Ventilation and Work Performance

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ABSTRACT

The paper evaluates the potential work performance benefits of increased ventilation. We analysed the literature relating work performance with ventilation rate and employed statistical analyses. The studies included in the review assessed performance of various tasks in laboratory experiments and measured performance at work in real buildings. Almost all studies found increases in performance with higher ventilation rates. The studies indicated typically a 1-3 % improvement in average performance per 10 L/s-person increase in outdoor air ventilation rate. The performance increase per unit increase in ventilation was bigger with ventilation rates below 20 L/s-person and almost negligible with ventilation rates over 45 L/s-person. The performance increase was statistically significant with increased ventilation rates up to 15 L/s-person with 95% confidence interval. This relationship has a high level of uncertainty; however, use of this relationship in ventilation design and feasibility studies may be preferable to the current practice, which ignores the relationship between ventilation and productivity. With an example we show that that an increase of ventilation rate from 6,5 or 10 L/s to 20 L/s per person results in much greater benefits with increased productivity than corresponding in crease in total energy consumption in a typical Finnish office building.

KEYWORDS

Economics, productivity, performance, ventilation rate, office building

INTRODUCTION

Ventilation rates (outdoor air) vary considerably within and among commercial buildings. HVAC design, installation, operation, and balancing, occupant density, and air infiltration in building envelopes are some of the factors that cause variability in ventilation rates. Ventilation rates are not well controlled in individual buildings due to lack of effective measurement and control systems and to infiltration. Variability in time average ventilation rates among buildings are due primarily to different HVAC operational practices and designs, including the presence or absence of economizers.

Some of the effects of ventilation rates have been long recognized. An increase of ventilation rate usually results in better-perceived air quality and a lower concentration of indoor generated pollutants. Low ventilation rates generally lead to higher prevalences of adverse health effects, including SBS symptoms and air borne infectious diseases (Seppänen et al. 1999).

In this paper, we present a summary of available scientific findings on how ventilation rate affects work performance. We have developed (Seppänen et al. 2006) the best possible quantitative relationship between ventilation rate and work performance for use in cost benefit calculations related to building design and operation, and show how it can be used in the engineering analyses.

METHODS

Ventilation rate could influence performance indirectly through its impact on short term sick leave due to infectious diseases, prevalence of SBS symptoms or satisfaction with air quality; however, for cost-benefit calculations we decided that it is most feasible to use the available data directly linking ventilation to work performance.

Relatively few studies report the effect of ventilation rate on objectively measured performance. We included in this review those studies that had used objective indicators of performance that are likely to be relevant in office type work, such as text processing, simple calculations (addition, multiplication), length of telephone customer service time, and total handling time per customer for call-center workers. We also included a study conducted in schools using the reaction times as an indicator of performance.

Through computerized searches and reviews of conference proceedings, we identified six relevant studies with data collected in the field, five in offices (Heschong Mahone Group, 2003; Federspiel et al. 2004; Tham and Willem 2004; Tham 2004; Wargocki P. et al. 2004.), one in schools (Myhrvold and Olesen 1997) and two studies with data collected in controlled laboratory environment (Bako-Biro 2004; Wargocki et all. 2000). All office studies were performed in call centres where the time required to talk with customers, the processing time between calls with customers, and other relevant information were automatically recorded in computer files. In these studies, the speed of work, e.g. average time per call or “average handle time”, was used as a measure of work performance. Laboratory studies typically assessed work performance by having subjects perform one or more computer-administered tasks that simulated aspects of actual work and by subsequent evaluation of the speed and/or accuracy of task performance. We calculated the quantitative effect on performance from adjusted data given in the papers, when available. Some of the studies compared only two ventilation rates, while some provided data comparing several ventilation rates. We included in the summary all reported data points regardless of the level of statistical significance, which actually was not reported in all studies.

The performance metrics varied among the studies. From each study, a performance change parameter was first calculated by subtracting the performance at the lower ventilation rate from the performance at the higher ventilation rate and dividing the difference by the performance at the lower ventilation rate. The resulting parameter was further normalized by dividing by the difference between the two ventilation rates in L/s-person, and multiplied by 10. The result is the fractional change in performance per increase in ventilation of 10 L/s-person. Positive values indicate an increase in performance with an increase in ventilation rate.

