Title

Ventilation and Work Performance in Office Work

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Publication Date

2005-07-01

To be submitted to Indoor Air
4/28/2005

VENTILATION AND WORK PERFORMANCE

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ABSTRACT

Outdoor air ventilation rates vary considerably between and within buildings. The purpose of this study was to evaluate the potential work performance benefits of increased ventilation. We analysed the literature relating work performance with ventilation rate and employed statistical analyses with weighting factors to combine the results of different studies. 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% CI and up to 17 L/s-person with 90% CI.

PRACTICAL IMPLICATIONS

We have demonstrated a quantitative relationship between work performance and ventilation within a wide range of ventilation rates. The model shows a continuous increase in performance per unit increase in ventilation rate from 6.5 L/s-person to 65 L/s-person. The increase is statistically significant up to 15 L/s-person. 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.

INDEX TERMS

Economics, productivity, performance, ventilation

INTRODUCTION

Ventilation rates[1] 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. Previous work in the US (Persily and Gorfain 2004) and Europe

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[1] In this paper the term ventilation refers to the rate of supply of outdoor air.

(Bluyssen et al. 1995) show large variation in measured ventilation rates between buildings and within buildings (Teijonsalo et al. 1996). In a significant fraction of buildings, particularly schools, the ventilation rates have been below guideline and standard values (Shendell et al. 2004). The outdoor air ventilation rates may be intentionally low due to design criteria or to save energy. Particularly in the US, air handling systems with no economizer and with a high percentage of recirculated return air in the supply air may provide low outdoor air flows.

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). We have previously estimated the relationship between ventilation rate and absence from work (Fisk et al. 2003).

In this paper we present results of an analysis of available scientific findings on how ventilation rate affects work performance. The goal was to develop the best possible quantitative relationship between ventilation rate and work performance for use in cost benefit calculations related to building design and operation.

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 Swedish performance evaluation system with reaction times as an indicator of performance.

Through computerized searches and reviews of conference proceedings, we identified seven relevant studies with data collected in the field (i.e., workplace studies), and three studies with data collected in controlled laboratory environment. Five of the field studies were performed in offices and two in schools. The studies are summarised in Table 1. The table also shows the performance indicators used in each study. 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. The range of the reported ventilation rates and other environmental conditions are included in Table 1. 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, as mentioned, 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 (1). The result, denoted by λ, is the fractional change in performance per increase in ventilation of 10 L/s-person. Positive values of λ indicate an increase in performance with an increase in ventilation rate. These calculations are as indicated in equation (1) below where $P(V_H)$ is the reported performance at the higher ventilation rate V_H, and $P(V_L)$ is the reported performance at the lower ventilation rate V_L.

$$\lambda = \frac{P(V_H) - P(V_L)}{P(V_L)} \cdot \frac{10}{V_H - V_L} \qquad (1)$$

The point estimate of λ at the midrange of ventilation rates in each study, is calculated as shown in equation (2). The equation is based on the fact that, assuming a locally approximately linear relationship between performance and ventilation rate from V_L *to* V_H, the performance at midpoint is $P(V_L) \cdot [1 + 0.5 \cdot (V_H - V_L) \cdot 0.1 \cdot \lambda]$.

$$\lambda_{mid} = \frac{\lambda}{1 + 0.05 \cdot \lambda \cdot (V_H - V_L)} \qquad (2)$$

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. 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. As shown in Table 1, 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' judgement 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.

Using command *fracpoly* in Stata 8.2 for Windows (a program that selects the best fitting fractional polynomial powers of explanatory variables), we fit 2-degree fractional polynomial models to the data for percentage change in productivity ($100 \cdot \lambda_{mid}$) vs. 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

Summary of individual studies

In laboratory studies, Bako-Biro 2004 and Wargocki et al. 2000 used short term tests of typical office tasks, such as simple calculations and word processing. In laboratory tests most of the confounding factors such as environmental conditions, working environment and workload were automatically controlled. In addition, the analyses assessed how performance changed within individuals as the ventilation rate was changed, thus, the effects of personal factors were also controlled by the study design. The ventilation rates and other environmental conditions suspected to be important, e.g., temperature, humidity, noise level, were kept constant during the experiments. The floor area per person (6 m^2/person) in these tests was smaller than the average in office buildings, and was closer to an open plan office environment.

