The effects of indoor air quality on performance and productivity

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THE EFFECTS OF INDOOR AIR QUALITY (IAQ) ON PERFORMANCE, BEHAVIOUR AND PRODUCTIVITY

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ABSTRACT

This paper describes a series of laboratory simulation experiments with exposures of up to 5 hours in which the performance of simulated office work was increased by removing common indoor sources of air pollution (floor-coverings and personal computers), or by increasing the rate at which clean outdoor air was supplied per person. Outdoor air supply rates from 3-30 L/s/p were studied. The resulting pollutant levels did not affect the perception of air quality by the occupants themselves, but they affected the headache and difficulty in thinking clearly they reported and the perception of air quality by visitors. These findings were validated in two 8-week field intervention experiments, which were carried out in call-centres in northern Europe and in the hot humid Tropics. They have far-reaching implications for productivity, the life cycle costing of buildings, and the efficient use of energy.

Keywords: IAQ, air quality, energy, SBS, offices, performance, productivity

INTRODUCTION

Modern societies have developed by using buildings to control the working environment, so that work performance is no longer dependent on the weather, the time of day or the time of year. Buildings represent the largest capital investment made by any society and more energy is used to enable buildings to transform the outdoor climate into an indoor climate than for any other purpose - on average about 40% of all energy is used to control the indoor climate in buildings. It is used to construct buildings, to heat, cool and light them as required, and not least, to ventilate them. Clearly each of these processes should be achieved as efficiently as possible, but here cost-benefit must be considered as well as energy conservation. In both cases, optimisation can only be achieved if the outcome of each process can be quantified in terms of how humans and human activities are affected.

The main justification for ventilation has historically been to create a healthy indoor environment. Ventilation removes air pollutants originating inside the building, including bio-effluents. The outdoor air supply rate that has been found by experience to provide subjectively acceptable indoor air quality and to prevent the accumulation of moisture in the building is generally sufficient to maintain the concentration of pollutants at healthily low levels. This was for many years the justification for current ventilation practices, but a survey in Norwegian schools showed that high CO_2 levels in classrooms due to poor ventilation were associated not only with increased prevalence of SBS symptoms but also with significantly reduced performance on a small set of computerized tests of mental ability (Myhrvold et al., 1996). SBS symptom prevalence was reduced and simple reaction time improved after CO_2 levels had been reduced by increasing ventilation (Myhrvold and Olsen, 1997). These studies are compatible with a causal relationship between air quality and performance but do not prove that one exists, as in both cases there are plausible alternative explanations for the observed results. In 1999 the first of a series of experiments was carried out by researchers at The International Centre for Indoor Environment and Energy (ICIEE) at the Technical University of Denmark (DTU) was published, proving that commonly occurring indoor sources of pollution may cause a reduction in the performance of office tasks and thus revealing a new mechanism by which indoor air pollution may reduce productivity, either in addition to or instead of having negative effects on comfort and health. These experiments form a well-defined body of work that demonstrates a reliable effect of indoor air quality on the performance of office tasks, and the main purpose of this paper is to provide a summary of these experiments and of their main findings. In a comparable study, Federspiel et al. (2002) reported that in a call centre in California in which qualified nurses provide medical advice, talk-time (the average time taken to complete each incoming call) increased at the intermediate ventilation rates of 20 and 53 L/s/p in comparison with the extreme values of 8 and 94 L/s/p. When the same data were used to derive a multi-factorial model predicting productivity (Fisk et al., 2002) this unexpected effect was transformed into a 2% reduction in average handling time (a productivity index combining talk-time and wrap-up time) at CO2 levels less than 75 ppm above outdoor values, in comparison with less well-ventilated conditions. It will be shown below that filter condition, not registered in the Californian study, may have caused the anomalous results that were suppressed in the mathematical model.

METHODS

The common methodological features of each sub-set of experiments are described in the sub-sections below. The reader is referred to the original reports cited for each experiment for further details of particular experiments.

