AT-84-20 No. 1

Characterization of Indoor Air Quality and "Sick Buildings"

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ABSTRACT

"Sick buildings" of the irritating type are receiving increased attention. Occupants complain of deteriorated indoor air quality and of subtle medical symptoms that may be related to the indoor air. The problem seems to coincide with energy economizing. Sensory reactions are typical for the sick building syndrome, and the cutaneous as well as the chemical senses are involved. To evaluate the actual quality of the air in a building, it is imperative to conduct field studies with mobile investigating units. By this approach, reliable field experiments can be performed on representative air samples taken from the building for immediate sensory and chemical analysis. From field experiments conducted in school and office buildings, it is concluded that by the energy-saving reduction in ventilation rate requirements, the margins to sensory irritation indoors have been reduced too far. An outdoor air rate of at least 5-6 liters per second and person is recommended in order to keep indoor odors at reasonably low levels. Recirculation of return air in HVAC systems affects the concentration of air pollutants differently for different compounds. Therefore, ventilation-by-demand systems using a single control substance should be adopted with great caution. If CO_2 is chosen as the control variable, the limit value should not be set higher than 0.08 vol%. Sick buildings are basically a physical environmental problem and not a psychogenic problem. Although sensations predominate in the reactions, the perceptual mechanisms are largely unknown. The indoor air of modern buildings contains complex patterns of pollutants, many of which are potential sensory stimuli. Simple causal relationships are not to be expected. The sick building syndrome may be better understood by assuming that the sensory systems perform a pattern-recognition analysis. A practical conclusion would be that far-reaching homogenization of the indoor climate may result in loss of recognizable stimuli patterns and may lead to sensory confusion. The sick-building syndrome may be partly the result of a change in sensitivity in the populations exposed. Furthermore, the symptoms may result from a summation of numerous subthreshold sensory stimuli or a local increase in receptor stimulation caused by gases-particles interaction, which may be influenced by their electrical charges.

INTRODUCTION

The expression "sick buildings" refers to modern buildings in which occupants display reactions and symptoms similar to those caused by formaldehyde exposure (Andersen et al. 1975), although the concentrations of formaldehyde are far below the reaction thresholds. Other types of sick buildings, not to be dealt with here, are buildings contaminated with i.a. radon, moulds, and contagious agents.

The "irritating" type of sick buildings are receiving increased attention, and the problem seems to coinside with energy economizing. Occupants complain of deteriorated indoor air

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quality and of subtle medical symptoms that may be related to the indoor air (Berglund and Lindvall 1983). In Sweden, this new kind of environmental problem seemingly has increased since the energy crises and the building codes of 1975 that emphazised energy savings. Also, an increasing number of new chemicals and products have been introduced in building technology and in furniture. For example, serious complaints have been registred in about 100 of 600 preschools built since the mid-seventies in the city of Stockholm.

The symptoms reported in the irritating type of sick buildings vary widely, but some salient features may be recognized. Repeatedly, the reported symptoms seem to be

- irritation of the eyes, the nose, and the throat
- sensation of dryness in the mucosa and the skin
- erythema of the skin
- mental fatigue
- weak but persistant odors

Only a few epidemiological studies have been directed to these problems, but a number of case studies have been reported by occupational safety and health control agencies. Investigations usually fail to isolate a specific chemical or a physical or an infectious agent that may be responsible for the problems. The symptoms related to sick buildings have also been investigated for possible psychogenic origins.

Sensory reactions are typical for the irritating type of the sick building syndrome. It involves the cutaneous as well as the chemical senses. The sense of smell is the main chemical sense for which at least some knowledge is available. Since its major purpose is to react to airborne chemicals, it has special relevance for the control of indoor air quality. Odors per se are also a frequent symptom in the sick building syndrome. Furthermore, the odor has since long been used as a major criterion variable for building ventilation (e.g., Klauss et al. 1970).

In the following, experimental data are presented on indoor odors and their relationship to CO_2, occupancy, building materials, and the building ventilation process. The second part of the paper deals with explanations of the sick building syndrome viewed from a physical as well as a psychological angle.

