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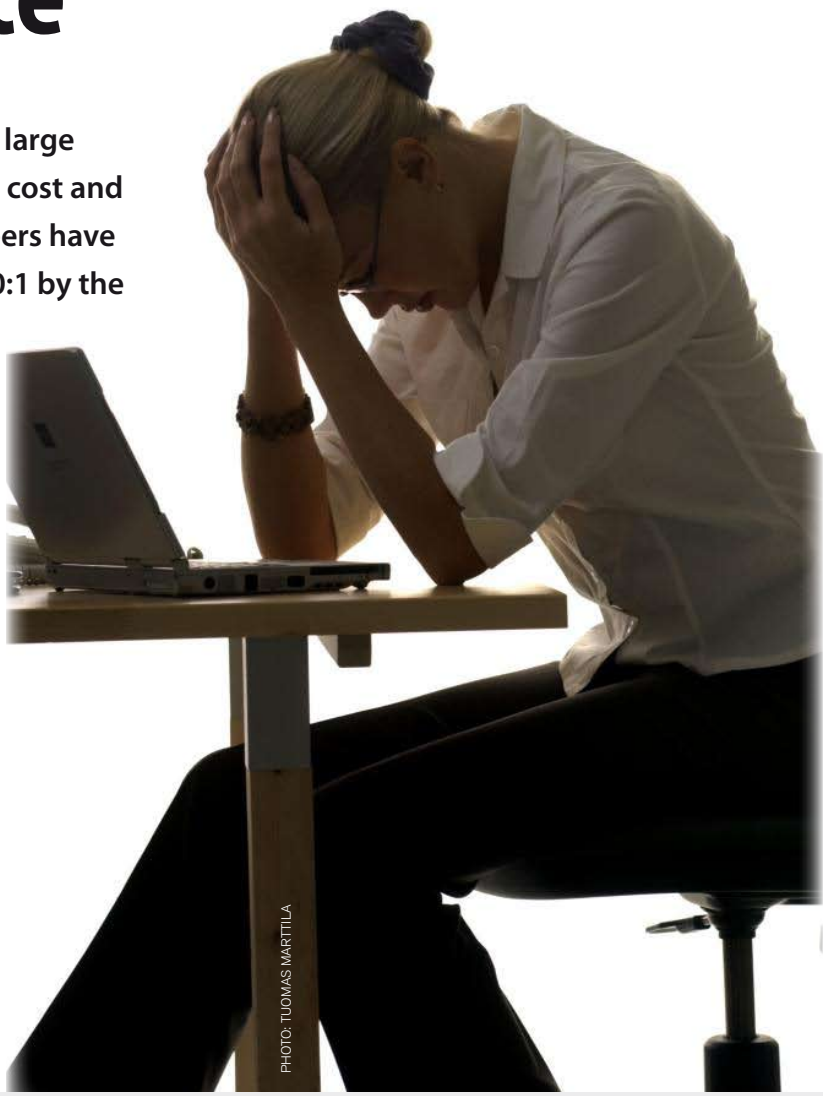
Effects of indoor environment on performance

Thermal and air quality control account for a large proportion of any commercial building's first cost and subsequent operating costs, so HVAC engineers have learnt to argue that they are outweighed 100:1 by the economic value of their positive effects on occupant performance, any positive effects on health and comfort being cited as additional benefits.



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Engineers are used to having to act on incomplete evidence, but if they are wise they like to have this evidence reviewed for them by specialists in any field that is outside their own experience and training. As experienced researchers in this particular field, we are often asked to give our best estimate of how and to what extent performance is affected by different aspects of indoor climate, so we now offer this very brief summary of our personal opinions, in the form of answers to 40 frequently asked questions (FAQs). Our answers are based on the results of the behavioral experiments that have been conducted to date. We offer no opinions on the long-term health effects of indoor environmental quality. We provide some references to where the relevant findings and a discussion of them may be found, but there is not enough space for all such references. We also list some questions we cannot answer as topics for future research in this area.

Relevance

Q1 Why should we be interested in thermal and air quality effects on performance?

There are four main reasons:

1) It is the added value of occupant performance that pays for indoor environmental quality (Fisk et al., 2011);
2) Performance is affected in the short-term by the combined effects of all indoor environmental factors, while subjective and physiological responses are usually selected because they are a function of one specific factor;
3) It turns out that thermal and air quality effects on performance can be observed even when there are no observable effects on comfort or on health-related symptom intensity (Wargocki et al.; 2004; Wyon, 2004; Wargocki and Wyon, 2006); and
4) The primary purpose of factory, office and school buildings is to provide an optimal indoor environment for work and for learning to work.

Effects

Q2 What effects do raised temperatures and poor air quality have on performance?

We have found that they usually reduce the rate of working, with little or no effect on accuracy (Wyon, 2004; Wargocki and Wyon, 2006).

Q3 Why is that?

In our experience, because people tend to reduce their rate of work until they are again able to achieve an acceptable error rate.

