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INDOOR AIR

The effects of indoor air quality on performance and productivity

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Abstract 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. Until 5 years ago this would have been the justification for current ventilation practices, but in 1999 the first of a series of experiments was published, revealing new mechanisms by which raised levels of indoor air pollution may reduce productivity, either in addition to or instead of having negative effects on comfort and health. It was shown in realistic experimental exposures lasting up to 5 h that the performance of simulated office work could be significantly increased by removing common indoor sources of air pollution, such as floor-coverings, used supply air filters and personal computers, or by keeping them in place and increasing the rate at which clean outdoor air was supplied from 3 to 10 to 30 $l\ s^{-1}$ per person. These short-term effects were demonstrated repeatedly even at pollutant levels that had no measurable effects on the perception of air quality by the occupants themselves, although there were effects on subclinical SBS symptoms such as headache. Temperature and noise distraction have since been studied in directly comparable exposures. The prediction arising from these experiments, that the performance of real office work over time would be significantly and substantially affected by the changes in indoor environmental quality that take place in the course of normal building operation, have recently been validated in 8-week field intervention experiments carried out in call-centers in northern Europe and the Tropics. These findings have far-reaching implications for the efficient use of energy in buildings.

Key words: IEQ; Air quality; Temperature; Noise; Energy; Performance; Productivity.

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Practical implications

It has now been shown beyond reasonable doubt that poor indoor air quality in buildings can decrease productivity in addition to causing visitors to express dissatisfaction. The size of the effect on most aspects of office work performance appears to be as high as 6–9%, the higher value being obtained in field validation studies. It is usually more energy-efficient to eliminate sources of pollution than to increase outdoor air supply rates. The experiments summarized in this article have documented and quantified relationships that can be used in making cost-benefit analyses of either solution for a given building. The high cost of labor per unit floor area ensures that payback times will usually be as low as 2 years.

Introduction

A building transforms the outdoor climate in such a way that the resulting indoor climate is suitable for the human activities it is designed to contain and protect. Only the simple tasks on which primitive societies depend can be routinely performed outdoors, and then only in favorable climates and in favorable weather. 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 for this purpose. 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, optimization can only be achieved if the outcome of each process can be quantified in terms of how humans and human activities are affected. The whole purpose of a building is to protect its occupants and enhance their activities.

Outside working hours it is up to each individual to decide on how their economic resources and the energy at their disposal should be used to optimize the indoor environment in which they sleep, eat and engage in leisure activities. Some choose to endure suboptimal conditions and some have no choice but to do so, but most people are willing to expend time, effort, energy and money to optimize the indoor environments they personally control. They do so because on balance they prefer to. Their judgment is based on their experience of the consequences of a poor indoor environment, in terms of how it affects their sleep, their health, their comfort and their enjoyment of their leisure activities. Very little systematic research has gone into providing objective data on how any of these outcome variables are affected by the indoor climate, with the exception of health, and even in this case society is content to impose minimum standards and leave optimization to individual choice.

In working hours it is not only the individual occupants who have an interest in how their health, comfort and performance are affected by the indoor environment that is provided by the building that contains their workplace. Their employer must ensure that the work in which the building occupants are engaged is economically viable, and if it can be shown that the indoor environment is among the factors that affect productivity, it becomes part of the cost-benefit calculation. In the last analysis, the national economy, and thus society itself, is dependent on this calculation. Energy conservation is important to society but is often excluded from the short-term cost-benefit calculations made by an employer in deciding how to construct and operate a building. If using more energy will generate more profit, energy conservation becomes the responsibility of society rather than the employer. However, reliable information on how productivity is affected by the indoor environment is critical for decision-making at both levels.

