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Work performance, productivity and indoor air

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Temperature, relative humidity, and air quality all affect the sensory system via thermo receptors in the skin and the olfactory system. Air quality is mainly defined by the contaminants in the air. However, the most persistent memory of any space is often its odor. Strong, emotional, and past experiences are awakened by the olfactory sense. Odors can also influence cognitive processes that affect creative task performance, as well as personal memories and moods. Besides nitrogen and oxygen, the air contains particles and many chemicals that affect the efficiency of the oxygenation process in the blood, and ultimately the air breathed affects thinking and concentration. It is important to show clients the value of spending more capital on high quality buildings that promote good ventilation. The process of achieving indoor air quality is a continual one throughout the design, construction, commissioning, and facilities management processes. This paper reviews the evidence.

Key terms air quality; building design; carbon dioxide; review; ventilation; well-being; work environment; work performance.

The most persistent memory of any space is often its odor. Every building has its individual scent. The sense of smell is acutely sensitive. Strong emotional and past experiences are awakened by the olfactory sense. Odors can also influence cognitive processes that affect creative task performance, as well as personal memories. Odors can also affect mood (1). The olfactory epithelium is situated in the roof of the nasal cavity and contains thousands of cells that detect odors. Many different types of sensors line the surfaces of cells. Odor molecules from the air land on them, and they produce nerve impulses that are transmitted along the olfactory nerve to the brain. The olfactory epithelium looks like a mass of hairs (cilia) and strands. The cilia bear tiny studs that are thought to be the points of interaction between the air and the nerve receptor cell. Human beings have about six million sensory cells in their olfactory system. Chemical particles in the air we breathe first encounter these sensory cells before the air passes through the olfactory epithelium, which produces the mucus that helps to trap and hold airborne chemicals. This is the last filter before gaseous exchange occurs via the alveoli across the lungs to the blood stream. The nose is often referred to as the air conditioner of the body, and indeed it has many varying degrees of sensitivity. There also appears to be a second-tier olfactory system in which, according to the work of Berliner et al (2), there are receptors in what is called Jacobson’s organ (the physiological term being the vomeronasal organ), which deals with steroidal vomeropherins from human skin and sends messages about them to the limbic areas of the brain (3).

Freshness

According to my findings (4), the word *fresh* has quite a large span of meaning and can be associated with words like new, cold, cleanliness, salubrious, preserved, and ventilated. It is the *salubrious* and *ventilated* qualities that are being sought in environmental design. Other words, such as *airy*, can mean well-ventilated or drafty, but they usually have a narrower range of meaning. The antonyms could be *stale* (no longer fresh, musty) or *stuffy* (muggy, close, badly ventilated, musty). In general, warm-to-hot and airless environments are stuffy, whereas warm-to-cool ones are airy or fresh (4).

The impression and sensation of freshness, however, is stimulated along two sensory pathways. Air can have a cooling effect as it passes over the skin. The free or encapsulated nerve endings that are unevenly spread over the skin are very sensitive to temperature changes; variations of less than 0.0l°K/s can be perceived, according to Geldard (5), who concluded, however, that skin temperature is not a trustworthy predictor of thermal sensations. The strength of the stimulus can be interpreted as the pressure of an air stream on the skin, which can be expressed as the rate of change of momentum. This stimulus can cause heat exchange if there is a temperature difference between the air and the skin, a kinetic pressure on the skin, and a mass transfer occurs if the vapor pressure of the air stream differs from that at the surface of the skin. All these effects contribute towards the impression of freshness, the level of which depends on the sensitivity of the nerve receptors and their body location. The sensible cooling effect of the air depends on surface roughness, shape, and velocity magnitude. The latent cooling is proportional to the vapor pressure difference between the air and the skin; this feature becomes very important at about 28°C. The air velocity fluctuations in terms of frequency and turbulence intensity are also important because they cause changing stimulus and adaptation levels.

