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HEALTH AND PRODUCTIVITY GAINS FROM BETTER INDOOR ENVIRONMENTS AND THEIR RELATIONSHIP WITH BUILDING ENERGY EFFICIENCY[1]

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■ **Abstract** Theoretical considerations and empirical data suggest that existing technologies and procedures can improve indoor environments in a manner that significantly increases productivity and health. The existing literature contains moderate to strong evidence that characteristics of buildings and indoor environments significantly influence rates of communicable respiratory illness, allergy and asthma symptoms, sick building symptoms, and worker performance. Whereas there is considerable uncertainty in the estimates of the magnitudes of productivity gains that may be obtained by providing better indoor environments, the projected gains are very large. For the United States, the estimated potential annual savings and productivity gains are \$6 to \$14 billion from reduced respiratory disease, \$1 to \$4 billion from reduced allergies and asthma, \$10 to \$30 billion from reduced sick building syndrome symptoms, and \$20 to \$160 billion from direct improvements in worker performance that are unrelated to health. Productivity gains that are quantified and demonstrated could serve as a strong stimulus for energy efficiency measures that simultaneously improve the indoor environment.

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INTRODUCTION AND OBJECTIVES

Prior literature on the relationship of indoor environments to productivity has focused primarily on potential direct improvements in worker's cognitive or physical performance from changes in temperatures or lighting. The published literature consists primarily of reports on individual laboratory or field studies or reviews the current literature (e.g. 1–3), without estimates of the nationwide implications for health or productivity. Prior reviews have generally not considered the current evidence suggesting that indoor environmental conditions also affect the prevalences of several very common health effects. These health effects lead to health care costs plus the costs of sick leave and reduced performance during periods of illness.

Based on the available literature and statistical and economic data, Fisk & Rosenfeld (4) estimated the annual productivity gains in the United States potentially achievable from improvements in indoor environmental conditions that reduce these health effects or directly improve worker performance. An updated and much longer review of this issue will be published as a book chapter (5). This article summarizes the updated analyses, incorporates additional updates, and reviews the implications for building energy efficiency.

METHODS

Relevant papers were identified through computer-based literature searches, reviews of conference proceedings, and discussions with researchers. Evidence supporting or refuting the hypothesized linkages was synthesized based on these papers. The categories of health effects identified for further consideration are communicable respiratory illnesses, allergies and asthma, and acute nonspecific health symptoms often called sick building syndrome symptoms. The economic costs of these adverse health effects were estimated, primarily by synthesizing and updating the results of previously published cost estimates. The economic results of previous analyses were updated to 1996 to account for general inflation, health care inflation, and increases in population (6). Estimating the magnitudes of the decreases in adverse health effects and the magnitudes of direct improvements in productivity that could result from improved indoor environments was the most uncertain step in the analysis. These estimates are based on the reported strength of associations between indoor environmental characteristics and health outcomes and on our understanding from building and engineering science of the degree to which relevant indoor environmental conditions could practically be improved. Nationwide health and productivity gains were then computed by multiplying the estimated potential percentage decrease in illness (or percent direct increase in productivity) by the associated cost of the illness (or by the associated magnitude of the economic activity). With current information, estimates of the health and productivity gains potentially attainable from improvements in the indoor environment have a high level of uncertainty.

Improvements in the indoor environment depend on changes to building design, operation, maintenance, or occupancy. Many of these changes will influence building energy use. In 1998, a multi-disciplinary international committee (7) developed a list of building energy efficiency measures and identified the most common impacts of these measures on indoor environmental quality (IEQ). The committee's assessment, based on existing literature, scientific and technical knowledge, and professional experience, is the source for the discussion of energy implications within this paper.

To make this article understandable to a relatively broad audience, the use of potentially unfamiliar statistical terminology has been minimized. For example, as substitutes for the odds ratios or relative risks normally provided in the scientific literature, this article provides estimates of the percentage increases and decreases in outcomes (e.g. health effects) that are expected when building-related risk factors (e.g. mold exposures) are present or absent. Measures of statistical significance are included only within footnotes. The findings reported in this paper would generally be considered to be statistically significant (e.g. the probability that the findings are due to chance or coincidence is generally less than 5%). For the interested reader, Appendix 1 defines the odds ratio, the relative risk, the term adjusted, and the means of estimating percentage changes in outcomes from odds ratios or relative risks.

RESULTS AND DISCUSSION

Communicable Respiratory Illness

Evidence of Linkage The theoretical relationship of building and indoor environmental characteristics with the transmission of communicable respiratory illnesses depends on the mechanisms of transmission. In theory, disease transmission that occurs via inhalation of airborne infectious aerosols (small particles produced by coughing and sneezing that contain virus) may be influenced by the efficiency or rate of air filtration, the rate of ventilation (i.e. supply of outside air per occupant), the amount of air recirculation in ventilation systems, the separation between individuals (affected by occupant density and use of private work spaces), and air temperature and humidity, which affect the period of viability of infectious aerosols. As discussed in Fisk (5), infectious aerosols are thought or known to contribute substantially to transmission of common colds (e.g. rhinovirus infections), influenza, adenovirus infections, measles, and other common respiratory illnesses. Disease transmission from direct person-to-person contact or indirect contact via contaminated objects, may be largely unaffected by indoor environmental and building characteristics. Indoor environmental conditions may also influence occupants' susceptibility to respiratory infections. For example, there is some evidence, discussed below, that increased exposures to molds are associated with substantially increased numbers of respiratory infections.

