S.E.E. breeze: The impact of indoor air quality on education

Sean Coward

Triple bottom line reporting and the education sector

Despite the shift towards online learning and distance education, schools, universities and alternative institutes of adult education continue to depend on a wide variety of built structures for students; from lecture halls and classrooms to libraries and gymnasiums. All of these spaces pose a significant problem for designers and engineers: how can one optimise the quality of the indoor environment while accommodating densities far in excess of those housed in most other buildings? Typically, the education sector in most countries is poorly funded, with facilities usually the first to bear cutbacks (in terms of design, operation and maintenance). Part of the reason for this tight-fisted approach is that it is difficult to quantify the value of education in terms of a return on investment, particularly regarding any effects attributable to the physical environments in which learning takes place. However, the recent trend towards triple bottom line reporting suggests that educational facilities should be evaluated in terms of their *social* and *environmental,* in addition to *economic,* performance.

Needless to say, the best performing educational facilities will be those that contribute positively to all three reporting criteria. With regard to social issues, it has been claimed that high quality environments enhance the health and well-being of both students and teachers, leading to greater satisfaction and physical wellness. From an economic perspective, quality education provides the foundation for a successful national economy, such that any environmental variables linked to improved learning outcomes can be considered justified in a fiscal sense.[1] Finally, any educational facility should be designed to achieve these outcomes while exerting a minimal impact on the environment—the destruction of which can be safely assumed to have dire economic and social consequences. Wyon (2004) makes the point that social, economic and environmental needs must be balanced: there is no point in designing an environmentally sustainable or low cost educational facility which houses sick, uncomfortable, or inattentive occupants.

With respect to health, comfort and learning, indoor air quality (IAQ) is considered by many to be a crucial component in the experience of building occupants. The factors determining IAQ remain consistent across all building types; these being *indoor pollutants* and *thermal conditions.* Since existing research on thermal comfort is generally inconclusive (presumably because effects are confounded by a range of cognitive variables), the present paper will restrict its focus to the effects of indoor pollutants. So what impact can airborne contaminants have on the effectiveness of educational facilities, and can the steps taken to minimise their concentration be justified in terms of triple bottom line reporting? While the majority of research investigating human responses to IAQ pertains to the workplace,[2] it seems logical that the major outcomes measured —health and performance—are of relevance to the evaluation of educational facilities. More specifically, health is a concern as it relates to absenteeism (an absent student is deprived of valuable opportunities for direct teacher-student knowledge exchange) and certain indices of work performance are particularly relevant to learning (e.g. measures of attention / alertness, comprehension and test performance). Although the body of literature devoted to educational facilities is relatively small (particularly in terms of adult education), wherever possible the present review will refer to research conducted in this sector.

From an economic perspective, quality education provides the foundation for a successful national economy, such that any environmental variables linked to improved learning outcomes can be justified in a fiscal sense.

Absorbing information… and what else?

One of the major problems of built structures is that they contain numerous sources of airborne pollutants, many of which can have a deleterious effect on the health of occupants. Originally, the sole purpose of ventilation was to dilute these contaminants via the introduction of outdoor air in order to achieve concentrations considered harmless to humans. Research supports the effectiveness of this strategy, with low ventilation rates frequently associated with adverse health in occupants, such as sick building syndrome (SBS) symptoms and communicable diseases (Seppänen, Fisk, & Mendell, 1999). Fisk (2000) estimates that improving building standards via increased ventilation, reduced recirculation, improved filtration, ultraviolet treatment of air and HVAC components, and reduced occupant density could reduce respiratory illnesses in occupants by 15%, and SBS symptoms by 20–50%.

Ventilation standards developed by the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE, 2001) recommend a minimum ventilation rate of 7.5 L/s (litres per second) per person for classrooms. This is equivalent to a carbon dioxide (CO_2) concentration of approximately 1000 p.p.m. (parts per million), a criterion often not met by North American and European schools (Daisey, Angell, & Apte, 2003). CO_2 is a widely accepted measure of both ventilation rate and levels of human bioeffluents (CO_2 being produced by human metabolic processes) and, by extension, it is often considered to be a valid indicator of general pollutant levels (although it fails to account for many pollution sources unrelated to human activity).[3] Research also supports CO_2 levels as an indicator of pollutant concentration: Shendell, Prill, Fisk, Apte, Blake and Faulkner (2004) found that a 1000 p.p.m. increase in CO_2 concentration above outdoor levels corresponded to a 10–20% increase in school absenteeism. They argue that student absence reflects, among other things, communicable respiratory illnesses that are likely to proliferate in schools with poor ventilation.