INDOOR ODORS

The Relationship between Indoor Odors and CO_2

The interest in control of building ventilation has increased as a consequence of the new demands for energy savings. Ventilation control by the concentration of carbon dioxide (CO_2) is a means for a more cost-efficient use of ventilation air (Janssen et al. 1982). CO_2-controlled ventilation however, depends on careful consideration of several critical aspects, some of which are biological (Berglund, Johansson, and Lindvall 1982b). First, the control variables used must be biologically founded. Besides pollutants from occupants, pollutants from building materials, activities, and from the outdoor air must be observed. Second, the sensors for monitoring the control variables must be located so that they result in acceptable air quality in all occupied parts of the building.

In office buildings where pollution from building materials, furnishings, and activities is low, the odor criterion will often determine the ventilation requirement. In the late nineteenth century, von Pettenkoffer proposed a connection between body odor and CO_2 concentration. If CO_2 exceeds 0.1%, body odors become noticeable. Taking into account the ambient background level of CO_2 von Pettenkoffer's rule of thumb stipulates that the odor of room air becomes annoying at CO_2 concentrations beyond 0.15%.

Yaglou et al. (1936) pointed out a relationship between the odor of room air, occupant density, outdoor airflow, and room volume per person. For example, for "grade school children of average class" given about 10 m^3 air space per person they recommended minimum outdoor air rates of about 5 liters per second and person (l/sp), mainly for odor control. This relationship governs the requirement of outdoor airflow per person in the building codes of many countries. Cain and Leaderer (1982) recently argued that room volume per person is unimportant. They suggested an outdoor airflow of 4 l/sp independent of room volume per person for achieving acceptable odor-free indoor air, providing there is no tobacco smoking. In steady state with resting occupants, this airflow would give about 0.15% CO_2, which is close to the limit value suggested by von Pettenkoffer.

Apart from being used as an indicator of occupant-related odor, CO_2 at high concentrations can result in adverse health effects. The Swedish occupational threshold limit value for CO_2 is presently 0.5% for nonindustrial indoor environments. ASHRAE (1981), in the new ventilation standard, has applied a limit value for CO_2 of 0.25%. Provided the occupants only perform light work, this CO_2 value roughly corresponds to a need for an outdoor airflow of 2.5 l/sp. In contrast, the Nordic Committee for Building Regulations (Sundell 1982) has recommended a minimum outdoor airflow of 4 l/sp. The latter guideline is based on an assumed working activity among the occupants, on the occupational threshold limit value for CO_2, and on a safety factor of 3 to 5. The Nordic guideline should be regarded as a definitely minimum requirement, which is only recommended because of the great need for energy saving.

In CO_2-controlled ventilation-by-demand systems, the limit value should not be set higher than the CO_2 levels typically appearing in conventional office buildings (considered to be problem-free). In Scandinavia, typical CO_2 levels in office buildings are, at the most, 0.08% (e.g., Berglund, Johansson, and Lindvall 1982b; Södergren 1982).

To evaluate the actual air quality in a building, it is imperative to conduct field studies with mobile investigative units (Lindvall 1970). By this approach, reliable field experiments can be performed on representative air samples taken on-site from the building. Such a study was conducted in a high school building during winter (Berglund and Lindvall 1979), where the relationship between room odor and CO_2 was investigated. No spontaneous complaints of the air quality had been reported in the school. The classroom at study was 195 m^3 and the air exchange per hour was roughly 1.5-1.8. Besides mechanical ventilation, the room was also ventilated by the windows in a standardized way between class meetings. The air-sampling volume continously transferred to the mobile laboratory was 0.1% of the total air volume exchange during a class meeting.

Sensory analysis revealed a constant level of odor during the first 10-minutes of a class meeting, this level being equal to the background level of the empty room and independent of class size. During the last 10-minutes of a class meeting, the room was overloaded by odor when the class size exceeded 20 pupils. Originally, the room was dimensioned for classes of maximum 30 pupils. In this room, 0.13% CO_2 was registered at the most, which is below the von Pettenkoffer rule-of-thumb value. Yet even below 0.13% CO_2, observers (visitors) reported the room air to be uncomfortably intense in odor.