Several field studies, summarized in Table 1, provide evidence that building characteristics significantly influence the prevalence of respiratory illness among building occupants. Two studies were performed in military barracks. A large multi-year investigation by the US Army (8) determined that clinically-confirmed rates of acute respiratory illness with fever were 50% higher among recruits housed in newer barracks with closed windows, low rates of outside air supply, and extensive air recirculation compared with recruits in older barracks with frequently open windows, more outside air, and less recirculation.[2] In another barracks study, Langmuir et al (9) compared the rate of respiratory illness with fever among recruits housed in barracks with ultraviolet lights that irradiated the indoor air near the ceiling (a technology designed to kill infectious bioaerosols), to the rate of respiratory illness among recruits in barracks without ultraviolet lights. For the entire study period, the population housed in barracks with ultraviolet-irradiated air had 23% less respiratory illness.[3]

Several additional studies from a variety of building types provide relevant information on this topic. Jaakkola and Heinonen (10) found that office workers with one or more roommates were about 20% more likely to have had more than two cases of the common cold during the previous year than office workers with no roommates.[4] At an Antarctic station, the incidence of respiratory illness was twice as high in the population housed in smaller (presumably more densely populated) living units (10a). In an older study of New York schools (11), there were 170% as many respiratory illnesses[5] and 118% as many absences from illness[6] in fan-ventilated classrooms compared with window-ventilated classrooms, despite a lower occupant density in the fan-ventilated rooms. Unfortunately, ventilation rates were not measured in the classrooms. Another study investigated symptoms associated with infectious illness among 2598 combat troops stationed in Saudi Arabia during the Gulf War (12). The results suggest that the type of housing (air-conditioned buildings, non-air-conditioned buildings, open warehouses, and tents) influenced the prevalence of symptoms associated with respiratory illness. Housing in air-conditioned buildings (ever versus never housed in an air-conditioned

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[2] Adjusted relative risk $= 1.51$, 95% confidence interval (CI) 1.46 to 1.56.

[3] No test of statistical significance was performed.

[4] Adjusted odds ratio $= 1.35$(95% CI 1.00–1.82).

[5] Difference more than three times probable error.

[6] Difference greater than probable error.

TABLE 1 Associations of building characteristics with communicable respiratory illness

References	Populations Compared	Health Outcome	Findings (adjusted for time in building)
8	Recruits in modern (low ventilation) versus recruits in older US Army barracks	Respiratory illness with fever	33% (12.5%) lower prevalence incidence of respiratory illness in older barracks
9	Recruits in US Navy barracks with ultraviolet irradiation of air versus those in barracks without ultraviolet irradiation	Respiratory illness with fever	23% (9%) decrease in respiratory illness with ultraviolet irradiation
10	Office workers with ≥ 1 roommates vs. office workers without roommates	Common cold	Workers without roommates had 17% (17%) lower risk of >2 common colds per year
10a	Residents of smaller vs. larger quarters at Antartic station	Respiratory illness	50% (19%) lower incidence of respiratory illness for residents of larger quarters
11	Students in fan-ventilated versus window-ventilated classrooms	Respiratory illness and absence	41% (41%) less illness and 15% (15%) less absence in window-ventilated classrooms
14	Residents of nursing home with no recirculation of ventilation air and less crowding of common areas versus residents in three homes with recirculation and more crowding	Culture-confirmed type A influenza and total respiratory illness	76% (19%) less influenza and 50% (12.5%) less total respiratory illness in nursing home with no recirculation and less crowding
12	Gulf War troops ever vs. never housed in different types of buildings during Gulf War	Symptoms of respiratory illness	27% (10%) less cough and 16% (6%) less sore throat if never housed in air-conditioned building
13	$>7.4\ m^2$ vs. $<7.4\ m^2$ space per occupant in US jail and high vs. low CO_2 concentration	Pneumococcal disease	Significantly lower incidence if $>7.4\ m^2$ space; 49% (12%) lower incidence if in cell type with lower CO_2 concentration
15	Workers in 40 office, trade, and manufacturing buildings with high versus normal ventilation rate	Short term absence	35% (35%) less short term absence in high ventilation buildings
16, 17	168 residents in moldy Finish apartments versus 139 in nonmoldy apartments	Acute respiratory infection	54% (20%) fewer residents of nonmoldy apartments had ≥ 1 respiratory infection last year

building while in Saudi Arabia) was associated with approximately a 37% greater prevalence of sore throat[7] and a 19% greater prevalence of cough.[8]

Jails are not representative of other buildings because of severe crowding and residents that are not representative of the general public. However, disease transmission in jails is an important public health issue and indoor-environmental factors that influence disease transmission in jails may also be important, but less easily recognized, in other environments. An epidemic of pneumococcal disease in a Houston jail was studied by Hoge et al (13). There were significantly fewer cases of disease among inmates with 7.4 m^2 or more of space[9]relative to inmates with less space. The disease attack rate was about 95% higher in the types of jail cells with the highest carbon dioxide concentrations, i.e. the lowest volume of outside air supply per person.[10]

Drinka et al (14) studied an outbreak of influenza in four nursing homes located on a single campus. Influenza, confirmed by analyses of nasopharyngeal and throat swab samples, was isolated in 2% of the residents of Building A versus an average of 13% in the other three buildings[11] (16%, 9%, and 14% in Buildings B, C and D, respectively). After correction for the higher proportion of respiratory illnesses that were not cultured in Building A, an estimated 3% of the residents of Building A had influenza, a rate 76% lower than observed in the other buildings.[12] The total number of respiratory illnesses (i.e. influenza plus other respiratory illnesses) per resident was also 50% lower in Building A. Vaccination rates and levels of nursing care did not differ among the buildings. The authors suggested that architectural factors may have been the cause of the lower infection rate in Building A. The ventilation system of Building A supplied 100% outside air to the building (eliminating mechanical recirculation), whereas the ventilation systems of the other buildings provided 30% or 70% recirculated air. The Building A ventilation system also had additional air filters. Finally, the public areas of Building A were larger (per resident), reducing crowding, which may facilitate disease transmission.