Research on indoor pollutants generally focuses on three categories: volatile organic compounds (VOCs), formaldehyde and bioaerosol contaminants. A description of each classification and a brief summary of documented effects follow.

Volatile organic compounds (VOCs)

The term VOC is used to describe a wide range of chemicals that are emitted from (primarily) non-biological sources. VOCs can be released into the air from carpets and other types of flooring (e.g. PVC), adhesives and sealants, paints, furniture, cleaning products, and equipment such as computers and printers. Exposure to various VOCs has been linked to dry mucous membranes and other SBS symptoms (irritation of eyes, nose and skin; headache; fatigue), as well as decreased perceived air quality and increased odours (Mølhave, Bach, & Federsen, 1986). While olfaction is sometimes a useful indicator of harmful pollutants (e.g. petrochemical emissions from fresh paint) this is not always the case (e.g. radon, a radioactive gas linked to lung cancer, is odourless to humans): hence the assessment of IAQ using perceived air quality—as applied in certain ASHRAE standards—can be misleading. Moreover, unpleasant olfactory perceptions often disappear as occupants adapt (the human sensory system is designed to detect change), such that perceived air quality by visitors is often used to gauge IAQ. With this in mind, increasing ventilation rates have also been shown to increase occupant satisfaction with perceived air quality (see Figure 1). As can be seen, even at a ventilation rate of 10 L/s per person, 15% of occupants will remain dissatisfied—hardly a ringing endorsement of IAQ.

