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ABSTRACT

This paper estimates some of the benefits and costs of implementing scenarios that improve indoor environmental quality (IEQ) in the stock of U.S. office buildings. The scenarios include increasing ventilation rates when they are below 10 or 15 L/s per person, adding outdoor-air economizers and controls when absent, eliminating winter indoor temperatures greater than 23 °C, and reducing dampness and mold problems. The estimated benefits of the scenarios analyzed are substantial in magnitude, including increased work performance, reduced sick building syndrome symptoms, reduced absence, and improved thermal comfort for millions of office workers. The combined potential annual economic benefit of a set of non-overlapping scenarios is approximately $20 billion. While the quantitative estimates have a high uncertainty, the opportunity for substantial benefits is clear. Some IEQ improvement measures will save energy while improving health or productivity, and implementing these measures should be the highest priority.

KEYWORDS

dampness and mold, IEQ improvement, health, offices, temperature, ventilation

PRACTICAL IMPLICATIONS

Owners, designers, and operators of office buildings have an opportunity to improve IEQ, health, work performance, and comfort of building occupants, and to obtain economic benefits by improving IEQ. These benefits can be achieved with simultaneous energy savings or with only small increases in energy costs.

INTRODUCTION

This document presents estimates of the benefits and costs of selected improvements in indoor environmental quality (IEQ) conditions in U.S. offices. Factors considered include costs for equipment and energy and changes in health symptoms, comfort, work performance, and absence along with their associated economic implications. The analyses in this paper build upon many prior related analyses, e.g., (Fisk and Rosenfeld 1997; Mendell et al. 2002; Wargocki and Djukanovic 2005; Wargocki et al. 2006) and upon the work of scientists from around the world who have investigated the associations of IEQ parameters with people's health, comfort, and performance. The analysis methods in this paper also draw upon the methods developed and used routinely by others to economically quantify the benefits of improved health from reduced outdoor air pollution, e.g., (EPA 1999).

Today, it is possible to improve upon the first author's prior order-of-magnitude analyses (Fisk and Rosenfeld 1997; Fisk 2000) of the benefits of improved IEQ because of subsequent advances in our understanding of how IEQ affects people's health and work performance. In addition, recent meta–analyses and other syntheses of the scientific literature, cited subsequently in this paper, have developed estimates of the quantitative relationships of some IEQ parameters with health and work performance outcomes. These quantitative relationships provide a foundation for estimating the benefits of improved IEQ.

The estimated benefits of improved IEQ provide a basis for prioritizing efforts to improve IEQ and for prioritizing related research. The estimates, particularly the monetary estimates, also facilitate communication of the importance of IEQ to policy makers, building professionals, and the broader public.

METHODS

General approach

Unlike most prior analyses, the estimations in this paper start with data on existing IEQ conditions, e.g., ventilation rates, in the stock of U.S. office buildings and evaluate the impacts of implementing selected scenarios that change those conditions. We have selected scenarios that the authors consider to be readily achievable given today's knowledge and technology base. The IEQ improvement scenarios and the analyzed impacts of these scenarios are summarized in Table 1. Scenarios 1a and 1b increase total outdoor air ventilation rates (VRs) to target values of 10 and 15 L/s per person, respectively, in the subset of offices where existing VRs are lower than the targets. The target of 10 L/s per person is typical of the minimum VR prescribed in standards from around the world for offices and moderately above the minimum of 8.3 L/s per person for offices (with the default occupant density) in the current major U.S. standard (ASHRAE 2007). The value of 15 L/s per person is 50% higher, but still considered well within the capacity of most existing heating, ventilating, and air conditioning (HVAC) systems. Scenario 2 adds outdoor air economizers and controls (hereinafter referred to as economizers) to the 50% of the existing U.S. office floor space that does not have an economizer. An economizer is a control system that increases the supply of outdoor air (i.e., the VR) above a minimum value when the additional ventilation will reduce the energy costs of air conditioning, thus, economizers substantially increase annual-average VRs. In buildings with packaged (pre-fabricated) HVAC systems, economizer additions are generally simple; however, in some buildings with more complex (e.g., site-built) HVAC systems, economizers would be added as HVAC systems are updated or as the building stock is replaced. Scenario 3 eliminates winter indoor temperatures greater than 23 ^{o}C in offices, in many cases through simple adjustments of thermostat set points. Scenario 4 reduces the prevalence of dampness and mold in offices, which would be accomplished by better maintenance to prevent and fix water leaks, changes in design and construction practices, and improved humidity control systems in some buildings within hot and humid climates. The scenarios are examples -- no attempt was made to estimate all possible benefits or costs of improved IEQ.

The basic steps in the analyses of each scenario were:

I. Obtain values of relevant existing (pre-scenario) IEQ conditions (e.g., VRs, temperatures) in the office building stock.
II. Obtain average sick-building syndrome (SBS) symptom prevalence rates and absence rates in the existing office worker population. For SBS symptoms, estimate the existing prevalence rate in buildings subject to VR increases in (Scenarios 1a - 2). These buildings have low VRs and, thus, will have higher existing SBS symptom prevalence rates than the full set of U.S. office buildings.
III. Based on scenario definitions, determine values of final (post scenario) IEQ conditions.
IV. Calculate existing (pre-scenario), final (post-scenario), and change in symptom, performance, absence, and comfort outcomes.
V. Calculate energy impacts of scenario implementation (when applicable and possible).
VI. Perform economic analysis of the changes in symptom, performance, and absence outcomes and of changes in energy consumption.
VII. Perform analysis of cost of scenario implementation (when applicable and possible).