It is easy to justify heating and cooling buildings. Most of the work of a modern society could not be performed if people were shivering or sweating profusely, and even within these limits, where heat balance is achieved by vasodilatation and vasoconstriction and there is no risk to health, cold hands lead to unacceptably low levels of manual dexterity, and the lethargy and headaches caused by unsuitably warm environments have equally unacceptable negative effects on mental performance, so much so that even thermal discomfort, the traditional argument for providing adequate heating and cooling, is usually minimized by the time the thermal environment has been adjusted to maximize work performance (Wyon, 1993, 2001a,b).

Similarly, it is easy to justify lighting levels up to those required to provide the necessary visual acuity for work performance, and these will always be more than adequate for visual comfort. Lighting research is currently engaged in examining the non-visual effects of lighting, and it is more than likely that lighting quality as well as quantity will eventually be proven to have an effect on productivity. When this stage is reached, lighting quality will enter the cost-benefit calculation, but at present it is largely determined as a matter of taste, prestige and preference once minimum lighting levels have been attained. The effects of lighting on performance were not examined in the present series of experiments.

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. Until 5 years ago this would have been the justification for current ventilation practices, but in 1999 the first of a series of experiments carried out by researchers at The International Centre for Indoor Environment and Energy (ICIEE) at the Technical University of Denmark (DTU) was published, revealing new mechanisms by which indoor air pollution may reduce productivity, either in addition to or instead of having negative effects on comfort and health. The series consisted mainly of realistic laboratory simulation experiments, followed by field intervention experiments to validate their findings. In 1996 the present author became a part-time adjunct professor in the university department of which P.O. Fanger was head and so was part of the team that obtained funding in an internationally adjudicated competition to establish ICIEE in 1998 as a Center of Engineering Excellence. He became a full-time visiting professor on the staff of ICIEE in 2002, for a contract period of 3 years. The series was expanded to include an examination of the effects of temperature and noise distraction in open offices. Some of the experiments were repeated in cold dry northern Sweden and in hot humid tropical Singapore, to extend the validity of the results from temperate northern Europe to these two very different climatic regions and the climates that lie between. These 10 experiments form a well-defined body of work and have been uniquely successful in quantifying the effects of indoor environmental factors on performance, and in particular, the effects of poor indoor air quality, which had not previously been shown to affect performance. The purpose of this paper is to provide a summary of this set of related experiments and of the results that they have yielded up to the present time, with a list of references to the papers in which they have been reported.

Methods

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

Laboratory

A series of experiments to determine limiting criteria for human exposure to the very low levels of indoor humidity that occur in aircraft cabins at altitude (<10% RH) and in winter in cold countries (<20% RH) was performed in two climate chambers at ICIEE (ASHRAE, 2004). Although the main focus of this experiment was on subjective symptoms and objective signs, subjects performed simulated office tasks of the kind described below in order to ensure that their eyes remained open and potentially vulnerable to low humidity. Their performance of these tasks was compared between conditions (Wyon et al., 2003). Thirty subjects (17 female) were exposed in 5 groups of 6 for 5 h at 22 °C to RH values of 35, 25, 15 and 5% on the same weekday of four successive weeks. Subjects were assigned pseudo-randomly to each group to ensure that each group contained approximately the same number of male and female subjects and the same proportion of two subgroups expected to be sensitive to low humidity (contact lens wearers and subjects reporting that they routinely experience symptoms of hay fever in the Spring). Another 30 subjects (15 female) were similarly exposed to 18, 22 and 26 °C at a constant absolute humidity level of 2.4 g kg^{-1} dry air (corresponding to 15% RH at 22°C) and to 35% RH at 22°C.

Field laboratory (Denmark)

A standard 6 × 6m, $108m^3$ office with two 3-meter-wide East-facing windows, was used for all the other 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 2 m high partition, different sources of indoor air pollution could be placed without the subjects' knowledge (e.g., 36 m^2 of 20-year-old carpet taken from an office building with indoor climate problems, hung in strips from a rack, or new 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 HVAC 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 air quality series was extended to include an experiment in which the source of air pollution was replaced with a source of noise pollution (recorded sounds from an open office, replayed at 55 dBA, with clearly audible conversations 50% of the time). The air quality exposures were of 5 h and all 30 subjects were young females. The noise distraction exposures were of 3 h, repeated at three different air temperatures in a 2 × 3 design. In this case only 14 of the 30 similarly young subjects were female.

