PRODUCTIVITY AND VENTILATION RATE: ANALYSES OF TIME-SERIES DATA FOR A GROUP OF CALL-CENTER WORKERS

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ABSTRACT

We investigated the relationship of ventilation rates with the performance of advice nurses working in a call center. Ventilation rates were manipulated, temperatures, humidities, and CO_2 concentrations were monitored, and worker performance data, with 30-minute resolution, were collected. Multivariate linear regressions were employed to investigate the association of performance with building ventilation rate, or with indoor CO_2 concentration (which is related to ventilation rate per worker). Results suggest that the effect of ventilation rate on worker performance in this call center was very small (probably less than 1%) or nil, over most of the range of ventilation rate (roughly 12 L s^{-1} to 48 L s^{-1} per person). However, there is some evidence of performance improvements of 2% or more when the ventilation rate per person is very high, as indicated by indoor CO_2 concentrations exceeding outdoor concentrations by less than 75 ppm.

INDEX TERMS

Ventilation rates, Productivity, Offices, Field experiments, Carbon dioxide

INTRODUCTION

In previous studies, increased ventilation rates and reduced indoor carbon dioxide concentrations have been associated with improvements in health at work (Seppanen et al., 1999) and with increased performance in work-related tasks. Only a few studies have assessed the relationship of ventilation rates with productivity. In a study of 35 Norwegian classrooms, higher concentrations of CO_2, which indicate lower rates of outside air ventilation per person , were associated with poorer performance ($p < 0.01$) in computerized tests of reaction time (Myhrvold et al., 1996); however, the percentage change in performance was not specified. In a study by Nunes et al. (1993), workers who reported building-related health symptoms, known to be associated with lower ventilation rates (Seppanen et. al. 1999), took 7% longer to respond in a computerized neurobehavioral test of sustained visual attention ($p < 0.001$) and had 30% higher error rates in a test of symbol-digit substitution test of speed and coding ability. In laboratory experiments by Wargocki et al. (2000a) increasing the ventilation rate with a carpet from a complaint building present was associated with improvements of a few percent in speed or accuracy of several simulated work tasks such as text typing, addition, proof reading, and creative thinking ($p < 0.05$). The difficulty of defining and measuring the cognitive performance of workers has been one of the barriers to productivity studies in real work places. However, for a few types of cognitive work, worker performance has been clearly defined and routinely measured by the employer. For example, in call centers, large pools of workers interact with clients via the telephone and enter data or process information associated with the telephone calls. To track worker performance, call centers frequently have automatic systems that record data on worker speed along with the type or purpose of the calls. Consequently, call centers are an appropriate setting for studies of the dependence of work speed, but not work quality, on IEQ. This paper describes such a study in a call center operated by a health maintenance organization.

METHODS

The approach employed in this study was to manipulate outside air ventilation rates and monitor indoor air temperatures (which vary naturally), while collecting telephone call data quantifying worker performance in a call center located in the San Francisco Bay Area. Data were collected between July 28 and October 24, 2000 and analyzed with multivariate statistical models. The workforce was blinded regarding all aspects of the study, except they were aware that indoor air temperatures were being monitored.

The call center had a floor area of 4,600 m^2, sealed windows, carpeted floors, a no smoking policy, and a maximum worker density of 6.3 persons per 100 m^2. The call center was heated, cooled, and ventilated by variable air volume (VAV) air handling units (AHUs) that modulate the rates of supply of cool or warm air to maintain indoor air temperatures in the desired range. Each AHU has an "economizer" control system that modulates the rate of outside air supply, above a minimum rate established by the building code, with the goal of minimizing costs for heating and cooling; however, to prevent unplanned changes in outside air supply the economizer controls were deactivated during most experimental periods.

The workers were registered nurses (RNs) who provided medical advice. Each worker has a computer and telephone with a headset. Workers were present in the building at all times and days, although the number of workers was highly variable, with the largest workforce on weekday mornings. The maximum number of RNs in the building during this study was119.

We added equipment to each AHU enabling automatic manipulation and measurement of outside air ventilation rates. AHU supply flow rates were measured using arrays of pitot tubes in supply ducts, with the pressure differences logged. The outside air flow rate in each AHU was computed as the product of the supply airstream flow rate and the fraction of outside air (FOA) in this airstream. We used a CO_2 monitor calibrated weekly to measure concentrations of CO_2 every 7.2 minutes in the outside air, return airstream, and supply airstreams and employed a simple mass balance calculation to compute the FOA.