Table 1. IEQ improvement scenarios.

Description of Scenarios*	**Outcomes Evaluated**$^{+}$	**Sources of Information Relating IEQ Parameters with Outcomes**$^{+}$
1a) increase VR to 10, when less 1b) increase VR to 15 when less 2) add economizers if absent	performance, SBS Sx, short-term absence, energy	(Seppanen et al. 2006) for VR-performance, (Fisk et al. 2009) for VR-SBS Sx relationship, (Milton et al. 2000) for VR-absence, (Griffith et al. 2008; Benne et al. 2009) for VR-energy in scenarios 1a and 1b
3) eliminate T > 23 °C in winter	Performance, SBS Sx	(Seppanen et al. 2005) for T-performance, (Mendell and Mirer 2009) for T-SBS Sx
4) reduce number of buildings with dampness & mold by 30%	absence	(Sahakian et al. 2009) for dampness-absence (respiratory sick leave)

*VR = VR per person in L/s per person, T = indoor air temperature $^{+}$SBS Sx = SBS symptoms

Sources of data on existing IEQ conditions

The calculations used data on VRs (Persily and Gorfain 2008), indoor temperatures (Mendell and Mirer 2009), and SBS prevalence (Brightman et al. 2008; Mendell and Mirer 2009) from a U.S.-wide survey (EPA BASE Study) of 100 representative office buildings. This survey evaluated a study space in each building over a one-week period, generally in either the summer or winter. VRs were measured on Wednesdays and Thursdays, once in the morning and once in the afternoon – each of these measurements is considered a measurement event. Temperatures were measured at five-minute intervals; however, we have utilized only the prior analyses (Mendell and Mirer 2009) of temperature data for a nine hour period. The EPA BASE study also provided data on prevalence rates of SBS symptoms (Brightman et al. 2008; Mendell and Mirer 2009) that were used in the present paper. These EPA BASE data were assumed to apply to the full U.S. office building stock. The prevalence of dampness and mold in offices was based on a U.S. survey of 1396 office workers (Sahakian et al. 2009).

For scenarios 1a and 1b, two sets of calculations were performed, one set using "volumetric" VRs from the EPA BASE study and the other using "peak CO_2" VRs. The two measurement methods yielded substantially different values of VR (Persily and Gorfain 2008), for example the geometric mean (GM) of all VRs less than 15 L/s per person equals 7.2 L/s per person based on the "volumetric" method and 11.3 L/s per person based on the "peak CO_2" method. It is not known which measurement method is more accurate.

Relationships of IEQ factors with health symptoms, performance, absence, and comfort

The sources for estimated quantitative relationships of IEQ parameters with outcomes are identified in Table 1. The relationships of VRs and indoor temperatures with office work performance, and of VRs with SBS symptoms, were based on prior statistical analyses that synthesized the findings of multiple studies and are illustrated graphically in Appendix 1 with more details available at www.iaqscience.lbl.gov.

These subsequently described relationships of VRs and temperatures with work performance and symptoms, and the relationships of temperature with SBS symptoms, are non-linear. For the analyses of scenarios, calculations of changes in work performance and SBS symptom prevalence rates based on arithmetic mean or median values of existing VRs and temperatures would be inaccurate. Consequently, when feasible we have calculated the changes in work performance or SBS symptom prevalence rates assuming application of the scenarios to each individual building measurement event within the EPA-BASE Study, and then calculated the average changes in performance and SBS symptoms. This approach was not practical for analyses of scenario 2, thus, for this scenario the calculations used geometric mean values of VR. Independent calculations demonstrated that the results of using GM values of VRs were very similar to results obtained using the data from each building and measurement event.

Ventilation rates and SBS symptoms

For the relationship of VRs in offices with prevalence rates of SBS symptoms (Fisk et al. 2009), the following equation was employed:

$$RSP = \exp[0.00089x^2 - 0.0542x + 0.453] \qquad (1)$$

where *RSP* is the relative SBS symptom prevalence, equal to the expected SBS symptom prevalence with a VR of x (in L/s per person) divided by the expected SBS symptom prevalence with a VR of 10 L/s per person. This equation indicates the average relationship of SBS symptom prevalence with VR for a range of SBS symptom types across a range of VRs from 5 to 35 L/s per person.

For calculations of how changes in VRs in the office building stock influence SBS symptom prevalence, the following steps were employed:

1. We started with the VR data from the EPA BASE study (Persily and Gorfain 2008) and assumed these data are representative of the full U.S. office building stock.
2. For each building in the survey, and for each of the measurement events in the building, the measured VR was compared to the scenario's target VR. If the measured VR was less than the target VR, we assigned a final VR equal to the target VR, otherwise the VR was unchanged.
3. For each measurement event with a change in VR, equation 1 was used to calculate *RSP* at the existing VR. If the existing VR was less than 5 L/s per person, we calculated *RSP* at a VR of 5 L/s per person.
4. For each measurement event with a change in VR, equation 1 was used to calculate *RSP* at the final target VR.

5. Values of *RSP* from step 4 were divided by values of *RSP* from step 3, yielding ratios which indicate the changes in SBS symptom prevalence. The average of these ratios was calculated.
6. The average of the ratios from step 5 was multiplied by the estimated average (pre-scenario) SBS symptom prevalence in the buildings subject to a change in VR. This calculation yielded the change in SBS symptom prevalence in the affected portion of the work force.