The other sensory pathway is via the nose. This is a comparatively neglected area of research, and yet the air we breathe passes very quickly via the olfactory systems to the respiratory system, where oxygen from the air is transferred at the lung walls to the blood and hence is circulated around the body. The link from the external environment to the blood and the brain is almost immediate. Air contains several gases besides oxygen and nitrogen and, in addition, may have smoke particles, dust, formaldehyde, radon, or other bioeffluents.

The intensity of odors is measured in olfactie units; low levels are 10 to 14 olfacties for rubber, increasing to 400 olfacties for very odorous substances. Fanger (6) defines units for subjective evaluations of air quality in terms of the *olf* and the *decipol*. One olf represents the source strength or power of the air pollution in relation to a standard person. The olf is comparable to lumens of light or watts of noise. The perceived level of air pollution is quantified in decipols, analogous to lux or decibels, where one decipol is the pollution caused by one person ventilated by 10 1/s of unpolluted air (1 olf = 10 dpol). Fanger has suggested that outdoor air has a decipol range of 0.01 to 0.1; healthy buildings are rated at under 1 dpol and sick buildings at 10 dpol. Pollution strengths vary depending on the activity, whether people are smoking, the materials in the space, and the cleanliness of the airflow system. For example, a range of 1–11 olf covers people with activity levels of 1 to 6 MET (metabolic equivalents). Smokers average 6 olf, but the level can be as high as 25 olf. And materials may vary from 0 to 0.5 olf/m^2 of floor area.

There exists very few data on the optimum ranges of air conditions that are best for the nasal and respiratory airways. From personal experience, we know that dry air leads to stuffy noses and blocked sinuses; it also impedes the mucous flow over the respiratory membranes and therefore impedes the cilia motion and decreases their cleaning efficiency. Beyond this information, our knowledge is meager.

McIntyre (7) describes work that has studied people's reactions to combinations of air velocity and air temperature (0.35 m/s at 25°C, 1 m/s at 28°C, and 2.5 m/s at 29°C) have been found to be acceptable, but, in general, the cooling power of air is more effective if the temperature is changed rather than the air speed being increased. Standards such as those used in Germany express average or 50% air velocity values as 50 v_{50} =0.18 m/s at a resultant temperature of 22°C, and v_{50} =0.30 m/s at 27°C. However, *for freshness, it is change and contrast that are important*. The development of air diffusers incorporating twist vanes means that higher air velocities can be used nearer people with draft-free and quiet conditions. Task ventilation using local air outlets at desks in offices, beds in hospitals, or seats in auditoriums permit people to change the direction of the air stream to suit personal preference. Jones et al (8) concluded that there are economic, as well as comfort advantages to local air cooling.

It is important not to cause drafts, but some of the traditional work in this area constrains the environmental engineering designer. Modem equipment and flexibility of control are important because peoples' responses to air movement vary tremendously. McIntyre (7) argued that people nearly always detect air speeds over 0.35 m/s, but at traditional design values of 0.25 m/s and less, with temperatures of 23°C or less, 20% or more of a group will not feel anything.

Convection currents from lighting and people can, in highly occupied spaces, be over 0.25m/s (9). Whether people sense a draft depends on their metabolic rate, the background thermal conditions, including surface temperatures, the temperature gradients in the space, and the impingement point of the air on their bodies, the state of their health, how tired they feel, and the frequency of the air fluctuations. On the latter point, McIntyre refers to a work that shows that, at a mean air speed of 0.3 m/s, the discomfort is maximum at a fluctuation frequency of 0.5 Hz, decreasing below and above this value.

The value of freshness as the time variant aspect of thermal comfort providing contrast and change has been discussed by Clements-Croome & Roberts (9) and Purcell & Thorne (10) on the basis of the arousal level theory. These field experiments aimed at determining how freshness can be evaluated from the parameters commonly used by designers.

In a survey of office buildings, which included 23 offices constructed in 1960–1980, 228 people responded to a questionnaire that concentrated on freshness (4, 11). Two significant factors in judging freshness were found to be air temperature and fresh air supply rates. Multiple regressions established a following relationship for the mean freshness vote (MFV):

$$MFV = 1.97 - 0.231t_a + 1.8v + 3.15 lgFA - 1.08 lg.S + 0.103RH, \qquad \text{Equation 1}$$

where t_a is air temperature; v is air velocity (m/s); FA is fresh air supply (l/s per person); S is office space (m^3/person); RH is relative humidity.