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 36 m^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 tests 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. 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-centers, one in Denmark and one in Singapore. In modern call-centers, incoming calls are distributed to available operators by the computerized telephone exchange system, which keeps a record of the exact duration of each call (talk-time). 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-center in Denmark that provides a national directory inquiries service for a telephone company, 26 operators received an average of 400 calls each per hour in an air-conditioned open office. 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 2×2 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 or 20 $\mathrm{l\ s^{-1}\ p^{-1}}$ at peak occupancy, 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 center is on the 4th floor 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-center operated by the Inland Revenue Service of Singapore that provides an inquiries 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 2×2 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 $\mathrm{l\ s^{-1}\ p^{-1}}$ of outdoor air in the otherwise constant supply airflow, and the two thermal conditions were 22.5 or 24.5°C. The call center 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.

Subjective responses

Subjects marked visual-analog scales in all of the laboratory and field experiments to indicate their perception of environmental factors, including perceived air quality (PAQ), 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). The distance of the subject's mark from the left-hand end of each scale, in millimeters, was assumed to indicate symptom intensity at an ordinal level of measurement and the null hypothesis of no difference between conditions was tested using the non-parametric methods specified above for the analysis of performance. 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 10 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 and by a reference to the original publication. The main effects on performance are then summarized.

Indoor air quality (IAQ) ($10\ \mathrm{l\ s^{-1}\ p^{-1}}$ with/without carpet) Wargocki 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 acceptability of the air quality did not differ between conditions. Subsequent re-analysis reported by Wargocki 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 irritation of the throat ($p < 0.07$) during the exposure and more irritation of the nose ($p < 0.004$), but they reported reduced air quality ($p < 0.001$) only on returning to the room immediately after the exposure.

In short, IAQ influenced the symptoms and performance of occupants but not the PAQ they reported.

IAQ ($10\ \mathrm{l\ s^{-1}\ p^{-1}}$ with/without carpet) Lagercrantz 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 symptoms of the eyes, nose and throat, more odor and reduced air quality ($p < 0.05$).

In this case, IAQ influenced occupants' PAQ, symptoms and performance.

IAQ ($10\ \mathrm{l\ s^{-1}\ p^{-1}}$, combining the above) Wargocki et al. (2002)

In a meta-analysis of the two experiments summarized 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 odor 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, due to habituation of the olfactory sense. Subjects returning to the room after their exposure reported more odor ($p < 0.001$) and more irritation of the eyes ($p < 0.02$), nose ($p < 0.001$) and throat ($p < 0.05$) when the carpet had been present than when it had been 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 ($3/10/30\ \mathrm{l\ s^{-1}\ p^{-1}}$ with carpet) Wargocki et al. (2000a,b,c)

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 $10\ \mathrm{l\ s^{-1}\ p^{-1}}$ than at $3\ \mathrm{l\ s^{-1}\ p^{-1}}$. 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 ($p < 0.04$). As in the previous experiments, they could not distinguish between conditions in terms of perceived air quality during their exposure, but did so reliably on first entering ($p < 0.002$) and on re-entering immediately after their exposure ($p < 0.01$), i.e., when their olfactory sense was refreshed they could perceive a difference in air quality whether bio-effluents were present or not. Measurements of room CO_2 *levels indicate that subjects exhaled significantly less* CO_2 *at lower outdoor air supply rates* ($p < 0.05$), corresponding to a decrease in metabolic rate from 1.35 met at $30\ \mathrm{l\ s^{-1}\ p^{-1}}$ to 1.0 met at $3\ \mathrm{l\ s^{-1}\ p^{-1}}$.

In short, IAQ influenced the symptoms, metabolism and performance of occupants but not the PAQ they reported.

