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SUMMARY

This paper summarizes the current scientific evidence that improved indoor environmental quality can improve work performance and health. The review indicates that work and school work performance is affected by indoor temperature and ventilation rate. Pollutant source removal can sometimes improve work performance. Based on formal statistical analyses of existing research results, quantitative relationships are provided for the linkages of work performance with indoor temperature and outdoor air ventilation rate. The review also indicates that improved health and related financial savings are obtainable from reduced indoor tobacco smoking, prevention and remediation of building dampness, and increased ventilation. Example cost-benefit analyses indicate that many measures to improve indoor temperature control and increase ventilation rates will be highly cost effective, with benefit-cost ratios as high as 80 and annual economic benefits as high as $700 per person.

INTRODUCTION

Recently completed research, reviewed in this paper, indicates that there is a large untapped opportunity for economic benefits resulting from improvements in indoor environmental quality (IEQ) in non-industrial work places and homes. The most clearly established sources of economic benefits include improved work performance, e.g., work speed or quality, reduced absence, and reduced health care costs. There is also evidence that providing better IEQ can improve student learning which, in turn, should lead to more effective future workforces. At the societal level, economic value can also be assigned to the reduced suffering of ill health and to extended average lifetimes expected when IEQ is improved.

This paper will summarize the current scientific evidence that improved IEQ can improve work performance and health, building upon the conceptual framework of Seppanen et al. [1]. The paper will address only the thermal and air-quality-related aspects of IEQ. When possible, the relationship between IEQ parameters and health or performance outcomes will be expressed in quantitative terms that provide a basis for cost-benefit analyses applicable to building design and operation [2]. Calculations for hypothetical case studies will contrast the expected economic benefits with the required investment costs. The paper will also argue for using the most energy efficient options possible to bring about the improvements in IEQ.

METHODS

This paper is based on a review and analysis of the published scientific literature addressing the linkages of IEQ with health and work performance. The original scientific research employed a variety of study designs. Some of the research employed cross-sectional multi-building surveys of IEQ conditions and health, absence, or work performance outcomes.

These studies used statistical models to analyze the resulting data and quantify the effect of specific factors, such as ventilation rates, on outcomes (e.g., absence rates), controlled for other factors that also influence the outcome (e.g., student age and socioeconomic status). Other research has experimentally modified IEQ factors (e.g., temperature or ventilation rate) in real buildings and measured the resulting health or performance changes. Several of these studies were performed in call centers where workers interact with the public via telephone and use computers to obtain, input, and process information. Speed of work, such as average time to complete a call and associated information processing, was used as an indicator of work performance. Numerous experimental studies have also been performed in laboratories. With few exceptions, the laboratory spaces have been very similar to real workspaces, but the laboratory setting enabled more precise control of experimental variables. Normally the subjects performed simulated work tasks, such as addition, typing, and proof reading, with the speed and accuracy of task performance measured under different IEQ conditions.

In other papers reviewed, various approaches have been used estimate economic costs of health effects, so that the economic value of improved health from better IEQ can be estimated. In one approach, the total national annual cost of a health outcome, e.g., total annual cost of asthma in a country, was multiplied by the estimated fraction of ill health attributable to an IEQ risk factor, e.g., to moldy buildings. In another approach, each health outcome was assigned a unit cost per incident (e.g., cost per hospitalization for asthma) and this unit cost was multiplied by the estimated percentage decrease in the health incidents resulting from improved IEQ. One of two different types of unit costs are utilized. “Cost of illness” (COI) unit costs reflect the cost of health care and often also include the cost of lost work. “Willingness to pay”(WTP) unit costs are estimates of how much individuals are willing to pay to avoid a health effect, often based on surveys and analyses of consumer spending for safer products. WTP values, thus, assign an economic value for avoidance of pain or suffering or premature death from ill health and are often much larger than COI unit costs. COI and WTP values are available from various sources including the U. S. Environmental Protection Agency [3].

IMPACTS OF IEQ ON WORK AND SCHOOL PERFORMANCE

Temperature and office work performance

The influence of indoor air temperatures on objective (measured) work performance relevant to offices has been assessed experimentally, primarily in call centers and laboratory settings representative of real offices. A few additional studies used vigilance tests to measure ability to concentrate. Most of the studies experimentally manipulated temperatures while holding other factors constant to investigate the influence of temperature on performance, although one call center studied relied on natural changes in air temperature. Recently, a formal statistical meta-analysis of 24 of these studies was completed [4] to assess the average relationship between temperature and performance of work. The authors analyzed primarily office studies and laboratory studies that simulated office work, although three of 24 studies were performed in classrooms. Their analyses are the source of Figure 1 illustrating a best estimate of how office work performance varies with temperature. The graph in Figure 1 shows that performance increases with temperature up to 21 to 22 ^{o}C, and that performance decreases with temperature above 22 or 23 ^{o}C. The maximum performance, i.e., relative performance equal to unity, occurs at temperature of 21.8 ^{o}C. The equation for the curve in Figure 1 is

$$RP = 0.1647524 \cdot T_C - 0.0058274 \cdot T_C^{\,2} + 0.0000623 \cdot T_C^{\,3} - 0.4685328 \qquad (1)$$

where *RP* is relative performance, i.e., performance relative to maximum value, and T_C is room temperature, ^{o}C.

