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Indoor Environment, Productivity in Offices

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Scientific data has shown that a deteriorated IEQ is related to increased sick building syndrome symptoms, respiratory illnesses, sick leave, and to reduced comfort and productivity losses. Some calculations show the cost of deteriorated indoor environments is higher than building heating costs.[1] Macroeconomic estimates indicate that improving IEQ can generate large economic benefits, at least tens of billions of dollars per year in the U.S., and possibly more than $100 billion per year.[2,3]

A few sample calculations have shown that measures to improve IEQ are cost effective when the financial value of health and productivity benefits are considered.[2,4–10] An obvious need exists for models that enable economic outcomes of health and productivity to be integrated with initial, energy and maintenance costs in cost-benefit calculations.

This article presents models for estimating how the indoor environment quantitatively affects sick leave and work performance, two indicators of productivity. The models were developed using the existing data on the issue and acknowledging the high level of uncertainty associated with the models.

More detailed presentations of these models are provided,[11–13] as well as in the papers cited subsequently.

Multiple factors other than IEQ also affect work performance. An individual's performance is influenced by the working environment, personal motivation, and by the person's ability to perform the job. The working environment includes IEQ conditions, such as temperature, ventilation, noise, lighting, etc., but also facility services, such as e-mail service and infrastructure conditions such as workstation layout.[14]

Psychosocial aspects and the occupant's perceptions of the workplace environment may also affect productivity. It is through changes

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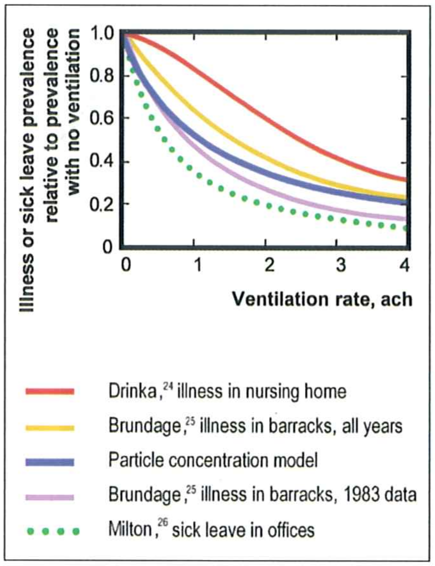

Figure 1: Predicted trends in illness or sick leave vs. air-change rate.[5] Different lines represent calibrations of the disease transmission model with empirical data, except the blue line. Particle concentration model is based on an assumption of airborne disease transmission risk, which is inversely proportional to the total removal rate for airborne infectious particles.

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in building design and operation that society can improve IEQ and realize associated productivity benefits. Hence, ASHRAE members have an important role to play if we are to attain these benefits.

Quantitative Relationships Between IEQ & Productivity

For engineering cost-benefit calculations, it is necessary to be able to quantitatively estimate how IEQ factors influence productivity. Based on research performed so far, we have estimated the following quantitative relationships:

- Relationship between ventilation rate and short-term sick leave and associated absence;
- Relationship between ventilation rate and work performance;
- Relationship between perceived air quality and work performance; and
- Relationship between temperature and work performance.

Ventilation Rate and Short-Term Sick Leave

Quantitative relationships between ventilation rate and short-term sick leave were estimated by calibrating a theoretical model of airborne transmission of respiratory infections with published field data in which ventilation rate was the independent variable and short-term sick leave or illness incidence were the outcomes.[5] The model accounts for the effects of ventilation, filtration, and indoor particle deposition on airborne concentrations of infectious particles and on the feedback process by which more disease transmission in a building leads to more sick occupants who are the source of infectious particles. The model is calibrated (i.e., it is fitted to several sets of empirical data), resulting in different curves relating ventilation rates with illness prevalence.

The resulting relationships are presented in *Figure 1*. Although the model has many sources of uncertainty,[5] the effect is large and may be economically significant. The curves in *Figure 1* indicate about a 10% reduction in illness for doubling of outdoor air supply rate.

Using these relationships, Fisk, et al.,[5] estimate that the economic benefits from reduced absence when an outdoor air economizer is used exceed the energy cost savings, which is often the sole reason for using an economizer, by a factor of approximately three to eight.