Milton et al (15) studied the association of the rate of outside air supply with the rate of absence from work caused by illness in 3720 workers located in 40 buildings with a total of 110 independently-ventilated floors. Although absence is not synonymous with respiratory disease, a substantial proportion of short-term absences caused by illness results from acute respiratory illness. Ventilation rates were estimated based on ventilation system design, occupancy, and selected end-of-day carbon-dioxide measurements, and buildings were classified as moderate

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[7] Adjusted odds ratio = 1.57 (95% CI 1.32–1.88).

[8] Adjusted odds ratio = 1.33 (95% CI 1.01–1.46).

[9] $p = 0.03$

[10] Relative risk = 1.95 (95% CI 1.08–3.48).

[11] $p < 0.001$, Cochran-Mantel-Haenszel statistics.

[12] $p < 0.001$, chi-square

ventilation ($\sim$12 L s^{-1} per occupant) or high ventilation ($\sim$24 L s^{-1} per occupant). The absence rate, controlling for age, gender, seniority, crowding, and type of workspace was 35% lower in the high-ventilation buildings.[13]

The association of mold problems in buildings with the incidence of respiratory infections has been investigated in a few studies. One study (16, 17) compared the rates of acute respiratory infection in 158 residents of apartments with verified mold problems to the rates of infection in 139 residents of apartments without mold problems. Approximately twice as many residents of the moldy apartments reported at least one acute respiratory infection during the previous year.[14] A complex multi-stage study examined the association of high mold exposures in day-care centers with common colds as well as other health outcomes in children (18, 19) with inconclusive results (i.e. one comparison suggests that mold significantly increased serious persistent respiratory infections, whereas other comparisons found small, statistically insignificant decreases in common colds with higher mold exposure.) The recent evidence that mold exposures may adversely affect immune system function (20) is consistent with the findings of a positive association between molds and respiratory infections.

Cost of Communicable Respiratory Illness The obvious direct costs of respiratory illness include health care expenses and the costs of absence from work. Additionally, respiratory illnesses may cause a performance decrement at work. In controlled experiments, Smith (21) has shown that viral respiratory illnesses, even subclinical infections, can adversely affect performance on several computerized and paper-based tests that simulate work activities. The decrement in performance can start before the onset of symptoms and persist after symptoms are no longer evident.

Estimates of the productivity losses associated with respiratory illness are based on periods of absence from work and restricted activity days as defined in the National Health Interview Survey (22). In the United States, 4 common respiratory illnesses (common cold, influenza, pneumonia, and bronchitis) cause about 176 million days lost from work and an additional 121 million work days of substantially restricted activity (23, adjusted for population gain). Assuming a 100% and 25% decrease in productivity on lost-work and restricted-activity days, respectively, and a $39,200 average annual compensation (6), the annual value of lost work is approximately $34 billion.[15] The annual health care costs for upper and lower respiratory tract infections total about $36 billion (23, adjusted for population gain and health care inflation). Thus, the total annual cost of respiratory infections is approximately $70 billion. Neglected costs include the economic value of reduced housework and of absence from school.

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[13] Relative risk is 1.53, 95% CI is 1.22 to 1.92.

[14] Relative risk is 2.2, 95% CI is 1.2 to 4.4, adjusted for age, sex, smoking and atopy.

[15] A similar estimate, $39 billion, is obtained based on the information in Reference 23a.

Potential Savings Without being able to substantially change the building-related factors that influence disease transmission, we cannot realize these health care cost savings and productivity gains. A number of existing, relatively practical building technologies, such as increased ventilation, reduced air recirculation, improved filtration, ultraviolet disinfection of air, reduced space sharing (e.g. shared office), and reduced occupant density have the theoretical potential of reducing inhalation exposures to infectious aerosols by more than a factor of two.

The studies cited above suggest that changes in building characteristics and ventilation could reduce indexes of respiratory illness by 15% (absence from school) to 76% (influenza in nursing homes). The amount of time spent in a building should influence the probability of disease transmission within the building. If efforts to reduce disease transmission were implemented primarily in commercial and institutional buildings[16] that people occupy approximately 25% of the time, smaller reductions in respiratory illness would be expected in the general population than indicated by the building-specific studies. To adjust the reported decreases in respiratory illness for time spent in buildings, we estimated the percentage of time that occupants spend in each type of building (100% of time in jails and nursing homes, 66% in barracks and housing, and 25% in offices and schools) and assumed that the magnitude of the influence of a building factor on the incidence of respiratory illness varies linearly with time spent in the building. After this adjustment, the 10 studies cited above yield 13 estimates of potential decreases in metrics for respiratory illness (some studies had multiple outcomes, such as influenza and total respiratory infections), ranging from 6% to 41%, with an average of 18%(see Table 1). Considering only the studies with explicit respiratory illness outcomes (i.e. excluding studies with absence or individual symptoms as outcomes) results in 9 estimates of decreases in respiratory illness, adjusted for time in building, ranging from 9% to 41%, with an average of 18%. The range is 9% to 20% if the outlier value of 41% (illness in schools) is excluded. This narrower range (9% to 20%) is adopted for the potential reduction in respiratory illness. With this estimate and statistics on the frequency of common colds and influenza (0.69 cases per person per year[17]), approximately 16 to 37 million cases would be avoided each year. The corresponding range in the annual economic benefit is \$6 to \$14 billion.