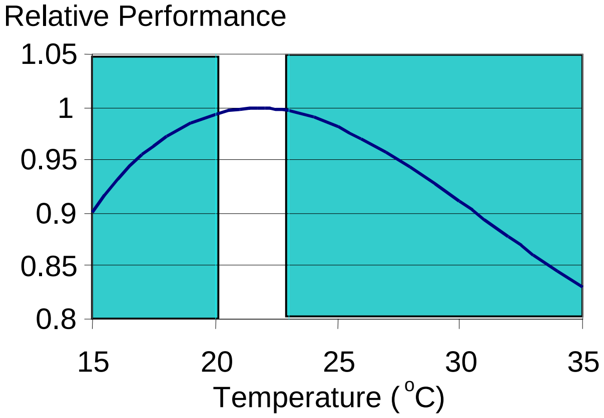

Figure 1. Relationship between office work performance and indoor temperature based on a statistical analysis of reported data. The shaded areas in the figure represents the regions where a statistical analyses indicates that decrements in performance have less than a 10% probability of being the result of chance.

Temperature and school work performance

Several studies conducted in the 1950s and 1960s found that students performed better in thermally conditioned classrooms than in classrooms without heating or cooling [5]. However, there have been few studies of the influence of temperature in thermally-conditioned classrooms on school work performance or learning. In the late 1960s, six groups, each with six students, were brought to a climate-controlled chamber at a U.S. university [5]. Each group of students performed simulated school work with chamber temperatures ranging from 17 to 33 ^{o}C. Error rates and speed of work were used as performance indicators. Two out of four performance measures, error rates and time required to complete assignments, were affected by temperature. The error rate was highest at 17 ^{o}C and lowest, about 20% lower, at 27 ^{o}C; however, students worked most slowly at 27 ^{o}C and fastest, about 10% faster, at 17 ^{o}C. Several similar studies were also performed in the 1960s [6]. Some of these studies performed in climate chambers and other studies in actual classrooms found reading speed, reading comprehension, and multiplication performance of school children to be poorer with temperatures of 27 to 30 ^{o}C, relative to 20 ^{o}C. In one case, the performance decrement was as large as 30%.

The influence of more moderately elevated temperatures on student performance was investigated recently via field studies conducted in classrooms [7, 8]. Classroom temperatures were manipulated by turning cooling systems on and off, while keeping all other factors constant to the degree possible, although, teachers opened windows “slightly more often when it was warm in the classroom”. Performance tasks representing eight aspects of schoolwork, from reading to mathematics, were embedded into the normal school work. The speed and accuracy of task performance was assessed. The average speed of eight simulated school work tasks was increased by approximately 2% per 1 ^{o}C as temperatures decreased from 25 ^{o}C to 20 ^{o}C, although from visual inspection of the data there appeared to be no significant change in performance as temperature decreased from 23 to 20 ^{o}C. The number of errors in school work was not significantly affected by temperature changes in this temperature range. Figure 2 provides more detailed results from this study.

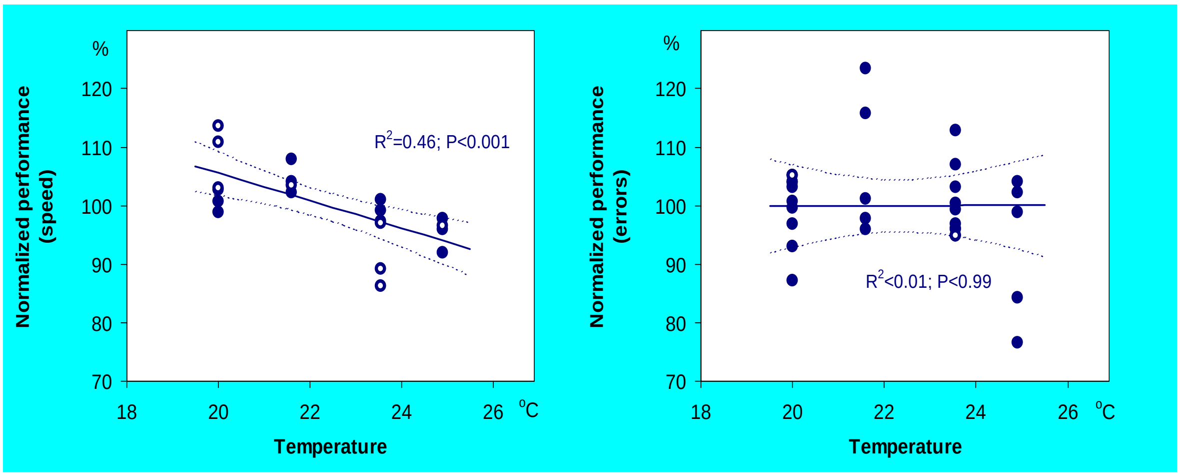

Figure 2. Student performance versus temperature based on study in Denmark [8]. Performance was based on the speed (left figure) and accuracy (right figure) of completing various school work tasks. Open dots represent tasks for which the performance increases with ventilation rate were statistically significant. [Figure 2 reproduced with permission.]