Ventilation Rate and Work Performance

An estimate of the relationship between ventilation rate and work performance was developed based on five studies in offices and two studies that collected data in a controlled laboratory experiment.[15] These studies quantified office work performance by measuring performance of simulated office work (typing, addition, proofreading) and by tracking speed of actual work in call centers. One study used a reaction time test to indicate performance. Each data point was weighted by

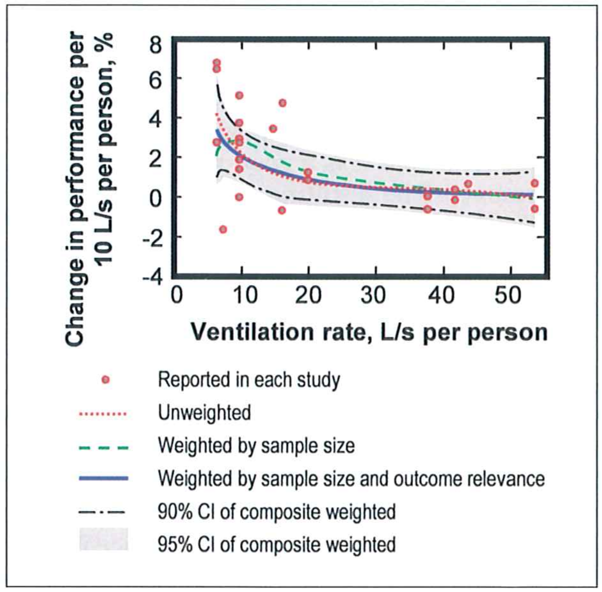

Figure 2: Increase in performance as a function of ventilation rate.[15]

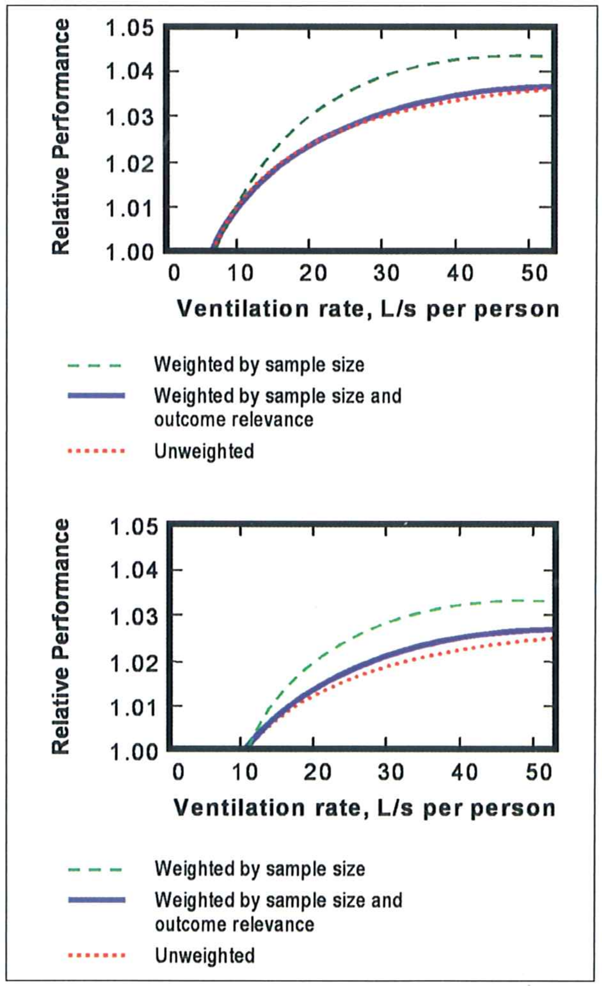

Figure 3: Effect of increasing ventilation rate on performance relative to performance at the reference ventilation rate of 6.5 L/s per person (top figure) and 10 L/s per person (bottom figure).[15]

the number of subjects in the study. The different studies also were assigned weighting factors according to the relevance of the productivity metric for overall office work performance, e.g., the reaction time metric was given a low weight because it is not clear that it is a good predictor of actual office work performance. The resulting normalized adjusted productivity (by percentage) vs. ventilation rate is plotted in *Figure 2* with best fit curves and 90% and 95% confidence intervals (CIs) shown. *Figure 2* shows the best fits to the normalized data: when the initial data were unweighted, weighted by sample size, and composite weighted, i.e., weighted by both sample size and by the relevance of the performance outcome for total work performance. The curves suggest that doubling the outdoor air supply rate will improve the work performance on average by 1.5%. The curves indicate that performance would improve with increased ventilation up to approximately 40 L/s (85 cfm) per person, but performance increases are statistically significant (i.e., 95% CI excludes zero) for ventilation rate increases up to about 15 L/s (32 cfm) per person.

To provide a more practical tool, we used the best fit curves in *Figure 2* to develop curves of relative performance vs. ventilation rate. The results are plotted in *Figure 3* in which the reference ventilation rates were set to 6.5 and 10 L/s (14 and 21 cfm) per person. Due to limitations of data, the ventilation range in the figure cannot be extrapolated.