Field laboratory (Denmark): A standard 6x6m, 108m^3 office with two 3-metre-wide East-facing windows, was used for the laboratory experiments that were performed in Denmark. It presented a realistic appearance and had low-emitting surfaces (painted brick walls, polyolefin tiles), furniture and VDUs (>2 years old). There were 6 computer workstations, each with task lighting, at which 5 different groups of 6 subjects performed simulated office work during normal office hours. Behind a 2m high partition, different sources of indoor air pollution could be placed without the subjects' knowledge, e.g. 36m^2 of 20-year-old carpet taken from an office building with indoor climate problems, hung in strips from a rack, or new Personal Computers - PCs - with CRT/VDUs - Cathode Ray Tube Visual Display Units. In most of the air quality experiments the comparison was between two conditions (with and without the pollution source being present behind the partition), but in two experiments the source was always present. In one of these experiments (Wargocki et al., 1999a, b) outdoor air was supplied at three different rates and in the other (Kaczmarczyk et al., 2004) outdoor air was supplied either conventionally or via a personal ventilation system (PVS). Outdoor air was always drawn in directly through the façade at a carefully controlled rate, without passing through the building's ventilation system, and the temperature and humidity in the room could be controlled without any condensation on cooling plates that might have trapped air pollutants. Freestanding fans ensured that room air circulated behind the partition and was well mixed. The exposures were for 5 hours and all 30 subjects were young females.

Field laboratory (Sweden): The original with/without air pollution comparison was replicated in a similarly standard daylit office in northern Sweden (Östersund), using the same $36m^2$ of carpet as the hidden pollutant source behind a partition (Wargocki, Lagercrantz et al., 2002).

Simulated office work: Three different office tasks were simulated, including Text-typing from a hard-copy onto a computer screen, Proof-reading a printed text into which spelling, grammatical and logical errors had been inserted, and Addition of a column of five 2-digit random numbers, without zeros, printed conventionally. In these tasks, rate of working and percentage errors were examined separately. In the first air quality experiment (Wargocki et al., 1999a,b), a Performance Assessment Battery that has been widely used for military purposes was used instead of the Proofreading task, but as it proved insensitive to environmental conditions it was not used in subsequent experiments. Open-ended tasks of memory, recall and creative thinking were applied in most of the experiments (Wyon, 1996).

Data analysis of the laboratory experiments: Order of presentation of conditions was balanced as well as is possible with 5 groups of subjects and all exposures took place at the same time of day on the same day of the week (on successive weeks) for a given group, with an air temperature of 22°C. The Null Hypothesis of no difference between conditions in terms of the performance parameters was first tested in within-subject comparisons between conditions using non-parametric methods such as the Friedman test and the Wilcoxon Matched-Pairs Signed-Ranks test (Siegel, 1956), as appropriate. When the data were Normally distributed, analysis of variance was applied.

Field intervention experiments: The findings of the laboratory experiments described above were validated in two field intervention experiments in call-centres, one in Denmark and one in Singapore. In modern call-centres, incoming calls are distributed to available operators by the computerised telephone exchange system, which keeps a record of the exact duration of each call (talk-time). If the quality of service remains satisfactory, this can be used as a measure of productivity, because the number of operators on duty would have to be increased if talk-time became longer under adverse environmental working conditions. Operators usually work staggered shifts to provide a service outside normal working hours, and to match the number of operators on duty to the expected call-volume at different times of day.

In a call-centre in Denmark that provides a national directory enquiries service for a telephone company, 26 operators working in shifts received an average of 400 calls each per hour in an air-conditioned open office ($154m^2$, $447m^3$). They used PCs connected to the Internet and sophisticated expert systems to find the information required by each caller. The number of callers waiting was indicated in real time on the screen and it was found that operators reduced talk-time linearly as a function of this feedback, by up to 50%, in an attempt to provide a better service. In this operation, call-handling time was equal to talk-time, as the calls did not generate any subsequent work. Air quality was manipulated in a 2x2 design with one repetition over 8 weeks, each condition being maintained constant for a full week. The conditions were with a new or used supply air filter in place, and with 8% or 80% outdoor air in the otherwise constant supply airflow that was equivalent to 3.5 ach. The two conditions nominally provided 2.5 or 25 L/s/p at peak occupancy (14 operators present), although infiltration is likely to have affected these values, depending on wind speed and direction. The used filter had been in the system for 6 months prior to the experiment. The call centre is in a penthouse at the top of a 3-storey building in a small rural town with otherwise very low buildings. It has windows on both sides and the outdoor air is of good quality. Denmark is in Northern Europe and has a temperate climate.