Wargocki et al. (2000) used an old carpet as pollution source and ventilation rates of 3,10 and 30 L/s-person. They found a significant improvement in typing with higher ventilation rates, and significant improvement in creative thinking at a ventilation rate of 10 L/s-person compared to a ventilation rate of 3 L/s-person. Proof reading and addition tests also showed better results with higher ventilation rates. Significant learning effects were observed for the tasks at each ventilation rate but they did not alter the effect on performance.

Bako-Biro (2004) had a similar test setting as Wargocki et al. (2000) but used as pollution source common building materials, and carried out the tests with and without the pollution source. He found improvements in multiplication, and in addition tests with ventilation rates of 15 L/s-person compared to 4.7 L/s-person in test conditions with and without the source. In our summary we used adjusted test results for learning and errors given by Bako-Biro (2004)

In field studies, the control of confounding factors is much more difficult. The number of employees varies during the study period, the work load is affected by the market situation, and, in call centres, by the number of incoming calls.

Heschong (2003) measured the average handling time of individual call centre workers in California. In this study the performance of employees was continuously tracked by a computer system. The outdoor air flow rates were manipulated to achieve different levels of ventilation and recorded. The economizer in the VAV-system was disconnected for a certain period of time to obtain better control of outdoor air flow rates. In this study the results are based on a regression model of hourly performance. The regression modelling controlled for most of the environmental variables, and work related variables such as frequency of incoming calls. The data from Heschong (2003) indicate a 0.11% shorter handling time per 1 L/s-person increase in ventilation rate.

Federspiel et al. 2004 used two outcomes from a blinded intervention study of advice nurses working in a call centre. Ventilation rates were intentionally manipulated and estimated from CO_2 data and air flow rate measurements. The data were analysed in a multivariate regression model that controlled for temperature, humidity, time, backload of incoming calls, and other factors. They report effects on time spent talking with clients (talk time) and on subsequent information processing time (wrap-up time). They reported significantly higher average talk time (slower work) with lower ventilation rates compared to highest ventilation rate, and report also shorter wrap-up time (faster work) with lower ventilation rates compared to highest but the effects on wrap up time were not statistically significant. Adjusted data from both outcomes were used in the summary.

Myhrvold and Olesen (1997) report results from an intervention study in 35 classrooms. They used a reaction time test (Swedish Performance Evaluation System or SPES) that included three concentration tests: simple reaction time, choice reaction time and colour word vigilance. The administration of the study and control conditions followed a modified Salomo's four-group design. They report significant improvement in performance in the study group of pupils with increased ventilation rate and lower CO_2 –concentration. The study used two control groups that were taken from the schools with good and bad indoor environment, but reported only unadjusted results, which were used in the summary.

Tham and Willem (2004) report on a blinded 9-week intervention study in a call center in Singapore using 26 permanent operators as subjects. They report a statistically significantly better performance with higher ventilation rate than with lower ventilation rate when the temperature was 24.5^{o}C. They also report a small but not statistically significant reduction in performance with higher ventilation rate when temperature was 22.5^{o}C.

Tham (2004) report on a blinded 9-week intervention study in a call center in Singapore with 56 selected female customer service operators as subjects. He changed weekly temperatures (22.5 and 24.5^{o}C) and ventilation rates (5 and 10 L/s-person), and recorded the average talk time. He reports a significantly better performance (by 21.9%) as measured by average talk time with a higher ventilation rate (10 L/s-person) than with a lower ventilation rate (5 L/s-person) when the temperatures was 24.5^{o}C. He found a small but not statistically significant reduction in performance with higher ventilation rate when temperature was 22.5^{o}C.

Wargocki et al. (2004) report results from a blinded intervention in a call center for telephone directory services. They manipulated outdoor air flow rate by changing the recirculated air flow in the system, and report significantly better performance with higher ventilation rate when the particle filter in the supply air stream was new but significantly lower performance with higher ventilation rate when the particle filter was old and loaded with dust. The results were adjusted for changes in environmental conditions and thermal sensation of the operators.

Results of regression

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. (2003) 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. The following equation (3) is used to evaluate the ratio of performance under any two ventilation rates (see Appendix A). When ventilation rate increases from V_0 to V_1, the ratio of performance at V_1 $(P(V_1))$ to that at V_0 $(P(V_0))$ is

$$\frac{P(V_1)}{P(V_0)} = \exp\left[0.1 \cdot \int_{V_o}^{V_1} \hat{\lambda}(v)dv\right] \qquad (3)$$

where $\hat{\lambda}(v)$ is the fitted fractional change in performance per 10 L/s-person at ventilation v.

