IMPROVING INDOOR AIR QUALITY IMPROVES THE PERFORMANCE OF OFFICE WORK AND SCHOOLWORK

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ABSTRACT

Recent studies show that improving indoor air quality (IAQ) from the mediocre level prevalent in many buildings worldwide improves the performance of office work by adults and the performance of schoolwork by children. These results constitute a strong incentive for providing indoor air of a quality that is better than the minimum levels required by present standards. IAQ can be improved by reducing the pollution load on the air by selecting low-polluting building and furnishing materials and electronic office equipment, as well as reducing pollution in ventilation systems, and/or by increasing the outdoor air supply rate. Although these measures can increase somewhat the costs of running the buildings, especially as regards energy costs, they are highly cost-effective and their implementation has a short pay-back time if the benefits from increased productivity are included in calculations. This is because the economic benefits from improved productivity exceed considerably the costs involved. New intelligent design of the building envelope and the ventilation systems with careful selection of building and furnishing materials, and the use of advanced methods for cleaning the air can further reduce the costs of providing high IAQ in future buildings. This will not only improve productivity and learning, but will in addition promote health and comfort.

KEYWORDS

Indoor air quality; Performance; Office work; Schoolwork; Life-cycle costs

INTRODUCTION

It is well documented that thermal conditions within the thermal comfort zone can reduce performance by 5% to 15% (Wyon and Wargocki 2006a), but until now little has been known as regards direct effects of the air quality on human performance in offices (Wyon 1996) and schools (Mendell and Heath 2005). Recent laboratory and field studies provide new information on the effects of indoor air quality (IAQ) on the performance of office work by adults (Wyon and Wargocki 2006b) and schoolwork by children (Wargocki and Wyon 2006,2007a,2007b, Wargocki et al. 2007). The objective of the present paper is to summarize the results obtained in these experiments, to discuss their economic implications, and to suggest possible mechanisms of the observed effects.

THE EFFECTS OF IAQ ON THE PERFORMANCE OF OFFICE WORK

Laboratory experiments

In three independent field intervention experiments, the air quality in normal offices was altered while the health, comfort and productivity of the occupants were measured (Wargocki et al. 1999, 2000, 2002). Air quality was altered by: (1) decreasing the pollution load (by physically removing a pollution source), always maintaining an outdoor air supply rate of 10 L/s per person with six subjects present, which was the intervention used in offices situated in two different countries (Wargocki et al. 1999, 2002); or (2) by increasing the outdoor air supply rate from 3 to 10 or to 30 L/s per person with six subjects present, thus producing air change rates of 0.6, 2 or 6 per hour in one of these offices, with the same pollution sources always present (Wargocki et al. 2000). A major pollution source in all three studies was the same 20-year-old carpet, present behind a screen in a quantity corresponding to the floor area of the office in which each exposure took place, but the rather innocuous building, floor and furnishing materials, and the bioeffluents emitted by the subjects themselves were of course always present. Temperature, relative humidity, air velocity and noise level were kept constant, independent of the intervention. Ninety female subjects were exposed to different levels of air quality, 30 in each study. They could not see whether the source was present or perceive changes in noise level or air velocity when the ventilation rate was changed, and they remained thermally neutral by adjusting their clothing. In all three studies, subjects performed simulated office work during 4.5-hour exposures to different air

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quality levels and assessed the perceived air quality and the intensity of their Sick Building Syndrome (SBS) symptoms, in a repeated-measures design balanced for order of presentation. Simulated office work comprised text typing, proof-reading, addition and creative thinking, all being typical office tasks. The perceived air quality in the offices was assessed by asking the subjects to rate the acceptability of the air quality upon entering the office prior to and after the exposure. The intensity of a comprehensive list of specific and general SBS symptoms was indicated by the subjects at intervals throughout each exposure by marking visual-analogue (VA) scales.

Removing a pollution source from a space or increasing the ventilation rate significantly improved perceived air quality and the performance of simulated office work. Based on these data, the quantitative relationship was derived showing a 1.1% increase in performance of office work for every 10% reduction in the proportion of people dissatisfied with the air quality, in the range 25-70% dissatisfied (Figure 1).