Allergies and Asthma

Linkage Approximately 20% of the US population have allergies to environmental antigens (24) and approximately 6% have asthma (25). Symptoms of allergies and asthma may be triggered by a number of allergens in indoor air, including

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[16] There are no technical barriers to implementation of similar measures in residences; however, business owners will have a stronger financial incentive to take action than home owners.

[17] Averaging data from 1992 through 1994, the civilian noninstitutional population experienced 43.3 common colds and 25.7 cases of influenza per 100 population (6).

those from house dust mites, pets, fungi, insects, and pollens (24). Allergens are considered a primary cause of the inflammation that underlies asthma (26). There is evidence (e.g. 27, 28) that lower exposures to allergens during infancy or childhood can reduce the sensitization to allergens. Asthma symptoms may also be evoked by irritating chemicals, including environmental tobacco smoke (29). Viral infections, which may be influenced by building factors, also appear to be strongly linked to exacerbations of asthma, at least in school children. A recent study of 108 children, age 9 to 11, found a strong association of viral infections with asthma exacerbation (30). Viral infections were detected in 80% to 85% of asthmatic children during periods of asthma exacerbation. During periods without exacerbation of asthma symptoms, only 12% of the children had detectable viral infections.[18]

Building factors most consistently and strongly associated with asthma and allergic respiratory symptoms include moisture problems, house dust mites, molds, cats and dogs, and cockroach infestation (31, 24). Platts-Mills & Chapman (32) provide a detailed review of the substantial role of dust mites in allergic disease. In a recent review of the association of asthma with indoor air quality by the National Academy of Sciences (31), the prevalence of asthma or related respiratory symptoms is increased by approximately a factor of two[19] among occupants of homes or schools with evidence of dampness problems or molds. In the same review, environmental tobacco smoke exposure, indicated by parental smoking, is typically associated with increases in asthma symptoms or incidence by 20% to 40%.

Data from few office-based studies are available for asthma and allergy associations with indoor environmental conditions. In case studies, moisture and related microbiological problems have been linked to respiratory symptoms in office workers (33, 34). In a study of office workers (a case-control study of ∼17% of all workers in the buildings) (35), higher relative humidity, higher concentrations of alternaria (a mold) allergen in air, and higher dust mite antigen in floor dust were associated with a higher prevalence of respiratory symptoms.

Based on the scientific literature, we would expect significant reductions in asthma and allergy symptoms if the moisture problems were prevented or repaired, indoor smoking was reduced, and dogs and cats were maintained outdoors of the homes of allergic subjects; however, the benefits of these and other interventions have rarely been studied. Various measures have been found effective in reducing indoor concentrations of allergens in buildings (36–38). Unfortunately, except for studies involving air cleaners, relatively few published experimental studies of the effect of changes in building conditions on the symptoms of allergies and asthma have been identified. Measures to reduce exposures to dust mite allergen, such as improved cleaning and encasement of mattresses in nonpermeable materials, have reduced symptoms in some but not all studies (32, 36–39).

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[18] The difference between infection rates is statistically significant, $p < 0.001$.

[19] Neglecting one study in the review with a very high odds ratio of 16.

Overall, the evidence of a linkage between the quality of the indoor environment and the incidence of allergic and asthma symptoms is relatively strong. Additionally, the exposures that cause allergic sensitization often occur early in life and are likely to occur indoors; consequently, the quality of indoor environments may also influence the proportion of the population that is allergic or asthmatic.

Cost of Allergies and Asthma Table 2 summarizes the results of several recent estimates of the annual costs of allergies and asthma in the United States, updated to 1996 (although the costs have not been updated to account for the increase in asthma prevalence). The authors of these studies have generally characterized their estimates as conservative because some cost elements could not be quantified. Differences between cost estimates are due to reliance on different underlying data, different assumptions, and inclusion of different cost elements. For the purposes of this paper, the averages of the cost estimates for each outcome and cost category, provided in the last row of Table 2, have been summed, yielding a total estimated annual cost for allergies and asthma of $15 billion. A significant portion of the costs of allergies and asthma reflect the burden of these diseases in children.

Potential Savings from Changes in Building Factors There are three general approaches for reducing allergy and asthma symptoms via changes in buildings and indoor environments. First, one can control the indoor sources of the agents that cause symptoms (or that cause initial allergic sensitization). For example,

TABLE 2 Estimated annual costs of asthma and allergic disease in billions of dollars, updated to 1996

	Cost of Asthma		**Cost of Allergic Rhinitis**		**Cost of Other Associated Airway Diseases**[a]		
Study	**Health Care**	**Indirect**[b]	**Health Care**	**Indirect**	**Health Care**	**Indirect**	**Total Cost (sum of average cost)**
Weiss et al (39a)	5.0	3.1	NA	NA	NA	NA	8.1
McMenamin (39b)	3.7	2.7	1.2	1.2	2.7	0.2	11.7
Fireman (39c)	NA	NA	NA	>4.3	NA	NA	>4.3
Smith and McGhan (39d)	NA	NA	3.4	NA	NA	NA	3.4
Smith et al (39e)	5.5	0.7	NA	NA	NA	NA	6.2
Average	4.7	2.2	2.3	2.8	2.7	0.2	(14.9)

[a] Portion of costs of chronic sinusitus, otitis media with effusion, and nasal polyps attributed to allergies.

[b] Components of indirect costs vary among the studies; indirect costs account for lost work, lost school days, and in some cases, mortality.

indoor tobacco smoking can be restricted to isolated, separately-ventilated rooms, or prohibited entirely. Pets can be maintained outside of the homes of individuals that react to pet allergens. Measures that reduce the growth of microorganisms indoors are perhaps even more broadly effective. Changes in building design, construction, operation, and maintenance could reduce water leaks and moisture problems and decrease indoor humidities (where humidities are normally high). Known reservoirs for allergens, such as carpets for dust mite allergen, can be eliminated or modified. Improved cleaning of building interiors and heating/ventilation/air conditioning systems can also limit the growth or accumulation of allergens indoors. There are no major technical obstacles to these measures, but the costs and benefits of implementation are not well quantified.