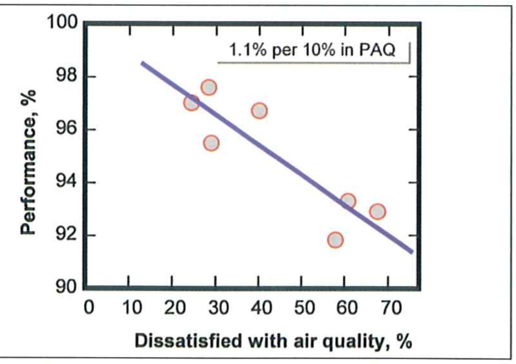

Figure 4: Performance of simulated office work as a function of proportion of dissatisfied subjects with air quality (R^2*=0.78; P=0.008).*[18]

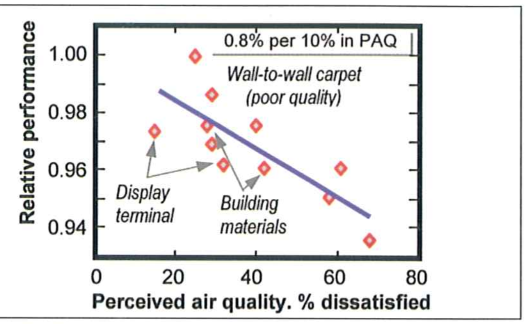

Figure 5: Performance of text typing as a function of the proportion of subjects dissatisfied with the air quality (R^2 *= 0.60).*[21]

Perceived IEQ and Work Performance

An estimated relationship between perceived air quality and performance of office work is presented in *Figure 4* based on three experiments with subjects performing simulated office work.[16–19] Air quality was modified by changing the outdoor air supply rate in an office polluted by a sample of a 20-year-old carpet from a problem building, or by removing this carpet from the office. The quantitative relationships indicate a 1.1% increase in performance for every 10% reduction in the proportion of dissatisfied subjects with the air quality, in the range 25%–70% dissatisfied subjects perceived by persons immediately after entering the space from the clean air. When the air quality is evaluated with this procedure, the typical percentage of dissatisfied subjects is 25%–60%.[20] Based on the relationships shown in *Figure 4*, one may predict that improving air quality in the buildings with the highest proportion of dissatisfied subjects to the levels observed in the buildings with the lowest proportion of dissatisfied subjects would improve the performance of office work by about 3%–4%.

The relationship in *Figure 4* was later verified[21] by combining the data from experiments in which carpet was a pollution source[18] with the data obtained in studies when the sources of pollution were personal computers with CRT monitors[22] and linoleum, sealant, and shelves with books and paper.[21] The combined data were used to create the relationship between performance and air quality presented in *Figure 5*. The resulting relationship, about 0.8% change in performance for every 10% change in proportion of subjects dissatisfied with air quality, is similar to that observed in studies with carpet.[18] However, the performance indicator was only text typing,[21] unlike in the studies with carpet,[18] where the performance outcome included performance of text typing, addition and proofreading.

Based on the relationships shown in *Figures 4* and *5*, one can estimate the effect of improving perceived air quality in office buildings on the performance of office work.

Temperature and Performance Of Office Work

Figure 6 shows a relationship between indoor air temperature and work performance based on 148 assessments of performance from 24 studies.[23] These studies tracked objectively measured indicators of work performance (e.g., talk time in call-centers), speed and accuracy of complex tasks or simple visual tasks, performance of vigilance tasks or manual tasks related to office work and measured the rates and accuracy of learning. The results of each study were weighted by the number of study subjects, and the different studies were assigned weighting factors according to the relevance of the productivity metric for overall office work performance. Then, study results were normalized by calculating percentage change in performance for every 1°C (1.8°F) change.

Figure 6 shows the normalized data and shows curve fits to the data with 90% confidence intervals. Positive values indicate that performance improves when temperature is increased and negative values indicate that performance is reduced when the temperature is increased. The curve crosses zero at about 22°C (72°F). Consequently, the data indicate that performance improves with increased temperature when temperature is below 22°C (72°F) and decreases with increased temperature above 22°C (72°F).

The relationship presented in *Figure 6* is replotted in *Figure 7* using 22°C (72°F) as a reference point. *Figure 7* indicates that performance changes by about 1% for every 1°C (1.8°F) change in temperature from the reference of 22°C (72°F).

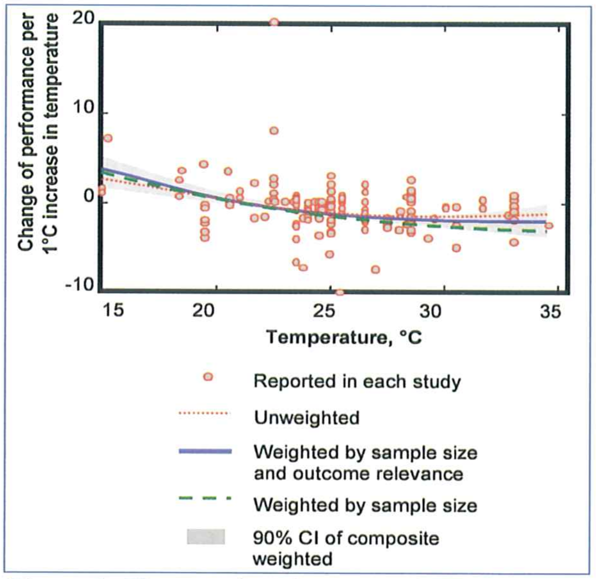

***Figure 6:** Change of performance (ΔP% per °C increase) as a function of temperature. Positive values indicate that performance is improved when temperature is increased, and the negative values show that performance is reduced when the temperature is increased.*[23]