The included studies also varied greatly in sample size and methods. In a meta-analysis, estimates from each study should be weighted by their precision. The Precision of each estimate is inversely proportional to its variance. However, since variance information is not provided for most of the studies, principles of meta-regression cannot be applied properly to estimate the precision of the overall effect. Regression weighted by sample size was chosen as the best alternative, because in general the higher the sample size, the lower the variance. The sample sizes range from 30 to 119, except for one study that has 600 subjects. To prevent the largest studies from having excessive influence on the regression, their weight is limited to 5 times that of the smallest study. Thus, the weighting factor is the number of subjects in the study divided by the number of subjects in the smallest study, but with a maximum value of five. Two laboratory studies reported multiple tasks for the same subjects. The results from these tasks may be highly correlated. In the case of multiple outcomes (i.e., performance tasks, for the same set of subjects under the same conditions), sample size weights were divided by the number of outcomes.

Secondly we also applied a weighting factor based on the authors' judgment of the relative relevance of the performance outcome to real work. For these judgments, we assumed that measurements of the performance changes of real work of call center workers was more representative of overall real-world work performance, and should be weighted higher than performance changes in computerized tasks, such as proof reading or typing, that simulate a portion of work. We also assumed that performance changes in simulated work was more relevant (deserved more weight) than performance changes in reaction time tests which were used in one study. We used the following weighing factors: overall work performance (1), single tasks (0.5) and reaction time (0.25). The sample size weight and outcome relevance weight are then added to get the final set of weights.

We fit 2-degree fractional polynomial models to the data for percentage change in productivity versus ventilation rate, unweighted, weighted by sample size, and weighted by combined final weight separately. The resulting three models are plotted in Figure 1. The very large (21.9%) improvement in performance reported by Tham (2004) at a ventilation rate of 10 L/s-person compared to 5 L/s-person (when the temperature was 24.5^{o}C) was a clear outlier among the data and was excluded from the final analysis. Figure 1 shows also the 90 and 95% confidence limits for the model with composite weights.

RESULTS

Most of the studies show an improvement in performance with increasing ventilation rate, i.e., the data points lie above zero on the vertical axis. There are some exceptions. Wargocki et al. (2004) report a 7.8 % decrease in performance with increase of ventilation rate from 2.5 to 25 L/s-person. The authors suggest that this was due to the loaded (dirty) filter in the air handling unit. Improvements in performance with increased ventilation rate were most clearly seen with initial ventilation rates below 20 L/s-person i.e., the performance increases with increased ventilation rate appear to diminish as ventilation rates become high. The curves in Figure 1 show the percentage change in performance per 10 L/s-person increases in ventilation rate. Based on the estimated polynomial models in Figure 1, the performance at all ventilation rates relative to the performances at reference ventilation rates of both 6,5 and 10 L/s-person are calculated and plotted in Figure 2 (Seppänen et al. 2006).

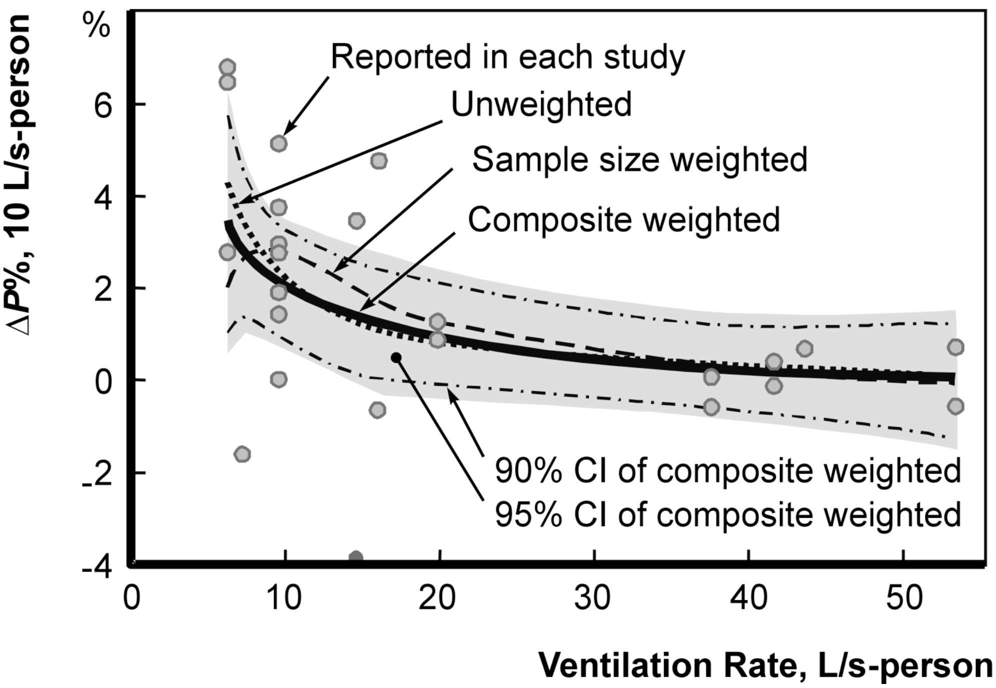

Figure 1: Percentage change in performance ΔP per 10 L/s-person versus average ventilation rate, fitted with 2-degree fractional polynomial regression models. One outlier data point (43.8% at 7,5 L/s-person) is excluded.