Ventilation rates and office work performance

The influence of ventilation rates (i.e., rates of outdoor air supply) on office work performance has been assessed experimentally in call centers and laboratory settings using the same methods described previously to assess how temperature affects work performance. Seppanen et al.[9] performed a statistical meta-analysis of eight studies of how ventilation rate affects office work, plus one study in schools of how ventilation rate affected concentration and vigilance, to assess the average relationship between ventilation rate and performance of work. Their analyses are the source of Figure 3 illustrating a best estimate of how office work performance varies with ventilation rate.

The curve in figure 4 is well fit by the equation

$$RP = (5.56 \text{ x } 10\text{-}8)\ V^{3} - (1.48 \text{ x } 10\text{-}5)\ V^{2} + (1.49 \text{ x } 10^{-3})\ V + 0.983 \qquad (2)$$

where RP is the relative performance and V is the ventilation rate in L/s per person.

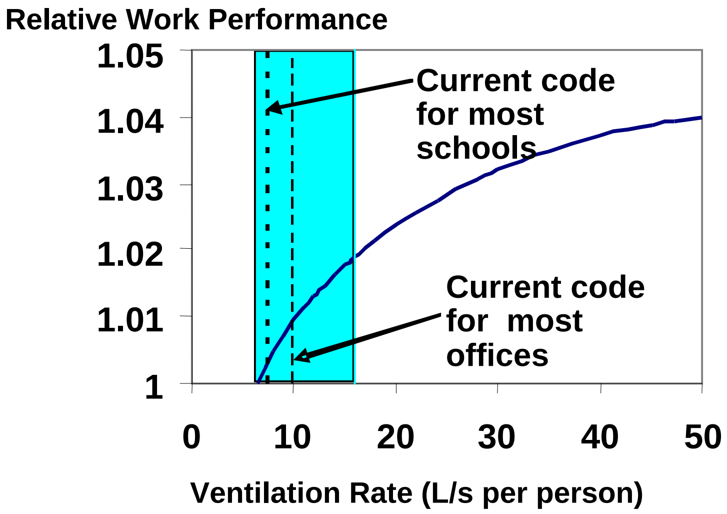

Figure 3. Performance of office work at various ventilation rates relative to performance with a ventilation rate of 6.5 L/s per person based on the meta analysis by Seppanen et al. [9]. In the shaded region, the trend of increased performance with ventilation rate has a 10% or smaller probability of being the result of chance.

Ventilation rates and school work performance

Four studies in schools have investigated the linkage of ventilation rates to objectively measured, as opposed to self-reported, school work performance. A Norwegian study [10] performed in 35 classrooms used reaction times to measure student concentration and vigilance. Reaction times were 5.4% less (i.e., faster) with a ventilation rate of 8.1 ach (12 L/s per person) compared to 2.6 ach (4 L/s per person). A U.S. study [11] in 5th grade classrooms from 54 schools, used student performance in standard academic tests as the measure of performance. Performance in both math and reading tests increased with ventilation rate. Test scores increased about 13% from classrooms with the lowest ventilation rates (less than 2.2 L/s per student) to classrooms with the highest ventilation rates (greater than 4.5 L/s per student); however, statistical analyses indicated greater than a 10% probability that the increases in performance were due to chance. In a Danish study in six classrooms [8], Wargocki and Wyon used performance tasks representing various aspects of schoolwork, from reading to mathematics that were embedded into the normal school work. The speed and accuracy of task performance were assessed. This study reported an 8% increase in speed of school-work tasks with a doubling of ventilation rate. There was no statistically significant influence of ventilation rate on the number of errors made by students. Figure 4 provides more detailed results from this study.

In Japan, college student performance in classroom settings and in a laboratory setting on standardized tests was evaluated at different ventilation rates [12, 13]. In three tests implemented in the field study, one on theory and two involving memorization, performance improved 5.4%, 8.7 %, and 5.8%, respectively, with increases in ventilation rate from 0.4 to 3.5 ach. The laboratory study included only tests of memorization performance, and had results similar to those from the field study. However, in these studies, the ventilation rates

