The effect of perceived indoor air quality on productivity

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ABSTRACT
A new derivation of productivity calculation model based on pollution loads and contaminant removal effectiveness is applied and the effect of the improved ventilation efficiency on productivity is estimated. The findings show that the proportion dissatisfied could be a suitable predictor of productivity loss due to indoor air quality in different kinds of office work. The proportion dissatisfied is possible to calculate from olf and decipol units. In a case of one person per 10 m^2 (0.1 olf/m^2) and low-emitted material (0.1 olf/m^2), the total sensory pollution load is 0.2 olf/m^2. If the airflow rate is increased from 0.5 l/s per m^2 to 2.0 l/s per m^2, it is possible to achieve 7.3% productivity improvement in the thinking task. The effect of the contaminant removal effectiveness on the productivity loss could be about 0.5–2% between displacement and mixing systems using the same airflow rate.

INDEX TERMS
Productivity; Perceived air quality; Indoor air quality; Productivity assessment method

INTRODUCTION

People spend 90% of their time in indoor environment. It is widely accepted that the indoor environment is important for public health and that a high level of protection against adverse health effects due to inadequate quality of the indoor environment quality should be provided and assured. This has been incorporated in the human rights to a healthy indoor environment as formulated in the WHO Constitution (WHO, 1985). In essence, the human right to a healthy indoor environment includes the right to breathe clean air (WHO/EURO, 2000), the right to thermal comfort and the right to visual health and visual comfort.

The results obtained by Wargocki *et al.* (1999) in an intervention experiment has indicated that reducing the pollution load on indoor air, as recommended by CEN CR 1752 (1998), is an effective way of improving the perceived air quality, reducing the intensity of some Sick Building Syndrome (SBS) symptoms and increasing some aspects of occupant productivity. In that experiment, a common pollution source was removed from a typical office space, while the ventilation rate and all other environmental parameters were kept unchanged. Lagercrantz *et al.* (2000) has repeated the same experiment and attained similar results. In a subsequent experiment, the outdoor airflow rate was altered at constant pollution load (Wargocki *et al.*, 2000a). Also, this study confirms the link between the pollution load and the perceived air quality.

This study reports on the assessment of productivity loss in air-conditioned office buildings using the perceived air quality approach and makes use of Wargocki's laboratory findings (Wargocki *et al.*, 1999, 2000a,b) as the basis to compare and to relate how the productivity loss could be minimized through improved sensory pollution load. This interpretation using the proportion dissatisfied as a prediction of the effect on productivity indicates the nature of productivity loss that was reported in earlier studies. In this paper, a new derivation of

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productivity calculation model based on pollution loads and contaminant removal effectiveness is applied and the effect of the improved ventilation efficiency on productivity is estimated.

METHODS

The results of three previous independent studies have shown that the performance of simulated office work improves when air quality increases (Wargocki *et al.*, 1999, 2000b; Lagercrantz *et al.*, 2000). A positive correlation was found between the acceptability of air quality and performance. The results indicate that every 10% decrease in the proportion dissatisfied with the air quality below the air quality level causing 70% to be dissatisfied can improve the performance of typing by 1.4%, of addition by 1.1% and of proof-reading by 2.3%. Thus, the productivity loss is strongly dependant on the nature of the task.

The following approach simplifies and uses of two main tasks: (1) typing of 1.4% per 10% of dissatisfied and (2) proof-reading of 2.3% per 10% of dissatisfied as a ‘creative thinking’ type of task. Hence, it possible to predict indoor air quality (IAQ) effects on different job descriptions by using time weighting factors for these two tasks.

These published findings provide the impetus to create a model to estimate the impact of perceived air quality on the productivity loss of workers in an office space. Results from Wargocki *et al.* (2000b) are therefore used in this study to create a generic productivity loss model using the proportion dissatisfied as a predictor. In that model, the effect of the contaminant removal effectiveness is also integrated.

Fanger (1988) has introduced the olf and decipol units to quantify and to compare the different types of pollution sources. Olf is a unit of perceived air pollution. One olf is the emission rate of air pollutants from one standard person. Building materials emissions have been estimated at 0.1–0.2 olf/m^2. The decipol unit quantifies the level of perceived air quality. Humans perceive air quality by their olfactory and chemical sense, being sensitive to odorants and irritants in the air. One decipol is defined as the pollution caused by one standard person (one olf) ventilated by 10 l/s of fresh outdoor air.

