Providing indoor air of high quality: challenges and opportunities

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ABSTRACT

Comprehensive field studies in different parts of the world have documented that high percentages of occupants in many offices and similar buildings find the indoor air quality (IAQ) unacceptable and suffer from SBS symptoms. This occurs even though existing ventilation standards and guidelines are met and even though measured concentrations of pollutants in the air are way below any limits or guideline values. A series of recent independent studies has documented that mediocre IAQ also has a negative impact on the productivity of office workers. This provides a strong economic incentive to design for high IAQ in the future. A paradigm change is needed where we try to satisfy even the most sensitive persons in a space.

Compared to today's practice, this may require that we improve IAQ by several orders of magnitude. This paper will discuss how such a dramatic improvement can be realized without increasing ventilation. Four methods are suggested as means to reach this ambitious goal of satisfying all people. Applying these simultaneously may even allow for reduced ventilation and energy consumption. Sensory measurements are of prime importance in this endeavour.

INDEX TERMS

Healthy indoor air; Personal computers; Filters; Personalized ventilation; Productivity

INTRODUCTION

The World Health Organization has published a report 'The right to healthy indoor air' (WHO, 2000). But what *is* healthy indoor air? A natural starting point would be to use WHO's general definition of health which requires a state of complete well-being and not merely the absence of disease. On this basis, healthy indoor air may be defined as air that does not provide any risk of disease and that ensures well-being for *all* occupants.

This ideal requirement is far from that pertaining in practice in real buildings today. Numerous large field studies among thousands of occupants working in hundreds of commercial buildings in different parts of the world have documented substantial rates of Sick Building Syndrome (SBS) symptoms and dissatisfaction with the indoor environment in many buildings (Skov *et al.*, 1987; Mendell, 1993; Sundell, 1994; Bluyssen *et al.*, 1996; Lee *et al.*, 1999; Bishof *et al.*, 2003; Sekhar *et al.*, 2003; Skyberg *et al.*, 2003). This occurs even though existing ventilation standards and guidelines are met (CEN, 1998; ASHRAE, 2001) and even though measured pollutants are way below any limits or guideline values. One of the main reasons is that the requirements of existing standards and guidelines are quite low. The philosophy of these documents has been to establish an indoor air quality where less than a certain percentage (e.g. 15, 20 or 30%) of people are dissatisfied with the indoor air quality while the rest may find the IAQ barely acceptable. The philosophy of the standards behind the design of HVAC systems has in practice led to mediocre air with rather large numbers of dissatisfied persons, as predicted.

Important new information is that a series of independent studies has documented that mediocre indoor air quality also has a negative impact on the productivity of office workers.

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These studies, which will be reviewed in the present paper, show that it pays to provide high indoor air quality. They form a strong economic incentive to design for high indoor air quality in the future. We need a paradigm shift where we try to satisfy even the most sensitive persons, i.e. to provide healthy indoor air for all occupants in a space. Compared to today's practice, this may require that we improve IAQ by several orders of magnitude. This paper will discuss how such a dramatic improvement can be realized. Four methods are suggested as means to reach this ambitious goal without increasing ventilation. They may even allow for a simultaneous decrement in ventilation and energy consumption. Sensory measurements are of prime importance in this endeavour.

PRODUCTIVITY AND INDOOR AIR QUALITY

A series of recent independent studies document that the quality of indoor air has a significant and positive influence on the productivity of office workers. In one study, a well-controlled normal office (field lab) was used in which two different air qualities were established by including or excluding a commonly used carpet as an extra pollution source, invisible to the occupants (Wargocki *et al.*, 1999). The two cases corresponded to a low-polluting and a non-low-polluting building as specified in the European guidelines for the design of indoor environments (CEN, 1998). The same subjects worked for 4.5 h on simulated office work in each of the two air qualities. The productivity of the subjects was found to be 6.5% higher ($P < 0.003$) in good air quality and they also made fewer errors and experienced fewer SBS symptoms. This study performed in Denmark has later been repeated in Sweden with similar results (Wargocki *et al.*, 2002a). A third study was performed in the Danish field lab with the same pollution sources present at three different ventilation rates: 3, 10 and 30 l/s per person (Wargocki *et al.*, 2000a). The productivity increased significantly with increased ventilation. The three studies involving seven experimental conditions and 90 subjects have been analysed as a whole, relating productivity to perceived air quality (Wargocki *et al.*, 2000b). Results show a significant positive influence of high indoor air quality on productivity in offices.