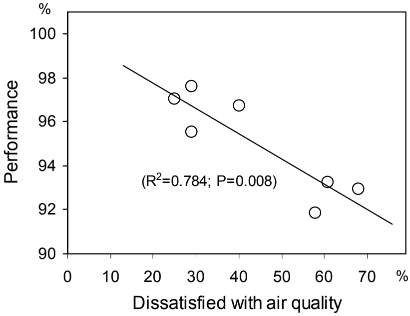

Figure 1. Performance of office work as a function of % dissatisfied with IAQ

The results of three experiments described above were obtained only for one type of indoor pollution source, namely a used 20-year old carpet. Two additional studies were consequently carried out, each with 30 subjects and each with the experimental protocol similar to that used in the three studies described above. Their purpose was to examine whether effects on work performance can be replicated when the air quality is improved by removing other types of indoor pollution sources: a mixture of a 3-year old linoleum, a 2-month old sealant and shelves with books and papers from the office ventilated at an outdoor rate of 5 L/s per person where six subjects were present at a time (Bakó-Biró 2004); and six 3-month old personal computers with cathode-ray-tube (CRT) monitors from the office ventilated at an outdoor air rate of 10 L/s per person, where six subjects were present at a time (Bakó-Biró et al. 2004). In the study of Bakó-Biró (2004) the performance of text typing increased by 1.5% when the mixture of pollution sources was removed and the percentage dissatisfied with the air quality was reduced from 42% to 28%. In the study of Bakó-Biró et al. (2004), the performance of text typing increased by 1.2% when PCs were removed and the percentage dissatisfied with the air quality was reduced from 32% to 15%. In both studies the degree of improvement of performance of office work was similar to the effects estimated using the relationship depicted in Figure 1. Thus, the results of these two experiments support the results obtained by Wargocki et al. (1999, 2000, 2002) and extend their applicability for indoor environments polluted by typical indoor sources.

Field experiments

The effects on performance observed in laboratory experiments with female subjects performing simulated office work in exposures lasting 4.6 hours, in a test chamber resembling a real office, required validation in actual office buildings with office employees performing real work and repeatedly exposed in their normal office environment for a full day at a time, 5 days a week. Two field studies pursued this issue (Tham 2004, Wargocki et al. 2004). In these studies work performed by operators in call centres was measured. Call-centres were selected because the work performed by operators, unlike almost all other types of office work, is routinely timed with great accuracy and constitutes a good paradigm for many other kinds of multitasking. Wargocki et al. (2004) conducted a 2x2 replicated field intervention experiment in a call-centre providing a national public telephone directory service: the outdoor air supply rate was adjusted to be 8% or 80% of the total airflow of 430 L/s (3.5 h^{-1}); and the supply air filters, serving both the outdoor and recirculated air, were either new or had been in place for 6 months. One of these independent variables was changed each week for 8 weeks. The 26 operators were blind to conditions. Room temperature and relative humidity averaged 24°C and 27%, and were fairly constant throughout the entire study. Increasing the outdoor air supply rate caused performance to significantly increase as indicated by reduced average talk-time with a new filter and to significantly decrease with a used filter, so that talk-time was about 10% lower with a new filter than with a used filter at a high outdoor air supply rate (Figure 2).

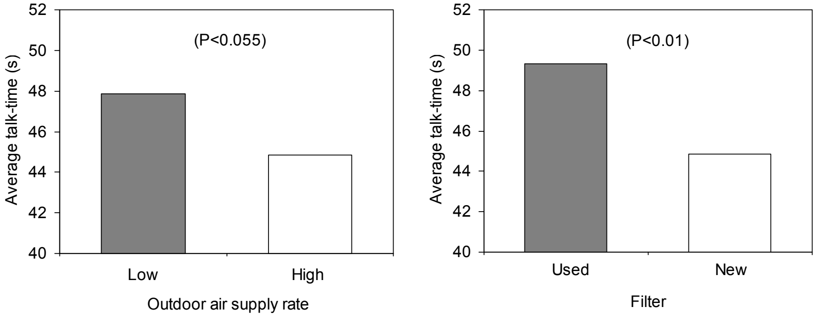

Figure 2. Average talk time as a function of outdoor air supply rate with new filter and filter age at high outdoor air supply rate

