Comprehensive textbooks on what we already know about olfaction, sensory irritation, chemical senses, and molecular neurobiology have been edited by Margolis and Getchell (1988), Brand, Cagan, Teeter, and Kare (1989), Green, Mason and Kare (1990), Getchell, Bartoshuk, Doty, and Snow (1991), and Doty (1995a). Much new information is received from the rapidly developing area of neuroinformatics—the study and development of information tools for brain and behavioral data—in which data from neuroscience and behavioral science are treated by scientific computer and information techniques (“from molecules to behavior”). A survey of this new area is presented by i. a. Koslow and Huerta (1997).

Structural organization. The olfactory system consists of three anatomical compartments: the *olfactory epithelium*, the *olfactory bulb*, and the *piriform cortex*. In the human nasal cavity the inferior, middle, and superior conchae are covered with epithelium that—depending on its location—is either nonsensory (respiratory) or sensory (olfactory) (e.g., Lanza & Clerico, 1995). The former warms, cleans, and humidifies inspired air before it reaches the olfactory region, located high in the superior region of the nasal cavity. At normal respiratory behavior only about 2-5 % of inhaled air reaches the olfactory epithelium. The morphology of the human *olfactory epithelium* has been investigated by scanning electron microscopy by Morrison and Costanzo (1990; 1992) and anatomy, structural organization, and sensory transduction of the olfactory system are studied and reviewed by, for example, Greer (1991), Kinnamon and Getchell (1991), and Morrison and Moran (1995). It is classified as a neuroepithelium and has an area of 100 mm² in each nostril (Lovell, Jafek, Moran, & Rowley III, 1982; Moran, Rowley, Jafek, & Lovell, 1982). The epithelium is composed of olfactory receptor neurons (10 to 30 million cells over the two nasal cavities), nonsensory supporting cells, basal cells, and microvillar cells, embedded in mucus secretions produced by the acinar cells of Bowman’s glands. Each olfactory receptor neuron sends a single dendritic process toward the epithelial surface where it terminates in a swelling called the olfactory knob. Each knob gives rise to several sensory cilia, that extend over the epithelial surface, and present a great surface area on which the chemoreceptive interaction with odorants takes place. The olfactory neurons are the only human central nervous system (CNS) neurons known that can replace themselves normally and when injured, their life span in humans is unknown, while in animals it appears to be up to one year. The supporting cells span the neuroepithelium, are closely associated with the olfac-

tory neurons, and play a role in regulation of the electrolyte concentration in the surrounding mucus. Several experiments indicate that new olfactory neurons may arise from some of the nonneuronal basal cells (Calof, Hagiwara, Holcomb, & Mumm, 1996; Sicard, Feron, Andrieu, Holley, & Mackay-Sim, 1998). The function of the rather recently discovered microvillar cells is still unknown, however, some animal experiments suggest that they may be chemosensory receptors (Rowley, Moran, & Jafek, 1989). From the basal region of the receptor cell, olfactory axons arise and project through the cribriform plate of the ethmoid bone in the skull and terminate directly in the *olfactory bulb*. The olfactory bulb is a cylindrical extension of the forebrain, one in each hemisphere. Here the input from the olfactory receptor neurons arrive in the glomerulus, that is, special clusters of cells, and then processed via local synaptic circuits at several levels and relayed to higher cortical regions of the *olfactory brain* (piriform cortex). The olfactory functions are clustered around the base of the brain at the end of the olfactory tract. The connections between the olfactory epithelium and the cortex are complex, and parts of the structure also serve other functions than olfaction (see e.g., Engen, 1982).

Physiological functions The airborne odorants are transported within the nasal chambers to the surface of the olfactory mucosa and are then fluid-borne within the mucosa to the chemoreceptive membrane of the olfactory receptor cilia. The viscosity of mucus is related primarily to its content of glycoproteins and water, with the lowest value, corresponding to pure water, at the surface and highest close to the cilia membranes. The mucus' electrolytic properties depend on its content of Na^+ , K^+ , Ca^{2+} , and Cl^- , which in turn is regulated by odorants and presumably also by other compounds that are inhaled. The odorants partition at the air-mucus interface largely as a function of their water solubility as defined by their air-water partition coefficients (K_{aw}) and from literature data of K_{aw} it may be stated that the partitioning favors the water-mucus phase by a factor of 10 for hydrophobic odorants such as certain musks and a factor of 100,000 for very hydrophilic odorants such as pyrroline (Kinnamon & Getchell, 1991). That is, the olfactory mucus may concentrate even relatively insoluble hydrophobic compounds, and thus, amplify the signal in the olfactory system. It is suggested that the odorant molecules may traverse the mucus layer in two ways, either through free diffusion or through a facilitated diffusion when attached to transport proteins, named odorant binding proteins, OBP (e.g., Pelosi, 1998).

The *olfactory receptor neurons* detect the odorants as chemical stimuli, transduce the information about the molecular identity, concentration, and duration of stimuli, to the olfactory bulb in the forebrain (Greer & Bartolomei, 1996). The complex signal recognition-transduction mechanisms are not fully explained, but, there is substantial evidence that the olfactory receptors of the neurons are transmembrane proteins, located in the olfactory cilia (e.g., Kinnamon and Getchell, 1991). When odor molecules bind to these proteins, second messengers within the cilium are activated and will open micro-channels in the cell membrane to admit Ca^{2+} and Na^+ into the cilium. The ions lead to membrane depolarization and the generation of action potentials that are conducted along the axons to the olfactory bulb and thus transduce the information about

the odorant. Experimental work indicates that each neuron typically is responsive to only about three to ten odorants (Firestein, 1996; Reed, 1998; Zhao, Ivic, Otaki, Hashimoto, Mikoshiba, & Firestein, 1998). On the other hand, according to Shipley and Ennis (1996), it is not yet clear whether there is one receptor for each odor or if many different receptors are required to distinguish among different odors.

In recent works of, for example, Buck and Axel (1991) and Zhao et al., (1998), specific genes that produce transmembrane olfactory proteins that are shown to be activated by only one type of odorant molecules (C_6 and C_7 aldehydes) are identified. Also, data from Ngai, Dowling, Buck, Axel, & Chess (1993) suggest that the brain may discriminate among odors by determining which neurons have been activated.

Possibly the discrimination of odors is accomplished by odorant binding properties of as many as 500-1000 different receptors (Ressler, Sullivan, & Buck, 1994; Firestein, 1996). Furthermore, Ressler, Sullivan, & Buck (1994) observed spatial zones of odorant receptor gene expression in the nose, indicating a broad organization of sensory information, and that this organization is maintained in the transmission of information to the olfactory bulb. That is, the discrimination of odors is also due to the spatial location of significant receptors in the olfactory epithelium. Shipley and Ennis (1996) present a comprehensive review on what is known today, about the functional organization of the olfactory system, including the complex transduction mechanisms within the olfactory bulb and in the higher order olfactory structures of the brain. Axel (1995) reviews recent research on how nose and brain may perceive scents.