Q4 What aspects of mental work are affected?

In general, tasks that require concentration (clear thinking and symbolic manipulation), memory and original thought (Wyon, 2004; Tham and Willem, 2005; Lan et al., 2011).

Q5 Are all kinds of performance affected to the same extent?

Most mental work involves concentration and is thus likely to be similarly affected.

Q6 What are the exceptions?

Excessive concentration can impair recognition memory and creative thinking, so as moderate warmth leads to lowered arousal it can paradoxically improve the performance of work that includes such tasks.

Q7 Does low relative humidity (RH) affect performance?

Not always, although levels below 15% RH were found to impair visual acuity and the performance of tasks requiring continuous acquisition of visual data, which are both crucial in process control, driving, piloting an airplane and work with PCs (Wyon et al., 2006).

Mechanisms

Q8 How do raised temperatures affect performance?

Raised temperatures have been found to increase end-tidal CO_2 ($ETCO_2$ is an indicator of mild "acidosis", which is an increase in the concentration of CO_2 in the blood) and to decrease oxygen saturation in blood (SpO_2), both of which are likely to be detrimental for mental work (Lan et al., 2011).

Q9 How does poor air quality affect performance?

Poor air quality may lead to mild acidosis, exactly as raised temperature does, because it has been found to reduce CO_2 emission from occupants (Bako-Biro et al., 2005). If so, this may be why both factors have such similar effects. Satish et al. (2012) have recently shown that increasing the ambient CO_2 concentration artificially can decrease performance, suggesting that ambient CO_2 may have to be regarded as a pollutant instead of as an indicator of low outdoor air supply rate.

Magnitude

Q10 What is the magnitude of the negative effects of the indoor environment on performance?

For adults, up to 5% in the laboratory (Wyon, 2004), up to 10% in the field (Wargocki et al., 2004). For schoolchildren, over 20% (Wargocki and Wyon, 2006).

Q11 Is work in transportation environments similarly affected?

It would seem so, as driver vigilance was found to be reduced by up to 30% by warmth in field intervention experiments lasting only 1 h (Wyon et al., 1996).

Q12 What are the estimated costs of allowing poor IEQ to reduce performance?

As staff costs per unit of floor area exceed operating costs by 100:1, the effects observed are seldom negligible (Fisk et al., 2011).

Q13 Surely children are less affected than adults because they are young and healthy?

We have found that their performance is more affected, not less, and believe that this is because children in school are by definition doing work that is new to them, while adult workers are usually very familiar with the work they do and thus are better able to cope with environmental effects that make their work more difficult.

Q14 Is factory work likely to be less affected by thermal and IAQ effects than office work?

We believe not, as most workers in modern factories have to interact with computers, just as office workers do.

Methodology

Q15 Does laboratory research really predict what happens in practice?

Many field studies have found that the negative effects of poor working conditions are greater in real workplaces than would have been predicted from laboratory experiments (Wargocki et al., 2004; Tham and Willem, 2005). This may be because laboratory experiments use paid subjects, who tend to exert more effort than they would routinely in the course of a necessarily brief laboratory exposure to poor IEQ.

Q16 Why do some laboratory experiments show no effects on performance?

If subjects are highly motivated they can sometimes maintain performance during short exposures to poor indoor environmental quality. Negative effects on fatigue may then be found instead. Additionally, some studies may simply have missed the subtle changes in performance that are caused by slightly sub-optimal indoor environmental conditions.

Q17 Do performance tests really predict productivity?

Logically, yes, and, although environmental effects on component skills have yet to be validated as predictors of overall productivity, call-centre results use "bottom-line" measures of the call volume achieved in practice (Wargocki et al., 2004; Tham and Willem, 2005), and schoolwork is what children do in school (Wargocki and Wyon, 2006; Haverinen-Shaughnessy et al., 2010; Bako-Biro et al., 2012).

Q18 Do field intervention experiments predict what happens in practice?

Yes. Field intervention experiments examine directly what does happen in practice, often over periods of several weeks or even months. Tests of year-end educational attainment have been found to support predictions based on short-term intervention experiments in classrooms (Wargocki and Wyon, 2006; Haverinen-Shaughnessy et al., 2010).

Q19 Can experiments of limited duration predict what happens in practice?

It depends on the length of exposure. Most continuous work is in fact performed in periods lasting less than 5 hours, followed by a break, and even laboratory experiments may include 5-hour exposures.

Q20 Does a decrease in the performance of schoolwork indicate reduced learning?

Not proven. But surely schoolwork is assumed by teachers to promote learning? Test scores used by teachers and regulators to observe progress in learning have been found to correlate with spot measurements of ventilation (Haverinen-Shaughnessy et al., 2010).

Q21 Are research findings on performance from Northern Europe valid in warmer climates?

Yes. Very similar results were obtained when the same experiments were repeated in Singapore (Tham and Willem, 2005).

Indicators

Q22 What seems to be the most reliable indicator of indoor air quality effects on productivity?