The second general approach for reducing allergy and asthma symptoms is to use air cleaning systems or increased ventilation to decrease the indoor concentrations of the relevant pollutants. Many of the relevant exposures are airborne particles. Technologies are readily available for reducing indoor concentrations of airborne particles generated indoors (e.g. better air filtration). Better filtration of the outside air entering mechanically-ventilated buildings can also diminish the entry of outdoor allergens into buildings. Filtration is likely to be most effective for the smaller allergenic particles such as cat allergens. Allergens that are large particles, e.g. from dust mites, have high gravitational settling velocities and are less effectively controlled by air filtration.

The influence of particle air cleaners on symptoms of allergies and asthma is reviewed by Committee on Asthma and Indoor Air (31). Many published studies have important limitations such as small air cleaners, a small number of subjects, or a focus on dust mite allergies that may be poorly controlled with air cleaners owing to the large size and high settling velocities of dust mite allergens. Only 4 of 11 studies involving subjects with perennial allergic disease or asthma reported statistically significant improvements in symptoms or reduced use of medication when air cleaners were used. However, in six of seven studies, seasonal allergic or asthma symptoms were significantly reduced with air cleaner use. Subjects were blinded, i.e. unaware of air cleaner operation, in only two of these studies; thus, results could have been biased by the subjects expectations.

Because viral respiratory infections will often exacerbate asthma symptoms, a third approach for reducing asthma symptoms is to modify buildings in a manner that reduces viral respiratory infections among occupants.

Given the available data, the magnitude of the potential reduction in allergy and asthma symptoms is quite uncertain, but some reduction is clearly possible using practical measures. The subsequent estimate is based on two considerations: (*a*) the degree to which indoor allergen concentrations and concentrations of irritating chemicals can be reduced and (*b*) the strength of the reported associations between symptoms and changeable building and IEQ factors. Regarding the first consideration, significant reductions in allergy and asthma symptoms would not be expected unless it was possible to substantially reduce indoor concentrations of the associated allergens and irritants. Based on engineering considerations, it is clear that concentrations of many allergens could be reduced very substantially. Filtration systems, appropriately sized, should be capable of reducing concentrations of the smaller airborne allergens by approximately 75%. Some of the source control measures, such as elimination of water leaks, control of indoor humidities, reduction or elimination of indoor smoking and pets, and improved cleaning and maintenance are likely to result in much larger reductions in the pollutants that contribute to allergies and asthma.

As discussed above, several cross-sectional studies have found that building-related risk factors, such as moisture problems and mold or environmental tobacco smoke, are associated with 20% to 100% increases in allergy and asthma symptoms, implying that 16% to 50% reductions in symptoms are possible by eliminating these risk factors. However, the complete elimination of these risk factors is improbable. Assuming that it is feasible and practical to reduce these risks by a factor of two, leads to a 8% to 25% estimate of the potential reduction in allergy and asthma symptoms. With this estimate, the annual savings would be ∼\$1 to ∼\$4 billion. Control measures can be targeted at the homes or offices of susceptible individuals, reducing the societal cost.

Sick Building Syndrome Symptoms

Linkage Characteristics of buildings and indoor environments have been linked to the prevalence of acute building-related health symptoms, often called sick-building syndrome (SBS) symptoms, experienced by building occupants. SBS symptoms, which include irritation of eyes, nose, and skin, headache, fatigue, and difficulty breathing, are most commonly reported by office workers and teachers, who make up about 50% of the total workforce (64 million workers[20]). In a modest fraction of buildings, often referred to as sick buildings, symptoms become severe or widespread, prompting investigations and remedial actions. The term sick building syndrome is widely used in reference to the health problems in these buildings. However, the syndrome appears to be the visible portion of a broader phenomenon. These same symptoms are experienced by a significant fraction of workers in “normal” office buildings that have no history of widespread complaints or investigations (e.g. 40–42), although symptom prevalences vary widely among buildings. The most representative data from US buildings, obtained in a 56-building survey (that excluded buildings with prior SBS investigations) found that 23% of office workers reported two or more frequent symptoms that improved when they were away from the workplace. (HS Brightman, Harvard School of Public Health, personal communication). Applying this percentage to the estimated number of US office workers and teachers (64 million), the number of workers frequently affected by at least two SBS symptoms is 15 million.

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[20] Based on statistical data (6), there are approximately 63 million civilian office workers plus teachers (49.6% of the civilian workforce). Assuming that 50% of the 1.06 million active duty military personnel are also office workers, the total is approximately 63.5 million.

Although psychosocial factors such as job stress influence SBS symptoms, many building factors are also known or suspected to influence these symptoms, including type of ventilation system, rate of outside air ventilation, level of chemical and microbiological pollution, and indoor temperature and humidity (43–46). In the review by Seppanen et al (46), 21 of 27 assessments meeting study quality criteria found lower ventilation rates to be significantly associated with an increase in at least one SBS symptom. All four assessments with respiratory illness and absence outcomes and seven of eight assessments with perceived air quality outcomes reported a significant worsening of outcomes with reduced ventilation. Extrapolating from one of the largest studies, a 5 L s^{-1} increase in ventilation rates in US office buildings would reduce the proportion of office workers with frequent upper respiratory symptoms from 26% to 16%. For eye symptoms, the corresponding reduction would be from 22% to 14%. In a set of problem buildings studied by Sieber et al (47), SBS symptoms were associated with evidence of poorer ventilation system maintenance or cleanliness. For example, debris inside the air intake and poor drainage from coil drain pans were associated with a factor of three increase in lower respiratory symptoms.[21] In the same study, daily vacuuming was associated with a 50% decrease in lower respiratory symptoms.[22] In some, but not all, controlled experiments, SBS symptoms have been reduced through practical changes in the environment such as increased ventilation, decreased temperature, and improved cleaning of floors and chairs (43, 45, 46). Therefore, SBS symptoms are clearly linked to features of buildings and indoor environments.