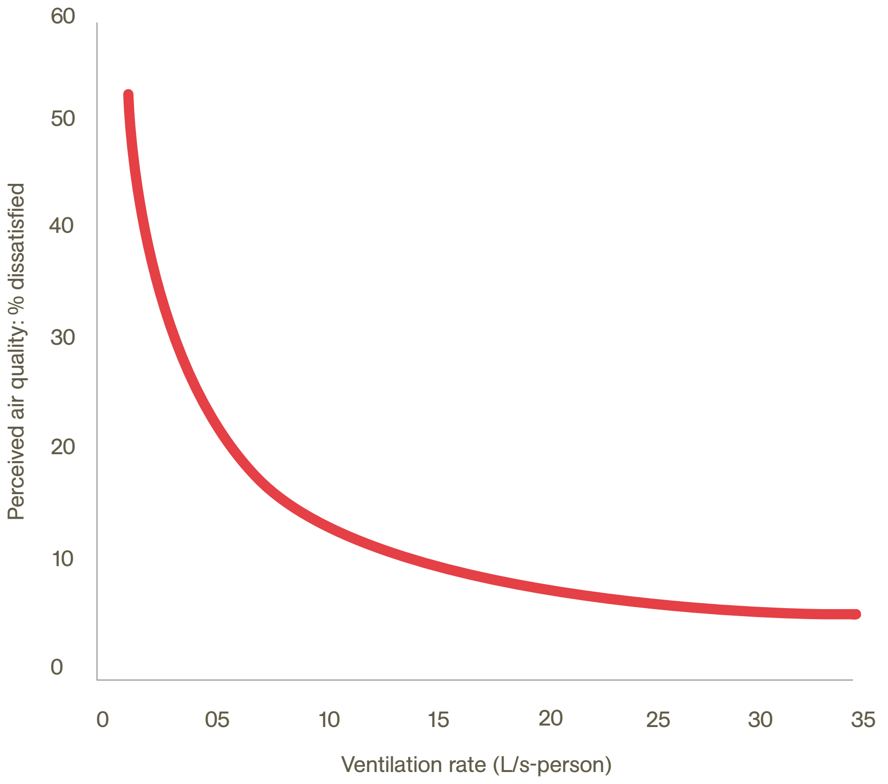


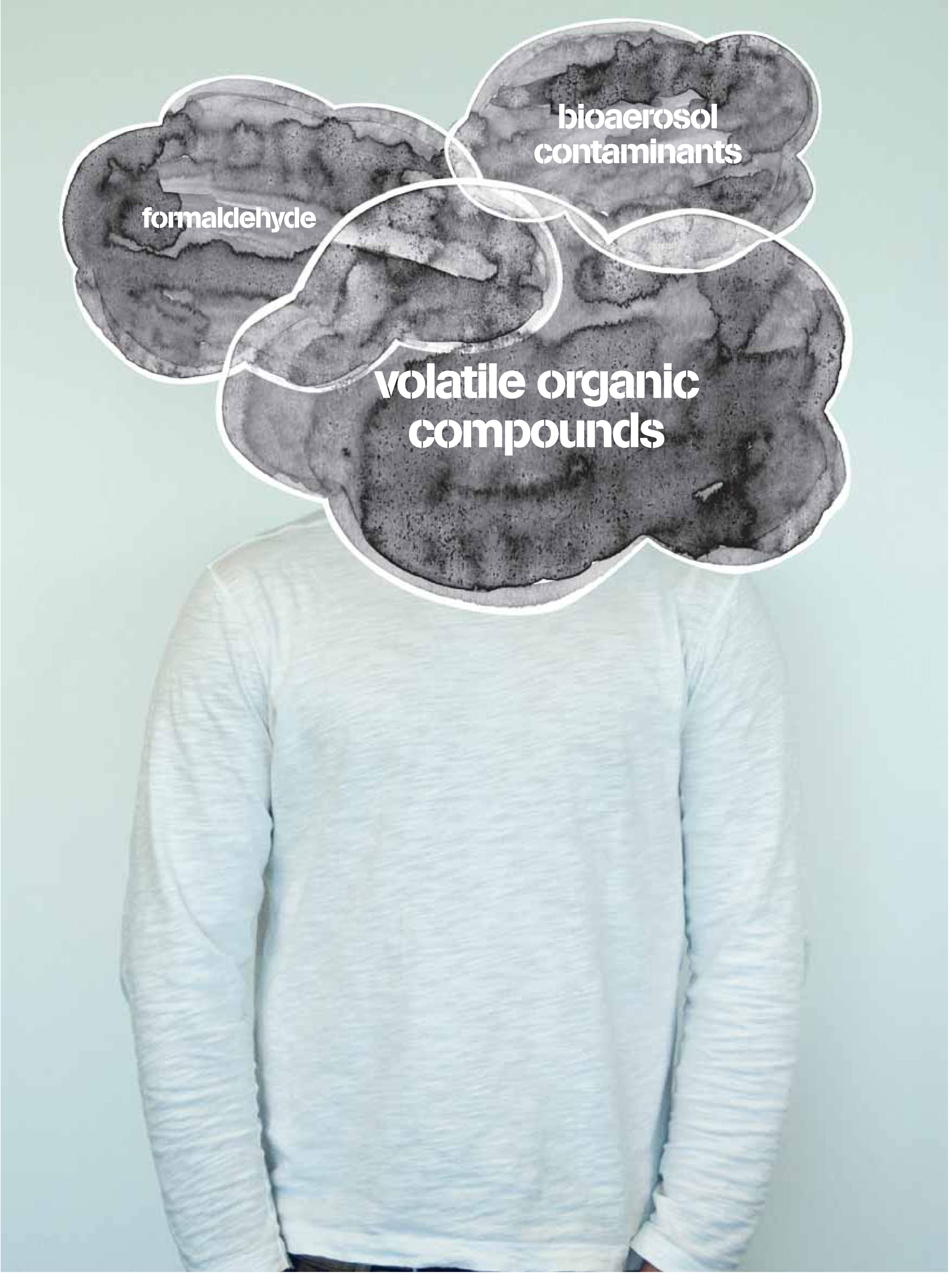
Figure 1. Percentage of occupants reporting dissatisfaction with perceived air quality as a function of ventilation rate. Reproduced with permission from Olesen, 2004.