To estimate the average existing SBS symptom prevalence in buildings subject to an increase in VR, we started with the average prevalence (16.8%) of weekly eye, nasal, headache, and tiredness/fatigue symptoms (Brightman et al. 2008) in the full EPA BASE survey, as these were the types of symptoms considered in the derivation of equation 1. Because the buildings in which VRs were increased -- a subset of all EPA BASE buildings -- had a lower average existing VR than the overall population of EPA BASE buildings – this survey-wide average SBS symptom prevalence rate was adjusted upward using equation 1. For this adjustment, we used the existing geometric mean (GM) VR for all buildings in the survey, and, with equation 1, predicted the average SBS symptom prevalence at the lower GM of the measured VRs in the subset of buildings subject to a change in VR. GM values of VR were used because the relationship of *RSP* with VR is approximately log-linear.

For the evaluation of scenario 2 (economizers), existing VRs were obtained from the BASE data from buildings without economizers (Persily and Gorfain 2008) and final (post-scenario) VRs were obtained from modelling as described subsequently. Equation 1 was used together with the GM values of existing and final (post-scenario) values of VR.

Ventilation rates and work performance

For the relationship of VRs in offices with office work performance (Seppanen et al. 2006), the following equation was employed

$$RWP_{VR} = \exp((-76.38x^{-1} - 078xLn(x)) + 3.87x - y_0)/1000) \qquad (2)$$

where RWP_{VR} is the relative work performance as affected by VR, x is the VR in L/s per person and y_0 is calculated as follows

$$y_o = -76.38X_R^{-1} - 0.78X_R Ln(X_R) + 3.87X_R \qquad (3)$$

where X_R is a reference value of VR set equal to 10 L/s per person. Equation 2 applies for VRs of 6.5 to 47 L/s per person. When existing VRs were less than 6.5 L/s per person, we used values of RWP_{VR} at 6.5 L/s per person. The calculation process was very similar to that described above for SBS symptoms, except there was no calculation step equivalent to step 6 in the SBS-symptom calculation. Step 6 was necessary for the SBS symptom calculations because only a fraction of office workers have SBS symptoms.

Ventilation rates and short-term absence

The findings of a single study in 40 buildings (Milton et al. 2000) were employed to estimate the quantitative relationship of office VR with short term absence. This study found that a 12 L/s per person increase in VR was associated with a 35% reduction in short term absence in office workers. (Short term absence excluded data from workers absent for greater than 50% of the year and data from workers who received short-term disability payments.) We assumed the relationship of short term absence with VR was linear and, in scenario analyses, estimated that short term absence diminished by 2.9% for each 1 L/s per person increase in VR. These estimates have higher uncertainty than those described above because of the reliance on the results of a single study; however, supportive findings are available from a study of VRs and absence in classrooms (Shendell et al. 2004) and there is a body of evidence (Li et al. 2007) indicating that lower VRs increase respiratory infections, which are a major cause of absence. The calculation procedures for evaluating the impacts of the scenarios on VRs were very similar to those described above for evaluating the impacts of scenarios on SBS symptoms or performance.

Indoor temperature and office work performance
The following equation was used to estimate the relationship of indoor office temperature with office work performance (Seppanen et al. 2005)

$$RWP_T = -0.469 + 0.165 \cdot T - 5.83 \times 10^{-3} T^2 + 6.23 \times 10^{-5} T^3 \qquad (4)$$

where RWP_T is the relative work performance as influenced by temperature, equal to the expected work performance at room temperature T (in ^{o}C) divided by the maximum value of work performance expected at 21.8 ^{o}C. The equation applies for 15 ^{o}C to 31.5 ^{o}C. A recently derived equation relating a measure of thermal comfort with office work performance was found to be consistent with equation 4 (Lan et al. 2010).

For evaluation of scenario 3 (eliminate winter temperatures greater than 23 ^{o}C), we started with the existing measured workday-average temperatures in buildings within the EPA BASE study and assumed these data applied to the full office building stock. We identified the buildings in which the winter workday-average temperature exceeded 23 ^{o}C and, in these buildings, assumed a final (post-scenario) temperature of 23 ^{o}C. In the other buildings, we assumed that temperatures were unchanged. For each building with a change in temperature, equation 4 was applied to calculate RWP_T at the existing workday-average temperature and at the final target temperature of 23 ^{o}C. The calculations used only data from EPA BASE buildings studied in the winter. Ratios of final to existing values of RWP_T were used in the economic calculations described subsequently.

Indoor temperatures and SBS symptoms
The relationship of office temperatures with SBS symptom prevalence rates was based on analyses of the EPA BASE study data (Mendell and Mirer 2009). This study found that SBS prevalence rates in winter increased as temperatures increased above 23 ^{o}C, and provided adjusted odds ratios (ORs) for the symptom prevalence increases for each nine degree hours above 23 ^{o}C. For the scenario analysis, the degree hours above 23 ^{o}C, denoted "*D*", was calculated for each building. For each building, the OR for elevated symptoms applicable to the building and SBS symptom type was calculated as follows