IAQ ($10\ \mathrm{l\ s^{-1}\ p^{-1}}$ with PCs) Bakó-Biró 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 et al., 2003) confirmed this finding: the average value for a CRT-VDU was 2.7 after 50 h operation, 1.8 after 400 h and 1.4 after 600 h, while PC towers and flat-screen TFT 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 errors ($p < 0.014$) while typing when the new PCs were present, and 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^{-1} p^{-1} with carpet, PVS/mixing) Kaczmarczyk et al. (2004)

Four IAQ conditions were compared, all with a room air temperature of 23°C, a 15 l s^{-1} p^{-1} outdoor air supply rate and 36 m^2 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 min 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 five of these indicate a monotonic improvement from Condition 1–2–3–4. 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 interindividual 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 Condition 4, when the PVS was present, than in the reference condition. As thermal votes in this second experiment indicate that subjects always felt cooler when the PVS was in operation, this must 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 temperature (15 l s^{-1} p^{-1} in open/private office) Witterseh et al. (2002)

Subjects clothed for comfort at 22°C were exposed for 3 h to 22, 26, or 30°C in quiet (35 dBA) or recorded open-plan office noise (55 dBA) conditions. The noise distraction was very realistic, replayed from a high-quality digital audio tape-recorder (DAT) through loudspeakers hidden behind the partition (instead of a source of air pollution) and during 50% of the time it included clearly audible conversation in a language understood by the subjects. Warmth decreased PAQ ($p < 0.01$) and increased odor intensity ($p < 0.05$) and stuffiness ($p < 0.01$). It increased eye, nose and throat irritation and headache intensity ($p < 0.05$) and decreased concentration ($p < 0.05$) and self-estimated performance ($p < 0.001$). Noise increased fatigue ($p < 0.05$) and decreased concentration ($p < 0.05$) but did not interact with any thermal effects on subjective perception. In the addition task, noise decreased the work-rate by 3% ($p < 0.05$), subjects who felt too warm made 56% more errors ($p < 0.05$) and there was a noise–temperature interaction ($p < 0.01$): the effect of warmth on errors was less in noise. Noise increased the speed of typing ($p < 0.05$) and proofreading ($p < 0.05$). In the noise distraction condition, the creative thinking task was performed worse at 30°C than at lower temperatures ($p < 0.05$). A full report of these results has been prepared (Witterseh, Wyon et al., 2004).

Temperature and noise distraction affect both symptoms and performance, but interact only for performance.

Low RH (60 l s^{-1} p^{-1}, 5/15/25/35% RH) Wyon et al. (2003)

This experiment took place in two large climate chambers. The outdoor air supply rate was unusually high and the 4 humidity conditions to which each subject was exposed in balanced order were all unusually low. Subjects performed simulated office work on a computer for 5 h, mainly to ensure that they kept their eyes open and potentially vulnerable to the low humidity. There were few significant differences between conditions in terms of subjective perceptions and the differences between conditions were unexpectedly small (Fang, Wyon et al., 2002, 2003; Wyon, Fang et al., 2002). Eye dryness ($p < 0.028$) and eye irritation ($p < 0.005$) both increased at low humidity. Blink-rate could only be shown to have increased at the lowest level of humidity ($p < 0.05$) but tear-film mucous quality still decreased ($p < 0.05$) below 25% RH. The most unexpected result was that lowering the humidity reduced the rate of performance of three simulated office tasks: text-typing (by 3%; $p < 0.0002$), proofreading (by 7%; $p < 0.03$) and serial addition of two 2-digit numbers appearing on a computer screen (by 5%; $p < 0.04$).

Dry air affected the eyes and reduced performance but had surprisingly little effect on subjective symptoms.