In a call-centre operated by the Inland Revenue Service (IRS) of Singapore that provides an enquiries service to taxpayers, 26 operators worked normal office hours in an air-conditioned open office. They used PCs connected to the IRS computer system to answer a wide range of queries and to provide assistance. Each call generated a variable amount of subsequent work, and call-handling time was on average considerably longer than talk-time. The data have to date only been reported with talk-time as the index of productivity. Air quality and temperature were manipulated within currently accepted limits in a 2x2 design with one repetition over 8 weeks, each condition being maintained for a full week. The two air quality conditions were nominally 10 or 23 L/s/p of outdoor air in the otherwise constant supply airflow, and the two thermal conditions were 22.5° or 24.5°C. The call centre is on the second storey of a high-rise office building in the downtown area of Singapore. The outdoor air is of relatively poor quality. Singapore is in the Tropics and the outdoor air is hot and humid all year.

In both field intervention experiments the number of operators present varied systematically during the day while the outdoor air supply rate did not vary. The outdoor air supply rate per person thus varied systematically and outside peak hours was well above the nominal values cited for peak occupancy.

Data analysis of the field experiments: Multivariate analysis was first used to determine which measured factors other than the differences between conditions had significant effects on talk-time. Within the work-periods in which these factors changed very little, the average talk-time for each operator and condition was derived by pooling all available data over the 8-week period.

Subjective responses: Subjects marked visual-analogue scales in the laboratory and field experiments to indicate their perception of environmental factors, including their specific symptoms (of the eye, skin, nose, throat, etc.), their general symptoms (of headache, fatigue, difficulty in concentrating, etc.) and their self-estimated performance. The specific and general symptoms addressed correspond to those of the Sick Building Syndrome (SBS). Subjects assessed air quality by marking a split scale of acceptability during whole-body exposure to the air. Group average marking of this scale is used to calculate Perceived Air Quality (PAQ) in decipols and the predicted percentage of the general population that would be dissatisfied with the air quality, in both cases by reference to the previous exposure of large numbers of other subjects to similar pollutants (Gunnarsen and Fanger, 1992). Subjects in the laboratory exposures assessed PAQ immediately on entering (with no bio-effluents present), at various times during the exposure and, after leaving the room and briefly refreshing their olfactory sense by breathing fresh air, on re-entering the room a few minutes after the end of their exposure (i.e. with bio-effluents present).

RESULTS

Each of the experiments in the present series, together with one meta-analysis combining two of them, is identified below by the environmental factor whose effects on performance were evaluated, by the outdoor air supply rate per person and by a reference to the original publication. The main effects on performance are then briefly summarised.

IAQ: 10 L/s/p with/without carpet. Wargocki, Wyon et al. (1999a, b)
The original analysis reported that subjects typed 6.5% more slowly ($P<0.003$) and reported more headaches ($P<0.04$) when the carpet was present behind the partition. The reported acceptability of the air quality did not differ between conditions. Subsequent re-analysis reported by Wargocki, Lagercrantz et al. (2002) indicates that the presence of the carpet caused subjects to type more slowly ($P<0.002$) and make more typing errors ($P<0.005$), to experience more headache ($P<0.05$), odour intensity ($P<0.05$) and throat irritation ($P<0.07$) during the exposure and more irritation of the nose ($P<0.004$), but their assessment of air quality was reduced by the carpet ($P<0.001$) only on returning to the room immediately after the exposure, as visitors. In short, IAQ influenced the symptoms and performance of occupants but not the PAQ they reported.