The curves in Figure 1 show a trend. They are above zero, indicating an increase in performance, up to approximately 45 L/s-person. As the ventilation rate becomes higher, a unit increase in ventilation rate has a diminished impact on performance. In other words, the positive effect of increases in ventilation rate is stronger with smaller ventilation rates, and weaker with higher ventilation rates. In the ventilation range 6,5 – 10 L/s-person, the increase in performance is 2-3,5 % per 10 L/s-person. In the 10 – 20 L/s-person, 20 - 40 L/s-person, and above 40 L/s-person ranges, the corresponding increases in performance are 1-2%, 0.5 – 1%, and < 0,5%. This trend could be explained by the general principles of ventilation in which the impact of a unit increase in ventilation rate on pollutant concentrations is much stronger with an initial low ventilation rate.

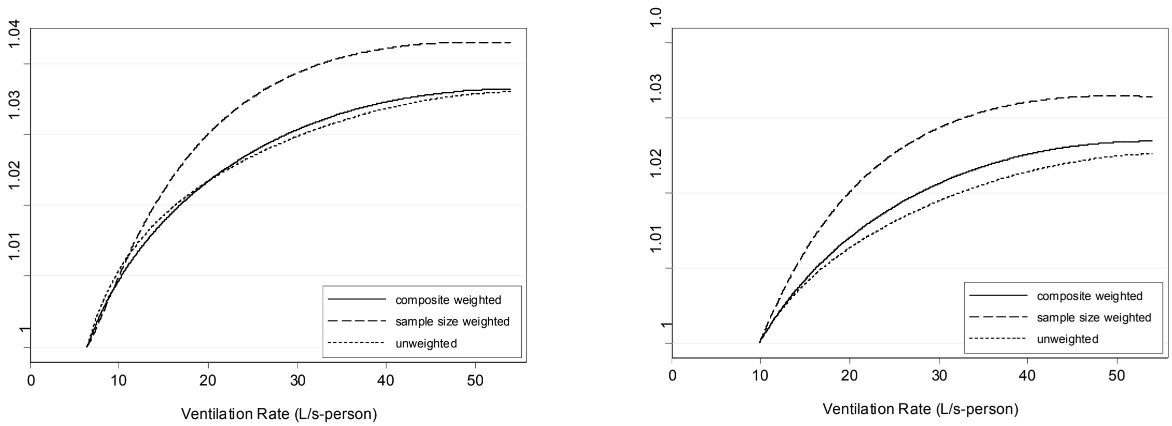

Figure 2: Relative performance in relation to performance at ventilation rate 6.5 L/s-person (on left) and 10 L/s-person versus ventilation rate. The outlier data point was not used.

EXAMPLE OF APPLICATION

A typical modern Finnish office building (Figure 3) was selected for the example (Heinonen et al. 2005, Wargocki and Seppänen 2006). It is a five-story office building used in Finnish studies to implement the Energy Performance Buildings Directive. Ventilation system of the office building was mechanical supply and exhaust with air-to-air heat recovery (temperature efficiency 75%). The supply and exhaust system was operating on weekdays from 6 to 20. Additionally, there was also mechanical exhaust from toilets running 24 hours a day and 7 day a week. The total gross floor area of the building was 4 580 m^2 and the floor area per employee was 14,7 m^2. The value of the annual work used in the example was 30 000 €/employee. The energy consumption was calculated using Helsinki reference year weather data.

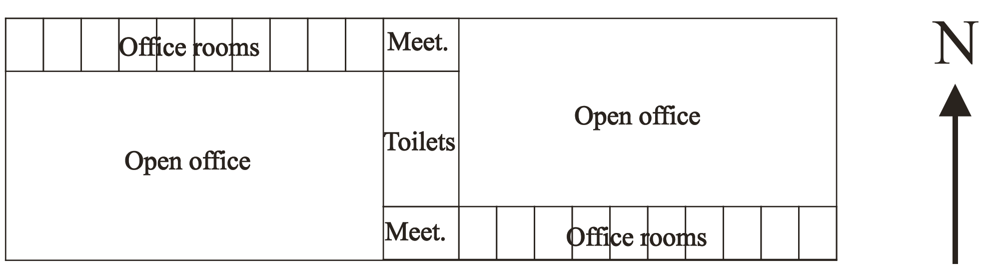

Figure 3: Floor plan of third floor in simulated office building

The effect of ventilation rates on performance and energy consumption was evaluated for a building located in Helsinki. Investment cost and energy costs were calculated for the design ventilation rates of 6,5; 10 and 20 L/s-person. The first costs of air conditioning system including the ventilation was estimated[1] to be 125; 141 and 170 €/m^2 respectively. The energy consumption was calculated with the building simulation programme IDA/ICE (Vuolle and Salin 2000). The curve in Figure 2 represented with a solid line was used to estimate the effect of ventilation on performance.