Formaldehyde
This chemical, a gas at room temperature, is typically used as a resin to bond wood in particleboards and fibreboards to make furniture. While formaldehyde is technically a VOC, it is usually discussed separately due to the increased health risks associated with exposure. Reported effects of off-gassing (the resin emits vapours after hardening) range from irritation of the eyes and respiratory tract to more serious conditions linked to its potentially carcinogenic qualities. Research suggests that exposure to formaldehyde may lead to an increased risk of allergic sensitisation in children (Garrett, M.A. Hooper, B.M. Hooper, Rayment, & Abramson, 1999). However, Daisey et al. (2003) warn that even concentrations lower than those associated with irritation may not protect against the long-term risk of cancer; accordingly, exposure should be limited as much as possible.

Bioaerosol contaminants
This term refers to a wide variety of biological agents, including viruses, bacteria (and any related endotoxins), allergens linked to dust mites and animal hair, and fungi (including associated allergens, toxins and irritants). Regarding the accumulation of these contaminants in indoor environments, low ventilation rates have been linked to respiratory illness caused by viruses (Brundage, Scott, Lednar, Smith, & Miller, 1988), and bacterial endotoxins are associated with flu-like symptoms (Rylander, Persson, Goto, & Tanaka, 1992). Exposure to animal and dust mite allergens has been linked to asthma, which is responsible for 20% of school absenteeism in children (Richards, 1986). Health problems associated with indoor mould include blocked sinuses, sore throats, runny noses, eye irritation, respiratory illness, and fatigue (Bates & Mahaffy, 1996, cited in Daisey et al., 2003).

Once again, while most of the published research on indoor air pollution focuses on adult workers in offices, one can assume that any effects should generalise to students. In fact, occupant densities in classrooms and lecture halls are invariably higher than those in offices, increasing the production of pollutants such as CO_2, communicable diseases, and even less toxic, yet nonetheless unpleasant, human bioeffluents such as body odour. The risk of health problems is of particular concern for young school children as they breathe a higher volume of air (relative to their body weight) than do adults, and any damage resulting from airborne pollutants may have lifelong consequences for developing tissues and organs (Faustman, Silbernagel, Fenske, Burbacher, & Ponce, 2000).

Reported effects of off-gassing ... range from irritation of the eyes and respiratory tract to more serious conditions linked to its potentially carcinogenic qualities.



Clean air, clear minds?

While ventilation was initially justified solely in terms of health concerns related to indoor pollutants, recent research has directed attention towards the potential impact of IAQ on human performance. For educational facilities, the question is how IAQ might affect the acquisition, comprehension and demonstration of knowledge. Of course, health and performance are not mutually exclusive: absenteeism decreases the amount of information transferred from teachers to students, and research suggests that symptoms resulting from indoor pollutants can inhibit learning, either as a direct result of the symptoms themselves (Smith, 1990) or via medications used to treat them.

As with IAQ research in general, most of the literature concerning performance relates to office work. However, certain performance indices may be considered relevant for assessing educational facilities, such as concentration, fatigue, and test results. Mendell and Heath (2005), in their review of literature relevant to the IAQ-performance relationship in schools, failed to reveal a direct causal relationship. They did, however, uncover several highly suggestive lines of evidence for an association between the two, particularly in terms of occupant exposure to indoor pollutants; a finding which supports the notion that poor IAQ may often inhibit task performance via decrements in either student or teacher health.