A more simplified form of the equation was found to be:

$$MFV = 7.24 - 0.417\, t_a + 2\, lg\, FA. \qquad \text{Equation 2}$$

Another regression analysis was used to determine the relationship between the percentage of people dissatisfied (PPD) and the mean freshness vote (MFV), which for this study was:

$$PPD = 100 \exp[-0.652(MFV + 3)]. \quad \text{Equation 3}$$

For a mean freshness vote of 0.3, the percentage of people dissatisfied will be 12%.

The fresh air supply rate (l/s per person) can be calculated from

$$\lg(FA) = 0.2085\, t_a - 3.37. \quad \text{Equation 4}$$

This work suggests that people need more fresh air than current standards specify and ventilation control systems need to respond sensitively to changes in air temperature conditions, which then require changes in the fresh air supply.

Content of indoor air

The air in a room may contain particulate matter, which includes dust; flakes of skin; gases, including volatile organic compounds; carbon dioxide (CO_2), as well as fumes from the external environment and smoking; electrical particles such as ions, which may be negative or positive; and oxygen, nitrogen and water vapor. Pollution usually arises from infiltrations into the building from outside, people, equipment, dust within the airflow systems, which can be discharged into the space if the systems are not maintained properly, and emissions of volatile organic compounds from building and furnishing materials.

Brown (12) reported experiments on emissions from photocopiers and laser printers. His results showed that, even when photocopiers were idle, they still show significant emissions than when they were switched off. The total volatile organic compounds emitted amounted to 1900 μg/m^3, and, of these, ethyl benzene (608 μg/m^3), m- and p-xylene (515 μg/m^3), and styreneo-xylene (390 μg/m^3) were the principal constituents. Of the remaining 10 volatile organic compounds, benzaldehyde, C_9 ester, and butenyl benzene were the next group of important constituents. The odor thresholds for various volatile organic compounds has been given by Devos et al (13) and the handbook of the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) (14).

The laser printers gave more variable emissions, and some emitted large amounts of ozone, but others did not. Seven of thirteen printers emitted more ozone, nitrogen dioxide, and particulates than the copiers, but lower levels of volatile organic compounds. The most common of these compounds were xylene, benzene, styrene, and nonanol. Some types of laser printers emitted acenaphthene.

Black et al (15) described investigations into the effectiveness of carpet cleaning practices. Two samples of carpet were used, but both were standard commercial grade with looped pile, nylon fiber, and styrene butadieme latex backing. Various biocontaminants were measured, including airborne and dust concentrations of allergens such as two species of dust mites, cockroach, cat dander, toxins, fungi, and bacteria. After cleaning, the fungi and bacteria in both carpet samples had decreased significantly although one carpet was much cleaner than the other.

Wargocki et al (16) used an old carpet for a pollution source and carried out a blind experiment, the results of which showed that people perceived a higher degree of dissatisfaction when the carpet was present and that there was significantly increased prevalence of headache and lower levels of reported work effort. Wargocki et al (16) quoted several references that show that increased indoor pollution caused by building materials and furnishings can cause complaints of poor air quality and consequently affect the health of building occupants by increasing the prevalence of ailments arising from mucus membrane, cutaneous, or general symptoms. The European Committee for Standardization (17) strongly recommends selecting materials so that the building can be characterized as low-polluting with a sensory pollution load of 0.1 olf/m^2 of floor area or as nonlow polluting with a sensory load of 0.2 olf/m^2 of floor area.

Growing significance of carbon dioxide

Normally, in buildings, the aim for carbon dioxide is to be under 1000 ppm, which is equivalent to a concentration of 0.1%. According to the Canadian Centre for Occupational Health and Safety (18), and also the ASHRAE standard (19), health effects can become acute at higher exposure levels. Carbon dioxide concentrations of 7.5% lead to headaches, dizziness, restlessness, the feeling of an inability to breathe, sweating, malaise, increased heart rate, and increased blood pressure, and visual distortion can become apparent. At 10% concentration levels, hearing can be impaired, accompanied by nausea and a loss of consciousness. At 30% concentrations convulsions, a state of coma, and death by asphyxiation can occur.