In figure 1, the perceived odor intensity of the room air (unadapted observers) is plotted against CO_2 concentration in ppm. These data refer to conditions of the empty classroom, as well as of repeated measurements during the class meetings with 5 to 29 pupils. Each data point is based on 20-240 observations collected over a five-week period. The symbols refer to measurements made during 10-minutes periods of 40-minutes class meetings with the number of pupils increasing along with the increase in CO_2 concentration.

Also in the empty room, the air had an easily identifiable background odor. In figure 2, the perceived odor intensity of room air (unadapted observers) is plotted against class size for both the first and last 10-minutes periods of the class meetings. If the inflexion point at which the occupant-related odor separates from the background odor (figure 2) is considered, the room cannot take more than 20 pupils during a 40-minutes class meeting. This inflexion point roughly corresponds to a CO_2 value of 0.08% and an outdoor air rate of 5-6 l/sp.

The authors suggest that, if a single value of CO_2 is selected as the indicator of the occupant-related odor in a room, 0.08% CO_2 should be chosen. From this level and up, the occupant-related odors are discriminable (unadapted observers) from the background odor of the building. Thus, approximately 5-6 l/sp of fresh air was required in order to keep the occupant-related odors below background level.

Berglund and Lindvall (1979) showed that with a class size close to the maximum number according to the building code, the perceived odor strength referable to body odors in the particular classroom is about one-third of the total perceived odor intensity of the room air. However, during a 40-minutes period with only mechanical ventilation, even the odor of the empty classroom increased with 30% over time (figure 2). About half of the odor intensity at the end of a class meeting with 30 pupils could be referred to occupancy. Apparently, the air of the empty classroom was continously contaminated by emissions from the classroom interior as well as from pollutants in the ventilation inlet air.

In figure 3, perceived odor intensity of room air is plotted against the supplied outdoor air rate per person to the classroom corresponding to 1.5 ach. The figure shows a characteristic declining function with a leveling off representing the background odor of the (empty) room. If the outdoor air rate is estimated to be 1.8 ach, then the curve is only slightly changed in its critical section.

At 3 l/sp the perceived odor intensity of the room is approximately the same as the odor intensity in an exhaust-fan-ventilated kitchen during the boiling of cabbage (see Berglund and Lindvall 1979).

It may be concluded that in a real-life situation in mechanically ventilated buildings, the outdoor air supplied is not as good in quality as the ambient air outdoors. Already Yaglou et al. (1936) pointed out that recirculation of air smells up the ducts and unless the ventilation system is flushed frequently with clean air, higher air quantities will be needed. Our data show that 4 l/sp of outdoor air is too little and 5-6 l/sp is more justified.

Odors in the Building Ventilation Process

From a number of indoor air samples analyzed by gas chromatography using a flame ionization detector (FID), between 60 and 120 chemical components (peaks) were found in the different samples (Berglund, Berglund, Lindvall, and Nicander-Bredberg 1982). Of these peaks, between 40% and 100% were odorous. The indoor air of an office building built according to the Swedish 1975 building code contained 1.4 times more volatile organic chemical components than the outdoor air and 1.6 times more odorous components. Odor is evidently an important characteristic of many contaminants in indoor air.

Studies of a newly built preschool (Berglund, Johansson, and Lindvall 1982a) have shown a buildup of concentration for all groups of compounds from the outdoor air through the ventilating system and through the rooms to the exhaust air. Also, in an office building it was shown that the number of detected organic compounds increased as readings went from indoor air, supply air, and return air (Berglund, Johansson, and Lindvall 1982b). All the concentrations measured in these buildings are low; single-compound concentrations are usually lower than 10 ppb. It has also been shown that strong odor components in the indoor air have outdoor as well as indoor sources (cf. Berglund, Berglund, Lindvall, and Nicander-Bredberg 1982).

The concentration of contaminants in a building with a HVAC system is, of course, dependent on the recirculation air rate. In table 1 the concentrations of carbon dioxide, carbon monoxide, and organic pollutants are presented as recirculation proportions (R) in percent,

$$R = [(C_s - C_o) / (C_r - C_o)] \times 100 \qquad (1)$$

i.e., the relationship between contaminant concentration in supply air (C_s) and in return air (C_r) corrected for contaminant concentrations outdoors (C_o) (Berglund, Johansson, and Lindvall 1982b).