In another blind study with a similar experimental set-up as the one described above, the air was polluted by 3-month-old personal computers as an extra pollution source (Bakó-Biró *et al.*, 2004). In this blind study the productivity was 9% lower ($P < 0.01$) when the extra computers were present and three times as many of the occupants were dissatisfied with the air quality. Each of the PCs polluted the air corresponding to 3 olf. This study was later extended to include the most common brands of PCs with CRT monitors and TFT (flat) screens (Wargocki *et al.*, 2003b). It showed results very similar to the previous study on sensory pollution and also showed that PCs with flat screens pollute much less.

The positive impact of high indoor air quality on productivity has recently been validated in a blind intervention study in the field in a call centre where the ventilation rate could be increased while particulate filters were either new or used (Wargocki *et al.*, 2003a). A significant positive effect of increased ventilation on productivity was documented but only when a new filter was used. It should be noted that in the field lab studies mentioned above showing a positive impact of ventilation on productivity, *no* filters were present. Federspiel *et al.* (2002) made also an intervention study in a call centre where ventilation rates were increased. Old used filters were present all the time in this study and may explain why the authors found only a marginal impact of increased ventilation on productivity. These studies indicate, as shown in several previous investigations, that particulate filters in the HVAC system can be a serious source of pollution (discussed further in the next section).

Providing high indoor air quality, compared with the mediocre air that is present in many existing office buildings worldwide, may increase productivity by an estimated 5–10%. An annual loss of this magnitude caused by mediocre indoor air quality will often be much higher than energy costs, capital costs and the cost of operating the building. Any life cycle cost analysis of office buildings should therefore include productivity losses caused by mediocre minimum IAQ prescribed by present standards. These losses will often be a dominating factor compared to all other costs related to the construction and operation of a building. It pays to provide high indoor air quality.

WHAT IS INDOOR AIR QUALITY?

When we want to provide indoor air of high quality it is of course essential to discuss what IAQ is and how it can be quantified. One indirect method often applied in standards is to use the outdoor ventilation rate or air change rate as an indicator of IAQ. This is often a poor indicator, however, since it does not take into account the indoor pollution sources. There may be poor IAQ in a space in spite of a high ventilation rate if the sources are strong. On the other hand, good IAQ may be achieved at a moderate ventilation rate if the sources are small. Using ventilation rate as a measure of IAQ is as primitive as it would be to relate human thermal comfort to the supply of cooling power to a space, rather than to the temperature in the space.

Another option is to express IAQ in chemical terms. We know that it is chemicals emitted from people, materials and processes that decrease the IAQ. Can we not just make sure that the concentration of each chemical in the air is below a certain guideline value? Unfortunately, this method does not work, the reason being that in non-industrial buildings there are typically hundreds or even thousands of chemicals in the air, each in very small concentrations, and we have only limited information on their impact on health and comfort. Guideline values are available for only a few dozen chemicals which only apply when they occur alone. How about odour or irritation thresholds that are available for a larger number of chemicals. The thresholds given in the literature vary considerably however, and provide information only on the concentration where 50% of people can perceive a specific chemical when it occurs alone. The most sensitive people may perceive the chemical at a concentration that is several orders of magnitude lower and may perceive a cocktail of hundreds of chemicals at even lower concentrations. Furthermore, some chemicals are perceived as very unpleasant while others may even be pleasant. A further obstacle is that many chemicals are difficult to measure at the very small concentrations where they still have a negative impact on people.

A third and obvious alternative is to use the human response directly to define IAQ. In general, quality is often defined as the extent to which human requirements are met. Using this definition, high indoor air quality would be air that is perceived as pleasant by all occupants and has no negative effects on health and productivity. To this end, sensory measurements using human panels have been used to evaluate IAQ already by Yaglou in the 1930s (Yaglou *et al.*, 1936) and were later used by Fanger (1988) to introduce sensory units: the perceived IAQ was expressed in decipol or % dissatisfied while the sensory pollution load was expressed in olf. Sensory measurements have often been shown to be superior to chemical measurements and they have formed for decades the basis for ventilation standards and guidelines (CEN, 1998; ASHRAE, 2001).