$$OR_n = OR^{(D/9)} \qquad (5)$$

where OR_n is the odds ratio in building n and OR is the odds ratio for each nine degree hours greater than 23 ^{o}C as reported by (Mendell and Mirer 2009). To calculate changes in the symptoms experienced, use of relative risk (RR) is preferable to use of ORs, because the difference between the computed OR and one (OR = 1) moderately overestimates the fractional change in the outcome prevalence. Consequently, calculations were employed to estimate values of RR from values of *OR* and SBS symptom prevalence rates. The calculations used the usual definitions of *OR* and RR (Fisk et al. 2009) and the resulting RR values differed by 0.04 or less from the OR values. These calculations were performed for each of the following SBS symptom categories; lower respiratory, upper respiratory, cough, eye, fatigue/difficulty concentrating, headache, and skin. Fractional changes in SBS symptom prevalence, calculated as the RR minus one, were multiplied by the existing average SBS symptom prevalence rates (Mendell and Mirer 2009) to obtain the absolute change in SBS symptom prevalence for each building and symptom type. For economic calculations, described subsequently, we assumed that SBS symptoms were only reduced during the winter as scenario 3 only modifies indoor temperatures in winter. These estimates have increased uncertainty because they rely on the temperature-symptom relationship from only a single study with its own limitations, which included associating building-related symptoms during the four weeks prior to the study week with the indoor temperatures encountered during only one day of the study week. While many studies have shown that air temperatures are associated with prevalence rates of SBS symptoms, there has been no meta-analysis of these study results. We have used only the results of the largest U.S. study -- the only study that examined how SBS symptoms vary with temperatures independently in summer and winter (Mendell and Mirer 2009).

Indoor temperatures and thermal comfort

The impacts of changes in indoor temperatures on the predicted percentage of occupants dissatisfied with thermal comfort conditions was estimated using a spread sheet implementation of a widely used thermal comfort model (ASHRAE 2009). We assumed that the mean radiant temperature equalled the air temperature, the relative humidity was 40% (the median winter value in the analyzed EPA BASE data), the clothing value was 1.0 Clo (a typical winter value), and the metabolic rate was 1.1 Met (a typical value for office workers).

Office dampness and absence

For analyses of scenario 4, estimates of the impact of office dampness with absence (respiratory sick leave) were based on results of a stratified random sample of 1396 office workers (Sahakian et al. 2009). This study found an adjusted relative risk (RR) of 1.3 ($p = 0.04$) for absence attributable to respiratory symptoms when workplace dampness was present and provided a value of 1.93 for the mean number of days of absence from respiratory symptoms. The prevalence of office dampness among these office workers was 23% (personal communication, Sahakian). With these inputs, the following equation (Coughlin et al. 1994) was employed to estimate the fraction of respiratory sick leave attributable to office dampness

$$AF = [F(RR-1)]/[F(RR-1)+1] \tag{6}$$

where *AF* is the attributable fraction, *F* is the prevalence of the risk factor (e.g., dampness and mold in offices), and *RR* is the relative risk (the risk in the exposed population divided by the risk in the non-exposed population). Although this analysis of scenario 4 relies on the findings of only this single study, a large body of evidence indicates that workplace and home dampness are associated with increased respiratory symptoms and respiratory infections (Fisk et al. 2007; Mudarri and Fisk 2007; Fisk et al. 2010).

Impacts of implementing scenarios in the full population of U.S. office workers

The prior text described the methods of estimating the fractional changes in SBS symptoms, performance, absence, and comfort if the scenarios were implemented. To estimate the impacts of the scenarios on symptoms, performance, absence, and comfort in the U.S.

population of office workers, the fractional changes in the outcomes were multiplied by the total number of U.S. offices workers and by the proportion of office workers subject to changes in IEQ conditions; e.g, VRs. For performance, absence, and comfort, this proportion was set equal to the fraction of buildings in which IEQ conditions were modified, which varied among the scenarios. For SBS symptoms, we also multiplied by the fraction of workers with symptoms.

Building simulations in support of the analysis of scenario 2

The analysis of scenario 2 relied on the methods described above to relate VRs before and after addition of economizers with SBS symptom prevalence rates, work performance, and short term absence; however, additional modelling was required to determine how much the addition of economizer systems affected work-time VRs. For this purpose, we employed a widely used building energy simulation program called EnergyPlus and modelled prototype small, medium, and large office buildings with and without economizers. The "enthalpy" economizer control option was selected. The prototype buildings have been designed to be representative of the office building stock. Modelling was performed for five representative U.S. climates (Baltimore, Chicago, Houston, Los Angeles, and Minneapolis). For existing VRs in buildings without economizers, we used the GMs of the measured rates in the EPA BASE study buildings without economizers based on the "volumetric" and "peak CO_2" measurement methods, 19 and 13 L/s per person respectively. The EnergyPlus annual simulations yielded hourly VRs when economizers were added, and the work-time annual GM values of VR were calculated. For use in analysis of how economizers affect absence rates, work-time arithmetic mean VRs were also calculated. The EnergyPlus program also provided the data needed to calculate the reductions in building gas and electricity use when economizers are employed. To estimate national average changes in symptom, performance, and absence outcomes, weighting factors were applied to each pair (with and without economizer) of model results. The weighting accounted for the variability of existing economizer utilization as a function of building size and climate as determined from the national database (http://www.eia.doe.gov/emeu/cbecs/).