Fanger (1988) has published the equation to estimate the number of the dissatisfied as a function of the perceived air pollution using the decipol unit. Equation (1) shows the correlation between the percentage of dissatisfied and the decipol level:

$$\mathrm{PD} = 395 \cdot \mathrm{e}^{(-3.25 \cdot C^{-0.25})} \qquad (1)$$

where PD is percentage of dissatisfied and *C* is perceived air quality (decipol).

Using Eqn (1) and the correlation between productivity and the perceived IAQ, it is possible to calculate the effect of different pollution loads and ventilation airflow rate for productivity.

In the basic approach (Fanger, 1988), it is assumed to have complete mixing. The maximum value of the contaminant removal effectiveness is deemed 100% with the mixing system. With the displacement ventilation, it is possible to reach better contaminant removal effectiveness (Mundt, 1996). This means that the systems like displacement ventilation and personal ventilation can improve indoor environment such that health and productivity may be enhanced.

It should be noted that in practice the perceived IAQ could be better because of infiltration. Normally, the infiltration is around 0.1–0.3 1/h (0.07–0.2 l/s per m^2 with 2.5 m free ceiling height). Anyhow, at the same time the ventilation system itself (air-handling unit and ductwork) could be a significant source of emissions and it could cause the IAQ problem.

RESULTS

Perceived Air Quality and Productivity

Figure 1 shows the linear correlation between perceived air quality and relative productivity loss. The nature of the task is handled as a parameter. It should be noted that only the effect of changes from the starting point is possible to analyze with Figures 1–3. In the other words, the productivity loss values as a function of the percent of the dissatisfied are not absolute.

As an example in thinking task, using Eqn (1) it is possible to calculate that the minimum proportion dissatisfied in normal design conditions (one person/10 m^2, 10 l/s per person and low-emitted material (1 olf)) is 26% (relative productivity loss of 5.9%). If the dissatisfied is reduced to 15% (relative productivity loss of 3.5%), it is possible to improve the productivity to 2.4%

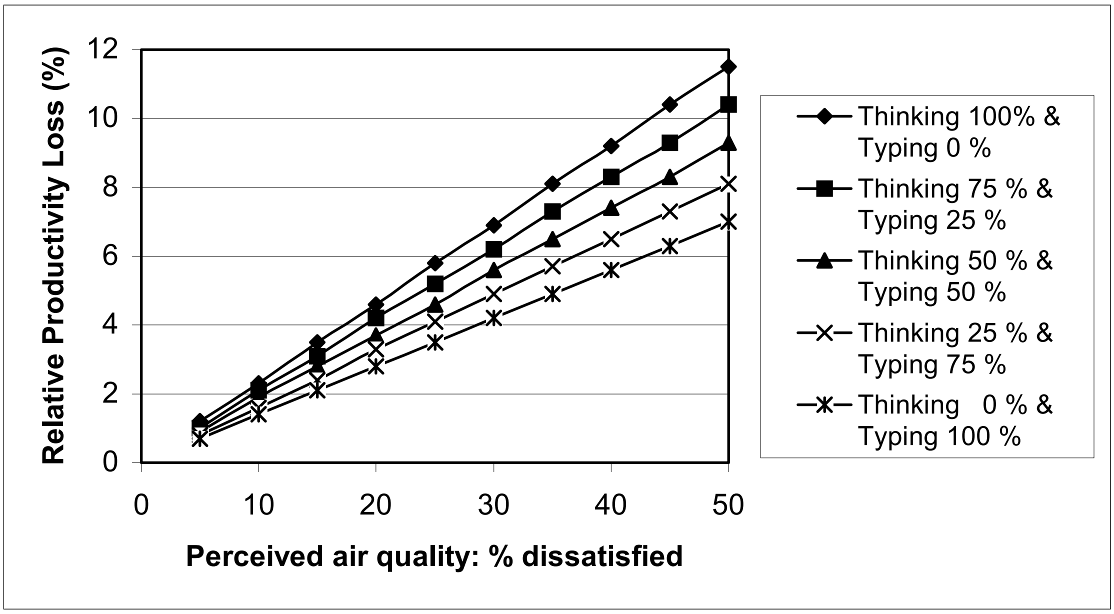

Figure 1 Relative productivity loss for different combination of tasks as a function of the percent of the dissatisfied with the air quality.

Another way to estimate the perceived air quality is via the decipol unit (see Eqn (1)) that combines a known pollutant load (olf) and outdoor airflow rate. Figure 2 shows the non-linear relationship between decipol and relative productivity.