While CO_2 concentration agreed well with the mechanical settings of recirculated return air, the concentrations of CO and organic contaminants were transferred from return air to supply air to a larger extent than was CO_2 at the low recirculation air rate. For example, for strong odor components, twice the amount was transferred from the return air compared to the CO_2 concentration. This should not be a surprising result, because some compounds can be expected to differ in ventilating efficiency, depending on sources of emission, emission rate, and reservoir function of the building.

It is concluded that recirculation of return air affects the concentration of indoor air pollutants differently for different compounds. For odors, it seems that sometimes twice the outdoor air rate is required to evacuate the strong odor components compared to what is required for CO_2.

THE "SICK BUILDING" SYNDROME

A Physical Explanation

Sensory reactions are typical for the sick building syndrome, but usually no single irritant can be held responsible-more complex causal mechanisms are probably at work. From the literature it is evident that a number of interactions are taking place in the sensory systems.

For example, many skin receptors respond to at least two classes of environmental stimuli, e.g., pressure and temperature (Hensel and Zotterman 1951). Sensory thresholds have also been shown to depend on the local conditions of the skin. Most important is the skin temperature. Warming and cooling the skin can affect the sensitivity to touch (Stevens 1979). It is likely that the activity of virtually all mechanoreceptors are modified by warming or cooling of the skin (Melzak and Wall 1962).

Nasal symptoms may depend on the conditions in the autonomic nervous system. Autonomic imbalance with parasympathetic dominance make the nasal mucosa hyperreactive to unspecific stimuli (Krajina, Harvey, and Ogura 1972). Exposure of the skin surface to infrared rays has been reported to result in changes in nasal airflow resistance (Hill 1931, 1932). Similarily, the warming of the skin causes a reflex nasal congestion (Cole 1954; Drettner 1961). According to Mygind (1979), hyperreactivity to a number of unspecific stimuli is a characteristic of the rhinitis as well as of the asthma patient. Therefore, the ambient air temperature, humidity, and content of dust, gases, vapors, and fumes may be causal for the development of nasal symptoms, singly or in combinations.

Low indoor air humidity in centrally heated buildings during wintertime are often believed to cause nasal symptoms. However, controlled observations in climate chambers have failed to demonstrate that ambient air humidity is significant per se for nasal symptoms in healthy persons (Andersen et al. 1973). Andersen et al. (1973) suggest that the complaints by healthy persons of dry air during winter periods are not caused by the low humidity but by, e.g., higher levels of dust and irritating pollutants. On the other hand, for hyperreactive patients, clinical observations indicate that artificial humidification may be beneficial during the wintertime (Sale, 1971).

A number of interactions are also known for the sense of smell. The absolute detection threshold varies widely, not only with the chemical substance, but also with a number of biological variables. Most important is the decrease in odor sensitivity with age. Sensitivity differences may also be the result of influences of environmental factors like air temperature, humidity, and particulates (for a review see Engen 1982).

It would seem that individual variability in thresholds is not necessarily the same for pure odors as for odors with a large irritating component or for complex mixtures of odors and irritants. It is known that trigeminal stimulation influences the parameters of the supra-threshold power function for odors (Cain 1974, 1976).

The various possibilities of odor interaction from the nasal cavity to the brain sum up to a perceptual interaction. At low near-threshold concentrations, cross-facilitation is a known phenomenon. By inhaling one odor substance, another odor substance appears stronger in intensity compared to its intensity when the system is unadapted (Corbit and Engen 1971; Berglund, Berglund, and Lindvall, 1978).

Recent research has resulted in several mathematical models that try to explain how the odor strength of odorant mixtures is related to the odor strength of the component odors. A vector model was proposed by Berglund, Berglund, Lindvall, and Svensson (1973), followed by alternative models by Patte and Laffort (1979). The models proposed are well founded in empirical data. These models all demonstrate an additional attenuating process in the olfactory system besides the attenuating mechanism reflected in the psychophysical power function. That is to say, qualitative differences between odorous compounds are accounted for by the interaction models suggested, while quantitative differences are accounted for by the psychophysical power function (cf. Berglund, Berglund, and Lindvall, 1976; Berglund and Berglund, 1981).