The following three recent examples show the superiority of sensory measurements:

The extra pollution source introduced in Wargocki *et al.*'s productivity study (1999) mentioned above was an old used common type of carpet that had a strong negative impact on perceived air quality, SBS symptoms and productivity, while the measured chemicals in the air emitted from the carpet occurred in very low and apparently harmless concentrations far below any limits of concern.

The same applied in the above-mentioned study on PCs (Wargocki *et al.*, 2003b; Bakó-Biró *et al.*, 2004). The air pollution from the PCs caused high dissatisfaction among people, SBS symptoms and a decrement in their productivity while the chemical measurements showed extremely low and apparently harmless concentrations in the air (Nakagawa *et al.*, 2003).

A third example is particle filters in HVAC systems. Fanger *et al.* (1988) documented already in the 1980s that the HVAC system could contain serious pollution sources that degraded the air quality even before the air reached the space to be ventilated. Later it was identified that it was especially the particle accumulation on the filter that had a negative impact on the perceived air quality (Pejtersen *et al.*, 1989; Clausen *et al.*, 2002a,b; Beko *et al.*, 2003). Still it has been extremely difficult to measure and identify individual chemicals being responsible for the poorly perceived air quality.

In the above examples, high percentages of people have been dissatisfied with the air quality due to widely differing pollution sources although the chemicals measured by conventional methods seem to be of no concern. In our future aim for much higher indoor air quality that can provide well-being even for the most sensitive persons, chemical concentrations in the air will be much lower. Human sensory measurements will, under these circumstances, be even more crucial. It does not mean that we should ignore indoor air chemistry. On the contrary, research in this area should continue and be intensified in parallel with sensory studies, so that we can better understand why indoor air is sometimes perceived as fresh and pleasant and in other cases as stale and stuffy. The chemistry of indoor air is often very complex, influenced by emissions, sorption and reactions, and it comprises often hundreds of chemicals in very low concentrations, including short-lived and stealth chemicals hard to measure (Weschler, 2003).

HOW TO PROVIDE HIGH INDOOR AIR QUALITY

The challenge is now to provide indoor air of high quality using sensory measurements. Our aim is to satisfy even very sensitive subjects. Most offices in practice have mediocre air quality with 20–60% dissatisfied.

Let us as an example consider a typical office with 40% dissatisfied. Our aim is to establish a much higher IAQ, where hardly any are dissatisfied, which for practical purposes may translate into 1% dissatisfied (see Table 1). Is such a dramatic improvement at all possible and if it is, how can it be accomplished? In the following sections, different methods that can contribute to this aim will be discussed and rough quantitative estimates will be given on how much each of these different methods can contribute to the ambitious goal of decreasing the dissatisfaction from 40 to 1%. These are the methods to be discussed:

- increased ventilation,
- source control,
- air cleaning,
- personalized ventilation,
- cool and dry air.

Table 1 Mediocre and high IAQ (Fanger, 1988)

	% dissatisfied	dp	Required ventilation rate, l/s·olf
Mediocre IAQ	40	4.1	2.5
High IAQ	1	0.1	100

Increased Ventilation

One method of improving the IAQ is to increase the ventilation. A 40% dissatisfaction corresponds to approximately 4 dp or a ventilation rate of 2.5 l/s olf (see Table 1). Let us assume a sensory pollution load in this typical office to be as given in Table 2, each office worker contributing one olf; the corresponding building is a non-low-polluting building, which provides 0.2 olf/m^2 floor (CEN, 1998) which with 15 m^2 floor per person contributes 3 olf. A PC less than 1-year old provides 1 olf. This provides a total sensory load of 5 olf per person. The actual ventilation rate in the building may therefore be 5 × 2.5 = 12 l/s per person. To reach 1% dissatisfied, which corresponds to 0.1 dp, would require a ventilation rate of 100 l/s per olf or an enormous rate of 500 l/s per person.

This estimation assumes that the sources are constant in the building and its HVAC system, which is not true. We know, for instance, that the emission or pollution from used traditional particle filters increases proportionally with airflow through the filter. With a normal used filter, increased ventilation has therefore only a marginal positive impact on perceived air quality. Even with a clean filter, ventilation would require an enormous rate if this method alone should let us reach our goal. Such a high rate would of course be prohibitive due to cost and energy use.