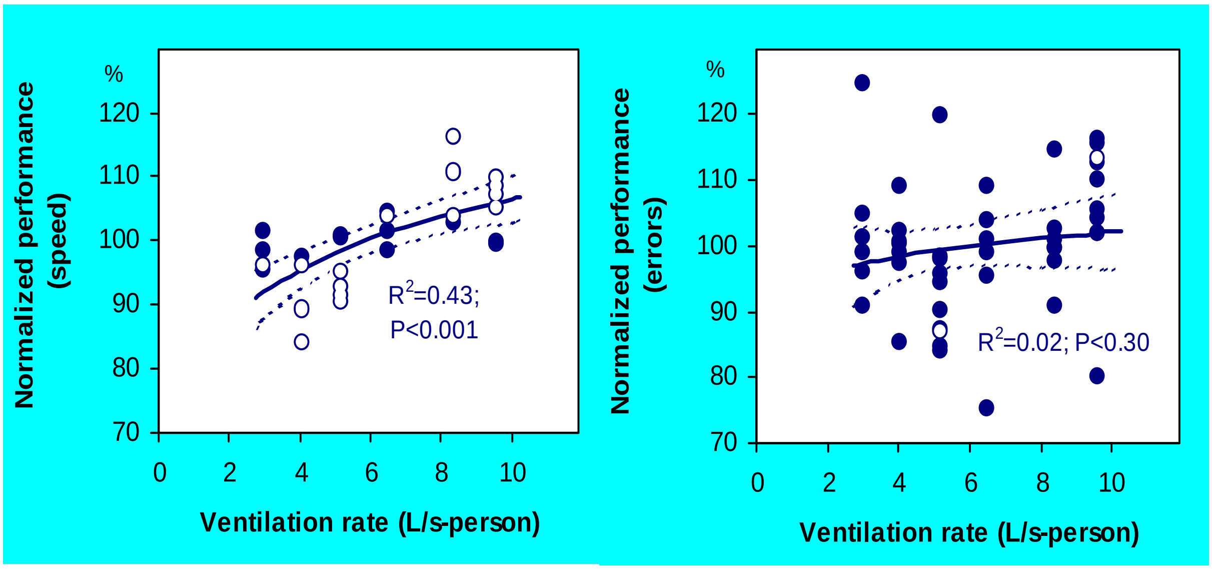

Figure 4. Student performance versus ventilation rate based on study in Denmark [8]. Open dots represent tasks for which the performance increases with ventilation rate were statistically significant. [Figure 4 reproduced with permission.]

per person at the lower air exchange rates were very low even for classrooms, e.g., less than 1 L/s per person. In addition, this study intentionally did not disentangle the effects of ventilation and temperature. Temperatures were higher by approximately 2 ^{o}C in the low-ventilation conditions, as they would be in building cooled by the outdoor air supply. Higher temperatures, in the temperature ranges encountered in this study, have been shown to reduce work performance [14]. Thus, these two studies do not provide information about how ventilation rates affect student performance when temperature is maintained constant.

Higher classroom ventilation rates have also been linked to a reduction in student absence [15], which, in turn, may improve student learning.

In summary, while the applicable research is limited, the available scientific literature indicates the potential for 5% to 10% increases in aspects of student performance with increased classroom ventilation rates. Ventilation rates in roughly half of U.S. public elementary school classrooms appear to be less than specified in codes [11, 15, 16]; thus, the opportunities for increasing student performance by increasing ventilation rates, at least in U.S. schools, may be substantial.

Indoor pollutant sources and performance

The improvements in work and school work performance with higher ventilation rates is presumed to be a consequence of the reduction in indoor concentrations of indoor-generated air pollutants with more ventilation. If this explanation is correct, we would expect performance to also increase if indoor pollutant concentrations were reduced by reducing the emissions from indoor pollutant sources, e.g., by removing indoor pollutant sources. We have limited research that directly assesses the effects of source reduction measures on performance, but the results of this research are at least qualitatively consistent with the finding that increased ventilation rates improve work performance. Most of the relevant studies were performed in a laboratory setting representative of real offices [17-19]. In these studies, subjects performed tasks representative of office work, such as proof reading of text, text typing, and simple arithmetic operations and speed and accuracy in these simulated work tasks was measured and used to indicate work performance. In three studies [17, 18], a section of carpet removed from a complaint building was placed in the laboratory, but hidden from the study subjects. Performance, based on typing, addition, and proof reading tests, was improved by approximately 4% by removing the carpet, as depicted in Figure 5.

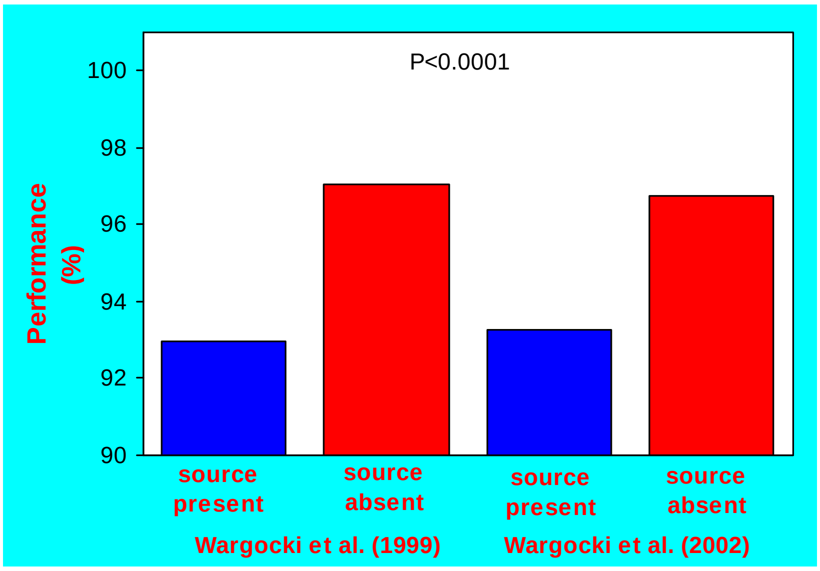

Figure 5. Controlled laboratory studies performed in Denmark show that performance, based on typing, addition, and proof reading tests, improved when a carpet taken from a complaint building was removed. [Figure 5 reproduced with permission.]

Bako-Biro [19] performed similar laboratory studies, but with three-month old personal computers with CRT monitors as the pollutant source. When the computers were removed, performance in proof reading and arithmetic calculations were unaffected; however, text typing errors diminished by 16% and typing speed improved slightly. The improvements in typing performance were statistically significant. Additional research by Bako-Biro [20] employed three-year-old linoleum flooring, shelves with books and paper, and three-month-old caulk sealant as the pollutant sources. Speed and accuracy in arithmetic calculations were used to assess work performance. In this study, few and only small statistically significant impacts of the pollutant sources on performance were identified, although there is some evidence of improved text typing when the pollutant sources were removed.