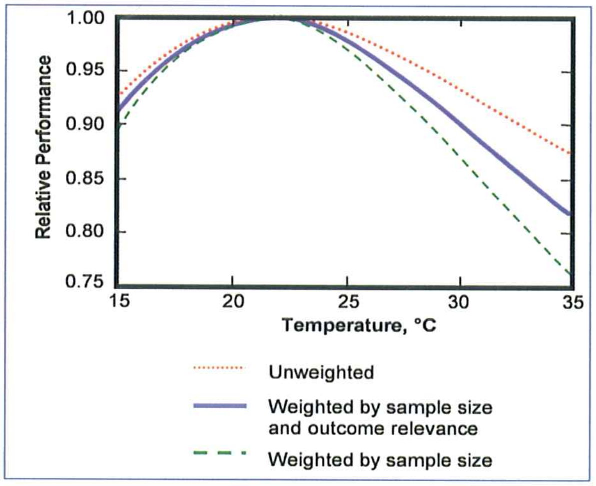

***Figure 7:** Relative performance as a function of temperature. The reference is performance at 22°C.*[23]

Who Receives the Benefits

Based on one's perspective, the cost effectiveness of investments for better building design and operation will vary. Consider the perspectives of the building owner plus employer (i.e., case of owner-occupied building), building owner (lessor), employer (lessee), and society.

In owner-occupied buildings, the owner/employer benefits directly from the improvements in the health and performance of his employees. Real benefits, of course, depend on the specific situation in the company such as: number of employees, type of work, and market situation. In leased buildings, the direct health and productivity benefits of IEQ improvements will be experienced by the lessee, although the lessor should benefit from an ability to increase the rent in a space with more healthy and productive occupants, and from an associated increase in the building's market value.

Hanssen[6] refers to a U.S. study concluding that, when a tenant does not renew the lease agreement (e.g., due to frequent IEQ complaints), the costs of lost rental income, remodelling, etc., to the owner will be equivalent to the rent of one-and-half years. In a building with superior IEQ, the lessor may additionally benefit from reduced maintenance costs resulting from fewer IEQ complaints. In general, neither the lessor nor the lessee benefit from reduced medical care costs, which are usually covered nationally or by insurance. However, the broader society will benefit from reduced medical care costs, and from improved health and productivity.

Conclusion

For cost-benefit analyses, it is not sufficient to have information demonstrating a statistically significant effect of IEQ on health or work performance—the size of that effect must be quantified. Here, we have shown that existing data are adequate to develop some quantitative estimates of relationships between IEQ, or related building design and operational characteristics, and people's health and performance.

Although these relationships may have large financial implications, they also have some limitations. Foremost among the limitations is the high uncertainty in the estimated quantitative relationships between IEQ, health and productivity outcomes. In addition, the relationship between indoor-related productivity outcomes and business is uncertain and case specific. Those concerned with these relationships should recognize the remaining high level of uncertainty, and that benefits of improved IEQ may be distributed among stakeholders.

The benefits of IEQ improvement measures will depend on the initial condition in the building. For example, increased ventilation will be more helpful in a building with strong indoor pollution sources or with an initially low ventilation rate. Hence, uncertainty about magnitude of benefits in specific buildings may inhibit investments in IEQ improvements, even when average benefits can be estimated. IEQ improvement measures should be most cost effective when targeted at buildings with poorer IEQ or more IEQ complaints. However, this does not preclude benefits with substantial net economic paybacks in buildings with average IEQ conditions.

Another consideration is that the susceptibility of occupants to different levels of IEQ may vary between and within buildings. It is possible that only a highly susceptible subpopulation is significantly affected by IEQ. Theoretically, it would be more cost effective to target remedial actions for those who suffer the most from poor IEQ. Such targeting often will be impractical, but there are exceptions (e.g., provision of individual temperature control with local heaters or providing personalized ventilation systems).

The authors acknowledge the high level of uncertainty associated with the incorporation of health and productivity effects in cost-benefit calculations related to building design and operation. At the same time, they believe that estimating productivity benefits using the best available information will generally lead to better decisions about building design and operation compared with the current practice of ignoring the potential benefits.

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