Table 2 Total sensory pollution load per person in a typical existing and in a new low-polluting building

Pollution source	Existing non-low-polluting building (0.2 olf/m^2), olf	New low-polluting building (0.02 olf/ m^2), olf
One office worker	1	1
Building, 15 m^2 floor per person	3	0.3
One PC (average during first year)	1	0
Total sensory pollution load	5	1.3

Other methods should therefore first be considered and they may even allow a high IAQ at a decreased ventilation rate to the benefit of cost and energy use.

Source Control

An obvious preferred method to improve IAQ is to reduce pollution sources in the building, including the HVAC system. There are three pollution sources that are of special concern: particle filters, building materials (including carpets) and PCs.

Particle filters are particularly serious since the air quality is degraded even before it is supplied to the ventilated space. Furthermore, increased ventilation, i.e. a higher airflow through the filter, increases, as mentioned previously, the emission of pollutants from the particles in the filter so that the air quality downstream of the filter does not improve (Alm *et al.*, 2000; Strøm-Tejsen *et al.*, 2003). This may help explain why increased ventilation in mechanically ventilated spaces in some cases improves IAQ only slightly or not at all. It may also explain why, in some cases, the air quality in mechanically ventilated or even air-conditioned buildings has been found to be worse than in naturally ventilated buildings (during winter). It is therefore recommended that traditional particle filters in HVAC systems should be changed very frequently or better, substituted by alternative equipment that can remove particles from the air to protect the HVAC system without accumulating the polluting dust in the airflow. R&D is obviously required.

The second source of pollution is building materials, including carpets. It is suggested that carpets in general should be avoided unless they have been very carefully tested. It is suggested that requirements for carpets and other materials in the future should be much higher than those specified at present by various recommendations and labelling criteria. Strict sensory requirements should be included in testing of materials.

Following the above recommendations for filters, materials and carpets, it is suggested that a realistic goal for the sensory load for low-polluting buildings that at present is 0.1 olf/m^2 floor in the building (CEN, 1998) be lowered to 0.02 olf/m^2 floor.

A third important pollution source is common brands of PCs with CRT screens. They pollute 3 olf in the beginning with an average of more than 1 olf during the first year. It is recommended to stop buying the common brands of PCs with CRT screens and instead purchase low-polluting PCs and use TFT (flat screens) that generate only a negligible pollution. Since a PC generation lasts only 3 years and the pollution decreases with a half-life of 4 months, the load from the existing stock of PCs would quickly decrease if the above recommendation is followed.

Following the above recommendations for source control, the total sensory pollution load in an office could be reduced as shown in Table 2, from 5 to 1.3 olf/person or by a factor of 4.

Air Cleaning

Cleaning of indoor air from gaseous pollutants is a method with a promising potential for improving IAQ and partly substituting ventilation. Different methods including sorption and photocatalysis are applied. The latter method has shown to provide interesting filtering efficiencies documented in relation to individual chemicals in the air (Zhao and Yang, 2003). For the typical cocktail of hundreds of chemicals occurring indoors in very low concentrations, a cleaning efficiency of above 80% may be feasible, i.e. air cleaning may decrease concentrations and improve IAQ by a factor of 5. But further R&D of the technology is obviously needed and studies to demonstrate cleaning efficiencies on perceived IAQ for typical indoor pollution sources are recommended.

Personalized Ventilation

In our example, 12 l/s per person of outdoor air is supplied to the office. Of this air, only 0.1 l/s per person, or 1%, is inhaled. The rest, i.e. 99% of the supplied air, is not used. What a huge waste! And the 1% of the ventilation air being inhaled is not even clean. It is polluted by bioeffluents, building materials and PCs in the space.