Economic calculations

Costs reported for prior years were updated to 2008 by adjusting for the consumer price index (CPI) for medical care costs, and the general CPI for other costs. Costs of SBS symptoms were based on estimates of the associated health care costs (annual average $182 after adjustment for inflation) (EPA 2007). The total cost savings from a reduction in SBS symptoms equaled the number of office workers in which symptoms were prevented multiplied by the average annual SBS symptom cost. This calculation was conservative because it did not account for the potential that multiple types of SBS symptoms may be prevented within the same worker. The value of a fractional change in work performance of office workers was the product of the fractional change, the number of office workers who experienced a change in work performance (which varies among scenarios), the employer's hourly cost for employee compensation http://www.bls.gov/news.release/archives/ecec_09102008.pdf, and an assumed 1920 hours of work per year. The office worker population, 41.3 million, was the sum of employees in a) management, business, and financial operations, and b) office and administrative support http://www.bls.gov/cps/cpsaat9.pdf. The employer's hourly cost of office work ($38.9) was a weighted value that accounted for the number of workers in each category. The resulting weighted-average annual total cost for office work was $74695. The economic value of a day of absence was eight times the employer's hourly cost of work.

The energy cost of changing office building VRs in scenarios 1a and 1b was based on simulations (Griffith et al. 2008; Benne et al. 2009) showing that building energy consumption varies approximately linearly with VR, with other factors constant. From the data provided from simulations of building energy use with and without mechanical ventilation, plus a typical floor area per office worker of 25 m^2 (Persily and Gorfain 2008), the office-sector annual changes in gas and electricity use were estimated to equal 0.346 and 0.008 kWh per square meter of floor area, respectively, for each 1 L/s per person change in VR. The cost of changing VRs in scenarios 1a and 1b reflected these unit costs, the magnitude of the changes in VR, the affected floor areas, and the 2008 U.S. average prices of gas ($0.043 per kWh) http://tonto.eia.doe.gov/dnav/ng/hist/n3020us3m.htm and electricity ($0.104 per kWh) http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html) for commercial customers.

Because implementation costs for scenarios 1 and 3 were expected to be small, possibly insignificant, relative to benefits (see Discussion), implementation costs were only estimated for Scenario 2, the addition of economizers, and the estimate is very approximate. We obtained unpublished estimates of the initial costs of economizer systems that were used in the development of a national building energy standard (ANSI/ASHRAE 2007). The cost varies from $219 per kW of cooling capacity for a very small 10.5 kW air conditioning system (within the size range of residential systems) to $25 per kW for a larger 105 kW system. We assumed that economizers would be added primarily to small systems with a cooling capacity of 26 to 52 kW, for which the cost ranges from $88 to $55 per kW. With a typical 54 L/s of supply air flow rate per kW of cooling capacity and the average 5.8 L/s design supply flow rate per each square meter of floor area in the EPA BASE Study (Persily and Gorfain 2008), one can estimate the cost of providing economizers per square meter floor area as $6 to $9. Based on service life data for comparable building equipment, we conservatively assumed a 15 year system life and consequently divided these initial costs by 15 to produce rough estimates of annual costs. For scenario 2, these annual costs were multiplied by the floor area served by the added economizer systems (5.7×10^8 m^2), which is 50% of the total U.S. office floor space (U. S. Energy Information Administration 2003).

RESULTS

Estimation of benefits of improved IEQ

Table 2 provides the estimated benefits of the IEQ improvement scenarios and the numbers of workers experiencing the scenarios or experiencing benefits. The magnitudes of the benefits of scenarios 1a, 1b, and 2, which increase VRs, depend strongly on the source of the data on existing office VRs. When using the "volumetric" VR data from the EPA BASE study, annual estimated benefits of increasing office VRs, when below the target of 10 L/s per person, include increased work performance on the order of 1% and reduction in SBS symptoms by 13% to 19% in 8 to 12 million workers, and four to ten million days of avoided absence. The total estimated annual economic benefits are $5.6 billion (scenario 1a) and $13.5 billion (scenario 1b), which compare to estimated energy costs of less than $0.04 billion. The estimated benefits of scenario 2 (economizers) are similar to those of scenario 1b, with $11.8 billion total savings, but this scenario has the advantage of reducing energy consumption.

The "peak CO_2" VR data from the EPA BASE study includes about 50% fewer measurement events than the "volumetric" VR data with VRs below the 10 L/s target of scenario 1a.

Consequently, when using these VR data as the existing condition, the benefits of scenario 1a are much smaller, with total estimated economic benefits of \$1.3 billion compared to \$5.6 billion with the "volumetric" VR data. The benefits of scenario 1b are also reduced, but more moderately to \$9.0 billion from \$13.5 billion. However, when using the "peak CO_2" VR data, the estimated benefits of scenario 2 (adding economizers) are approximately doubled to \$22 billion because, with the peak-CO_2 data, the existing GM VR (13 L/s per person) in buildings without economizers is considerably smaller than the existing GM VR from the "volumetric" VR data (19 L/s per person).

The estimated benefits of reducing winter temperatures greater than 23 ^{o}C are a 0.23% average increase in winter work performance in 40.4 million workers, prevention of 7.7 million weekly SBS symptoms during winter, a 12% reduction in winter thermal discomfort in 40.4 million workers, and annual economic benefits of \$3.4 billion.

A 30% reduction in dampness and mold in offices is projected to eliminate 1.5 million days of absence with a value of \$0.5 billion.

The largest projected source of economic benefit was improvement in work performance, followed by reduction in absence. The estimated economic benefits of reductions in SBS symptoms were much smaller despite the larger estimated fractional change in symptoms. The annual economic benefit of eliminating symptoms in a worker was only \$182 (based on an estimate of avoided medication costs), and only a modest fraction of workers have SBS symptoms. The analysis assigned no economic value to the improvement in a worker's quality of life when symptoms were avoided. In contrast, a year of work for an office worker was valued at \$74,695 and a day of absence was valued at \$311.