Robertson (20) shows that the pH value of the blood decreases as the atmospheric concentration of carbon dioxide increases. This is another reason, besides global warming, why the carbon dioxide content of the external atmosphere should be limited to <426 ppm—so that the blood pH values do not decrease to an unacceptable level. Metabolism is very sensitive to body fluid pH values. Extreme values of blood pH are usually considered to be from 6.8 to 7.8. An increase in the atmospheric concentration of carbon dioxide will reduce the blood pH, and at 426 ppm of carbon dioxide the estimated pH value of blood changes from a mean of 7.4 to a mean of 7.319, which is the current lower value of the range and means that acidosis is likely to onset (Robertson D, personal Communication by letter, 8 February 2007).

We spend over 90% of our time indoors (21) with carbon dioxide levels of about 1000 ppm, but the 10% of time spent outdoors with levels of 380 ppm is important to help keep the blood pH value within reasonable limits.

Studies being carried out by the University Reading in primary schools have shown that the carbon dioxide levels vary from 800 ppm to almost 5000 ppm. This finding is of particular concern because primary school children spend several hours a day in the same room, and hence the build-up of carbon dioxide is notable in the morning and in the afternoon. So far, the tests show that there is a relationship between carbon dioxide levels and the effectiveness of some learning tasks (22). Other relevant recent studies on schools include the work of Godwin & Batterman (23) on indoor air quality in 64 Michigan primary and secondary schools, and Kim et al (24) on respiratory symptoms, asthma, and allergen levels in Korean and Swedish schools.

Environment, energy and well-being

The World Health Organization (25) describes the effect of indoor pollutants on health. The sick building syndrome gives rise to eye, nose and throat irritation, dry mucous membrane and dry skin, erythema (skin redness), mental fatigue, headaches, a high frequency of airway infections and coughs, hoarseness and wheezing, itching and nonspecific skin hypersensitivity, and nausea and dizziness. Common symptoms characterized by nasal dryness or congestion, such as a stuffy blocked nose or a runny nose, and also mental effects, such as difficulty to concentration, can arise.

The largest impact of buildings on the outdoor environment during the whole life cycle comes from the energy used to ensure a comfortable and healthy indoor climate. According to Orme (26), ventilation accounts for 25–30% of the total building energy use. There are large disparities in the energy consumption of similar buildings in similar locations, due to various levels of thermal insulation, services system efficiencies, differences in building construction, more or less effective use of passive design techniques, occupancy behavior, and building management. The behavior of occupants reflects their expectancies and lifestyles, which are demonstrated in their workplace as well as in their homes. Facilities management is now recognized as an art that not only looks after systems that make the building operate, but also cares for the people. Roulet et al (27) provided the *total energy index* (annual energy use divided by the gross heated floor area) for 56 European office buildings. In this sample, the largest energy consumption was more than six times the smallest level. This variation can be reduced in the case of highly insulated buildings, but overall it is occupancy behavior that contributes the largest part of this variation.

Roulet (28) has shown how the energy index varies in relation to the *building symptom index* (average number of symptoms experienced per occupant during the past month selected from a list of twelve) in 56 European office buildings. In general, energy consumption is greater in less healthy buildings. In this particular case study, the correlation coefficient was 0.43 with a 95% probability (P=0.05–0.07).

The variation in the energy consumption of buildings arises in the design, construction, commissioning, and facilities-management stages. Many buildings give the occupant very poor control of their environment, and this lack of control is not only inconvenient, it is psychologically unacceptable because the occupants do not feel that they have a role in controlling their surroundings.