The study by Wargocki et al. (2004) was carried out in a mechanically ventilated call-centre located in a moderate climate. Tham (2004) conducted his experiment in an air-conditioned call-centre with electrostatic filters in a tropical climate to examine whether the results can be replicated in this part of the world. He used a study design and experimental protocol similar to that of Wargocki et al. (2004). The two interventions implemented included reduced air temperatures, from 24.5°C to 22.5°C, and an increased outdoor air supply rate, from 10 to 23 L/s per person. At the higher temperature, the increased outdoor air supply rate significantly improved the performance of call centre operators by 8.8%, thus confirming the findings obtained in a call-centre located in a moderate climate.

The effect of air quality on performance in the two field experiments described above was 5% to 10%. The size of this effect is similar to that observed in the laboratory simulation experiments. The results of field studies provide thus field validation of predictions based on laboratory experiments showing that improved IAQ improves the performance of office work. They extend the applicability of laboratory findings to actual workplaces in which normal office workers perform real work.

Economic implications

To examine whether the positive effects of improved IAQ on work performance observed in laboratory and field experiments described above are economically justified, life-cycle costs of investments for improving air quality in an office building were compared with the resulting revenues from increased office productivity; benefits from reduced health costs and sickness absence were not included (Wargocki and Djukanovic 2005). The costs of improving IAQ were simulated in a 11,581 m^2 non-low-polluting office building (CEN CR 1752 1998) with 864 employees, ventilated by a constant air volume system with heat recovery, and located in a cold, a moderate and a hot climate. It was assumed that the air quality in the building caused 50% dissatisfied. The air quality was improved by increasing the outdoor air supply rate, from 6 to 60 L/s per person, and by reducing the pollution loads from 0.2 to 0.1 olf/m^2floor to reduce the percentage of dissatisfied to 10%. The change in air quality was assumed to be the only parameter that influenced work performance. Other factors such as noise and thermal conditions were supposed to be constant and were not considered in the simulation. The upgrades to IAQ involved increased energy and maintenance costs, first costs of a HVAC system and building construction costs. These costs were compared with the increase in office productivity predicted using the experimental relationship showing a 1.1% increase in performance of office work for each 10% decrease in the percentage dissatisfied with the air quality upon entering a space (Figure 1), corresponding to an annual economic benefit of $368.75 per person, assuming a salary of $19.4/hour per person. The calculated costs and revenues were used to perform life-cycle cost analysis: the life-time of the building was set at 25 years and the real discount rate at 3.2%.

The analysis showed that improving IAQ is highly efficient: the benefits from improved IAQ can be up to 60 times higher than investments; the investments can generally be recovered in no more than 2 years (Figure 3), the pay-back times are similar to the pay-back of 1.4 years suggested by Dorgan et al. (1998); and the rate of return can be up to 7 times higher than the minimum acceptable interest rate.

Similar economic benefits were obtained in cold and in hot climates, because the benefits from improved productivity become a dominant factor in the life-cycle cost analysis and considerably exceed the increased investment costs. The estimates do not include benefits resulting from reduced health costs and reduced absenteeism; lower absenteeism from an increased outdoor air supply rate can result in additional annual savings of $400 per employee (Milton et al. 2000). The above estimates imply that improving IAQ from the “mediocre” level (50% dissatisfied) to the “excellent” level (10% dissatisfied) will, e.g., in a small-size office building with 100 employees, result in an annual revenue of approx. $100,000 over a period of 25 years. It is expected that they can be applied generally to most countries of the developed world even though they were obtained by carrying out simulations and depend upon the set of assumptions used in the simulations.