One cannot add the results of scenarios 1a and 1b, or add the results of 1a or 1b, with the results of scenario 2, because of substantial overlaps in how the scenarios affect VRs. If we neglect possible interactions in the impacts of interventions on people, e.g., the possibility that reducing SBS symptoms by increasing VRs may lead to a diminished opportunity to reduce symptoms by avoiding high temperatures, one can estimate the total potential benefit by adding the larger of the impacts of scenarios 1a, 1b, or 2 with the impacts of scenarios 3 and 4. The resulting estimated total economic benefits of these "non-overlapping" scenarios are \$17 billion if one utilizes the "volumetric" VR data as the initial condition and \$26 billion if one uses the "peak-CO_2" VR data as the initial condition. In addition, to these economic benefits, SBS symptoms and adverse health effects that cause absence are prevented in approximately 10 to 20 million workers.

Table 2. Estimated benefits of selected IEQ improvement scenarios^.

Scenario	**Annual Benefits and Costs***	**Annual Economic Benefits ($ billion)***
1a) increase VRs to 10 L/s per person	avg. 0.7% (0.3%) increase in performance in 7.8 (4.2) million workers	$4.2 ($1.1)
	Average 13.2% (5.3%) decrease in weekly SBS symptoms in 7.8 (4.2) million workers	$0.06 ($0.01)
	4.5 (0.7) million days of short-term absence avoided	*$1.4 ($0.2)*
	Increased energy consumption	-$0.02 (-$0.003)
	Total economic benefit	**$5.6 ($1.3)**
1b) increase VRs to 15 L/s per person	avg. 1.1% (0.6%) increase in performance in 12.4 (16.1) million workers	$10.2 ($6.9)
	Average 18.8% (10.2%) decrease in weekly SBS symptoms in 12.4 (16.1) million workers	$0.11 ($0.06)
	10 (6.7) million days of short-term absence avoided	*$3.2 ($2.1)*
	Increased energy consumption	-$0.04 (-$0.02)
	Total economic benefit	**$13.5 ($9.0)**
2) add economizers when absent[#]	avg. 0.47% (1.0%) increase in performance for 20.7 million workers	$7.2 ($15.6)
	Average 7% (17%) decrease in weekly SBS symptoms in 20.7 million workers	$0.05 ($0.13)
	15.2 (21.2) million days of short-term absence avoided	*$4.7 ($6.6)*
	Energy savings	$0.12 ($0.17)
	Annualized economizer installation cost	-$0.22 (-$0.22)
	Total economic benefit	**$11.8 ($22.3)**
3) eliminate winter indoor T > 23 °C	avg. 0.23% increase in winter performance in 40.4 million workers	$2.3
	prevent 7.7 million weekly SBS symptoms in winter	*$1.1*
	reduce winter thermal comfort dissatisfaction by 12% in 40.4 million workers	----
	Total economic benefit	**$3.4**
4) reduce dampness and mold 30%	*1.5 million days of absence avoided*	*$0.5*
	Total economic benefit	**$0.5**

^ benefits in italics have higher uncertainty as they depend on quantitative results of a single study

* numbers not in parenthesis use the "volumetric" VRs, and numbers in parenthesis use the "peak CO_2" VRs from the EPA BASE study as the existing condition

DISCUSSION

The estimated benefits of the scenarios analyzed are substantial in magnitude, including work performance increases, reductions in SBS symptoms, absence reductions, and thermal comfort improvements in millions of office workers. The combined potential annual economic benefit of the non-overlapping scenarios is either $17 billion or $26 billion, depending on the source of data on existing VRs.

Fisk (Fisk 2000) described a prior analysis of the benefits attainable from improving IEQ conditions in U.S. buildings, but only general comparisons of results are possible because of differences in the scope of the prior and current analyses. The current paper considered only offices, selected changes in IEQ parameters, and selected human outcomes. The prior paper considered a broader workforce, additional health outcomes, and benefits of some IEQ improvements in homes and projected potential health-related benefits valued at $17 to $48 billion and work performance benefits of $20 to $160 billion. The total estimated benefits in the current paper are smaller, not because current data indicate smaller impacts of IEQ on health and performance, but because the current analysis had a much narrower scope.

Although we are unable to quantitatively estimate the uncertainties in the magnitudes of the projected health and economic benefits, we believe that the uncertainties are large, perhaps a factor of two or three. There are two main sources of uncertainty, plus additional smaller sources. Our very approximate understanding of how IEQ parameters affect health, performance, and absence is the first main source of uncertainty. A strength of the analyses in this paper, relative to prior published estimations of the benefits of improved IEQ, is our reliance on the results of meta-analyses to relate VRs with work performance and SBS symptoms, and to relate temperatures with work performance; however, substantial uncertainty remains because of limitations in the number and scope of underlying studies. To the best of our knowledge, alternative meta-analyses of the relationship of VR with performance and VRs with SBS symptoms are not available. There have been other synthesis of the relationship of temperature (or thermal comfort) with work performance, recently summarized by (Lan et al. 2010). The relationship employed in this paper matches well with the relationship derived by (Lan et al. 2010). Two other models described by (Lan et al. 2010) indicate substantially larger decrements in performance as temperature (or thermal comfort) deviates from the optimum value for work performance. One of these models projects that performance is maximum at a temperature below that which optimizes thermal comfort. If we had relied on the alternate models of the temperature-performance relationship, the benefits of scenario 3 would have been either substantially unchanged or substantially increased.