The basic intention of buildings is that they should be planned, designed, built, and managed to offer an environment in which occupants can carry out their work and feel well and, to some extent, be refreshed by the environment. Unhealthy buildings result in a loss of productivity, and every workhour lost costs as much as a kilowatt hour; hence the occupants' well-being in monetary terms is even more important than energy use (28). Salaries usually amount to about 90% of the total cost of an organization, and therefore very small changes in productivity will be economically viable. Many case studies have been described earlier (1), and the conclusion was reached that it is beneficial to spend more on designing good indoor air quality systems, as they considerably improve the occupants' well-being and result in a payback period of under 2 years for a typical office building. Geens & Griffiths (29) carried out a small-scale study of public houses and found that a better ventilation system increased the profits from increased food and drink sales, which gave an average payback of under 3 months.

With all our current knowledge about indoor air, it is strange that asthma is increasing in many countries. Zhao (30) has written a doctoral thesis on this topic in relation to China.

Ventilation rates

Seppänen et al (31) and Wargocki et al (32) have made a comprehensive review of over 20 studies with over 30 000 persons and found that ventilation rates below 10 1/s per person results in lower air quality and worsening health problems. Risk of the sick building syndrome is reduced, and perceived air quality is improved, when the ventilation rates increase from 10 l/s to about 20 1/s per person. The work also indicated that carbon dioxide concentrations below 800 ppm are preferable. An indoor carbon dioxide concentration of 800 ppm responds to a fresh air ventilation rate of 11.6 1/s per person with sedentary activity according to ASTM D 6245–98 (33). This assumption assumes that the concentration of carbon dioxide in the outdoor air is about 350 ppm. The results of Jaakkola (34, 35) indicate that each 1/s per person change in the ventilation rate over the range 0 to 25 1/s per person is associated with a relative risk of 1.1 for experiencing symptoms. Thus a decrease of 5 1/s per person in the ventilation rate would increase the proportion of occupants with frequent upper respiratory symptoms from 25% to 40% with a similar increase in eye symptoms.

Li et al (36) reviewed the role of ventilation in the airborne transmission of infectious agents in the built environment and believed that there is an association between ventilation, the control of airflow direction, and the transmission and spread of infectious diseases. They concluded, however, that there is insufficient evidence to specify minimum ventilation rates in hospitals, schools, offices, and other indoor environments. They suggested a multidisciplinary approach using available molecular biology test methods, current computer modeling, and experimental methods for investigating ventilation requirements.

Ventilation rates for acceptable indoor air quality are currently assessed by using ASHRAE standard 62.1 (37). In this standard there are two procedures for estimating the amount of fresh air required. The first is referred to as the *ventilation rate* and is a *prescriptive approach* stating that, for office buildings, there is a requirement of 10 1 of fresh air per second per person (nonsmoking). A comparison of standards for the indoor environment is given in F9.2 of the ASHRAE *Handbook on Fundamentals* (14).

The second procedure is based on a *performance approach* using public knowledge about indoor air quality. This approach originated in Europe (38, 39). In these proposals, the ventilation requirements are computed for health and comfort purposes, and the higher of the resulting values is recommended for application to the particular building being designed. This approach is based on the olfactory process using the *olf* and *decipol* (6). People can sense pollution in the atmosphere through their olfactory system. There are objective and subjective reactions to pollutants.

The ventilation rate for acceptable indoor air quality can be calculated from

$$Q = 10\ G/(C_i - C_0).(1/\varepsilon_v) \qquad \text{Equation 5}$$

where Q is the ventilation rate (1/s), G is the equivalent strength of all pollution sources in the space and the ventilation system (olf), C_i is the perceived indoor air pollution (decipol), C_0 is the perceived outdoor air pollution (decipol), and ε_v is the ventilation efficiency, which depends on the type of system.

The perceived quality of indoor air C_i can be assessed in terms of the percentage of people dissatisfied (PD%) by

$$C_i = 112\{\ln(PD) - 5.98\}^{-4}. \qquad \text{Equation 6}$$

Giaccone et al (40), in recommending this approach to problems with indoor air quality, stated that more research is still needed and there is currently a lack of data concerning the pollution loads of building materials and the contents of buildings. He also showed how the energy demand rose from about 15 GJ to 65 GJ when the air change rate rises from 0.5 to 3 in Milan (2404 degree days) and from 9 Gj to 40 GJ with the same range of air changes per hour difference in Messina (707 degree days).