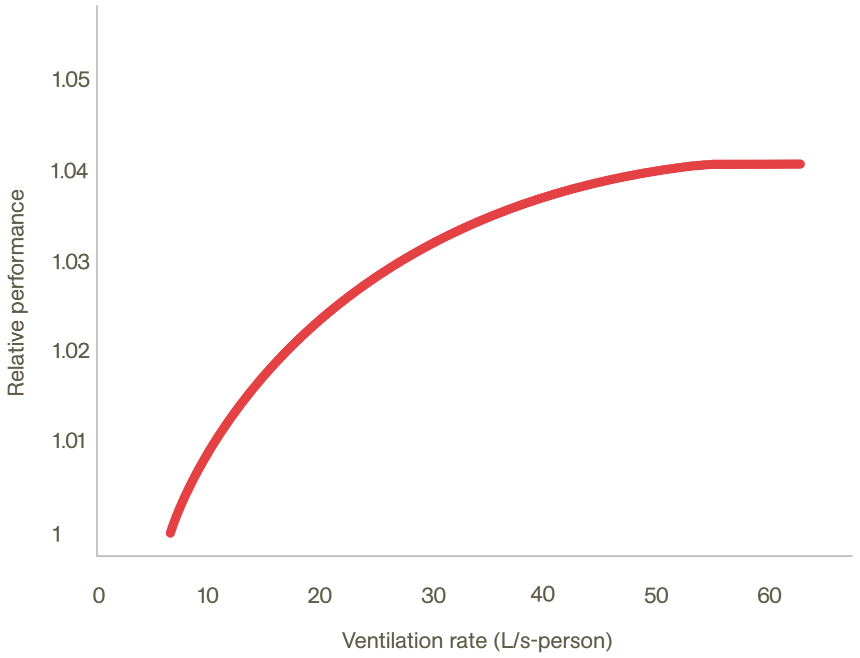
Most of the research supporting the association between IAQ and performance use ventilation rate to indicate pollutant concentrations. Wargocki, Wyon, Sundell, Clausen, and Fanger (2000) found that increases in ventilation rate improved both speed and accuracy of typing, addition and proof reading, while also enhancing creative thinking and clarity of thinking. The authors calculated an average increase in performance of 1.7% for every twofold increase in ventilation rate between 3 and 30 L/s per person. In their review of the literature, Seppänen, Fisk, and Lei (2006) concluded that an increase in outdoor ventilation rate of 10 L/s per person results in a 1–3% improvement in work performance (up to approximately 45 L/s per person, after which the curve plateaus—see Figure 2). This relationship between ventilation rate and performance makes sense in light of the fact that total VOC levels have been associated with impaired memory and ability to concentrate (Mølhave et al., 1986). In fact, there do not appear to be any theoretical explanations for the relationship between indoor pollutants and performance that do not rely on occupant health as a mediator.

A breath of fresh air: Rethinking educational facilities

The available evidence leaves little doubt that ventilation is an effective means of diluting indoor pollutants and reducing associated health problems. However, mixing contaminated air with fresh air is surely not an ideal solution. Fanger (2000) illustrates the limitations of this approach by comparing co-occupation in a building interior with a crowded swimming pool: few people could be convinced to drink pool water using the argument that the contaminated liquid has been diluted with an influx of fresh water. He also makes the point that, in a room provided with outdoor air at the rate of 10 L/s per person, only 1% is ever inhaled. A further problem with ventilating indoor spaces with outdoor air is that polluted locations, such as cities, may introduce toxins into the building. Outside air may be contaminated further, prior to reaching the occupied space, by poorly maintained HVAC systems (Seppänen & Fisk, 2004). Finally, increased ventilation rates mean increased energy use—with associated costs to the environment.

If current minimum ventilation standards provide more breathable air than can be consumed, and if ventilation systems are capable of *introducing* contaminants, then the best way to reduce the impact of indoor pollutants is by avoiding internal sources of air pollution wherever possible (i.e. source control). Improving IAQ without relying on high ventilation rates is also a more environmentally sustainable and fiscally prudent practice, as the percentage of total building energy used to ventilate air in schools is in the order of 10–20%. The reduction of indoor pollutant concentrations can be achieved via the selection of low VOC and low formaldehyde emission products. Carpets should be avoided due to their VOC emissions and because they provide an ideal environment for the proliferation of mould and other bioaerosol allergens. Buildings must be kept dry, with pitched roofs reducing the risk of water leakage. Commissioning also plays a crucial role by emphasising the need for regular and thorough cleaning and maintenance of buildings and HVAC systems. This may include the irradiation of air outlets and cooling coils with UV lights, which have been linked to a reduction in SBS symptoms (Menzies, Popa, Hanley, Rand, & Milton, 2003).

Figure 2.
Relative task performance in relation to the reference ventilation rate of 6.5 L/s per person. Reproduced with permission from Seppänen, Fisk and Lei, 2006.