The projected impacts of VR, and of dampness, on absence and the projected impacts of indoor temperatures on SBS symptoms are particularly uncertain because each of these projections relied on the results from a single study. Supporting data exist, as discussed previously, but these supporting data cannot be used quantitatively to improve the estimates in this paper.

The uncertain existing IEQ conditions in the building stock are the second main source of uncertainty in the estimated benefits. This point is illustrated by the large impact of source of VR data on the estimated benefits of scenario 1a. Reliance on the estimated benefits associated with the “peak CO_2” existing VRs may be more appropriate, because the “peak-CO_2” VR method accounts for ventilation by both infiltration and mechanical outdoor air supply. In contrast, the “volumetric” VR data depend on a measurement technique that neglects ventilation by air infiltration. Thus, the “volumetric” method has a source of error that could be expected to result in an overestimate of the number of buildings with low VRs, which are the buildings subject to scenarios1a and 1b. The benefits of scenarios 1a and 1b depend highly on the fraction of buildings that currently have VRs below the targets and on the magnitude by which the current VRs in these buildings fall below the targets.

We note that there is clear evidence of errors in the VR measurements used for this paper. Compared to the “peak-CO_2” measurement method, the “volumetric” measurement method tended to yield higher VRs in buildings with high VRs, while equal (with no infiltration) or lower (with infiltration) “volumetric” VRs would be expected. No definitive explanation for this discrepancy is evident from an examination of the data; however, there are several known or suspected sources of measurement error. In “volumetric” measurements of VRs, the highly variable air speeds and airflow directions (Fisk et al. 2005b) are one key potential source of error. Additionally, VRs based on the peak CO_2 measurement method could be biased if true indoor-average CO_2 concentrations were consistently higher or lower than the average of the measured CO_2 concentrations, if office workers generated a different amount of CO_2 than assumed in the calculations of VRs from the CO_2 data, and because of a failure to reach equilibrium CO_2 concentrations in the buildings within the survey.

Although the calculations relied on existing data from the only large representative survey of IEQ conditions in U.S. offices, these data were collected approximately 15 years ago. The survey was clearly not perfectly representative of the full building stock, for example, it did not include small offices. Additionally, VRs, temperatures, pollutant sources, and IEQ management practices in the current office building stock could differ from those at the time of the survey. Given the strong interest in energy efficiency and the reduction in the minimum VRs prescribed for offices in the leading minimum VR standard (ASHRAE 2010), one may expect lower VRs in the current stock; however, insufficient data are available to test this hypothesis.

The uncertain economic value of SBS symptoms is among the other sources of uncertainty. The documentation supporting the unit costs for SBS symptoms is sketchy (EPA 2007). However, given that the estimated economic benefits from reduced SBS symptoms are small relative to other projected economic benefits, this source of uncertainty has a small impact on our overall estimates of economic benefits. We note that SBS symptoms sometimes lead to lawsuits and expensive investigations. The benefits of avoiding these lawsuits and investigations are not included in our analyses. Also, there is some evidence that SBS symptoms reduce work performance (Fisk 2000), another factor not considered in this paper but important to address in future research.

The estimates of the energy cost of increasing VRs in scenarios 1a and 1b were derived from the model predictions of others (Griffith et al. 2008; Benne et al. 2009). To provide a rough check of these estimates, we calculated energy costs using the results of our modelling for the evaluation of scenario 2 of prototypical small, medium, and large office buildings located in five climates. The modelled increases in energy use of buildings as minimum VRs changed from 13 to 19 L/s per person in buildings with economizers, and also in buildings without economizers, were weighted to account for the distributions of building sizes and economizer use with climate. The resulting predicted increases in energy use and cost, for each 1 L/s per person increase in VR, were approximately double the values used to estimate energy costs for scenarios 1a and 1b in Table 2. While the estimates based on Griffith and Benne and colleagues are expected to be more accurate since they better account for the diversity of office buildings and climates, the comparison suggests substantial uncertainty in the energy cost estimates. Despite this uncertainty the energy costs remain small relative to the projected benefits of scenarios 1a or 1b.

If one considers a combination of the scenarios analyzed, there may be interactions (overlaps or synergies) among the effects of multiple interventions and these interactions have not been analyzed. For example, as noted above, if SBS symptoms are diminished by increasing VRs, the potential to also diminish SBS symptoms by modifying temperatures may be diminished. In this case, the level of interaction is probably modest, because each intervention has a modest impact on the number of symptoms experienced.

Another source of uncertainty is the assumed 30% reduction in dampness and mold in scenario 4. While there is little doubt that we have the knowledge and technical means for much larger reductions in dampness and mold, we relied only on engineering judgement when assuming that a 30% reduction is a realistic goal. Our results can be scaled for other percent reductions in dampness and mold.

The estimates of costs, and of possible benefits, are incomplete. Equipment and installation costs were only estimated for scenario 2. The implementation costs for scenarios 1a and 1b are likely to be small. In most buildings, only adjustment of damper settings will be necessary to increase VRs. In some buildings, the capacity of heating and cooling equipment may be insufficient to accommodate the increased heating and cooling loads during periods of severe cold or hot weather. However, over 50% of existing buildings already have VRs above the target values associated with scenarios 1a and 1b. Thus most office buildings have VRs above the targets and apparently have adequate heating and cooling capacity. In most buildings the heating and cooling equipment is oversized. Also, benefits of scenarios 1a and 1b would be reduced very little if VRs were set back to their initial values during brief periods of coldest and hottest weather.