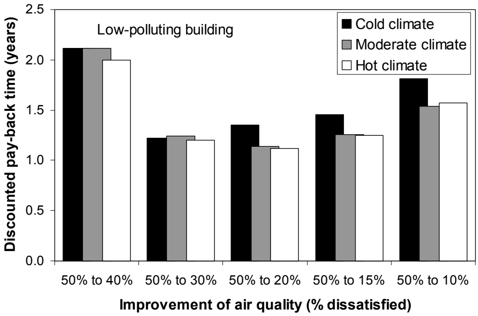

Figure 3. Discounted pay-back time of investments for improving IAQ in a low-polluting building

THE EFFECTS OF IAQ ON PERFORMANCE OF SCHOOLWORK

The effects of increasing the outdoor air supply rate

In three independent field intervention experiments carried out in late summer and in winter in four identical classrooms in an elementary school in Denmark, the classroom air quality was improved by increasing the outdoor air supply rate from about 3 to 10 L/s per person (Wargocki and Wyon 2006, 2007a,2007b). The outdoor air supply rate was increased using the existing mechanical ventilation. The interventions were implemented in a cross-over design balanced for order of presentation. Each experiment was carried out in two parallel classrooms at a time and each condition lasted for a week. For each condition, tasks representing up to eight different aspects of schoolwork, from reading to mathematics, were performed by 10 to 12-year-old children. The tasks were selected so that they could have been a natural part of an ordinary school day. The tasks were presented to children by their teachers at fairly regular intervals throughout each experimental week, according to the lesson timetable, and each task lasted no more than 10 min. At the end of each week the pupils assessed the environmental conditions in the classrooms and the intensity of any health-related symptoms. Both teachers and pupils were blind to interventions. During experiments, the teachers and pupils were allowed to open the windows as usual, and no changes to the lesson plan or normal school activities at school were made, so as to ensure that the teaching environment and daily routines remained as normal as possible. In each condition a sensory panel assessed the air quality in classrooms after the lessons had ended and children had left the classrooms, so as to avoid any disturbance of school activities.

The results of the experiments show that an increased outdoor air supply rate significantly improved the performance of many tasks, mainly in terms of how quickly each pupil performed the task. The pupils indicated that the air was significantly fresher in classrooms when the outdoor air supply rate was increased. The latter was confirmed by the sensory panel assessments of air quality in classrooms without children, indicating that IAQ was improved. Symptoms were in general unaffected. Using the performance of individual tasks, a relationship was established between the performance of schoolwork and classroom ventilation (Figure 4). The relationship suggests that doubling the outdoor air supply rate would improve the performance of schoolwork in terms of speed by about 8%; if data only from those tasks in which performance was significantly affected by the interventions were used to establish the relationship, doubling the outdoor air supply rate would improve the performance of schoolwork in terms of speed by about 14%. Increasing the outdoor air supply rate would not have a measurable effect on the performance of schoolwork in terms of % errors.

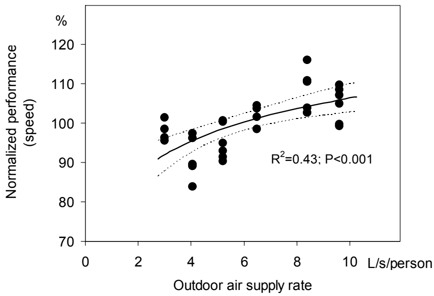

Figure 4. Performance of school work as a function of the outdoor air supply rate

The results of these three experiments indicate that improving IAQ in classrooms by increasing the outdoor air supply rate can substantially improve the performance of a wide range of tasks characteristic of schoolwork, from rule-based logical and mathematical tasks requiring concentration and logical thinking to language-based tasks requiring concentration and comprehension. The magnitude of the effects on performance of schoolwork is greater than for the performance of office work by adults, probably because children are more susceptible to environmental conditions and because schoolwork is not quantified in monetary terms, adults being able for some time to overcome any negative effects of indoor environmental conditions in order to meet deadlines, to complete projects, to follow orders, etc. The results clearly demonstrate that classroom air quality is a very important factor in the learning process and should, together with teaching materials and methods, become an urgent educational priority. Until now, however, classroom air quality has been neglected and was often much worse in classrooms than in the offices where adults work (Daisey et al. 2003).