IAQ: 10 L/s/p with/without carpet. Lagercrantz, Wistrand et al. (2000)
In a replication in Sweden of the above experiment, subjects typed more slowly ($P<0.04$) and made more errors in an addition task ($P<0.05$) when the carpet was present, presumably as a result of experiencing more difficulty in thinking clearly ($P<0.05$), more dizziness ($P<0.05$) and more fatigue ($P<0.05$). The presence of the carpet also caused subjects to report increased symptom intensity of the eyes, nose and throat, increased odour and reduced air quality ($P<0.05$). In this case, IAQ influenced occupants' PAQ, symptoms and performance.

IAQ: 10 L/s/, combining the above. Wargocki, Lagercrantz et al. (2002)
In a meta-analysis of the two experiments summarised above, the data from each experiment were combined as if they had been obtained in a single experiment with twice as many subjects. This made it possible to show that the presence of the carpet during the exposure caused subjects to type 6.5% more slowly ($P<0.002$), to commit 18% more typing errors ($P<0.03$), to experience more headache ($P<0.02$), more irritation of the throat ($P<0.02$), more dryness of the nose ($P<0.03$) and increased odour intensity ($P<0.01$), and to report that the air was drier ($P<0.05$). When the carpet was present they reported that the air quality was less acceptable both when first entering the room ($P<0.009$) and when returning to the room immediately after the exposure ($P<0.001$), although perceived air quality did not differ between conditions during the exposure, contrary to the finding of the second experiment. Subjects returning to the room after their exposure reported increased odour ($P<0.001$) and more irritation of the eyes ($P<0.02$), nose ($P<0.001$) and throat ($P<0.05$) when the carpet was present than when it was absent. An alternative meta-analysis, treating the two experiments as independent trials of the same hypothesis and combining the probabilities obtained in each, confirmed these findings, although in this analysis the effects on throat irritation and perceived dryness of the air just failed to reach formal significance ($P<0.06$). Combining both experiments, IAQ influenced the symptoms and performance of occupants but not the PAQ they reported.

IAQ: 3/10/30 L/s/p with carpet. Wargocki, Wyon et al. (2000)

Indoor air quality was improved in this experiment by increasing the outdoor air supply rate without removing the source of air pollution, instead of by removing it as in the previous experiments. By integrating speed and accuracy into an overall measure it was possible to show that the performance of the Text-typing ($P<0.03$), task improved when the outdoor air supply rate was increased. Performance of the Addition ($P<0.06$) and Proofreading ($P<0.16$) tasks showed the same trend but the effects did not reach significance. In an open-ended test of creative thinking, subjects provided more ($P<0.025$, 1-tail) and more original answers ($P<0.046$, 1-tail) at 10 L/s/p than at 3 L/s/p. Subjects reported feeling better during the exposure at higher outdoor air supply rates ($P<0.0001$); dryness of the throat ($P<0.0006$) and mouth ($P<0.0004$) decreased, it became less difficult to think clearly ($P<0.001$) and they reported less fatigue ($P<0.04$). The reported intensity of throat irritation increased slightly ($P<0.03$) at the two lower outdoor air supply rates. As in the previous experiments, subjective assessments of air quality did not differ between conditions during the exposure, but did so reliably on first entering ($P<0.002$) and on re-entering immediately after their exposure ($P<0.01$), i.e. subjects perceived a difference in air quality whether bio-effluents were present or not when their olfactory sense had recently been refreshed. Measurements of room CO2 levels indicate that subjects exhaled CO2 at a significantly lower rate at lower outdoor air supply rates ($P<0.05$), corresponding to a decrease in metabolic rate from 1.35 met at 30 L/s/p to 1.0 met at 3 L/s/p. In short, IAQ influenced the symptoms, CO2 exhalation rate and performance of occupants but not the PAQ they reported.