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 using equation (3) and plotted in Figure 2.

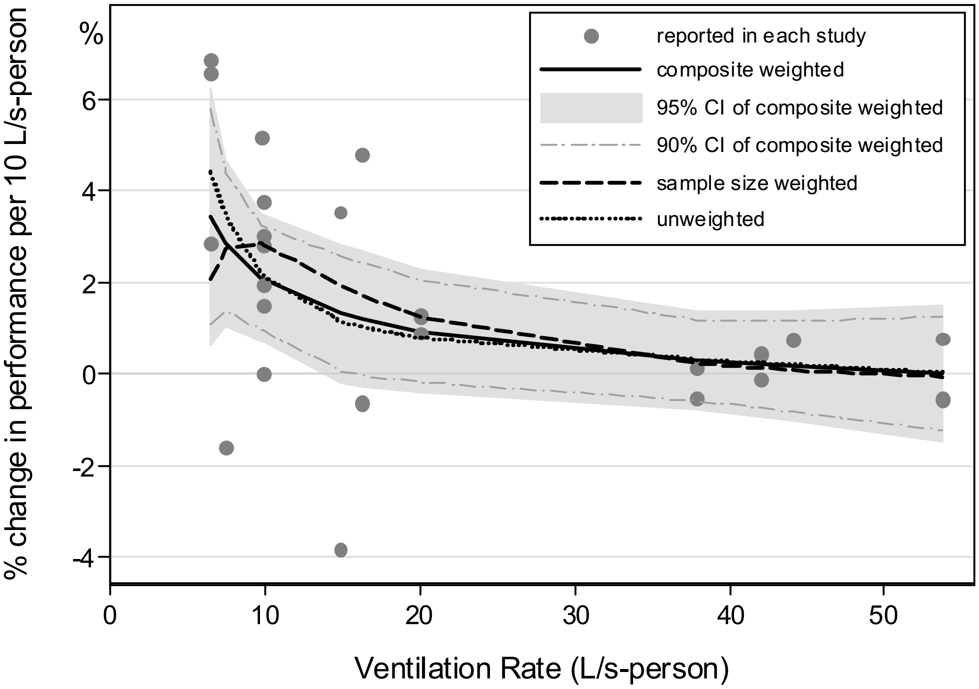

Fig 1. Percentage change in performance per 10 L/s-person, $100 \cdot \lambda_{mid}$, versus average ventilation rate, fitted with 2-degree fractional polynomial regression models. One outlier data point (43.8% at 7.5 L/s-person) is excluded.