One additional study of the effects of pollutant source removal on work performance was performed in a call center with the time required to talk with customers used as an measure of work performance [21]. The pollutant source was a 6-month old particle filter in the building's ventilation system. When the used filter was replaced with a new filter, at times unknown to the call center workers, average talk time decreased by approximately 10%.

Perceived Indoor Air Quality and Work Performance

Peoples' perceptions of indoor air quality, as reported on questionnaires, have often been used as subjective indicators of the quality of indoor air. The questionnaires normally ask subjects to rate air quality on a scale ranging from clearly acceptable to clearly unacceptable. Research, performed primarily in the laboratory [18-20, 22-24] , has found that improved perceptions of, or satisfaction with, indoor air quality are associated with improvements in some aspects in work performance. In this research, performance of some tasks has increased by approximately 1% for each 10% reduction in the percentage of the occupants dissatisfied with indoor air quality. However, it is not known if an increased satisfaction with indoor air actually causes people to work better. It could be that the indoor environmental exposures, e.g., pollutants, directly cause both poorer work performance and dissatisfaction with indoor air, leading to a correlation of performance with perceived air quality.

HEALTH-RELATED ECONOMIC BENEFITS OF IMPROVED IEQ

Eliminating Environmental Tobacco Smoke

Environmental tobacco smoke (ETS) is the tobacco smoke to which non-smokers are exposed. Most ETS exposures occur indoors. Based on reviews of a very large body of research, various organizations or panels of experts have concluded that ETS is the cause of an increased number of several health outcomes including premature death from lung cancer and cardiovascular disease, and cases of asthma exacerbation. A critical review by a California health organization provides estimates [25] of annual ETS-caused health effects in the U.S.. Fisk [26] used these data and unit costs for health outcomes to estimate the preventable cost of ETS exposures, assuming that ETS exposures are 100% preventable. The results are shown in Table 1.

Table 1. Estimated annual health effects and preventable costs ($U.S.) in the U.S. of indoor ETS exposures in 2000.

Heath Effect	**Annual U.S. Cases (1000s)**	**Unit Cost ($ U.S.) [cost type^]**	**Total Cost in U.S. (billions of $U.S.)**	**Cost per U.S. smoker[#] ($U.S.)**
Death	40.5 – 68.8	6300K [WTP] (2100K–10600K)	$260 - $430* $85 - $730+	$4000 - $6600* $1300 - $11000[+]
Asthma induction	8.1 - 26	$33K [WTP]	$0.27 - $0.86*	$4 - $13
Day of asthma exacerbation	400 – 1000	$42 [WTP]	$0.017 - $0.042*	$ 0.26 - $0.65
Bronchitis or pneumonia hospitalizations	7.6 – 15.2	$11K [COI]	$0.084 - $0.170*	$1.30 -$2.63
Acute Bronchitis or Pneumonia	150 – 300	$59 [WTP]	$0.009 - $0.018*	$0.13 – $0.28
All morbidity			$0.38 – $1.09	$5.87 - $16.80

[#]based on 64.7 million smokers in the U.S. in 2000 [27] *range in costs reflects only the range in number of health effects [+]range in costs reflects the range in number of health effects and the range in the estimated unit costs per health effect, when available ^ WTP = willingness to pay, COI = cost of illness

From the numbers in this table, it is evident that the health-related costs of ETS are still very large in the U.S., despite considerable progress in reducing smoking rates. On average, each smoker is responsible for 3100 to 8500 € ($4000 to $11000) of cost per year from premature death in non-smokers and for 5 to 12 € ($6 to $16) in annual health costs for morbidity. The estimated health cost imposed per smoker may be roughly similar in other regions of the world with similar living standards.

Dampness and Mold

Many studies have found that dampness or mold is common in homes and is associated with increases in asthma exacerbation and various respiratory symptoms [28]. To estimate the cost of asthma from indoor dampness and mold (C_{DM}), Fisk [26] used the following equation

$$\boldsymbol{C_{DM}} = \text{(attributable fraction of asthma) X (total cost of asthma)} \qquad (2)$$

The same basic approach was used by Nguyen et al. [29] for the asthma attributable to dampness or mold in Finland. The fraction of asthma symptoms attributable to dampness and mold was estimated using a standard equation for calculating the attributable fraction (AF)

$$AF = [P(RR-1)]/[P(RR-1)+1] \qquad (3)$$

where P is the prevalence of the risk factor (e.g., household mold contamination) and RR is the relative risk, which indicates the increased prevalence of the health effect in the population with the risk factor. Using the results of four large studies, three from North America and one from Europe, approximately 13% of asthma symptoms were attributable to asthma and mold in housing [26]. The total annual cost of asthma in the U.S. in year 2000, was estimated to be between 5.8 to 10.7 billion € ($7.5 to $13.9 billion U.S.) [26]. Thus, the annual cost of asthma in the year 2000 attributable to dampness and mold in housing is 13% of this range or approximately 0.8 to 1.4 billion € ($1 to $1.8 billion U.S.). This equals 19 to 35 € ($25 to $45 U.S.) of annual asthma-related costs for every home with dampness and mold, given that the U.S. had 121 million housing units [27] in 2000 and roughly one third of homes have visible dampness or mold [26]. This 19 to 35 € ($25 to $45 U.S.) estimate may be a reasonable initial estimate of the annual asthma-related costs for damp homes in other countries with similar living standards. Based on the prior analyses of the asthma health cost of dampness and mold in Finland in 1996 [29], one can estimate that the cost was 18 € ($29) per home or apartment in need of repair due to moisture. The costs of other health effects of dampness in mold have not been estimated but may be substantial. In addition, dampness and mold in workplaces and schools is common and is expected to impose additional health costs.