Another important factor may be the interaction between volatile chemicals and particulate matters. Adsorption to particles may concentrate gaseous irritants so that locally at the mocosa the sensation threshold is passed. It is not known whether the electrical changes of the airborne particles indoors affect their deposition on the body surfaces.

Pattern-recognition analysis of indoor air samples points to the joint importance of a large number of chemical and sensory components for the qualitative character of air (Berglund, Berglund, Lindvall, and Nicander-Bredberg 1982). Probably the chemical senses perform a similar pattern analysis of the exposure to complex air pollution. This would be in line with the theory suggested by Nafe (1929). Such pattern recognition of complex air pollution may also take place across sensory systems.

The indoor air contains a complex pattern of sensory stimuli. Therefore, in the sick buildings one cannot expect any simple causal relationship between sensation and stimulus pattern. With regard to the sensory mechanisms affected, the authors favor a holistic explanation over a reductionistic one (cf. Berglund and Lindvall 1983) because

- the sensory systems involved are largely nonspecific
- the resulting perceptions are largely unitary despite their multisensory origin
- sensory interactions are known to occur

Using the concepts of pattern recognition applied by mathematicians (e.g., Andrews 1972), three stages or spaces in the pattern analysis are conceptualized. The physical world is sensed by the human organism and the resulting data are put into a pattern space. The overwhelming dimensionality of the pattern space is then reduced by the sensory systems to a manageable feature space in which the discriminatory power is maintained for classification purposes. The third space is the decision stage in which the system classifies the information. By such a data-reducing procedure important dimensions of the sensory sampling are selected, e.g., the strong and distinct irritating characteristics of the indoor air in a sick building. By use of the inherent decision rules, the air sample is finally classified as, for example, stuffy.

The authors propose that the sensory symptoms tied to sick buildings of the irritant type may result from one or several of the following causes (cf. Berglund and Lindvall 1983).

- The symptoms may arise from extreme multisensory adaptation to the indoor air. It is achieved either by exhaustive stimulation or by a sensory deprivation of signals important to optimal levels of sensory variation (sensoristasis, Schultz 1965). By extreme homogenization, the indoor climate may have lost all recognizable stimulus patterns (cf. Wohlwill 1974) but still is perceivable. This would lead to sensory confusion and strain on the system when trying to interpret the signals.

- The symptoms may simply be caused by an increased sensitivity in the populations exposed. This would either be the result of a tuning process of the sensory system, thereby changing its range of measurement, or other factors may change the host sensitivity of populations in the industrialized societies. For example, psychosocial stress may induce a sensitizing imbalance in the autonomous nervous system, the increased prevalence of allergies makes mucosal hyperreactivity more common, and other stimuli in manmade environments may increase sensory sensitivity, like skin warming by thermal overload.

- The symptoms may be the net result of a summation (or interaction) of numerous subthreshold sensory stimuli involving several sensory systems. Furthermore, volatile compounds may be enriched on particles and, thus, locally forming more efficient stimuli on the receptor areas. Such a molecular transport may be influenced by the electrical charge of the particles and of the human surfaces.

A Psychological Explanation

The symptoms related to sick buildings of the irritating type have been regarded by some as mainly psychogenic in origin. Epidemics of mass hysteria in workplaces are known (e.g., Colligan and Murphy 1979; Colligan et al. 1979). These epidemics have been regarded mainly as social phenomena involving malfunctioning in otherwise psychologically normal people (Colligan 1981). It seems that many mass hysteric reactions have been triggered by stress of different kinds. Colligan (1981) points out that physical stressors, like air pollution at low concentrations, may have a diffuse and nonspecific psychological effect. He assumes that there are two probable processes at work. For example, an increasing number of workers experience anxiety and symptoms of stress independently of one another, and when a new stimulus is introduced, e.g., a noxious odor, a second process is triggered leading to an epidemic with overt symptoms.

In the mass hysteria syndrome, the pattern of symptoms is commonly tied to a specific illness (e.g., Colligan, Pennebaker, and Murphy 1982), and the symptoms generally pass quickly, although relapses are common. The outbreaks of mass hysteria usually involve hyperventilation, headache, nausea, dizziness, and the like. In contrast, the sick building syndrome is dominated by sensory reactions. Faust and Brilliant (1981) warn against using the diagnosis of mass hysteria as an excuse for not investigating the possibility of low-level environmental contamination.