As an example with assumptions of two persons per 10 m^2, 5 l/s per person and material emission of 0.2 olf/m^2, the decipol value is 4 (relative productivity loss of 9.1%). If the decipol value is reduced to 2.0 (relative productivity loss of 5.9 %) by increasing airflow rate to 10 l/s per person, the productivity improves 3.2%.

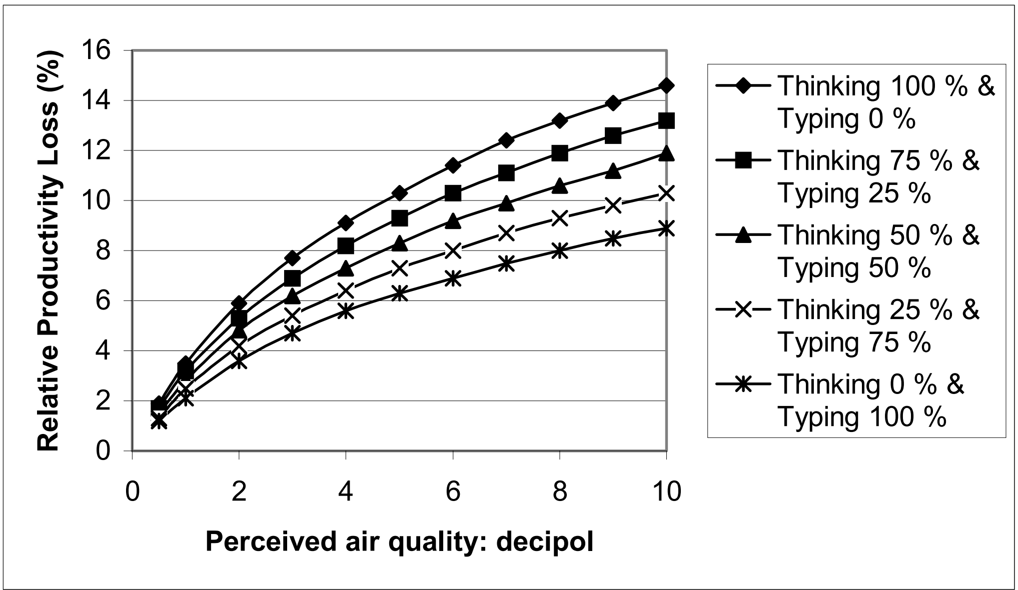

Figure 2 Relative productivity loss for different combinations of tasks as a function of perceived air quality using decipol unit.

Ventilation Efficiency Impact on Productivity

Ventilation efficiency has been classically divided into two groups: one for ability of a system to exchange the air in the room and one for the ability of a system to remove contaminants (Mundt, 1996). In this study, the average air contaminant removal effectiveness in the occupied zone is used to estimate the effect of the ventilation system on the productivity loss.

The contaminant removal effectiveness is a measure of how efficiently the airborne contaminants are removed from the room. Theoretically, the maximum value of the contaminant removal effectiveness is 100% in complete mixing ventilation system. However, in real applications perfect mixing is not possible and the efficiency is usually less than 100%. On the other hand, measurements with displacement ventilation have shown higher values such as 150–200% (Mundt, 1996). Indicating lower pollutant level in the occupied zone, this could aid improving productivity in different working places at the same outdoor airflow rate.

Figure 3 shows the effect of the contaminant removal effectiveness on relative productivity loss with different airflow rates in a thinking task. In Figure 3, the infiltration is 0.1 l/s per m^2, material emission 0.1 olf/m^2 and occupant density is one person per 10 m^2.

In displacement ventilation, the supply airflow rate is typically 3–6 l/s per m^2. In cold and temperate climates where the heat recovery system is normally used, the supply airflow rate is the same as that of the outdoor airflow rate. In the Tropics, the return air is used and the requested outdoor airflow rate is adjusted for the demand of different applications, e.g. in offices could be as low as 0.5 l/s per m^2.

The effect of contaminant removal effectiveness on productivity loss could be about 0.5–2% between ideal mixing (efficiency of 100%) and displacement ventilation (efficiency of 150–200%) systems if both of these systems have the same airflow rate per m^2.