At present, we do not have a defensible estimate the portion of dampness and resultant indoor mold that is preventable. Many dampness problems, possibly a majority, result from water leaks that could be prevented through better building maintenance and improved design and construction. Better ventilation in winter and use of dehumidifiers in summer could reduce dampness problems that result from high indoor humidity. Thus, it is technically feasible to eliminate a large majority of the dampness problems. However, poverty, insufficient training of homebuilders, lack of public awareness, and resistance to behavioral changes remain substantial obstacles.

Communicable Respiratory Illnesses and Sick Leave

The limited data available suggest that occupants of buildings or spaces with higher ventilation rates on average have fewer communicable respiratory illnesses, e.g., common colds and influenza, and less absence from work or school. These data are from buildings in which multiple occupants share the same airspace, i.e., air is transported from person to person. Much of the research has been performed in buildings with a high occupant density such as jails or military barracks. Three studies have investigated linkages between ventilation rates and absentee or sick-leave rates in more typical buildings; two were performed in offices [30, 31] and one in elementary grade classrooms [15]. One office study [31] found no association of sick leave with building carbon dioxide (CO_2) concentrations, as indicators of ventilation rates; however, this study included only two buildings and had experimental periods that did not integrate over the yearly cycle of respiratory disease. The two much larger studies, one of offices [30] and the second of classrooms [15], assessed absence over full-year periods. In the office study, short term sick leave was 25% less in buildings with 24 L/s-person compared to 12 L/s-person of outdoor air. In the classroom study, a CO_2 concentration decrease corresponding to a 10 L/s per person increase in ventilation rate was associated with a 9% to 17% decrease in total student absence.

From the office building study, one can estimate the economic benefit of the 12 L/s-person increase in ventilation rate. In the office workers, the total average sick leave rate was 1.71% or 4.3 days assuming 250 work days per year. The 25% lower sick leave in the buildings with 12 L/s-person more ventilation corresponds to an average annual reduction in absence of 1.1 days per person. If the annual salary plus benefits is 77,000 € ($100,000 U.S.), the reduction in sick leave is worth $338 € ($440 U.S) per worker.

COST EFFECTIVENESS OF IMPROVEMENTS IN IEQ

To inform decisions about investments in building design, retrofit, or operation, it is common to employ cost-benefit analyses that account for initial equipment costs, energy costs, maintenance costs, and taxes. The economic value of changes in work performance, absence, and health are normally neglected. However, using the information provided above, it is now possible to account for some of these changes in human outcomes. Although uncertainty about the magnitudes of changes in performance, absence, and health remain high, application of best available estimates should lead to better decisions than the current practice of neglecting these factors. This section provides some examples.

Night Time Ventilative Cooling

In buildings without mechanical cooling, work-time air temperatures can be diminished by using fans (or by opening windows) to ventilate the building during the cooler night-time periods. The night-time ventilation reduces the temperature of thermal mass in the building and, by absorbing heat during the subsequent workday, this cooled thermal mass reduces workday temperatures. Kolokotroni et al [32] report temperatures in a Finnish office building with and without ventilative cooling. We previously used these temperatures with a very simple temperature-performance relationship [33], to compare the value of predicted work performance increases with the costs of running the fans to ventilate the building at night. We assumed that 2.5 kW of fan power was required per each 1 m^3/s of ventilation, a 4 air change per hour ventilation flow rate, 83 m^3 of indoor air volume per occupant, 8 hours of fan operation, and that salary, benefits, and overhead cost the employer 25 € per hour per worker. We now provide an updated analysis using the temperature-performance relation in equation 1. For each hour of the workday, the percent decrease in work performance and equivalent lost working time were calculated using the indoor temperatures with and without night-time ventilative cooling. Table 2 shows the calculation of lost working time. It was estimated that ventilative cooling reduces the lost work time from 26.1 to 8.8 minutes per day, which has a value of 7.2 € per worker per day. If the electricity to operate fans cost 0.10 € per kWh, the daily energy cost is 0.18 € per person. The benefit-cost ratio is then 7.2/0.18 or 40. With electricity costs of 0.05 and 0.15 € per kWh, the benefit-cost ratios are 80 and 27, respectively.

Table. 2. Example calculation of work performance gains from night time ventilative cooling in an office building without air conditioning.