According to traditional engineering practice, full mixing of clean supply air and pollutants in the room air seems to be an ideal. What is needed in the future are systems that supply rather small quantities of clean air direct to the breathing zone of each individual. The idea is to serve to each occupant, clean air that is as unpolluted as possible by the pollution sources in the space. In an office, this personalized ventilation may be provided from an individual movable outlet on a desk (Figure 1). Under ideal conditions, each person can inhale clean air from the core of the jet where the air is unmixed with polluted room air and has a low velocity and turbulence which do not cause draught. Such systems are now being developed and studied (Kaczmarzyk *et al.*, 2002; Melikov *et al.*, 2002; Bolashikov *et al.*, 2003). Based on these studies, it seems realistic that a properly developed outlet may reach a ventilation effectiveness as high as 10 or more, i.e. personalized ventilation may increase the quality of the inhaled air by one order of magnitude. An essential feature is that each person has easy control over the position of the outlet, of the flow and even of the temperature of the supply air.

Figure 1 The principle of personalized ventilation: small amounts of cool, dry and clean air should be supplied directly and gently to a person's breathing zone and be easily controllable by the individual.

Cool and Dry Air

Comprehensive studies by Fang *et al.* (1998a,b, 1999) and Toftum *et al.* (1998) have shown that perceived air quality is also influenced by the humidity and temperature of the air we inhale. People prefer rather dry and cool air. They like a sensation of cooling of the respiratory tract each time air is inhaled. This causes a sensation of freshness which is felt pleasant. A high enthalpy of the air means a low cooling power of the inhaled air and therefore an insufficient convective and evaporative cooling of the respiratory tract, and in particular the nose. This lack of proper cooling is closely related to poorly perceived air quality.

Fang's studies indicate that decreasing the air temperature 2–3 K, e.g. from 23–24°C to 21°C may improve the perceived IAQ by a factor of two. Decreased humidity has also a beneficial effect on perceived IAQ down to 20% RH. Below that, dry air may have negative effects on eye blinking rate and productivity (Wyon *et al.*, 2002; Fang *et al.*, 2003).

Combined Effect of all Methods

What happens if we simultaneously use all methods to improve the IAQ? Compared to the typical reference office at 23–24°C with 40% dissatisfied and a ventilation rate of 12 l/s per person, we may by source control, air cleaning and personalized ventilation, decrease the pollutant concentration and the perceived IAQ by a factor of $4 \times 5 \times 10 = 200$, without increasing the ventilation rate. These rough estimates assume that the outdoor air is clean.

By decreasing temperature (and humidity), we may furthermore improve perceived IAQ by a factor of two, i.e. to a level 400 times better than the reference. This is even ten times better than our ambition of 1% dissatisfied (0.1 dp) and may leave room for simultaneous energy savings by reduced ventilation.

CONCLUSIONS AND RECOMMENDATIONS

The indoor air quality in many offices and similar buildings is rather mediocre and gives rise to high percentages of dissatisfied persons as well as SBS symptoms, even though present standards and guidelines are met. Recent studies document that mediocre IAQ also decreases productivity. This will be a strong incentive to search for high IAQ, i.e. truly healthy air, satisfying even the most sensitive persons. The following methods are recommended to meet this ambitious goal:

- Avoid unnecessary pollution sources:
  - Particle filters in HVAC systems are a serious pollution source. They need to be changed frequently or substituted by new technology.
  - Personal computers with CRT screens are a serious pollution source, at least during the first year of operation. When purchasing new PCs, select TFT (flat) screens.
  - Low-polluting building materials should be selected based on much stricter criteria than hitherto. Avoid carpets.
- Cleaning the air of gaseous pollutants is a promising technology that needs to be further developed as an alternative or supplement to ventilation.
- Small amounts of clean air should be offered where it is consumed, i.e. as personalized ventilation close to the breathing zone of each person and easily controllable by the individual.
- The air should preferably be offered rather cool and dry.

Applying these four methods has the potential of increasing the quality of the air we breathe by several orders of magnitude, i.e. of satisfying all persons while maintaining the same or even a lower ventilation rate and energy consumption.

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REFERENCES

Alm, O., Clausen, G. and Fanger, P.O. (2000). Exposure-response relationships for emissions from used ventilation filters. *Proceedings of Healthy Buildings 2000*, Vol. 2, pp. 245–250.

ASHRAE Standard 62-2001 (2001). *Ventilation for Acceptable Indoor Air Quality*. Atlanta, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Bakó-Biró, Z., Wargocki, P., Weschler, C. and Fanger, P.O. (2004). Effects of pollution from personal computers on perceived air quality, SBS symptoms and productivity in offices. *Indoor Air* (accepted).