Various factors trigger an increase in the air-change rate, including a decrease in ventilation efficiency, a decrease in perceived air quality, an increase in the perceived outdoor air quality, the presence of smokers or other contaminant sources, and emergencies such as fire.

Problems in ventilation design

Like all environmental problems, there are several confounding factors that influence the choice of ventilation rate. Personal characteristics, work-related factors, building-related factors, as well as indoor environmental factors, all need to be appreciated when environmental design problems are dealt with. Table 1 presents some of the potential confounding factors that can trigger particular reactions in the environment and can lead to the sick building syndrome.

Indoor-air quality and building design

Woods (41) devised a rational model that relates human response, exposures, systems, environmental sources, and economics. In this model, the sources of impacts can be related to temperature, contaminants, lighting, or sound. These loads are imposed on the systems that comprise the building structure, envelope, services, or enclosures and incur operating costs. People within the building are exposed to these effects and sense these factors and respond to them, all of which results in energy patterns of use. At a more subtle level, human responses affect the health and well-being of people, and they form a large contributory factor to productivity.

Woods (41) proposed a control strategy by developing a concept of *building energy efficiency*. This model focuses on design alternatives for requirements to achieve acceptable exposures but, at the same time, minimizes energy wastes. It recognizes that energy *effectiveness* relies on the use of energy where and when it is needed, whereas the term *energy efficiency* only crudely refers to output and input without any concern as to the distribution. This work emphasizes the interdependent nature of health, energy, and management.

In the September 2006 issue of the *Building Services Journal* (42), there was a questionnaire on heating and ventilation in school buildings, and the results are reported in table 2. This survey shows variations in opinions, but ventilation and its effect on learning is a firm belief, based largely on the experience of many.

Table 1. Examples of potential confounding factors in studies of ventilation rates and symptoms of the sick building syndrome (32).

Personal characteristics	Work-related factors	Building-related factors	Indoor environment factors
Gender	Job stress or satisfaction	Type of ventilation system	Air temperature
Atopy (allergic disposition)	Use of carbonless copy paper	Type of humidification	Mean radiant temperature
History of asthma	Use of or proximity to photocopy machines	Quantity of carpet or textile surfaces	Air humidity
Smoking history	Use of video display terminals	Sealed windows	Air movement
Job type		Building age	Environmental tobacco smoke
Medical treatment (especially for asthma and atopy)	Filtration	Dusty surfaces	

Table 2. Results of the heating and ventilation in school buildings according to the September 2006 issue of the *Building Services Journal* (42).

Question	Majority response
1. What is the biggest factor influencing your choice of a heating system for a modern, well-insulated classroom?	The biggest factors were energy efficiency and low surface temperature.
2. Which of the following do you prefer to use in a modern classroom environment?	Natural ventilation, followed by a combination of mechanical and natural ventilation solutions.
3. Poor air quality will have a very detrimental affect on a pupil's performance in the classroom	Air quality was agreed to have a detrimental effect.
4. Is it advantageous to have ventilation systems in schools?	Most people agree it is advantageous to have ventilation.
5. How many air changes per hour would be ideal for a ventilating system in a classroom with around 25 pupils?	Four to six air changes per hour.
6. If ventilation requirements could be linked to carbon dioxide levels in classrooms, how do you think it would affect the number of air changes/hour?	Fewer air changes would result, but a significant number of respondents believed the number of air changes would increase.
7. What are the biggest threats facing schools with a poor heating and ventilation system?	Most thought that poor air quality would mean higher carbon dioxide levels, and consequently pupils' health and their ability to focus would suffer. Inadequate temperature control was another problem.
8. Which of the following do you prefer in an educational building?	Programmable thermostats controlled from room to room and thermostatic radiator valves were preferred.
9. What proportion of the building for education expenditure should go to heating and ventilation systems in secondary schools?	Five to fifteen percent, but a significant number of respondents believed this could be as high as 25%.
10. Is sustainability the most important issue to consider when heating and ventilation in schools is specified?	There was an equal opinion that sustainability was or was not the most important issue.
11. Has Building Bulletin 101 been useful?	It was agreed that Building Bulletin 101 had been useful.