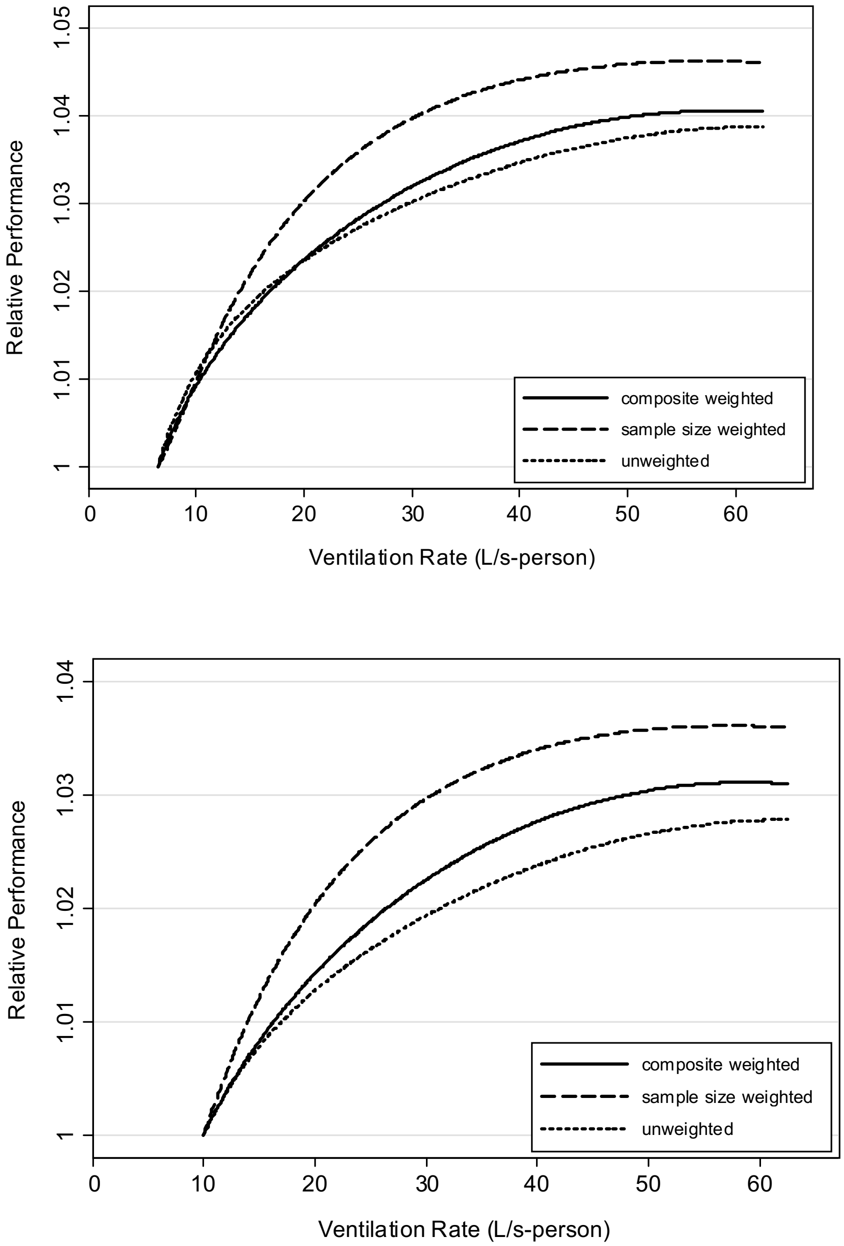

Fig 2. Relative performance in relation to the reference values 6.5 L/s-person (upper) and 10 L/s-person (lower) versus ventilation rate. The outlier data point is not included.

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 air flows. In the ventilation rage 6.5[2] – 10 L/s-person the

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[2] The relationship cannot be extrapolated to ventilation rates below 6.5 L/s-person due to lack of data.

increase in performance is 2-3.5 % per 10 L/s-person, in the range 10 – 20 L/s-person 1-2%, in the range 20 - 40 L/s-person 0.5-1%, and above 40 L/s-person below 0.5% per 10 L/s-person. 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. The data indicate a very small increase in performance per unit increase in ventilation rate when ventilation rates exceed approximately 45 L/s-person; thus, the lines in Figure 2 become approximately straight for ventilation rates above 45 L/s-person. Performance is improved statistically significantly in the ventilation rage of 6.5 - 17 L/s-person with 90% CI and up to 15 L/s-person with 95% CI.

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 specific tasks, the developed weighted relation may well represent average work in the office and may be applicable in many office environments. The relation may also represent less routine type work; for example, Wargocki et al. (2000) report also an improvement in creative thinking in a laboratory test with a ventilation rate of 10 L/s-person compared to 3 L/s-person but he does not give quantitative data.

The curves in Figure 2 show a continuous increase in work performance with ventilation rate up to 50 L/s-person. This may not reflect the actual situation in real buildings – at some high ventilation rate indoor pollutant concentrations will essentially equate to outdoor concentrations and performance should stabilize. If fact, at very high ventilation rates draft and high levels of noise from the airflow could diminish performance. From Figure 1, we show that the trend of increasing performance with increased ventilation rate is statistically significant at ventilation rates up to approximately 17 L/s-person with 90% CI and up to 15 L/s-person with 95% CI. In practise the equipment and energy cost also limit the ventilation rates. The results are more uncertain with the higher ventilation rates due to scatter and fewer data points. The lowest ventilation rate in the studies was 3 L/s-person, and the lowest average ventilation rate in the assessments was 6.5 L/s-person, to which ventilation rate the results are valid. It is likely that the adverse effects of low ventilation rates below 6.5 L/s-person become stronger than with higher ventilation rates. However, it is unusual to have ventilation rates below 6.5 L/s-person in office buildings. A random sample of US office buildings showed that ventilation rates based on air flow measurements was below 6 L/s-person in only 10 % of the sample (Persily and Gorfain 2004).