Beko, G., Halás, O., Clausen, G., Toftum, J. and Weschler, C.J. (2003). Initial studies of oxidation processes on filter surfaces and their impact on perceived air quality. *Proceedings of Healthy Buildings 2003*.

Bischof, W., Bullinger, M., Kruppa, B., Müller, B.H. and Schwab, R. (2003). Expositionen und gesundheitliche Beeinträchtigungen in Bürogebäuden—Ergebnisse des ProKlimA-Projektes. Stuttgart: Fraunhofer IRB Verlag (in press).

Bluyssen, P.M., de Oliveira Fernandes, E., Groes, L., Clausen, G., Fanger, P.O., Valbjørn, O., Bernhard, C.A. and Roulet C.A. (1996). European indoor air quality audit project in 56 office buildings. *Indoor Air* **6**, 221–238.

Bolashikov, Z., Nikolaev, L., Melikov, A., Kaczmarczyk, J. and Fanger, P.O. (2003). New for terminal devices with high efficiency for personalized ventilation application. *Proceedings of Healthy Buildings 2003*.

CEN (1998). *Ventilation for Buildings: Design Criteria for the Indoor Environment*. Brussels: European Committee for Standardization (CR 1752).

Clausen, G., Alm, O. and Fanger, P.O. (2002a). The impact of air pollution from used ventilation filters on human comfort and health. *Proceedings of Indoor Air 2002*, Monterey, Vol. 1, pp. 338–343.

Clausen, G., Alm, O. and Fanger, P.O. (2002b). Sensory source strength of used ventilation filters. *Proceedings of Indoor Air 2002*, Monterey, Vol. 1, pp. 344–349.

Fang, L, Clausen, G. and Fanger, P.O. (1998a). Impact of temperature and humidity on perception of indoor air quality during immediate and longer whole-body exposure. *Indoor Air* **8** (4), 276–284.

Fang, L., Clausen, G. and Fanger, P.O. (1998b). Impact of temperature and humidity on the perception of indoor air quality. *Indoor Air* **8** (2), 80–90.

Fang, L., Wargocki, P., Witterseh, T., Clausen, G. and Fanger, P.O. (1999). Field study on the impact of temperature, humidity and ventilation on perceived air quality. *Proceedings of Indoor Air '99*, Vol. 2, pp. 107–112.

Fang, L., Wyon, D. and Fanger, P.O. (2003). Sick building syndrome symptoms caused by low humidity. *Proceedings of Healthy Buildings 2003*.

Fanger, P.O. (1988). Introduction of the olf and decipol units to quantify air pollution perceived by humans indoors and outdoors. *Energy and Buildings* **12**, 1–6.

Fanger, P.O., Lauridsen, J., Bluyssen, P. and Clausen, G. (1988). Air pollution sources in offices and assembly halls, quantified by the olf unit. *Energy and Buildings* **129**, 7–19.

Federspiel, C.C., Liu, G., Lahiff, M. *et al.* (2002). Worker performance and ventilation: analyses of individual data for call-center workers. *Proceedings of Indoor Air 2002*, Monterey, USA, Vol. 1, pp. 796–801.

Kaczmarczyk, J., Zeng, Q., Melikov, A. and Fanger, P.O. (2002). The effect of a personalized ventilation system on air quality perception, SBS symptoms and occupant's performance. *Proceedings of Indoor Air 2002*, Monterey, CA, Vol. 4, pp. 1042–1047.

Lee, S.C., Chan, L.Y. and Chiu, M.Y. (1999). Indoor and outdoor air quality investigation at 14 public places in Hong Kong, *Environment International* **25**, 443–450.

Mendell, M.J. (1993). Non-specific symptoms in office workers: a review and summary of the epidemiologic literature. *Indoor Air* **3**, 227–236.

Melikov, A.K., Cermak, R. and Mayer, M. (2002). Personalized ventilation: evaluation of different air terminal devices, *Energy and Buildings* **34**, 829–836.

Nakagawa, T., Wargocki, P., Tanabe, S., Weschler, C.J., Baginska, S., Bakó-Biró, Z. and Fanger, P.O. (2003). Chemical emission rates from personal computers. *Proceedings of Healthy Buildings 2003*.