The energy costs used in the calculations reflect the average energy cost in Helsinki, for heating 0,04 €/kWh was used and 0,1 €/kWh for electricity. The calculated electrical energy in Table 1 includes all electricity used per room: lighting, office equipment, fans, and mechanical cooling (COP=2,5). Heating energy includes all energy used for heating.

Table 1: Annual energy consumption in the simulated office building with three ventilation rates 6,5; 10 and 20 L/s-person. Cost of electricity 0,1 €/kWh and for heat 0,04 €/kWh (district heating).

Vent rate	Electricity			Heat			Total		
L/s-person	kWh	kWh/m^2	€/m^2	kWh	kWh/m^2	€/m^2	kWh/m^2	€/m2	€/person
20	304788	66,5	6,65	354791	77,5	3,1	144,0	9,75	143,2
10	287454	62,8	6,28	257101	56,1	2,25	118,9	8,53	125,1
6,5	284819	62,2	6,22	229424	50,1	2,0	112,3	8,22	120,7

The increase of ventilation rate from 6,5 to 10 or 20 L/s-person increases total energy consumption by 6,6 or 31,7 kWh/a,m^2 respectively or 4,4 or 22,5 €/a per person (Table 2). The corresponding increase of performance is 300 or 690 €/a, person. Taking also into account the increase of investment cost the example show the benefit to cost ratio of 9,4 with increase of ventilation from 6,5 to 10 L/s-person and 7,0 with 6,5 to 20 L/s-person.

Table 2: Annual increase of energy consumption, first cost and benefits of increased productivity in the simulated office building with three ventilation rates 6,5; 10 and 20 L/s-person. Annual value of the work 30 000 €/person.

Change in ventilation rate, L/s-person	Increase in energy consumption, €/a-person	Increase in the first cost, €/a-person*	Increase of maintenance cost (2%), €/a-person	Increase in productivity, %	Increase in productivity, €/a-person	Benefit to cost ratio: productivity increase/increase in energy consumption and first cost
6,5-10	4,4	22,5	4,7	1,0	300	9,4
6,5-20	22,5	63	13,3	2,3	690	7,0
10-20	18,1	41	8,5	1,4	420	6,2

*Reference is the system with the ventilation rate of 6,5 L/s,m^2. Annual cost of increase in investment cost is calculated using estimated investment cost, interest rate of 5%, and lifetime of 15 years for the air conditioning system. This gives an annuity factor of 0,096.
** Maintenance cost of air handling systems 2% from the difference of the first cost

[1] Estimated by Climaconsult Finland Oy consulting company

DISCUSSION

The laboratory studies show a consistent improvement in performance in tasks typical of office work when ventilation rates increase. Field studies with more complex tasks in call centres also generally show the improvement in the performance with higher ventilation rates, but the findings are not as consistent. The tasks in the reviewed studies are quite simple, and it is not clear how well the data apply to performance in actual office environments. However, as the reviewed studies include different tasks, the developed weighted relation may well represent average work in the office and may be applicable in many office environments.

The example compares the costs on energy and the benefits of improved performance when ventilation rates are increased in a typical office building in Finnish conditions. Higher energy or investment cost than in the example will decrease cost to benefit ratio, higher value of the work will improve it.

Our analysis does not account for all of the current and future environmental costs of using energy, such as the health effects from pollutant emissions produced when fossil fuels are burned and the potential risks of global warming. Therefore, to prevent or minimize these adverse environmental effects, energy efficient technologies and practices should be used whenever possible when ventilation rates are increased in order to improve productivity.

CONCLUSION AND IMPLICATIONS

We have demonstrated a quantitative relationship between work performance and ventilation within a wide range of ventilation rates. This relationship has a high level of uncertainty; however, use of this relationship may be preferable to the current practice which ignores the relationship between ventilation and productivity. The quantitative relationship between ventilation and productivity may vary among buildings depending on other building features, such as pollution sources, and on the characteristics of building occupants and their type of work. Remedial measures will generally also be more cost effective in buildings that have low initial ventilation rates.

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