The measurements of performance varied greatly from study to study. Unweighted and sample size weighted regression models are based on the assumption that all measurements reflect underlying productivity equally well. Although the combined weights take into consideration the relevance of different productivity measurements, the assignments of weights is rough and involves subjectivity. Another important assumption is the independence of studies. This assumption is violated in studies performed on the same set of subjects.

Equation (2) is based on the assumption that the performance changes linearly with ventilation rate within the range of the study. Due to the apparent nonlinear relationship shown in Figure 2, the estimate of λ_{mid} is less accurate for studies with larger ventilation range.

Uncertainties in building ventilation rates may have contributed to the scatter in the data points on Figure 1. The method used to measure ventilation rates varied among the studies. Some ventilation rates were based on measurements of the rate of flow of outdoor air supplied mechanically, which neglects air infiltration, and some ventilation rates were measured with tracer gases which include air infiltration. In addition, for some studies we used the reported number of occupants to calculated ventilation rates on a per person basis, while recognizing that occupancy usually varies over time.

None of the field studies were performed in problem buildings. Thus they represent typical indoor environments. With two exceptions all studies were conducted in cold or moderate climates. As far as the other environmental parameters are reported, the values are typical; however, variations in temperature may have an effect on the results. It is know from earlier summaries that performance is affected by temperature. Actually Tham and Willem (2004) and Tham (2004) report lower performance with higher ventilation rate when the temperature set point was 22.5^{o}C, and higher performance with higher ventilation rate when the temperature set point was 24.5^{o}C. This result may be affected by other environmental conditions, as the humidity in the study was high (55-78% RH) and an indoor temperature of 22.5^{o}C may be slightly low for the tropical conditions in Singapore, where these studies were conducted.

In most of the studies the occupant density was high. The floor area per person in laboratory studies was 6 m^{2}/person. Most of the field studies (except Federspiel, 2004) were made in open plan offices, where the occupant density was also on the high side compared to the average in the U.S. or Europe.

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 rate or more existing adverse health effects.

ACNOWLEDGEMENT

This work was supported by the Finnish Academy. This work was also supported by the Indoor Environments Division, Office of Radiation and Indoor Air, Office of Air and Radiation of the U.S. Environmental Protection Agency through interagency agreement DW-89-92175001-0 with the U.S. Department of Energy. The authors would like to thank Mark Mendell and David Mudarri for his valuable comments.

REFERENCES

Bako-Biro Z. (2004) Human perception, SBS symptoms and performance of office work during exposure to air polluted by building materials and personal computers. Ph.D. Thesis, International Centre for Indoor Environment and Energy, *Technical University of Denmark*.

Bluyssen P, de Oliviera Fernandes E, Groes L, Clausen G, Fanger PO, Valbjørn O, Bernhard C, Roulet C. (1996) European indoor air quality audit project in 56 office buildings, *Indoor Air J.* **6**, 221-238

Federspiel CC, Fisk WJ, Price PN, Liu G, Faulkner D, Dibartolemeo DL, Sullivan DP, Lahiff M. (2004) Worker performance and ventilation in a call center: analyses of work performance data for registered nurses, *Indoor Air J,* **14,** Supplement 8, 41-50.

Fisk WJ, Seppänen O, Faulkner D, Huang J (2003) Economizer system cost effectiveness: accounting for the influence of ventilation rate on sick leave, In*: Proceedings of Healthy Buildings 2003*, December 7 – 11 at the National University of Singapore, Vol 3, 361-167

Heschong Mahone Group. (2003) Windows and offices: A study of office workers performance and the indoor environment. Prepared for *California energy commission*. Fair Oaks, California.

Myhrvold A and Olesen E. (1997) Pupil's health and performance due to renovation of schools, In: *Proceeding s of Healthy Buildings/IAQ 1997*, Vol 1, pp. 81-86

Persily A and Gorfain J. (2004) Analysis of ventilation data from the U.S. Environmental Protection Agency building assessment survey and evaluation (BASE) study, *National Institute of Standards and Technology*, Report NISTIR 7145.

Seppänen OA, Fisk WJ, Mendell MJ. (1999) Association of ventilation rates and CO_2-concentrations with health and other responses in commercial and institutional buildings. *Indoor Air J,* **9**, 252-274.