Pejtersen, J., Bluyssen, P., Kondo, H., Clausen, G. and Fanger, P.O. (1989). Air pollution sources in ventilation systems. *Proceedings of CLIMA 2000*, Sarajevo, Vol. 3, pp. 139–144.

Sekhar, S.C., Tham, K.W. and Cheong, K.W. (2003). Indoor air quality and energy performance of air-conditioned office buildings in Singapore, *Indoor Air* (in press).

Skov, P., Valbjørn, O. and DISG (1987). The sick building syndrome in the office environment: the Danish Town Hall study. *Environment International* **13**, 339–349.

Skyberg, K., Skulberg, K.R., Eduard, W., Skåret, E., Levy, F. and Kjuus, H. (2003). Symptoms prevalence among office employees and associations to building characteristics. *Indoor Air* **13**, 246–252.

Strøm-Tejsen, P., Clausen, G. and Toftum, J. (2003). Sensory pollution load from a used ventilation filter at different airflow rates. *Proceedings of Healthy Buildings 2003*.

Sundell, J. (1994). On the association between building ventilation characteristics, some indoor environmental exposures, some allergic manifestations and subjective symptom reports. *Indoor Air*, Supplement No. 2.

Toftum, J., Jørgensen, A.S. and Fanger, P.O. (1998). Upper limits for air humidity to prevent warm respiratory discomfort. *Energy and Buildings* **28** (1), 15–23.

Wargocki, P., Wyon, D.P., Baik, Y.K., Clausen, G. and Fanger, P.O. (1999). Perceived air quality, sick building syndrome (SBS) symptoms and productivity in an office with two different pollution loads. *Indoor Air* **9** (3), 165–179.

Wargocki, P., Wyon, D.P., Sundell, J., Clausen, G. and Fanger, P.O. (2000a). The effects of outdoor air supply rate in an office on perceived air quality, Sick Building Syndrome (SBS) symptoms and productivity. *Indoor Air* **10** (4), 222–236.

Wargocki, P., Wyon, D.P. and Fanger, P.O. (2000b). Productivity is affected by the air quality in offices. *Proceedings of Healthy Buildings 2000*, Vol. 1, pp. 635–640.

Wargocki, P., Lagercrantz, L., Witterseh, T., Sundell, J., Wyon, D.P. and Fanger, P.O. (2002a). Subjective perceptions, symptom intensity and performance: a comparison of two independent studies, both changing similarly the pollution load in an office. *Indoor Air* **12**, 74–80.

Wargocki, P., Wyon, D.P. and Fanger, P.O. (2002b). Pollution source control and ventilation improve health, comfort and productivity. *Proceedings of Cold Climate HVAC 2000*, Sapporo, pp. 445–450.

Wargocki, P., Wyon, D.P. and Fanger, P.O. (2003a). Call-centre operator performance with new and used filters at two outdoor air supply rates. *Proceedings of Healthy Buildings 2003*.

Wargocki, P., Bakó-Biró, Z., Baginska, S., Nakagawa, T., Fanger, P.O., Weschler, C. and Tanabe, S. (2003b). Sensory emission rates from personal computers and television sets. *Proceedings of Healthy Buildings 2003*.

Weschler, C.J. (2003). Indoor/outdoor connections exemplified by processes that depend on an organic compound's saturation vapor pressure. *Atmospheric Environment* **37** (accepted).

World Health Organization (2000). The right to healthy indoor air, Copenhagen, Regional Office for Europe, Report on a meeting, Bilthoven, 15–17 May 2000 (EUR/00/5020494).

Wyon, D.P., Fang, L., Meyer, H.W., Sundell, J., Weirsøe, C.G., Sederberg-Olsen, N., Tsutsumi, H., Agner, T. and Fanger, P.O. (2002). Limiting criteria for human exposure to low humidity indoors. *Proceedings of Indoor Air 2002*, Monterey, Vol. 4, pp. 400–405.

Yaglou, C.P., Riley, E.C. and Coggins, D.I. (1936). Ventilation requirements. *ASHRAE Transactions* **42**, 133–162.

Zhao, J. and Yang, X. (2003). Photocatalytic oxidation for indoor air purification: a literature review. *Building and Environment* **38**, 645–654.