Cost of SBS Symptoms SBS symptoms are a hindrance to work and can cause absences from work (47a) and visits to doctors. When SBS symptoms are particularly disruptive, investigations and maintenance may be required. There are financial costs to support the investigations, and considerable effort is typically expended by building management staff, by health and safety personnel, and by building engineers. Responses to SBS have included costly changes in the building, such as replacement of carpeting or removal of wall coverings to remove molds, and changes in the building ventilation systems. Some cases of SBS lead to protracted and expensive litigation. Moving employees imposes additional costs and disruptions. Clearly, these responses to SBS impose a significant societal cost, but information is not available to quantify this cost.

Calculations indicate that the costs of small decreases in productivity from SBS symptoms are likely to dominate the total SBS cost. Limited information is available in the literature that provides an indication of the influence of SBS symptoms on worker productivity. In a New England survey, described in the US Environmental Protection Agency's 1989 report to Congress (48), the average self-reported productivity loss due to poor indoor air quality was 3%. Woods et al (49) completed a telephone survey of 600 US office workers, 20% of whom

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[21] For debris in air intake, relative risk $= 3.1$ and 95% CI $=$ 1.8 to 5.2 For poor or no drainage from drain pans, relative risk $= 3.0$ and 95% CI $= 1.7$ to 5.2.

[22] Relative risk $=$ 0.5, 95% CI $=$ 0.3 to 0.9.

reported that their performance was hampered by indoor air quality, but the study provided no indication of the magnitude of the productivity decrement. In a study of 4373 office workers in the U.K. by Raw et al (50), workers who reported higher numbers of SBS symptoms during the past year also indicated that physical conditions at work had an adverse influence on their productivity. Based on the data from this study, the average self-reported productivity decrement for all workers, including those without SBS symptoms, was about 4%.[23] In an experimental study (51), workers provided with individually-controlled ventilation systems reported fewer SBS symptoms and also reported that indoor air quality at their workstation improved productivity by 11% relative to a 4% decrease in productivity for the control population of workers.[24]

In addition to these self-reported productivity decrements, measured data on the relationship between SBS symptoms and worker performance are provided by Nunes et al (52). Workers who reported any SBS symptoms took 7% longer to respond in a computerized neurobehavioral test[25] and error rates in this test decreased nonsignificantly. In a second computerized neurobehavioral test, workers with symptoms had a 30% higher error rate,[26] but response times were unchanged. Averaging the percent changes from the 4 performance outcomes yields a 14% decrement in performance among those with SBS symptoms. Multiplying by the estimated 23% of office workers with 2 or more frequent symptoms yields a 3% average decrease in performance.

Other objective findings were obtained in a study of 35 Norwegian classrooms. Higher concentrations of carbon dioxide, which indicate a lower rate of ventilation, were associated with increases in SBS symptoms and also with poorer performance in a computerized test of reaction time[27](53); however, the percentage change in performance was not specified. Renovations of classrooms with initially poor indoor environments, relative to classrooms without renovations, were associated

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[23] The data indicate a linear relationship between the number of SBS symptoms reported and the self-reported influence of physical conditions on productivity. A unit increase in the number of symptoms (above two symptoms) was associated with approximately a 2% decrease in productivity. Approximately 50% of the workers reported that physical conditions caused a productivity decrease of 10% or greater; 25% reported a productivity decrease of 20% or more. Based on the reported distribution of productivity decrement (and productivity increase) caused by physical conditions at work, the average self-reported productivity decrement is about 4%.

[24] $p < 0.05$ for the reduction in SBS symptoms and $p < 0.001$ for the self-reported change in productivity.

[25] $p < 0.001$.

[26] $p = 0.07$.

[27] Correlation coefficient $= 0.11$ and p value $= 0.009$ for performance versus carbon dioxide. Correlation coefficient $= 0.20$ and P value $= 0.000$ for performance versus a score for headache, heavy headed, tiredness, difficulty concentrating, and unpleasant odor. Correlation coefficient $= 0.11$ and P value $= 0.008$ for performance versus a score for throat irritation, nose irritation, runny nose, fit of coughing, short winded, runny eyes. Correlation coefficients are controlled for age.

with reduced SBS symptoms and with improved performance by 5.3% in the reaction time tests (54) (measures of statistical significance are not included in the paper).

Another investigation (55) providing evidence that SBS symptoms reduce productivity is a laboratory-based, blinded, controlled, randomized experimental study with all indoor environmental conditions constant except for the presence or absence of a 20-year-old carpet that was not visible to study participants. Thirty female subjects (age 20–31) rated the quality and acceptability of air, reported the current intensity of their SBS symptoms, completed a standardized performance-assessment battery, performed simulated office work, and completed a self-assessment of performance. These tests and assessments were completed several times with and without the presence of carpet. The study design and data analyses controlled for the effects on performance of learning when tasks were repeated. The major relevant findings were that removing the carpet was associated with the following outcomes:[28] (*a*) small decreases in selected pollutants; (*b*) better perceived air quality; (*c*) decreased intensity of some SBS symptoms, particularly headache and dizziness; (*d*) 6.5% increase in amount of text typed in the simulated office work; (*e*) 2.5% and 3.8% increases in performance in two additional tests; (*f*) a 3.4% increase in performance in a logical reasoning test; (*g*) a 3.1% increase in performance in a reaction time test; and (*h*) one conflicting finding—a 2% decrease in performance in a code substitution test. The self assessments of performance suggested that performance increases may be a consequence, in part, of increased effort by the workers when the carpet was absent. The author's interpretation was that performance increases in the typing test were most likely a consequence of the reductions in headache. Other performance increases were not associated with a reduction in SBS symptoms.