The implementation cost of scenario 3 (reducing winter temperatures) is also expected to be modest relative to the benefits. In many buildings, temperature set points can be adjusted via a computerized control system. In some instances, thermostat recalibration or replacement, or adjustment of the balance of air supply to different rooms, or a broader retro-commissioning of building systems, may be necessary. However, we anticipate that much of the projected benefit could be obtained by simple low-cost adjustments in winter temperature set points. To obtain a sense of the upper limit of expected implementation costs, we assumed that, in 50% of the full office stock, improved temperature control requires building retro-commissioning performed every five years at a cost of $3.3 per square meter (Mills 2009). The annual retro-commissioning cost would be $0.36 billion which is small relative to the estimated annual benefit of $3.4 billion. This estimate of implementation cost is likely higher than the true cost because only a subset of the normal retro-commissioning protocol would be necessary to address temperature control problems. Additionally, the median payback period for retro-commissioning in existing buildings, considering only the resulting energy savings, has been estimated as 1.1 years (Mills 2009).

We note that we have not included an estimate of the energy savings from scenario 3. Prior modeling (Hoyt et al. 2009) for a medium-size (8633 m^2 plus basement) office building projected HVAC energy savings of 7% to 14% for a 1 ^oC decrease in the heating set point temperature from 21.5 ^oC to 20.5 ^oC. Expected savings are increased in smaller offices and decreased, and sometimes negative, in larger offices which sometimes require cooling in the winter. However, because 57% of the U.S. office floor space is in buildings with a floor area less than 9,300 m^2, the expected overall impact of the scenario 3 is a savings in energy.

The implementation costs of retrofitting and remediating existing buildings to achieve scenario 4 (dampness and mold) may be considerable given the necessary measures, e.g., repairs in roofs, building envelopes, and plumbing systems to reduce water leaks, and changing the way thermal insulation and air and moisture barriers are used in some building envelopes. We were unable to identify data with which to estimate the implementation costs. However, we have also not included estimates of potentially large benefits associated with scenario 4, including reduced health care costs, reduced mold remediation costs, and reduced costs of repairing or replacing moisture-damaged building materials. The costs of improving design and construction practices in new construction, as needed to reduce dampness and mold problems over time as the building stock changes, would likely be much less than the cost of reducing dampness and mold through remediation of existing building problems.

Given the large uncertainties, one may question the value of estimating the benefits of these scenarios. In our view, it is preferable to use uncertain but credible estimates of benefits when making decisions about building operation practices and related guidelines and policies than to ignore the impacts on health and performance. We also note that, to some extent, current operation practices, guidelines, and policies reflect expectations about impacts on health and performance. The uncertainties of the estimates in this paper are substantially reduced relative to the first author’s prior order of magnitude estimates (Fisk 2000), primarily because of improvements in knowledge about the relationship of IEQ with health and work performance. Overall, it seems clear that the potential benefits are large in magnitude.

There is a common perception that improvements in IEQ come at the cost of increased energy consumption. Among the scenarios analyzed, only 1a and 1b increase energy costs, and the increases are small relative to the projected benefits. However, given the expected adverse consequences of climate change, preference should be given to IEQ improvement scenarios that save energy, such as scenarios 2 and 3, or to energy-neutral scenarios (e.g., scenario 4).

We close by mentioning that the benefits analyses for this paper represent examples of a much larger set of potential benefits from possible IEQ improvements. One could expand the interventions to other parts of the building stock and implement additional types of interventions that improve IEQ.

CONCLUSIONS

The weight of available evidence indicates that practical IEQ interventions in offices could prevent SBS symptoms, and absence in millions of U.S. office workers while also improving work performance by an economically significant amount. The attainable combined projected annual economic benefits of the non-overlapping scenarios analyzed for this paper is either $17 billion or $26 billion, depending on the source of data on existing VRs. While there are some conflicts between the goal of maximizing IEQ, health, and productivity and the imperative to reduce building energy consumption, there are IEQ improvement scenarios that are energy neutral and scenarios that save energy. Implementing the scenarios that save energy should be the highest priority.

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Appendix 1. Graphical illustrations of equations 1 – 4.

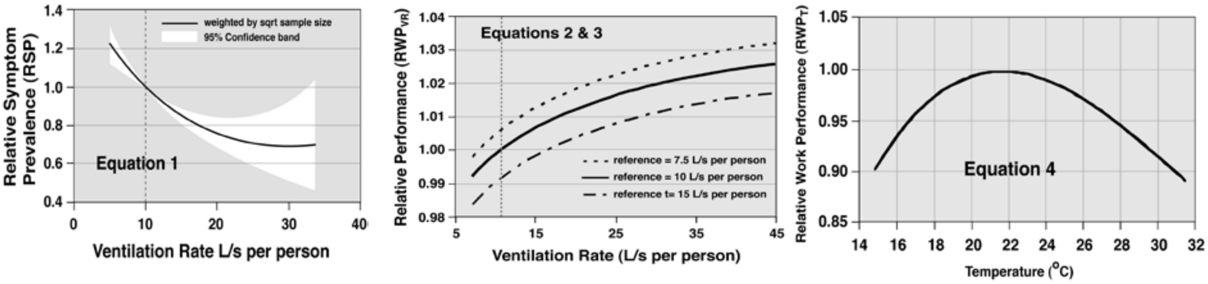

Figure A1. Graphical illustrations of equations 1 – 4.