A salient feature of mass hysteria is that women are overrepresented. This may be explained by the fact that women frequently have monotonous and otherwise stressful work and also that they are more easily aroused in their autonomous nervous system and may attend more to internal signals from the body (Pennebaker and Brittingham 1982).

According to Wohlwill (1974), stress-induced over- or underestimulation may be explained by a number of psychological phenomena in stimulus interpretation. Plurality in the stimulus pattern is an important feature; a deprived stimulus pattern may result in understimulation and a too complex pattern in overstimulation. Similarly, a homogenization of the perceptual pattern in a sick building may result in understimulation, while a random pattern complexity may give overstimulation. It is assumed that the attempts of the observer to find a structure in a random or homogenous stimulus pattern may lead to stress.

Considering the possible explanations of the sick building syndrome, it appears unlikely that it is a case of mass hysteria. Of course, psychogenic factors, including nonspecific stress reactions, may play a modifying role for the overt symptoms. However, the major cause of the sick building syndrome is most probably physical.

CONCLUSIONS

It is concluded that:

1. Sick buildings are basically a physical environmental problem and not a psychogenic problem.

2. Sensations dominate reactions to sick buildings of the irritating type, but the perceptual mechanisms are largely unknown. Several sensory systems are involved.

3. The indoor air of modern buildings contains complex patterns of pollutants, many of which are potential sensory stimuli. One cannot expect to find simple causal relationships between these contaminants and the sick building syndrome.

4. In interpreting the sensory reactions, a holistic rather than a reductionistic view is favored. The chemical and somesthetic senses especially are largely nonspecific, and the resulting perceptions are largely unitary but multisensory in origin. Finally, sensory interactions are known to occur.

5. The sick building syndrome may be better understood by assuming that the sensory systems perform a pattern-recognition analysis. Theories of perceptual learning make us expect changes in sensory sensitivity. Climatic distress may arise, not only from exhaustive stimulation, but also from far-reaching homogenization of the indoor climate resulting in a loss of recognizable stimuli patterns. The latter would lead to sensory confusion and strain on the organism when trying to interpret the signals.

6. The sick building syndrome may be partly the result of a changed sensitivity in the populations exposed. A number of factors affecting host sensitivity are possible. The symptoms may result from a summation of numerous subthreshold sensory stimuli or a local increase in receptor stimulation caused by gases-particles interaction, which may be influenced by their electrical charges.

7. By the energy-saving reduced-ventilation requirements, the margins of sensory irritation indoors have diminished. This gives us reasons to worry. Although the data available are limited, field experiments lead to a recommended outdoor air rate of at least 5-6 l/sp in order to keep indoor odors at a reasonably low level.

8. As recirculation of return air in HVAC systems affects the concentration of air pollutants differently for different compounds, ventilation-by-demand systems using a single control substance should be adopted with great caution. If CO_2 is chosen as the control variable, the limit value should not be set higher than 0.08 vol%.

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ACKNOWLEDGMENTS

This research was sponsored by grants from the Swedish Council for Building Research and the Swedish Council for Research in the Humanities and Social Sciences.

TABLE 1

Relationship (Percentage) between Contaminant Concentrations in Supply Air and Return Air Corrected for Outdoor Concentrations

Setting (1)	CO (2)	Outdoor Organic Compounds (3)	Indoor Organic Compounds (4)	Strong Odor Components (5)	MEAN (2-5)	CO_2
80	81	80	88	80	82	80
50	60	71	48	61	60	47
20	53	57	33	40	46	24