Hour	**No Ventilative Cooling**			**With Ventilative Cooling**		
	T ^{o}C*	**RP**	**Lost Min**	**T ^{o}C***	**RP**	**Lost Min**
8 - 9	27.0	0.954	2.73	23.4	0.991	0.55
9 - 10	27.2	0.952	2.90	23.5	0.990	0.58
10 - 11	27.6	0.946	3.24	23.9	0.988	0.74
11 - 12	27.8	0.943	3.42	24.2	0.985	0.88
13 - 14	27.8	0.943	3.42	25.2	0.976	1.42
14 - 15	27.8	0.943	3.42	25.4	0.974	1.55
15 - 16	27.9	0.941	3.51	25.4	0.974	1.55
16 - 17	27.8	0.943	3.42	25.4	0.974	1.55
Total			26.08			8.83

*Estimated operative temperature as average of air and slab temperatures
Lost time each hour = (1 – RP from equation 1 at T*) x 60 minutes

Comparison of Building Cooling Strategies

In another set of example cost-benefit analyses [34], the following options for cooling an office building located in Helsinki were compared: a) base case with no mechanical cooling and a 2 L/s-m^2 supply air flow 10 h per day; b) mechanical cooling with capacity of 20 W/m^2, c) base case but with the ventilation system operation increased from 10 to 24 h per day; d) base case but with the ventilation system operation increased from 10 to 24 h per day and supply flow rate increased to 4 L/s per m^2; e) base case plus all measures in b, c, and d. The assumed value of an hour of work was 32.3 € and the cost of heat and electricity were 0.04 €/kWh and 0.1 €/kWh, respectively. Other assumptions are provided in reference [34]. The key results of this analysis are provided in Table 3.

Table 3. Comparison of life cycles costs of cooling an office building in Helsinki [34]

Factor	**Base Case**	**Mechanical Cooling**	**Increased Operation Time (No Mech. Cooling)**	**Increased Outdoor Air Flow (No Mech. Cooling)**	**All Meas -ures**
Increased annual energy cost per person, €	--	1.6	6.3	40.0	39.9
Increased first cost, € per person	--	9.5	0	10.0	19.5
Effective lost work hours per person-year, h	21.2	15.5	12.6	6.5	4.4
Value of lost work hours per person-year, €	686	501	408	211	141
Value of improved work, €	--	184	278	475	545
Total annual savings per person, €	--	131	272	380	398

This example analysis projects annual savings of 131 € to 398 € per worker from implementing the various measures for space cooling. In the Helsinki climate, with relatively few days where cooling is needed, the mechanical cooling option consumes less energy than increasing ventilation time or flow rate.

Addition of an Outdoor Air Economizer

In an air-conditioned building, an economizer system increases the outdoor air supply above the minimum amount required by codes whenever doing so eliminates the need for energy-intensive mechanical cooling. Normally, economizers are used in buildings with air recirculation by reducing the amount of recirculation and increasing the outdoor air supply. Economizer systems save energy. In many climates, economizers also dramatically increase time-average ventilation rates. Economizer systems are common in large U.S. HVAC systems with air conditioning, but are often considered too costly for small HVAC systems.

A prior paper [35] evaluated the energy savings and projected financial benefits from reduced sick leave when an economizer system was used in an office building located in Washington, DC. A building energy simulation model predicted hourly ventilation rates and energy consumption with and without an economizer system. A model of airborne disease transmission calibrated with empirical data on the relationship of ventilation rates with respiratory disease and absence was employed to estimate sick leave rates with and without the economizer. The doubling of the work-time average ventilation rate, from 10 to 20 L/s per person, when an economizer was used saved about 23 € ($30) in energy costs per person per year and reduced annual sick leave by an estimated 0.9 to 1.2 days per person. With each day of sick leave valued at 154 € ($200 U.S), corresponding to an annual cost of salary plus benefits of 38,500 € ($50,000 U.S.), the annual value of the reduced sick leave is approximately 160 € ($210 U.S.) per person.

One can instead easily use the ventilation rates in this paper and estimate the work performance benefits from increased ventilation via Figure 4 or equation 2. The annual value of the projected 1% increase in work performance is $380 € ($500 U.S.)

Table 4 summarizes the results of these two analyses. Decisions about whether or not to use an economizer would normally be based on a comparison of the economizer system costs with the 23 € ($30) per person projected annual energy savings. However, when best estimates of the impacts of ventilation rate on absence and work performance are considered, the economizer saves roughly 570 € ($740 U.S.) per person per year.

Table 4. Example analyses of financial benefits of an economizer system in an office building located in Washington, DC.

Increase in annual average ventilation rate	10 L/s-person
Normally considered benefit Annual Energy cost savings	 $30 U.S. (23 €) per person
Normally neglected benefits Annual value of reduced absence Annual value of productivity increase	 $210 U.S. (160 €) per person $500 U.S. (380 €)

Increased Ventilation Rates in an Office Building

Another example analysis [34] compared the energy and equipment costs of providing a higher ventilation rate in an office building with the value of work performance increases estimated from Figure 4 or Equation 2. The office building had a typical design for a medium-size northern-European, mechanically-cooled building with supply and exhaust air flows, no recirculation, and air-to-air energy recovery with a 75% temperature efficiency. Energy consumption and energy costs were estimated with a simulation program, Helsinki climate data, and energy costs of 0.04 € per kWh for heat and 0.1 € per kWh for electricity. The annual value of work per employee was 30,000 C. Table 5 summarizes the main results from this analysis. Increasing the ventilation rate results in a 4.4 to 22 € increase in annual energy cost per employee, a similar magnitude increase in maintenance costs, a 22 to 63 € annualized increase in first costs, performance increases of 1% to 2.4 % valued at 300 to 690 € per person per year. The estimated benefit-cost ratio ranges from 6.2 to 9.4. The largest benefit-cost ratio was predicted for increasing ventilation rates from 6.5 to 10 L/s per person, but further economic benefits are predicted from increasing the ventilation rate from 10 to 20 L/s per person. This example analysis neglected the value of reduced health effects and absence from increased ventilation.