The AHUs have dampers for modulation of the FOA. Fixed damper positions for low ventilation rate periods were selected to match the code-minimum outside air supply rate of 12.0 L s^{-1} per occupant at maximum occupancy (0.76 L s^{-1} per square meter of floor area and 292 persons). The fixed damper positions for medium and high ventilation rates were selected to provide approximately twice and four-times the code minimum. In a fourth ventilation setting, the normal control systems for the AHUs outside air supply, including the outside air economizers, were activated. We anticipated that this mode of operation (called economizer mode) would typically provide a ventilation rate greater than eight times the code minimum. In practice, ventilation rates in economizer mode varied considerably.

Using these methods, we scheduled periods of ventilation in each of the four control modes: low, medium, high, and economizer mode. The intent to have randomized ventilation rates that changed daily during weeks 3 – 6 and 8 - 10, was met reasonably well. During weeks 1,2, 7, 11 and13, we intended to fix the ventilation rates at the low, medium, high, or economizer setting for one-week periods; however, the control system failed during some periods. The resulting schedule of ventilation control modes is provided in Table 1. The control system resulted in a wide range of ventilation rates; however, these ventilation rates were not sufficiently repeatable to use the control mode as a categorical surrogate for the ventilation rate. Thus, measured ventilation rates and carbon dioxide concentration were used in analyses of the productivity data.

Table 1. Ventilation control schedule. L, M, and H refer to fixed damper positions for low, medium, and high ventilation rates. E refers to control of ventilation rates by the economizer.

Day	**Week**												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
F	L	H	E	H	L	E	M	M	H	M	E	E	E
Sa	L	H	L	E	H	M	M	M	M	L	E	E	E
Su	L	H	H	L	M	L	M	M	E	M	E	E	E
M	L	H	E	H	L	M	M	M	M	H	E	E	L
Tu	L	H	M	E	H	L	M	L	H	E	H	H	E
W	L	H	H	L	E	H	M	M	L	E	H	E	--
Th	L	H	M	H	M	E	M	L	E	E	H	E	--

With an accuracy of approximately 0.3 ^{o}C, air temperatures were measured every one minute at 25 locations approximately one meter above floor level.

The call center's automated call distribution (ACD) system monitors several performance-related parameters. Worker performance for each half-hour period is summarized with the "average handle time"(AHT) of all of the calls that ended during that period. The AHT is the average time (averaged over all RNs and over the entire half hour) taken for each call from beginning to end, starting when the call was answered and ending when the RN completely finished all tasks associated with the call. For each half-hour period, the call center's computer calculates a number, called "nets", that is an estimate of how many extra RNs were on hand, compared to the number needed to have the average wait experienced by callers equal to a target wait time. For periods when the target wait times were exceeded, nets is negative. Nets is used as a variable in the data analyses, as a measure of the work demand on RNs.

Our primary interest was the relationship between ventilation rate and RN performance measure by AHT. Ventilation rate was expected to influence AHT by at most a few percent, which is less than the variation due to several other sources. To estimate effects of ventilation-related variables with useful precision we excluded some data from the analyses and controlled for other sources of variation in AHT using multivariate regression models. We discarded data outside the normal work week (Monday – Friday, 7:30 a.m. – 6:00 p.m.) when few workers were present. Data from Labor Day and the following day were excluded, and data from two additional days were excluded due to changes in computer software.

As a proxy for ventilation per agent, we used the difference between the indoor and outdoor concentration (ΔCO_2) [linear, categorical, or piecewise linear] as the explanatory variable of primary interest. Linear regression was our main tool for analyzing the data: we regressed log(AHT) on explanatory variables that are expected to be relevant. To control for potential confounding, we included a number of other variables in the regression models: number of RNs present, average relative humidity, a time-of-week indicator variable for each half-hour period [which accounted for about 35% of the variation in log(AHT)], building-average temperature (Celsius) – 23 ^{o}C , and (building-average temperature-23 ^{o}C)^2 to account for the possibility of a non-linear relationship between temperature and performance. We also included a normalized "nets" (piecewise linear), normalized to the number of workers on duty. Each data point was weighted by the number of calls received during the half hour, although the weights were not highly variable, nor were they very influential. As described in Fisk et al (2001), the linear regressions adjusted for the temporal correlation of the residuals.