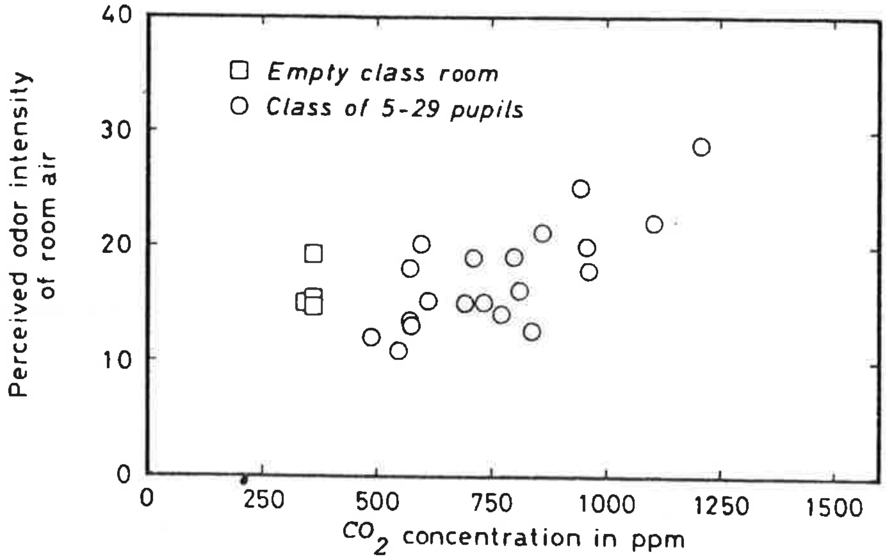

Figure 1. Odor strength of classroom air shown as a function of Co_2 concentration. The data points are averages over 10 minute periods of a 40 minute class period. (Circles = occupied room; squares = empty room)

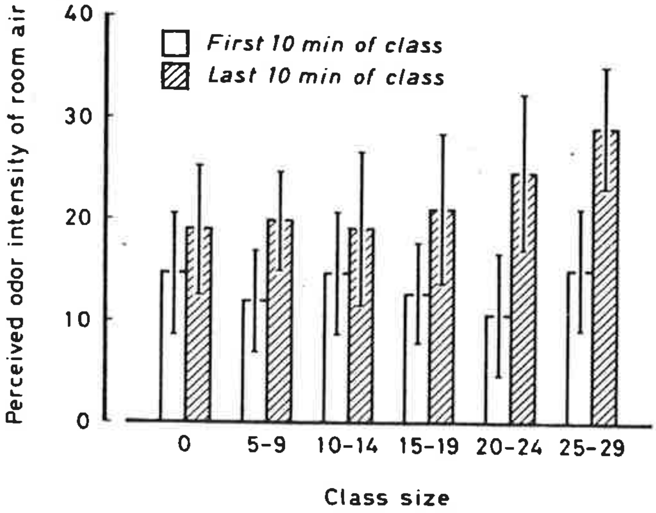

Figure 2. Odor strength of classroom air during first 10 minutes and last 10 minutes of 40 minute class. Odor strength is shown as a function of class size. (Berglund and Lindvall, 1979)

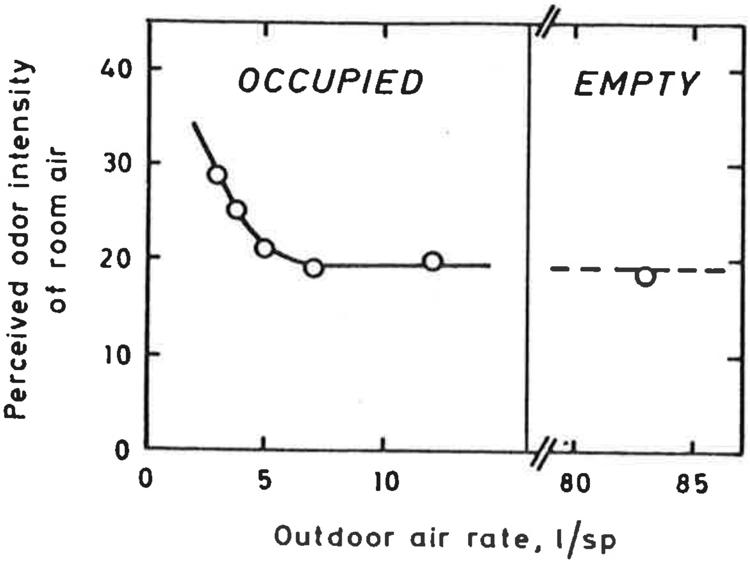

Figure 3. Odor strength of classroom air shown as a function of outdoor air rate expressed in litres per second and person (l/sp) for both occupied and empty room.