The effects of removing particles by electrostatic particle filtration

Two independent field intervention experiments were carried out in winter and early spring in 5 pairs of mechanically-ventilated classrooms receiving 100% outdoor air, each pair in a different school (1 school in Denmark and 4 schools in Sweden), involving a total of about 190 pupils (Wargocki et al. 2007). Electrostatic air cleaners were installed in classrooms and either operated or disabled to modify particle concentration in classrooms, while the performance of schoolwork was measured. The conditions were established for one week at a time in a blind crossover design with repeated measures on 10-12 year-old children. Pupils performed six exercises exemplifying different aspects of schoolwork (numerical or language-based) as part of normal lessons and marked VA-scales to indicate their environmental perceptions and the intensity of any symptoms, similar to the protocol in the experiments described above in which the outdoor air supply rate was modified (Wargocki and Wyon 2006). The experiments were performed outside the pollen season, to eliminate any influence of this factor.

Operating the electrostatic air cleaners considerably reduced the concentration of particles in the classrooms, the effect being greater the lower the outdoor air supply rate, but there were no consistent effects of this reduction on the performance of a wide range of tasks selected as being characteristic of schoolwork, from typical rule-based logical and mathematical tasks requiring concentration and logical thinking to language-based tasks requiring concentration and comprehension, as well as on the environmental perceptions and on the symptoms reported by pupils. The results suggest thus that there are no short-term (acute) effects of particle removal outside the pollen season. Similarly, no consistent effects of operating electrostatic air cleaners on the performance of schoolwork were observed in another study, this time carried out in the pollen season (Mattsson and Hygge 2005) in which the electrostatic air cleaners were also operated for one week at a time but the performance was measured using psychological tests examining cognitive skills.

These results tend to support the findings of a major review of the literature on the health effects of particles in indoor air (EUROPART) which recently concluded that in the 1725 relevant publications there was “inadequate scientific evidence that airborne indoor particulate mass or number of concentrations can be used as generally applicable risk indicators of health effects in non-industrial buildings” (Schneider et al. 2003). This conclusion was derived in spite of the reliable epidemiological evidence showing that the particles found in outdoor air do have negative health effects for both adults and children (e.g., Ward and Ayres 2004, Dominici et al. 2006). Consequently it still remains unclear whether respirable particles in indoor air have negative effects on health and work performance although it is likely that the long-term operation of electrostatic air cleaners will provide health benefits for allergic or asthmatic children. This issue could not be investigated in the experiments of Wargocki et al. (2007) because the electrostatic air cleaners were operated only for one week, no measurements of allergens were made in the classrooms and no information was available on how many children in the study were allergic and possibly sensitive to the presence of allergens.

Economic implications

It is difficult to express the observed effects on the performance of schoolwork in monetary terms. The results imply, however, that improving IAQ in schools will lead to more time for learning and leisure, and that more and more difficult schoolwork can be performed. This is especially the case for those children who find schoolwork to be difficult and are unable to exert the additional effort that enables them to overcome poor working conditions in schools. Even in their case, the additional effort could be better used in performing more, and more difficult, schoolwork than in overcoming poor air quality. For both categories of child, therefore, high IAQ would make the process of educating children more efficient, and could therefore have a large and positive effect on the international competitiveness of the workforce and hence on the national economy. Considering that the highest ventilation rate studied in the experiments was close to the minimum ventilation rate recommended for adult workplaces, the results suggest that simply upgrading ventilation requirements for schools to the minimum required for offices would provide a very good return on investment in terms of the future achievements of any society that depends upon the educational level attained by its children.

POSSIBLE MECHANISMS OF THE EFFECTS OF IAQ ON PERFORMANCE

Laboratory studies in which IAQ was modified and the performance of simulated office work was measured show that improving air quality by removing the pollution sources or increasing the outdoor air supply rate caused subjects not only to perform office tasks more effectively but also to report a lower increased intensity of such symptoms as headache and difficulty in concentrating (Wargocki et al. 1999,2000,2002). They thus suggest that SBS symptoms caused by poor air quality negatively affect performance, as would be expected and implied by the results of studies with adults (Nunes et al. 1993) and with pupils (Myhrvold et al. 1996). In addition, these laboratory studies show that changes in IAQ caused changes in the metabolic rate of subjects performing simulated office work, as indicated by different carbon dioxide (CO_2) levels under different exposure conditions. Under the conditions with improved IAQ the metabolic rate was higher and this effect was attributed to an increased muscular tonus given by the higher work rate.