RESULTS

ΔCO_2 concentrations were rarely below 100 ppm or above 450 ppm. ΔCO_2 values tend to cluster into three wide clumps, corresponding to low, medium, and high damper settings, with "economizer" settings also tending to lead to fairly low or very low values of ΔCO_2.

The AHUs held the building-average temperature within a very narrow range during working hours. Ninety percent of the half-hourly work-day temperatures were between between 22.9 ^{o}C and 23.5 ^{o}C. Building average humidity almost never strayed outside the range 46% to 47%. Unsurprisingly, then, the regression coefficients associated with temperature variables and relative humidity, are all very small compared to their uncertainties.

We fit several dozen regression models, using different definitions for the bin boundaries for number of calls, normalized nets, and ΔCO_2, and using different subsets of the data. Measures of model fit were very similar for all models that included the full set of explanatory variables. In every model, the "nets" variables were found highly influential.

We now discuss three specific models for log(AHT) in some detail. Each model includes the time-of-week, temperature, and "nets" variables. The three models differ in their handling of ΔCO_2. Model A has no ΔCO_2 variable. Model B includes three ΔCO_2 categorical variables, indicating whether ΔCO_2 for each half hour was: 0-150 ppm, 150-300 ppm, or over 300 ppm. In Model C, the two lower ΔCO_2 categories within Model B have been split, thus, Model C has five ΔCO_2 categorical variables: 0-75 ppm, 75-150 ppm, 150-225 ppm, 225-300 ppm, or over 300 ppm. Figure 1 shows the estimated model coefficients associated with each ΔCO_2 bin, for Models B (lower plot) and C (upper plot). For each bin, the horizontal bar shows the range of ΔCO_2 spanned by the bin, and the vertical error bar covers plus or minus one standard error. In each case, the lowest bin is defined to have no effect, a coefficient of 0.00.

In Model B with only three ΔCO_2 bins, there is no evidence that lower ΔCO_2 is associated with lower (faster) AHT -- indeed, the relationship points the other direction: the estimate for the high-ΔCO_2 bin is about 1% faster than that for the lowest bin. (An effect of -0.009 on log(AHT) corresponds to a factor of exp(-0.009)=0.991 on AHT, which is very close to a 1% speed-up). However, this estimate is not very precise, with an uncertainty (one standard error) of approximately ± 0.6 percentage points. In contrast, the results from Model C with five bins suggest that very low ΔCO_2 concentrations are associated with lower AHT (faster work) than are higher concentrations. All of the estimated coefficients for ΔCO_2 concentrations over 75 ppm are around 0.025 to 0.035, corresponding to handle times that are 2.5% to 3.5% slower than at the lowest ΔCO_2. Moreover, these effects are all highly statistically significant ($p < 0.05$ for all bin coefficients). However, as we discuss below, we think the relationship between AHT and ΔCO_2 is still far from conclusive.

Neither the Model B nor Model C results provide evidence that handle time increases with ΔCO_2 over most of its range. A dependence of log(AHT) on ΔCO_2 is apparent only for ΔCO_2 below about 150 ppm. When the 0-150 ppm ΔCO_2 category in Model B is split into two categories to produce Model C, the 0-75 ΔCO_2 category has the lowest (fastest) values of log(AHT), after adjusting for the other explanatory variables.