Table 5. Predicted costs and benefits from increasing ventilation in an office building [34].

Change in Ventilation Rate (L/s-person)	Annual Cost Increase (€ per person)			Increase in Performance		Benefit-Cost Ratio
	Energy Consumption	Maintenance	Equipment (annualized)	%	€ per person	
6.5 to 10	4.4	4.7	22.5	1.0	300	9.4
6.5 to 20	22.5	13.3	63	2.3	690	7.0
10 to 20	18.1	8.5	41	1.4	420	6.2

DISCUSSION

Main findings

Based on the information presented above, we have fairly compelling evidence that indoor environmental factors and related building operating conditions affect health and work performance. Higher ventilation rates are associated with improved health and better work and school performance. Removal of pollutant sources is associated with improved work performance, at least in some cases. Indoor temperatures in the 21 to 22 ^{o}C range are associated with maximum overall work and school performance. We now have estimates of quantitative relationships between some of these indoor environmental factors and health or performance outcomes. These quantitative relationships enable an accounting of some health and productivity benefits in cost-benefit calculations pertaining to building design and operation. Example cost-benefit analyses indicate that many measures to improve indoor temperature control and increase ventilation rates will be highly cost effective, with benefit-cost ratios as high as 80 and annual economic benefits as high as 500€ ($700) per person.

Implications

The research findings and cost-benefit analyses summarized in this paper suggest that more effort and investment be devoted to improvement of IEQ, which will often lead to more productive and healthy workers and financial benefits that greatly exceed costs. Designers and those who construct buildings must be educated about the technologies and practices needed to enable good IEQ. To assure that good IEQ is maintained over the life of buildings, periodic or continuous commissioning and building and HVAC system maintenance will be necessary. It would be helpful to develop and utilize lease and maintenance contracts that incentivize building owners and maintenance providers to maintain good IEQ. In addition, building operators and maintenance staff should be educated about means of maintaining good IEQ.

Limitations

There remain substantial uncertainties in the quantitative relationships between indoor environmental factors and health and work performance outcomes. The limited body of related research is one source of uncertainty. In addition, much of the research completed to date uses the speed and accuracy of simulated work tasks as the work performance outcome. While such outcomes are clearly relevant to real work, the quantitative relationship between average performance of these simulated work tasks and average performance of overall real-world work remains uncertain. In particular, speed and accuracy of simulated work tasks, such as addition, typing, and proof reading, might not be a good predictor of higher-level cognitive functioning such as the decision making of many managers and executives. Another limitation of the currently available quantitative relationships is that they are not tailored for specific building conditions, types of work, or types of workers. Rather, the existing quantitative relations presented in this paper are estimates of the average relationships for the average building, type of work, and worker. In specific situations, larger or smaller improvements in health and performance may be expected. For example, an increase in ventilation rate would seem more likely to substantially improve health or work performance in a building with initially poor IEQ due to the presence of strong indoor pollutant sources. Despite the substantial uncertainties, application of the best information available today should lead to better decisions about building design and operational practices than the current practice of totally neglecting impacts on health and work performance.

Who Benefits and Who Pays?

Users of quantitative relationships between IEQ factors and health and productivity must recognize that costs and benefits may affect different parties. For example, in a leased building, the building owner usually pays for building or HVAC improvements while the employer benefits most directly from improved work performance and reduced absence. However, the owner of a leased building may indirectly benefit the improved worker health and work performance through increased rent, higher property values, and longer tenant retention when IEQ is improved and the building has a more positive reputation. The employee and health care insurer may directly benefit from reduced health care costs, but often the associated financial benefits will not be passed on to the employer. In an owner-occupied building, the incentive for investments to improve IEQ may be greatest because the owner-employer benefits directly from both improved work performance and reduced absence.

Energy use concerns

Because increased ventilation rate is associated with improved work performance and better health, and often increases energy use, there is a conflict between energy efficiency and health/productivity goals. Given the broad concerns about global climate change resulting from use of fossil fuels for energy, there is a strong need for technologies and practices that bring about the productivity benefits without increasing energy use, and ideally with simultaneous energy savings. The economizer system, described above, is an example of such a technology. In the longer term, we should be able to identify and utilize pollutant source control measures and air cleaning technologies to bring about the same health and productivity benefits as increased ventilation, but with no or minimal increases in energy use.

Priority research needs

While there are many research needs related to the subjects discussed in this paper, the following are suggested as high priority research needs:

- the influence of IEQ factors on high-level cognitive performance such as decision making;
- the influence of IEQ factors on quality and speed of real work, as opposed to simulated work tasks;
- the relationship between performance of school work tasks and student learning;
- the relationship between worker health, which has already been shown to be associated with many IEQ factors, and work performance;
- means of obtaining the health and productivity benefits of increased ventilation with minimal increase in energy use, or ideally with energy savings.

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