One innovative approach to improving IAQ while achieving sustainability targets is to use indoor plants. Some species are known to metabolise certain indoor pollutants, primarily through micro-organisms living in the *rhizosphere* (the region of soil immediately surrounding the root structure of plants). Despite some enthusiastic reporting by the media (e.g. Allenby, 2006), empirical evidence for the notion that indoor plants can effectively filter substantial concentrations of air-borne pollutants is inconclusive. In fact, some research conducted on indoor plants has investigated the possibly *negative* impact of biofiltration on IAQ (e.g. via the release of microbial spores and metabolic by-products), with little support for this hypothesis (Darlington, Chan, Malloch, Pilger, & Dixon, 2000). While some studies suggest modest beneficial effects (e.g. Dingle, Tapsell, & Hu, 2000, found an 11% reduction in formaldehyde levels with twenty plants), others claim that biofiltration can have a significant positive impact on IAQ (e.g. the rapid removal of large amounts of benzene, a model VOC, as reported by Orwell, Wood, Tarran, Torpy, & Burchett, 2004).

The range of reported effects may be at least partially explained by the complexity of the biomass employed; from the simple addition of potted plants, to ecologically integrated biofiltration systems comprising bioscrubbers (air plenums faced with wet, porous volcanic rock), hydroponic plants and aquariums. Perhaps the most promising solution involves *bioaugmentation,* which consists of the inoculation of plant foliage with bacteria to enhance the absorption and metabolisation of pollutants (De Kempeneer, Sercu, Vanbrabant, Van Langenhove, & Verstraete, 2004). Such treatment enables the *phyllosphere* (surfaces of the plant above ground) to contribute significantly to the removal of indoor pollutants, greatly increasing the effectiveness of biofiltration.

The preceding recommendations are not intended to devalue the importance of ventilation, but to emphasise that the task of managing indoor pollutant levels should not be the sole responsibility of HVAC engineers. Architects, interior designers, and facility managers have equally important roles to play in realising optimal IAQ within learning environments. It has been argued here that increased attention to indoor pollutants in particular, and environmental quality in general, is well-justified in terms of triple bottom line reporting via improvements in health, learning outcomes and—pending the integration of non-ventilation-based strategies for pollution management—energy consumption. Furthermore, Wyon (2004) claims that the cost of improving IAQ above current minimum standards is counterbalanced by benefits by a factor of sixty, leading to a payback of investment within two years.

Unfortunately, if the views of Olesen (2004) are representative of those in the design industry, it seems that the aspirations for modern architecture, including schools, are somewhat modest: “The main purpose of most buildings and installed heating and air conditioning systems is to provide an environment *that is acceptable and does not impair* [italics added] health and performance of the occupants” (p. 18). Fanger (2000) claims that the goal for IAQ is even less ambitious, with many official standards allowing for up to 30% of occupants to be dissatisfied. Is it too much to expect an educational environment capable of inspiring occupants and which, physiologically and psychologically, enhances their sense of well-being and preparedness to learn? Thankfully, Fanger believes that a paradigm shift is on the horizon, where excellent indoor environments will promote optimal health while enhancing occupant satisfaction and productivity. Surely this should be the goal, if not the standard, for any building assisting in the cultivation of our planet’s intellectual resources.

SEE Breeze

Notes

1 Schools in the US have a more immediate economic concern, with a significant proportion of government funding allocated according to student attendance. Some authors (eg Mendell & Heath, 2005) have pointed out that improved facilities are capable of reducing the rate of absenteeism, thus attracting funds which can then be used to further upgrade services and facilities.

2 A significant portion of this literature comes from a large-scale research programme carried out by The International Centre for Indoor Environment and Energy (ICIEE), who have since received funding to extend their research to IAQ in schools.

3 Contrary to popular opinion, ventilation has little to do with increasing oxygen levels. Oxygen is consumed at the rate of 0.36 L/minute per person for seated occupants (ASHRAE, 2001); significantly less than even the most impoverished ventilation rate. The dilution of CO_2 - which is produced much more quickly than oxygen is consumed - is of comparably greater concern.

References

Allenby, G. (2006, April 15). Toxin-eating plants can breathe new life into your home. *The Australian*, p. 106.

ASHRAE (2001). *Standard 62, Ventilation for acceptable indoor air quality.* Atlanta, GA: American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc.