The estimate of the productivity loss from SBS symptoms must be based on the limited information available. The objective data reviewed above suggest that SBS symptoms are associated with decrements on the order of 3% to 5% in specific aspects of performance averaged over the population; however, it is not clear how to translate these specific performance decrements (e.g. increases in response times and error rates, and decreases in typing performance) with the magnitude of an overall productivity decrement from SBS symptoms. The self-reports discussed above suggest a productivity decrease, averaged over the entire work population, of approximately 4% owing to poor indoor air quality and physical conditions at work. Although SBS symptoms seem to be the most common work-related health concern of office workers, some of this self-reported productivity decrement may be a consequence of factors other than SBS symptoms. Also, dissatisfied workers may have provided exaggerated estimates of productivity decreases. To account for these factors, we will discount the 4% productivity decrease cited above by a factor of two, leading to an estimate of the productivity decrease caused by SBS

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[28] The associated p values for outcomes c through h are as follows: (*c*) $p < 0.04$ (severe headache); (*d*) $p < 0.003$; (*e*) $p < 0.06$; (*f*) $p < 0.8$; (*g*) $p < 0.10$; and (*h*) $p < 0.009$.

equal to 2%, recognizing that this estimate is highly uncertain. This 2% estimate is the basis for subsequent economic calculations.

SBS symptoms are primarily associated with office buildings and other nonindustrial indoor work places such as schools. According to Traynor et al (56), office workers are responsible for approximately 50% of the US annual gross national product. Statistical data on the occupations of the civilian labor force are roughly consistent with this estimate (6), i.e. 50% of workers have occupations that would normally be considered office work or teaching. Because the gross domestic product of the United States in 1996 was $7.6 trillion (6), the gross domestic product associated with office-type work is approximately $3.8 trillion. Multiplying the number of office workers and teachers (64 million) by the annual average compensation for all workers ($39.2K) results in a similar estimate of $2.5 trillion. Averaging these two estimates yields $3.2 trillion. Based on the estimated 2% decrease in productivity caused by SBS symptoms, the annual nationwide cost of SBS symptoms is on the order of $60 billion.

Potential Savings from Changes in Building Factors Because multiple factors, including psychosocial factors, contribute to SBS symptoms, we cannot expect to eliminate SBS symptoms and SBS-related costs by improving indoor environments. However, strong evidence cited by Mendell (43), Sundell (44), and Seppanen et al (46) of associations between SBS symptoms and building environmental factors, together with our knowledge of methods to change building and environmental conditions, indicate that SBS symptoms can be reduced. Many SBS studies[29] have found individual environmental factors and building characteristics to be associated with changes of about 20% to 50% in the prevalence of individual SBS symptoms or groups of related symptoms.[30] A smaller number of studies have identified a few building-related factors to be associated with an increase in symptoms by a factor of two or three (e.g. 47, 57). The review by Seppanen et al (46) suggests that a 5 L s^{-1} per person increase in building ventilation rates in the building stock would decrease prevalences of upper respiratory and eye symptoms by $\sim$35%.

In summary, the existing evidence suggests that substantial reductions in SBS symptoms, on the order of 20% to 50%, should be possible through improvement in individual indoor environmental conditions. Multiple indoor environmental factors

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[29] Most of these studies have taken place in buildings without unusual SBS problems; thus, we assume that the reported changes in symptom prevalences with building factors apply for typical buildings.

[30] Adjusted odds ratios for the association of symptom prevalences to individual environmental factors and building characteristics are frequently in the range of 1.2 to 1.6. Assuming a typical symptom prevalence of 20%, these odds ratios translate to risk ratios of approximately 1.2 to 1.5, suggesting that 20% to 50% reductions in prevalences of individuals' SBS symptoms or groups of symptoms should be possible through changes in single buildings or indoor environmental features.

can be improved within the same building. For the estimate of cost savings, we will assume that a 20% to 50% reduction in SBS symptoms is practical in office buildings. The corresponding annual productivity increase is on the order of $10 to $30 billion.

Direct Impacts of Indoor Environments on Human Performance

Background Indoor environmental conditions may directly influence the performance of physical and mental work, without influencing health symptoms. This section discusses the evidence of a direct connection between worker performance and thermal conditions and lighting. Existing standards define the boundaries of recommended thermal and lighting conditions because conditions far from optimal have an obvious adverse influence on comfort and performance. Research on this topic is difficult because of the complexity of defining and measuring performance in real-world environments and because many factors, including worker motivation, influence performance. Indicators of human performance have included measures of actual work performance, results of tests of component skills (e.g. reading comprehension) relevant to work, and subjective self-estimates of performance changes.