In studying open-plan offices, Pejtersen et al (43) found that poor air quality and stuffy air were more pronounced in larger offices then in cellular ones. In his study, the size of the office was a stronger predictor of symptoms and complaints than the type of ventilation. However, many studies, such as that of Mendell & Smith (44), have found a higher prevalence of symptoms and complaints in mechanically ventilated buildings than in naturally ventilated ones. Another confounding factor is that some kinds of work are more suitable for open-plan offices than other types of work, and this difference may have some bearing on the occupants' perceptions and symptoms, whereas, according to Pejtersen et al (43), the psychosocial factors are not associated with office size.

Mendell et al (45) believes that the best prevention strategies for building sickness symptoms are to control the moisture of building exteriors, to operate ventilation systems according to design intent, to provide at least the minimum recommended ventilation rates, and to maintain indoor temperatures at 22^{o}C (±1^{o}C). van Dijken et al (46) studied the indoor environment and its impact on pupils' health in primary schools. Their results confirmed that indoor air quality in primary schools in the Netherlands is poor, with a mean carbon dioxide concentration ranging from 888 to 2112 ppm. The classroom and the home were major factors with regard to pupils' health.

Shendell et al (47) illustrated that a 10–20% increase in students' absence rates occur with a 1000 ppm differential increase in the carbon dioxide concentration. A continuous measurement of air quality in schools in the United States by Grimsrud et al (48) showed that many schools need to improve their ventilation and called for a remedial training program in schools regarding the importance of ventilation and its possible implications for learning.

Roulet et al (49, 50) collected data from apartment and office buildings looking for correlations between characteristics and perceived comfort and health. Significant correlations were found between perceived air quality and thermal, acoustic and lighting comfort and also between perceived comfort and building-related symptoms. Low-energy buildings are, on the average, healthier and more comfortable, thus showing there is not a conflict between comfort and energy use.

Moschandreas et al (51) described the Indoor Environmental Quality Conceptional Model, which can be used as a proactive management tool to improve and maintain good indoor environment quality. The model uses the indoor environmental index (IEI) to assess the model. The IEI is a composite index aggregating the indoor air pollution index (IAPI) and the indoor discomfort index (IDI). For the best environmental indoor air quality, the IEI approaches zero, and the IEI approaches 10 for poor air quality.

Achieving acceptable indoor air quality

Woods (41) proposed the idea of continuous accountability using a system of building diagnostics. A useful analogy is made between medical diagnostics in which steps are taken to develop (i) knowledge of what is to be measured, (ii) the use of appropriate instrumentation for measurements, (iii) an intelligent interpretation of the results, and (iv) a capability to predict likely performance over time. Building diagnostics can be used throughout the life of a building, beginning with the planning and design stage and ending with adaptive reuse or demolition. This approach has been used by the Department of Labor and the Occupational Health and Safety Administration in the United States (41). The following five steps are described by Woods (41): (i) *planning and concept design*: building owners, financiers, and designers establish basic performance criteria, (ii) *detailed design*: performance criteria are translated into prescriptive criteria, (iii) *commissioning*: the evaluation of building performance before occupancy by an independent firm or agency, (iv) *building operation*: building performance evaluated by a qualified team of professionals (the building owner is fully accountable for the success of the building at this stage), and (v) *building use*: buildings and systems are designed for specific uses and conditions so that, if these are exceeded, or the systems are tampered with, then system performance decreases.

Various purification systems are available. Tri-air Developments Ltd claim that, in 2006, they developed an air decontamination technology with a 99.9999% kill rate that can protect against a wide range of airborne viruses and bacteria, including H5N1 (bird flu), influenza, SARS (severe acute respiratory syndrome), anthrax, and unpleasant odors, by creating "clean air" environments. The unit creates a continual supply of hydroxyl radicals to destroy microbes, including flu and cold viruses and bacteria, both in the air and on surface contact. Hydroxyl radicals are found naturally in abundance in outdoor fresh air, with high concentrations found in forested mountain areas. Hydroxyl radicals from the unit condense onto particles and destroy their potency.