The impact of IAQ on changes in metabolic rate was investigated by Bako-Biro et al. (2005) who examined the CO_2 production rates of subjects participating in two independent experiments, described earlier, in which female subjects (having roughly the same average body size of 1.7 m^2 ($\pm$0.1 SD)) were exposed to various air quality conditions in a real office space and performed simulated office work (Bako-Biro 2004, Bako-Biro et al. 2004). The measured CO_2 concentration in the office and the measured outdoor air supply rate were used to calculate the CO_2 production rate using a mass-balance model. The calculated CO_2 production rate was plotted against the air quality in the office during exposure assessed by the subjects upon re-entering the office immediately after exposure (Figure 5). The relationship obtained suggests that subjects start to produce less CO_2 as the air quality decreases (increased % dissatisfied): a change of 13% when the percentage dissatisfied with the quality of air changes from 8% to 40%.

The results of the analyses made by Bako-Biro et al. (2005) indicate that the pollution level of inhaled air may significantly affect the CO_2 production rate of occupants. This must be assumed to be due to changes in metabolic rate. It may have a psychological origin, reflecting people's unwillingness to work in poor air quality conditions, or it may be due to intensified SBS symptoms resulting from exposure to indoor pollutants (e.g., headache) that reduce the work rate. The question of how these symptoms are caused then arises. Changes in breathing pattern may affect the CO_2 content of exhaled air: if breathing does not correspond to metabolic demand, i.e. if the rate at which CO_2 is produced at the cellular level is greater than the rate at which it is exhaled, due to shallow breathing or other dysfunction in the respiratory system, CO_2 concentration in the blood will increase, inducing physiological effects such as symptoms similar to SBS (Paulev 2000). If this leads to a decrease in the work rate, the metabolic rate will be reduced and less CO_2 will be exhaled. Alteration in the breathing pattern as a result of exposure to environmental chemicals has been reported in mouse bioassays (Larsen et al. 2000) and in human subjects (Danuser 2001), supporting the present hypothesis. That gaseous pollutants are expected to cause negative effects on performance is to some extent supported by the results of experiments in schools which showed that increasing the outdoor air supply rate to classrooms improved the performance of schoolwork by children (Wargocki and Wyon 2007a,2007b) but reducing the concentration of airborne particles by operating electrostatic air cleaners in the classrooms did not affect the performance of schoolwork (Wargocki et al. 2007). Further studies on the mechanisms behind the effects of IAQ on performance are essential.

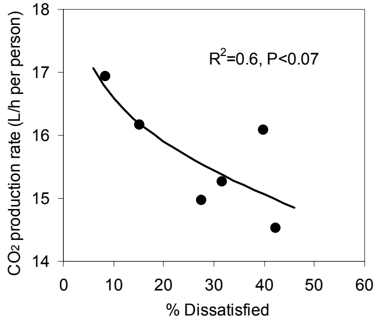

Figure 5. CO_2 production rate per person as a function of the % dissatisfied with IAQ

CONCLUSIONS

- Laboratory and field experiments show that improving IAQ improves the performance of office work by adults and schoolwork by children.
- Poor air quality may cause changes in the breathing pattern (shallow breathing) or a slower work rate. An alteration of the breathing pattern may induce further physiological effects in humans, including symptoms similar to SBS.
- The benefits of improving IAQ by reducing pollution sources or increasing outdoor air supply rates are much higher than the costs involved.
- The present results constitute a powerful argument and strong incentive for providing indoor air of a better quality than the minimum levels required by present standards.
- IAQ should be improved while decreasing energy. New and energy-efficient technologies to improve IAQ are thus required; understanding the mechanisms by which IAQ affects humans would aid the development of such technologies.

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