Shendell DG, Prill R, Fisk WJ, Apte MG, Blake D, Faulkner D. (2004) Association between class room CO_2 concentrations and student attendance in Washington and Idaho. *Indoor Air J.* **14**, 333-341

Tham KW, Willem HC. (2004) Effects of reported neurobehavioral symptoms on call center operator performance in the tropics, In: *Proceedings (in CD) of RoomVent 2004 Conference*. Coimbra. Portugal

Tham KW. (2004) Effects of temperature and outdoor air supply rate on the performance of call center operators in the tropics. *Indoor Air J,* **14**, Suppl 7, 119-125.

Teijonsalo J, Jaakkola JJ, Seppänen, O. (1996) The Helsinki office environmental study: Air change in mechanically ventilated buildings. *Indoor Air J,* **6**, 111-117

Wargocki P, Wyon DP, Fanger PO. (2004) The performance and subjective responses of call-center operators with new and used supply air filters at two outdoor air supply rates. *Indoor Air J,* **14**, Suplement 8, 7-16.

Wargocki P, Wyon DP, Sundell J. (2000) The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS): symptoms and productivity. *Indoor Air J,* **10**, 222-236.

Appendix A Derivation of the relation between the change in performance in % per 10 L/s person increase in ventilation rate and relative performance at any ventilation rate.

If we divide an arbitrary ventilation interval (V_0, V_1) into M very small intervals of length Δv ($\Delta v = (V_1 - V_0)/M$), the fractional change of performance per 10L/s-person, $\lambda(v)$, can be considered approximately constant in the interval. The relative performance change for the interval $(v, v+\Delta v)$ is $r(v)\cdot\Delta v$, where $r(v) = \lambda(v)\cdot 0.1$. $r(v)$ is the relative change of performance per 1L/s-person. If we further divide the interval into n equal intervals of length $\Delta v / n$, the relative performance change for each further divided interval is $r(v)\cdot\Delta v / n$. The ratio of performance (P) at $v+m\cdot\Delta v/n$ to that at $v+(m-1)\cdot\Delta v/n$ is therefore

$$\frac{P(v + m\cdot\Delta v / n)}{P(v + (m-1)\cdot\Delta v / n)} = 1 + r(v)\cdot\Delta v / n, \text{ where } m = 1,2,3,\ldots,n$$

Applying the above equation iteratively, we have

$$\frac{P(v+\Delta v)}{P(v)} = [1 + r(v)\cdot\Delta v / n]^n \xrightarrow{n\to\infty} \exp(r(v)\cdot\Delta v).$$

The performance ratio for interval (V_0, V_1) is therefore

$$\frac{P(V_1)}{P(V_0)} = \exp\left[\sum_{i=0}^{M} r(V_0 + i\cdot\Delta v)\cdot\Delta v\right]$$

As $M \to \infty, \Delta v \to 0,$ *and* $\sum_{i=0}^{M} r(V_0 + i\cdot\Delta v)\cdot\Delta v \to \int_{V_0}^{V_1} r(v)dv$. Therefore,

$$\frac{P(V_1)}{P(V_0)} = \exp\left[\int_{V_o}^{V_1} r(v)dv\right] = \exp\left[0.1\cdot\int_{V_o}^{V_1} \lambda(v)dv\right]$$

Table 1 Summary of the studies assessing the effect of ventilation on various performance (productivity) indicators