Air temperature at low RH (10 l s^{-1} p^{-1} with carpet) Wyon et al. (2003)

In a second climate-chamber experiment at low air humidity, an equivalent but different set of subjects were exposed to normally polluted indoor air at temperatures of 18, 22 and 26°C in balanced order at the same absolute level of humidity (2.4 g kg^{-1} dry air), corresponding to 15% RH at 22°C. In this experiment the outdoor air supply rate was much lower and the incoming air passed over realistic amounts of carpet and linoleum before entering the climate chamber. The effects on subjective symptoms were again small. Tear-film mucous quality decreased above 22°C ($p < 0.05$). At 18°C errors in the addition task increased (by 28%; $p < 0.01$) and reading speed was reduced (by 7%; $p < 0.05$). As these effects are in the opposite direction to the expected beneficial effect of increasing the relative humidity by reducing the temperature, they seem likely to be due to thermal discomfort. Air temperature affected the eyes at low absolute humidity but the effects of thermal discomfort on performance were larger than those of the associated changes in relative humidity.

Air temperature and IAQ (10/23 l s^{-1} p^{-1}, call-center, Tropics) Tham et al. (2003a)

Call-center 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^{-1} p^{-1}. It improved by 8.8% when the outdoor air supply rate was raised to 23 l s^{-1} p^{-1} 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 affected. The productivity of call-center operators in the Tropics can be improved by increasing the outside air supply rate and maintaining conditions on the cool side of thermal neutrality.

IAQ (2/20 l s^{-1} p^{-1}, new/used filter, call-center) Wargocki et al. (2003, 2004)

Call-center 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^{-1} p^{-1} 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^{-1} p^{-1}, performance was decreased by replacing a clean supply air filter with a used filter ($p < 0.01$), confirming that a used filter is a very significant source of indoor air pollution. The measured improvement in performance that could be achieved by changing the filter at 20 l s^{-1} p^{-1} 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). The performance of call-center operators in temperate regions can be greatly improved by ensuring that the supply air filter is clean, even in a region with clean outdoor air. Increasing the outdoor air supply rate through a used filter can be counter-productive.

Discussion

Buildings have always been ventilated, throughout history, either by unintended and uncontrolled infiltration through cracks in the façade or by design, first through operable windows and later by means of mechanical ventilation. The improved air quality, however achieved, has always come at a high energy and economic cost. It is remarkable that society has been willing to pay this cost for thousands of years on the basis of subjective judgments. The negative olfactory perceptions of people entering a poorly ventilated room from outside soon disappear, and long-term occupants are subjectively satisfied with much poorer air quality provided that they are thermally comfortable. With a few exceptions such as nighttime cooling, buildings can be heated and cooled more economically by recirculating room air, or by circulating water at an appropriate temperature, than by replacing room air with outdoor air. Minimum ventilation levels have been set well above what is required for the health of the building or its occupants by appealing to the olfactory sense of visitors. This is due in some part to pride—occupants and their employers do not wish to give the impression to visitors that they are prepared to work in levels of air quality at which visitors literally and metaphorically turn up their noses—but it is due in large part to good sense. The olfactory sense, like hearing, is to a very large extent a watchdog sense. It responds to change and its purpose is to protect us from harm. Developmentally, the first impression we gain of an enclosed volume we are about to enter is important while we still have the chance to withdraw. If we then decide rationally that it is safe to enter and spend time in the space, it would be counter-productive to be continually reminded of the poor air quality—it would become a distraction—so the olfactory sense habituates rapidly and we would be able to proceed undisturbed with our intended activity, whether it is sleeping, recreation or working, were it not for the negative perception of visitors. We fortunately had the good sense to listen to their opinions, and to set minimum ventilation standards according to the olf/decipol system that was introduced by P.O. Fanger and his co-workers at DTU to quantify air quality perception by visitors, but we have not previously been provided with any quantitative evidence that ventilation benefits any measure of human response except visitor perception.