IAQ: 10 L/s/p with PCs. Bakó-Biró, Wargocki et al. (2004)
The presence behind the partition of one 3-month old PC per subject caused a decrease in PAQ on entering ($P<0.0005$), during the exposure ($P<0.015$) and on re-entering after the exposure ($P<0.0001$). From these PAQ data, the sensory pollution load of each new PC was estimated to be more than 3 times that of a standard person. Subsequent assessments of 4 different brands of PCs (Wargocki, Bakó-Biró et al., 2003) confirmed this finding: the average value for a CRT-VDU was 2.7 after 50h operation, 1.8 after 400h and 1.4 after 600h, while PC towers and flat-screen TFT (Thin Film Transistor) monitors were not significant sources of pollution. During the exposure the air was judged to be more stuffy ($P<0.005$) when the new PCs were present. Although the difference between conditions in terms of typing speed were small, more subjects typed slowly ($P<0.03$) and all subjects made more typing errors ($P<0.014$) when the new PCs were present. Proofreading was affected negatively but not significantly. Combining the observed effects on speed and accuracy of typing and the decrease in speed of proofreading, it could be shown that overall text-processing would be performed 9% more slowly if new PCs were present. When the pollutant source was a VDU, IAQ influenced occupants' PAQ and performance but not their reported symptoms.

IAQ: 15 L/s/p with carpet, PVS/mixing. Kaczmarczyk, Melikov et al. (2004)
Four IAQ conditions were compared, all with a room air temperature of 23°C, a 15 L/s/p outdoor air supply rate and 36m^2 of used carpet present behind the partition: 1) A reference condition, with conventional mixing ventilation; 2) A placebo condition with re-circulated room air supplied through the PVS; 3) Outdoor air supplied through the PVS at room temperature; and 4) Outdoor air supplied through the PVS at 20°C. When subjects reduced the PVS air supply rate, the remainder of the constant outdoor air supply was mixed with room air instead. Differences between these conditions

could be demonstrated for PAQ 3 minutes after entering ($P<0.01$), headache ($P<0.03$) difficulty in thinking clearly ($P<0.01$), ability to concentrate ($P<0.03$) and feeling bad/good ($P<0.03$). All 5 of these indicate a monotonic improvement from Condition 1 to 2 to 3 to 4. Self-estimated performance improved likewise in the Text-typing ($P<0.01$) and Addition ($P<0.04$) tasks, but no effects on objectively-measured performance could be shown, quite possibly because subjects introduced a powerful source of inter-individual variance by using the degrees of freedom of the PVS (airflow, position, direction) very differently. When subjects were obliged to use the PVS more uniformly, by raising the room air temperature to 26°C in a second comparison of Conditions 1 and 4, subjects made fewer errors on the Text-typing task ($P<0.05$) in when the PVS was present, than in the reference condition. This should be regarded as a combined effect of IAQ and thermal comfort. When a PVS was used to manipulate IAQ and thermal comfort, occupants' PAQ and performance were affected but their reported symptoms were not.

Air T & IAQ: 10/23 L/s/p, call-centre, Tropics. Tham, Willem et al. (2003a)
Call-centre operator performance in the Tropics, as indicated by average talk-time, improved by 4.9% when the air temperature was decreased by 2°C from 24.5°C ($P<0.05$) at the normal outdoor air supply rate of 10 L/s/p. It improved by 8.8% when the outdoor air supply rate was raised to 23 L/s/p at the original indoor air temperature of 24.5°C ($P<0.04$). A subsequent analysis in terms of total call-handling time, as yet unpublished, confirms the reversibility of these effects. Headache intensity and difficulty in concentrating were reduced by 19% ($P < 0.03$) and 13% ($P < 0.02$), respectively, when the outdoor air supply rate was approximately doubled (Tham, Willem et al., 2003b). Thermal discomfort increased at the lower temperature but no other subjective symptoms were significantly affected. The performance of call-centre operators in the Tropics was improved both by increasing the outside air supply rate and by maintaining conditions on the cool side of thermal neutrality.