Impact of indoor air on work performance

Fanger (52) discussed the impact of indoor air quality on productivity in offices, learning in schools, and the growth of allergic and asthmatic diseases. He went on to discuss solutions, including air cleaning, personalized ventilation, and the need for cool (21°C) dry air. Other work suggests that relative humidity below 40% can increasingly give rise to dry throats, and below 20% it may have negative effects on the eye blinking rate. A range of 40–60% is acceptable. Bakó-Biró & Olesen (53) concluded that (i) indoor air quality can significantly improve the performance of people, (ii) according to laboratory studies a 10% increase in dissatisfaction decreases performance by 1%, (iii) field studies also show significant improvements in performance with improved indoor air quality (fewer pollution sources, higher ventilation rates), and (iv) with improved indoor air quality significant savings in health care costs are possible (sick building syndrome, sick leaves, etc).

However there are some fundamental factors that need to be borne in mind at the concept stage of an architectural design. For example, it is important to plan the *occupancy density* in relation to the ventilation, as crowded work spaces often give rise to problems. It is also important to have *heights of spaces* that allow the stagnant layer of air to rise above the head level. Building occupants need to have some *personal control* over ventilation. This control begins with the open window, wherever possible, and then comes more local control, especially in air-conditioned buildings using personal environmental control systems. Increasingly, people are sealed in buildings, especially in cities, when the option for opening windows becomes more limited due to pollution, including noise, but case study evidence suggests that the risk of sick building syndrome is slightly higher in air-conditioned buildings than in ones with natural ventilation.

Escombe et al (54) found that pre-1950s hospital design with natural ventilation gave a more reduced risk of infection than did 1970–1990 hospitals with natural ventilation, or those post-2000 with mechanical ventilation. The height of the space together with large windows arranged to give effective cross airflow in the pre-1950s meant natural ventilation was effective. Low spaces and smaller windows that were not always well located for promoting good air movement led to stuffy conditions with higher airborne contagion.

The guidebook *Indoor Climate and Productivity in Offices* of the Federation of European Heating & Air-Conditioning Association (REHVA) (32) attempts to quantify the effects of the indoor environment on office work and also discusses how to include these effects in the calculations of building costs. At this stage, much of the evidence is concerned with the thermal environment and indoor air quality, and hence there is little information given about the impact of noise and light. The economic benefits for the client are led by designing environments that improve productivity; there will be less sick leave and fewer complaints. This situation means that the environment contributes towards increasing the built asset value and making the building more marketable. It is also likely that the churn rate or the turnover of staff will be less in a building with good environmental conditions. The following conclusions were drawn: (i) a 1% increase in office work can offset the annual costs of ventilating a building, (ii) the full cost of installation and running the buildings can be offset by productivity gains of just under 10%, (iii) doubling the outdoor air supply rate can reduce illness and the occurrence of the sick building syndrome roughly by 10% and increase office work by roughly 1.5%, (iv) every 10% reduction in the percentage dissatisfied with air quality can increase the performance of office work by roughly 1%,

(v) an increase in indoor air temperatures above 22°C by 1°C can roughly decrease the performance of office work by 1%, and (vi) payback time for investments to improve indoor environment quality is generally below 2 years. Much of the evidence for these conclusions has been described in the book *Creating the Productive Workplace* (1).

Concluding remarks

Indoor air quality is a vital factor for the health of occupants in buildings. The olfactory sense is very important psychologically, as well as physiologically. The air we breathe ultimately affects the efficiency and effectiveness of our thinking. There is considerable value in demonstrating to clients the value of spending more capital on high-quality buildings that promote good airflow characteristics through the use of natural, mechanical, or air-conditioning systems. The process of achieving indoor air quality is a continual one throughout the design, construction, commissioning, facilities management, and renovation stages of a building's life. The constituents of the air are many more than we ever realized, and they need much more monitoring so that we develop a deeper understanding of them and hence ultimately produce healthier workplaces for people and give good value for money.

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