Author	**Type of study and no of subjects**	**Performance indicators**	**Ventilation rates**	**Conditions**	**Effect on performance 1)**		
Bako-Biro Z. 2004.	Controlled laboratory study with 30 female students in simulated office environment	Multiplication (units per hour) Addition (units per hour) Text typing (characters per min) All adjusted for errors and learning	4.7 - 15 L/s-person	T=23 °C RH=46-48% v=0.06-0.15 m/s 6 m^2/ person		with source	w/o source
					Multiplicat.	3.9 2)	3.1
					Addition	2 P<0.01	2.9
					Typing	1.54	0
Heschong Mahone Group. 2003.	Longitudinal, field study with some interventions in a call center with over 100 workers, number varied per hour	Average handling time	17.8 – 70.5 L/s-person.	T=22.1-25.5 °C 7.1 m^2/person	Average handling time was 4 % shorter per 1 cfm per sqft = 0.8 % per L/s,m^2 =0.11% per 1 L/s-person P<0.1		
Federspiel CC, Fisk WJ, Price PN et al. 2004	Longitudinal field study in a call center, 13 weeks, 119 nurses	Average talk-time	9.2-78.7 L/s-person	T=22.9 – 23.5 °C RH =46-47 % 15.8 m^2/person	Average talk time 0.83 % shorter with 9.2– 78.2 L/s, person 2.36 % shorter with 18.9-78.7 L/s-person (P=0.007) 2.2 % shorter with 46.3-78.7 L/s-person (P=0.003)		
Federspiel CC, Fisk WJ, Price PN et al. 2004		Average wrap-up time	9.2-78.7 L/s-person	T=22.9 – 23.5 °C RH =46-47 % 15.8 m^2/person	Average wrap-up time was 3.2 % longer with 9.2– 78.2 L/s, person 0.57 % longer with 18.9-78.7 L/s-person 1.52 % longer with 46.3-78.7 L/s-person		
Myhrvold A and Olesen E. 1997	Intervention study in eight renovated schools, 35 class rooms with 600 pupils	Reaction time test SPES (Swedish Performance Evaluation System)	CO_2 - concentration before 1515 ppm corresponding, 2.6 ach CO_2- concentration after 735 ppm corresponding, 8.1 ach Vent rates from CO_2 –levels 4.6 and 15 L/s-person	T=21.0-20.7 °C	Reaction time was 5.4 % shorter with 15 than 4.6 L/s-person		
Tham KW, Willem HC. 2004.	Blinded 9 weeks intervention with 2x2 design at call center with 26	Average talk-time improved 8.8 % with increase in	9.8 vs. 22.7 L/s-person	T= 24.5 °C and 22. °C 14.3 m^2/pers.	6.2% better performance with 22.7 than with 9.8 L/s-person at 24. °C (P=0.04) and 0.8% worse performance at		

<table>
<tr><td></td><td>permanent operators</td><td>ventilation at 24.5^{o}C but not at 22.^{o}C</td><td></td><td></td><td colspan="3">22. ^{o}C</td></tr>
<tr><td>Tham KW. 2004.</td><td>Blinded 9 week intervention with 2x2 at call center with 56 selected female customer service operators</td><td>Average talk time</td><td>5 L/s vs. 10 L/s per person</td><td>T=24.5^{o}C and 22.5^{o}C
RH=55-78 %</td><td colspan="3">21.9 % higher productivity with 10 than with 5 L/s-person at 24.5^{o}C (P<0.01)
0.8% lower productivity with 10 L/s-person than with 5 at 22.5 ^{o}C</td></tr>
<tr><td>Wargocki P, Wyon DP, Fanger PO. 2003.</td><td>Blinded 2x2 designed intervention in call center with 26 call center operators for telephone directory service</td><td>Average talk-time</td><td>1.3 and 13.2 L/s-person with full occupancy load
2.5 and 25 L/s-person with actual load</td><td>T = 24 ^{o}C
RH=27 %
6.4 m^2 per work station
10.2-11 m^2 per operator in shift</td><td colspan="3">7.2 % better performance with 25 than with 2.5 L/s-person with clean filter
(P<0.055)
7.8% worse performance with 25 than with 2.5 L/s, person with dirty filter
(P<0.05)</td></tr>
<tr><td rowspan="5">Wargocki P, Wyon DP, Sundell J. 2000</td><td rowspan="5">Controlled laboratory study with 30 female students in simulated office environment, old carpet as the source of pollution</td><td rowspan="5">Text typing
Addition
Poof reading
Creative thinking</td><td rowspan="5">Ventilation rates 3, 10, 30 L/s-person</td><td rowspan="5">T=const= 22^{o}C
RH=40%
L$_p$= 48 dB(A)
v<0.2 m/s
6 m^2/person</td><td>L/s-person</td><td>3-10</td><td>10-30</td></tr>
<tr><td>typing</td><td>2.0
P<0.03</td><td>2.5
P<0.03</td></tr>
<tr><td>addition</td><td>4.8
P<0.06</td><td>1.8
P<0.06</td></tr>
<tr><td>proof reading</td><td>4.5
P<0.16</td><td>2.6
P<0.16</td></tr>
<tr><td>Creative thinking</td><td>Improved (P<0.025)</td><td>NS</td></tr>
</table>

1) Effect on performance calculated by subtracting from the performance at the higher ventilation rate the performance at the lower ventilation rate, dividing the difference by the performance at the lower ventilation rate, and multiplying by one hundred.
2) If P-value is not indicated in the table P>0.1 or was not reported
3) This study is not included in the summary and models (Figure 1).