Brundage, J. F., Scott, R. M., Lednar, W. M., Smith, D. W., & Miller, R. N. (1988). Building-associated risk of febrile acute respiratory diseases in army trainees. *Journal of the American Medical Association, 259,* 2108-2112.

Daisey, J. M., Angell, W. J., & Apte, M. G. (2003). Indoor air quality, ventilation and health symptoms in schools: An analysis of existing information. *Indoor Air*, 13, 53-64.

Darlington, A., Chan, M., Malloch, D., Pilger, C., & Dixon, M. A. (2000). The biofiltration of indoor air: Implications for air quality. *Indoor Air,* 10, 39-46.

De Kempeneer, L., Sercu, B., Vanbrabant, W., Van Langenhove, H., & Verstraete, W. (2004). Bioaugmentation of the phyllosphere for the removal of toluene from indoor air. *Applied Microbiology & Biotechnology,* 64, 284-288.

Dingle, P., Tapsell, P., & Hu, S. (2000). Reducing formaldehyde exposure in office environments using plants. *Bulletin of Environmental Contamination & Toxicology*, 64, 302.308.

Fanger, P. O. (2000). Indoor air quality in the 21st century: Search for excellence. *Indoor Air,* 10, 68-73.

Faustman, E. M., Silbernagel, S. M., Fenske, R. A., Burbacher, T. M., & Ponce, R. A. (2000). Mechanisms underlying children’s susceptibility to environmental toxicants. *Environmental Health Perspectives*, 108, 13-21.

SEE Breeze

References

Fisk, W. J. (2000). Health and productivity gains from better indoor environments and their relationship with building energy efficiency. *Annual Review of Energy & the Environment*, 25, 537-566.

Garrett, M. H., Hooper, M. A., Hooper, B. M., Rayment, P. R., & Abramson, M. J. (1999). Increased risk of allergy in children due to formaldehyde exposure in homes. *Allergy, 54*, 330-337.

Mølhave, L., Bach, B., & Federsen, O. F. (1986). Human reactions to low concentrations of volatile organic compounds. *Environmental International,* 12, 167-175.

Mendell, M. J., & Heath, G. A. (2005). Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. *Indoor Air,* 15, 27-52.

Menzies, D., Popa, J., Hanley, J. A., Rand, T., & Milton, D. K. (2003). Effect of ultra-violet germicidal lights installed in office ventilation systems on workers' health and well-being: Double blind multiple crossover study. *The Lancet,* 362, 1785-1791.

Olesen, B. W. (2004). International standards for the indoor environment. *Indoor Air, 14*, 18-26.

Orwell, R. L., Wood, R. L., Tarran, J., Torpy, F., & Burchett, M. D. (2004). Removal of benzene by the indoor plant/substrate microcosm and implications for air quality. *Water, Air, & Soil Pollution, 157,* 193-207.

Richards, W. (1986). Allergy, asthma, and school problems. *The Journal of School Health*, 56, 151-152.

Rylander, R., Persson, K., Goto, H., & Tanaka, S. (1992). Airborne beta-1,3-glucan may be related to symptoms in sick buildings. *Indoor Environment, 1,* 263-267.

Seppänen, O., & Fisk, W. J. (2004). Summary of human responses to ventilation. *Indoor Air, 14,* 102-118.

Seppänen, O., Fisk, W. J., & Lei, Q. H. (2006). Ventilation and performance in office work. *Indoor Air, 16,* 28-36.

Seppänen, O., Fisk, W. J., & Mendell, M. J. (1999). Association of ventilation rates and CO2-concentrations with health and other responses in commercial and institutional buildings. *Indoor Air, 9*, 252-274.

Shendell, D. G., Prill, R., Fisk, W. J., Apte, M. G., Blake, D., & Faulkner, D. (2004). Associations between classroom CO2 concentrations and student attendance in Washington and Idaho. *Indoor Air, 14,* 333-341.

Smith, A. P. (1990). Respiratory virus infections and performance. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 327,* 519-528.

Wargocki, P., Wyon, D. P., Sundell, J., Clausen, G., & Fanger, P. O. (2000). The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity. *Indoor Air, 10,* 222-236.

Wyon, D. P. (2004). The effects of indoor air quality on performance and productivity. *Indoor Air, 14,* 92-101.

Image credits
Green field: Craig Rogers