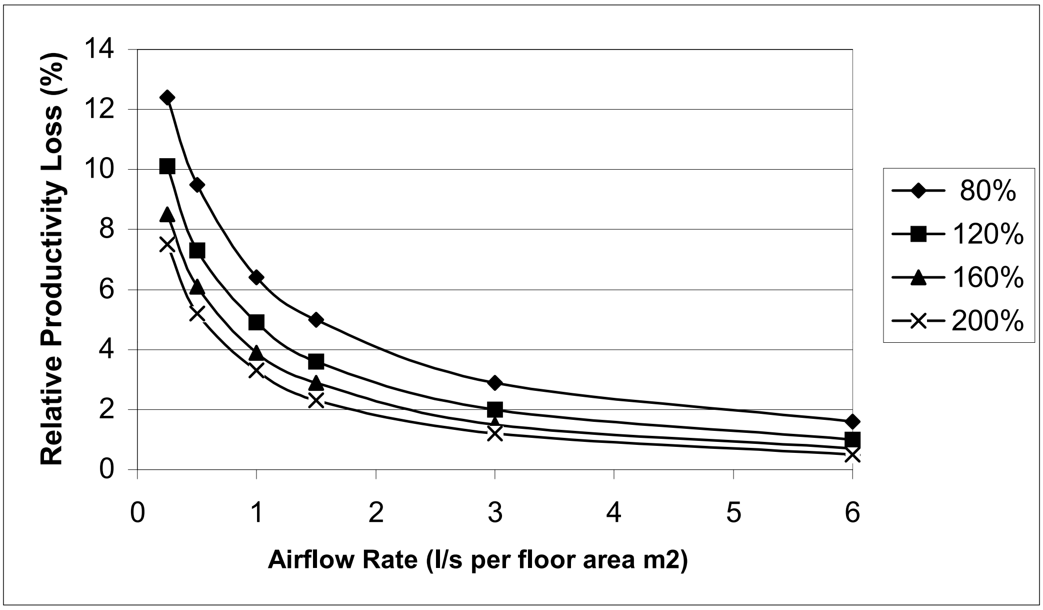

Figure 3 Relative productivity loss as a function of the specific outdoor airflow rate with different contaminant removal effectiveness in a thinking task.

Even, the productivity loss of 0.5–2% sounds quite small, the economic impact is about the same level as the annual cost of the total air-conditioning system (Woods, 1989). Salaries of workers in the US office buildings have exceeded the cost of building energy, maintenance, annualized construction and rental by a factor of 100. Thus, even a 1% increase in productivity should be sufficient to justify an expenditure equivalent to a doubling of the construction and maintenance costs. It should also be noted that in tandem 1–2% reduction in the loss of productivity is equivalent to reduce 5–10% of the proportion dissatisfied.

DISCUSSION

The main factors affecting perceived air quality are pollution load and the outdoor airflow rate. These factors could be used to calculate the estimation for the productivity loss difference in different design conditions at the various ventilation efficiency levels. It should be noted that the described method is only feasible to estimate the effect of changes from the selected reference point. At the moment, the estimation of the absolute values of productivity loss at different IAQ conditions is not possible.

Typically, the minimum admissible outdoor airflow rate is 0.5–1.0 l/s per m^2 in office spaces. In a case of two persons per 10 m^2 (0.2 olf/m^2) and material emission of 0.2 olf/m^2, the total sensory pollution load will be 0.4 olf/m^2. If the minimum airflow rate is increased from 0.5 to 2.0 l/s per m^2, it is possible to achieve 7.3% productivity improvement. Hence, the usage of minimum-airflow-rate design principle would affect significantly on productivity. This productivity reduction is conscious or unconscious development during the design process when the outdoor airflow rates are adjusted.

Displacement ventilation can help to improve IAQ through better contaminant removal effectiveness and hence enhance productivity. On comparison between the mixing and displacement system illustrates that the potential of the ventilation efficiency improvement could be 0.5–2%. It should be noted that the economic impact of 1% productivity loss is equivalent to the annual costs of the total air-conditioning system.

A few outstanding issues remained to be resolved in future work: (1) The effect of different pollutants on the perceived air quality needs to be understood more concisely; (2) the absolute values of the productivity loss at different IAQ conditions should be studied; (3) the effect of ventilation efficiency should be investigated on perceived air quality; (4) more detailed work is needed before we are able to estimate the contaminant levels in the breathing zone with different ventilation system and (5) productivity loss for different office tasks must be determined.

CONCLUSION

Based on the developed model, increasing the airflow rate from the minimum-airflow-rate design value, it is possible to improve productivity easily by 7%. Displacement ventilation can help to improve IAQ through better contaminant removal effectiveness and hence enhance productivity. The effect of the improved contaminant removal effectiveness on the productivity loss could be about 0.5–2%.

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