Until we know which pollutants are causing the negative effects on people, the outdoor air supply rate per person seems to be the most reliable indicator (Seppänen et al., 2006).

Q23 Can indoor air quality as assessed by visitors predict performance?

It has been experimentally shown that it does (Wyon, 2004), except in the case of pollutants with no odor.

Q24 Can subjective assessments of indoor air quality by occupants be used to predict performance effects?

No. Sensory habituation ensures that increasingly poor air quality may be underestimated, except by visitors (Wyon, 2004).

Q25 Can occupants reliably assess their own productivity?

So far there is no reliable evidence that they can. Self-estimated productivity may simply indicate the effort they are aware of exerting (Wyon, 2004), and/or wishful thinking and a desire to placate management.

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Q26 What is the most reliable indicator of thermal effects on performance?

Air temperature is not a reliable indicator in any absolute sense, because performance is a function of the heat balance of the body (which is affected by clothing, metabolic rate, air velocity, etc.), but in a given work situation it is a very useful basis for comparison. In the cold, manual dexterity is progressively impaired as the body actively reduces finger temperature to conserve heat, and in slightly warm conditions, mental performance has been found to decrease when finger temperatures approach their maximum value of about 36C and sweating must be initiated to maintain the body's heat balance. Finger temperatures in the 30-34C range are therefore a reliable indicator that thermal conditions are optimal for most kinds of performance.

Q27 Do occupants' assessments of thermal discomfort predict effects on performance?

Not always, because they may be able to avoid discomfort by working less. This implies that the adaptive model of thermal comfort should NOT be used in isolation to justify energy conservation measures, because that could lead to conditions that cause sub-optimal performance and productivity (Lan et al., 2011).

Q28 Can we use sick building syndrome symptoms to predict effects on productivity?

Yes, in theory, because they do co-vary. But the data is still too meager to create a robust relationship (Tham and Willem, 2005).

Q29 Is absenteeism a useful indicator of effects on productivity?

Poor ventilation does increase absenteeism (Milton et al, 2000), but so do many other factors.

Mitigation

Q30 Is there a simple way to avoid indoor air quality effects on performance?

Generations of experienced teachers ensured that children spent brief but regular periods in fresher air, i.e. outdoors, even in cold weather. Although this strategy does not seem to have been validated experimentally, our view is that it might work just as well for adults as for children.

Q31 Can the presence of windows that can be opened provide this effect?

No, because they will not be opened spontaneously unless it is also warm and because opening windows will often be seen as a waste of heating or cooling energy.

Q32 Can personalized ventilation providing fresh and cool air directly to the breathing zone be used for this purpose?

Yes, to the extent that users are aware that ambient conditions are sub-optimal.

Q33 Does increased outdoor airflow always improve performance?

No. It can even have the reverse effect if it passes through particulate filters that are full of dust (Wargocki et al., 2004).

Q34 Does airborne dust affect performance?

There is no evidence that it does, even though dust is expected to have negative effects on chronic health problems. Short-term effects of poor air quality on the performance of school work remained after airborne dust had been removed, so the negative effects observed were attributed to gas-phase air pollutants (Wargocki et al., 2008).

Q35 Can we allow indoor temperatures to drift upwards, to conserve energy in buildings?

No, because negative effects on performance will increase progressively, even if some subjective habituation takes place (Kolarik et al., 2009).

Q36 Are thermal effects on performance a function of air temperature only?

No. They are a function of the heat balance of the body.

Q37 Does this mean that it may be possible to maintain performance at raised temperatures?

Anything that increases heat loss from the body makes raised air temperature more tolerable.

Q38 What about physiological acclimatization to heat?

Physiological acclimatization to heat requires hard physical exertion well beyond what is necessary for the performance of office work.

Going forward

Q39 What are the most commercially important questions for future research?

We have identified the following 10 high priority research topics:

1) Are the combined effects of temperature and indoor air quality additive?
2) How does performance vary with self-estimated performance?
3) Which component skills are affected by indoor temperature and air quality effects?

4) Is high-level work involving decision-making and creative thinking similarly affected?
5) Are leisure activities negatively affected by poor indoor environmental quality?
6) Is sleep affected by temperature and IAQ and if so does this affect next-day performance?
7) What is the economic impact of all these effects on different kinds of productivity?
8) What is the most cost-effective way to reduce the negative effects of poor IEQ?
9) How can energy be conserved without affecting performance?
10) How do energy certification schemes affect productivity?

Q40 Which underlying mechanisms are worth investigating?

We believe that that the following 4 topics should be addressed by future research:

1) Do thermal and indoor air quality effects on acidosis decrease performance?
2) Is the acidosis caused by shallow breathing or by decreased gas exchange in the lungs?
3) Which gas-phase indoor air pollutants have this effect, and can it be prevented?
4) Are any other mechanisms involved?

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REFERENCES

The references are in the web version of the article at www.rehva.eu ■