The experiments summarized above now provide incontrovertible 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 outdoor air at an increased rate. The conclusions that were drawn after the first field laboratory experiments (Wargocki et al., 2000a) have been validated for other sources of indoor air pollution and even 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 et al., 2000b). A strong economic case for improving indoor air quality beyond the minimum required to avoid visitor dissatisfaction can now be made for a wide range of climatic regions (Wargocki & 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. This does not factor in new evidence, based on epidemiological research performed elsewhere, that the economic cost of employee sick-leave appears to be considerably lower in offices with twice the minimum outdoor air supply rate, in comparison with offices with the minimum recommended outdoor air supply rate (Milton et al., 2000). This finding is at present at the level of an association. A causal relationship remains to be demonstrated, for example by performing intervention experiments of the kind that were carried out in the present series to validate indoor environmental effects on performance (Wyon, 2003).

The next task is to determine *why* these effects occur. At present we do not know which substances in indoor air cause them, nor what mechanisms are involved. We simply know that indoor air pollution increases the intensity of reported symptoms and that this reduces the performance of the many while increasing the sick leave taken by the few who are most severely affected. Research at ICIEE is currently investigating the influence of intervening variables such as ozone, ozone elimination in chemical reactions taking place indoors, the intermediate oxidation products of ozone including ultra-fine particles, gaseous and particulate emissions from the dust retained by used filters, adsorption and desorption processes on surfaces during the diurnal changes that take place in a building and the possibility that indoor air pollutants at concentrations below their olfactory detection level can have effects on respiratory physiology.

The present series included an experiment in which temperature and the noise distraction of an open office were shown to have measurable effects on the performance of office work. This was achieved by using exactly the same experimental methods as for indoor air quality. The effect of temperature was later validated as part of one of the field experiments, and it will be necessary to similarly field-validate the predicted effects of open-office noise distraction. If the same effects are observed the finding should have far-reaching effects on office layout.

Field validation has until now been achieved by taking call-center productivity as a paradigm of general office work. ICIEE is currently developing a new approach that will make it possible to measure the performance of different aspects of office work remotely, anywhere in the world and in any language, with automatic presentation and analysis of the results. The simulated office work that was used successfully in the laboratory to show the adverse effects of indoor air pollution, temperature and noise distraction can now be applied over the internet. This has been designated as Remote Performance Measurement (RPM). Pilot experiments indicate that there is no difference in measured performance between subjects assigned at random to be tested in the field, using RPM, or to be tested under supervision at the laboratory, as in the present series, with verbal instructions and the opportunity to question the experimenters. Automatic presentation and analysis mean that large numbers of building occupants can be tested with zero incremental cost, although it is still necessary to undertake the interventions (changing supply air filters, outdoor air supply rates, humidity or temperature set-points, solar screening, etc.) whose effects on performance are of interest.

The present series is now being extended to include children at school as well as adults at work. ICIEE has recently obtained an ASHRAE contract (1257-RP) to carry out field experiments on air quality in schools. If it can be shown that poor indoor air quality affects children as much as it affects adults, or perhaps more than this, it would be a powerful argument for improving classroom ventilation. Although this would not provide any immediate economic benefit, as children have not yet entered the economy, if it enabled them to remain healthy and learn more, the long-term economic benefits could be very large.

Conclusions

1. Poor indoor air quality can reduce the performance of office work by 6–9%.
2. Field intervention experiments in two call-centers demonstrate that the decrement in performance can be larger in practice than it is in realistic laboratory simulation experiments.
3. There is an approximately linear relationship between the percentage dissatisfied with indoor air quality (from 20 to 70%) and the measured decrement in performance.
4. The same experimental approach confirmed the previous findings that moderately raised air temperatures have a negative effect on office work performance.
5. The same experimental approach demonstrated that noise distraction in open offices at 55 dBA has negative effects on the performance of complex office tasks, although it may increase the rate of performance of simpler office tasks.
6. Negative indoor environmental effects on performance were accompanied by negative effects on general symptoms such as headache and concentration.
7. It is possible that these symptoms are what caused the observed reduction in the performance of office work.

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