IAQ: 2/20 L/s/p, new/used filter, call-centre. Wargocki, Wyon et al. (2003, 2004)
Call-centre operator performance in a temperate region, as indicated by average talk-time, was unexpectedly improved by decreasing the outdoor air supply rate from 20 to 2 L/s/p with a used supply air filter in place ($P<0.05$), indicating that the air quality was better maintained by allowing a small amount of outdoor air to infiltrate through the façade than by passing a larger amount of outdoor air through a used filter. At 20 L/s/p, performance was decreased by replacing a clean supply air filter with a used filter ($P<0.01$), confirming that a used filter is an avoidable source of indoor air pollution. The measured improvement in performance that could be achieved by changing the filter at 20 L/s/p was 9%, i.e. IAQ had a larger effect on the actual performance of office work in the field than would be predicted from the field laboratory experiments described above. With a clean supply air filter in place, the expected tendency for performance to be increased by raising the outdoor air supply rate approached significance ($P<0.055$). This change also alleviated many subjective symptoms, as did changing from used to new supply air filters, although the effect of a filter change on subjective symptoms was unexpectedly greater at the lower outdoor air supply rate than at the higher, contrary to what would be expected from the observed effects on performance (Wargocki, Wyon et al., 2002). This may indicate that odours affect symptom reporting more than they affect actual performance. The

performance of call-centre operators in a temperate region with clean outdoor air was improved by replacing a used supply air filter with a clean filter. Increasing the outdoor air supply rate through a used filter was counter-productive.

DISCUSSION

The experiments summarised above provide evidence of the very considerable benefits of providing good indoor air quality, whether it is achieved by careful selection of building and furnishing materials and office equipment or by providing clean outdoor air at an increased rate. The conclusions that were drawn after the first field laboratory experiments (Wargocki, Wyon and Fanger, 2000a) have been validated for other sources of indoor air pollution and in the field. While the increase in performance as a function of outdoor air supply rate per person follows a positively decelerated curve, so that most of the improvement takes place when very low ventilation rates are improved, performance decreases linearly as the proportion of visitors dissatisfied with the air quality increases over the range 20-70% dissatisfied (Wargocki, Wyon at al., 2000b).

Talk-time can only be used as an index of productivity if quality of service is maintained. When operators reduce talk-time on purpose to reduce the number of callers waiting, as they did by up to 50% in the directory enquiries operation, it seems likely that quality of service may have been reduced. However, when talk-time was reduced by improving the air quality, it seems more likely that operators who are feeling better and experiencing fewer symptoms of distress will be able to provide an increased quality of service. Talk-time would then be a conservative indicator of productivity.

The unexplained drop in performance (increased talk-time) at intermediate levels of outdoor air supply rate reported by Federspiel et al. (2002) is compatible with present finding that providing more supply air can increase talk-time if a used filter is in place. At the extreme and uneconomic outdoor air supply rate of 94 L/s/p the negative effects of this additional source of indoor air pollution on performance were overcome. Taken together, these results indicate that the pollution source strength of a used filter may increase with the proportion of outdoor air in the airflow, up to a maximum level. This would be the case if the emission of pollutants affecting performance from the dust-mat in the filter were driven by their partial pressure in the upstream supply air. Identification of the active agents and confirmation of the validity of this interpretation must await further research.

An economic case for improving indoor air quality beyond the minimum required to avoid visitor dissatisfaction can been made for a wide range of climatic regions (Wargocki and Djukanovic, 2003): economic calculations based on the present series of experiments indicate that benefits exceed costs by a factor of about 60, and that payback times will usually be about 2 years. It is important to remember that increasing the outdoor air supply rate is not the only way to improve indoor air quality (Wyon, 2001). The present series of experiments is now being extended to include children at school as well as adults at work.

CONCLUSIONS

1. Poor indoor air quality can reduce the performance of office work by 6-9%

2. There are many different sources of indoor air pollution. Used supply air filters are among them.
3. Field intervention experiments in two call-centres demonstrate that the decrement in performance can be larger in practice than it is in realistic laboratory simulation experiments.
4. There is an approximately linear relationship between the percentage dissatisfied with indoor air quality (from 20-70%) and the measured decrement in performance.
5. Negative indoor environmental effects on performance were accompanied by negative effects on general symptoms such as headache and concentration.

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