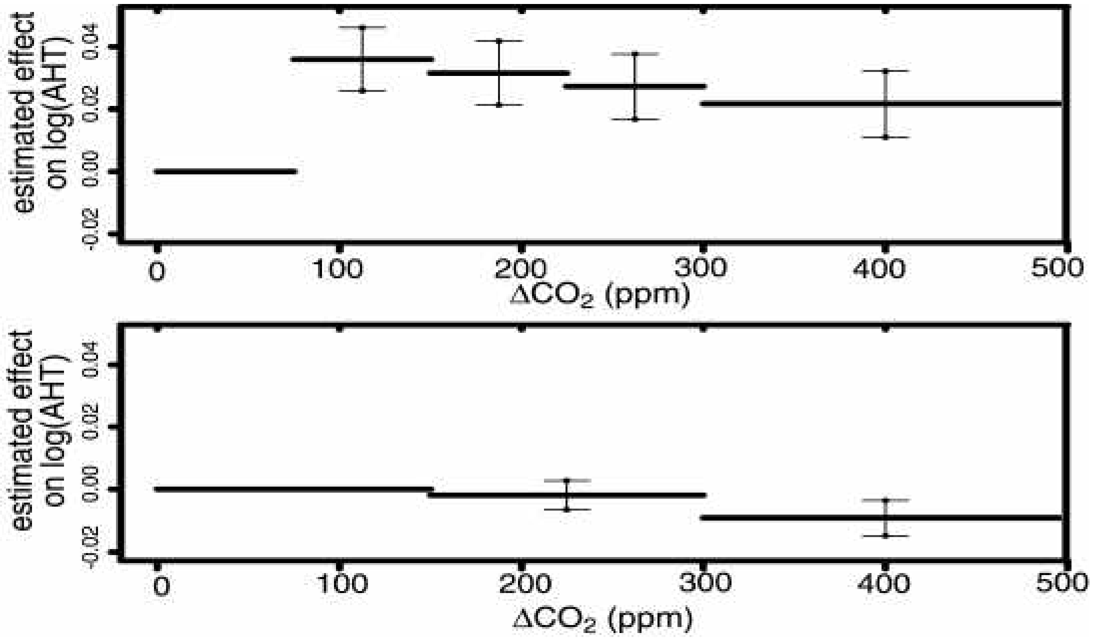

Figure 1. Model coefficients for bins of ΔCO_2 concentration, indicating the effect of ΔCO_2 on log(AHT) with the lowest ΔCO_2 bin used as the reference. The lower and upper plots are results of Model B and Model C, respectively. Horizontal bars indicate ΔCO_2 bin boundaries and vertical error bars represent ± standard deviation.

We also performed regressions using ventilation rate categories rather than ΔCO_2 categories. There is no evidence for a dependency of AHT on ventilation rate. Even for the highest ventilation rates there is no evidence of reduced AHT. To the extent that there is an apparent ventilation-related effect in this study, it is due to ventilation rate per person (as indicated by ΔCO_2) rather than ventilation per unit indoor volume.

DISCUSSION

We anticipated that performance differences associated with ventilation would be a few percent at most. It is very hard to study causes of such small performance differences in real work. The present study has inadequate statistical power to find effects smaller than about 2%; however, such small changes in productivity could still be economically important.

In the present study, there were only forty half-hour periods (out of 1051) in which ΔCO_2 was below 75 ppm. Nineteen of these periods occurred on a single day (the 78th day of the study, a Friday), and all of the rest occurred during the following week. The entire apparent speed-up in AHT indicated by Model C, for the below-75 ppm bin relative to the other bins, is based on data from only six different days, and 65% of those data are from two consecutive Fridays. Consequently, in spite of the low p-values, we do not consider the results of Model C to conclusively indicate a faster work-rate when ΔCO_2 was very low and ventilation per worker was very high. If the very high values of ventilation had occurred on 6 days spread throughout the study period, and the same results were found, we would have confidence that the observed effect is really due to ventilation. In the present case, though, we are not sure.

A limitation of these analyses is the incomplete separation of time of day from ΔCO_2. As time of day increases, ΔCO_2 generally increases (then decreases late in the day); therefore; controlling for time of day via the regression models could have partially obscured a relationship of ΔCO_2 with worker speed. Including "nets" in the regression models may also have partially obscured a relationship of ΔCO_2 with worker speed, because a decrease in work speed caused by higher ΔCO_2 would result in a decrease in "nets".

The results of the present analysis may not apply to other buildings. For instance, it may be that in this building there are no strong indoor sources of pollutants that influence performance, but that in other buildings such sources exist.

CONCLUSIONS

If we exclude periods of very high ventilation rates per occupant (indicated by very low ΔCO_2), we can rule out effects of ventilation rate on AHT that are greater than about 2%. There is some evidence that very high ventilation rates per occupant (very low ΔCO_2) may lead to lower AHT (faster work rates), but the possibility of uncontrolled confounding makes this result less than conclusive in spite of high statistical significance ($p < 0.05$).

ACKNOWLEDGMENTS

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, Office of Building Research and Standards of the U.S. Department of Energy (DOE) under contract No. DE-AC03-76SF00098 and by the Center for the Built Environment at U.C. Berkeley.

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