Linkage Between Thermal Environment and Performance Many studies have investigated the relationship of the thermal environment with aspects of work performance, and there are several reviews of this topic, including Wyon (1, 2, 2a, 58) and Fisk (5). The results of many studies indicate that changes in temperature of a few degrees Celsius within the 18°C to 30°C range can significantly influence performance in several tasks including typewriting, factory work, signal recognition, time to respond to signals, learning performance, reading speed and comprehension, multiplication speed, and word memory. However, other studies have not found such associations. For complex or creative mental work, optimal thermal comfort and optimum performance may approximately coincide. For other types of mental work, slight thermal discomfort that increases arousal (e.g. slightly cool temperatures) may increase performance. Given that the optimum temperature depends on the nature of the task, will vary among individuals, and will vary over time, some researchers have advocated the provision of individual control of temperature as a practical method to increase productivity (58, 59). A study in an insurance office (59) suggested that provision of individual temperature control increased productivity by approximately 2%. However, studies of individual control cannot be performed blindly. Wyon (58) has estimated that providing workers ± 3°C of individual control should lead to about a 3% increase in performance for both logical thinking and very skilled manual work, and approximately a 7% increase in performance for typing relative to performance in a building maintained at the population-average neutral temperature.

Linkage Between Lighting and Human Performance As discussed by NEMA (3), lighting has the theoretical potential to influence performance directly because work performance depends on vision, and indirectly because lighting may direct attention, or influence arousal or motivation. Several characteristics of lighting, e.g. illuminance (the intensity of light that impinges on a surface), amount of glare, and the spectrum of light may theoretically affect work performance. Obviously, lighting extremes will adversely influence performance; however, the potential to improve performance by changing the lighting normally experienced within buildings is the most relevant question for this paper.

It is expected that performance of work that depends very highly on excellent vision, such as difficult inspections of products, will vary with lighting levels and quality. The published literature, though limited, is consistent with this expectation. For example, a 6% increase in the performance of postal workers sorting mail was recorded after a lighting retrofit that improved lighting quality and also saved energy (60). A review by NEMA (3) provides additional examples, such as more rapid production of drawings by a drafting group after bright reflections were reduced.

Many laboratory studies have investigated subjects' performance on special visual tests as a function of illuminance, spectral distribution of light, and the contrast and size of the visual subject. Many statistically-significant differences in people's performance on these visual tests with changes in lighting (e.g. 3, 61, 62) have been reported; however, the relationship between performance in these visually-demanding laboratory tests and performance in typical work (e.g. office work) remains unclear.

Several studies have examined the influence of illuminance on reading comprehension, reading speed, or accuracy of proofreading. Some of these studies have failed to identify statistically significant effects of illuminance (63, 64). Other studies have found illuminance to significantly influence reading performance; however, performance reductions were primarily associated with unusually low light levels or reading material with small, poor-quality, or low-contrast type (65, 66). Low levels of illuminance seem to have a more definite adverse influence on the performance of older people (3, 65), a finding that may become increasingly important as the work force ages.

There have been anecdotal reports of the benefits of full-spectrum lighting on morale and performance, relative to the typical fluorescent lighting. However, based on the published literature (3, 67, 68) there seems to be no strong or consistent scientific evidence of benefits of full spectrum lighting.

A few studies have examined the influence of different lighting systems on self-reported productivity or cognitive task performance. The lighting systems compared resulted in different illuminance and lighting quality (e.g. differences in reflections and glare). In a study by Hedge et al (69), occupants reported that both lensed-indirect and parabolic downlighting supported reading and writing on paper and on the computer screen better than a recessed lighting system with translucent prismatic diffusers.[31] Katzev (70) studied the mood and cognitive performance of subjects in laboratories with four different lighting systems. The type of lighting system influenced occupant satisfaction, and one energy-efficient lighting system was associated with better reading comprehension.[32] Performance in other cognitive tasks, (detecting errors in written materials, typing, and entering data into a spreadsheet) was not significantly associated with the type of lighting system. In a laboratory study, Veitch & Newsham (71) found that the type of luminaire influenced performance of computer based work. Also, energy-efficient electronic ballasts, which result in less lighting flicker than magnetic ballasts, were associated with improvements in verbal-intellectual task performance.

A recent study (72) examined the association of daylighting in classrooms with students' performance. The strongest component of this research examined the change in performance on a standardized test over a school year in classrooms with various levels and types of daylighting. In classrooms with the most daylighting or window area, the improvements in math and reading performance were 16% to 26% larger, controlling to the degree possible for the influence of confounding factors. Results from two other school districts, based on a weaker study methodology, suggested 7% to 18% increases in performance with increased daylighting.

Based on this review, the most obvious opportunities to improve performance through changes in lighting are work situations that are very visually demanding. The potential to use improved lighting to significantly improve the performance of office workers seems to be largely unproved; however, it appears that occupant satisfaction and the self-reported suitability of lighting for work can be increased with changes in lighting systems. Most of the studies that incorporated measurements of performance had few subjects; hence, these studies were not able to identify small (e.g. a few percent) increases in performance that would be economically very significant.

Potential Value of Productivity Gains Once again, the limited existing information makes it difficult to estimate the magnitude of direct work performance improvements that could be obtained from improvements in indoor environments. Extrapolations from the results of laboratory studies to the real work force are the only avenues presently available for estimating the potential values of productivity gains. There are reasons for estimating that the potential productivity increases in practice will be smaller than the percentage changes in performance reported within the research literature. First, some of the measures of performance used by researchers, such as error rates and numbers of missed signals, will not directly reflect the magnitudes of overall changes in productivity (e.g. decreasing an error rate by 50% usually does not increase productivity by 50%). Second, research has often focused on work that requires excellent concentration,

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[31] $p < 0.01$.

[32] $p < 0.01$.

quick responses, or excellent vision, although most workers spend only a fraction of their time on these types of tasks. Third, changes in environmental conditions (e.g. temperatures and illuminance) within many studies are larger than average changes in conditions that would be made in the building stock to improve productivity.

To estimate potential productivity gains, we consider only reported changes in performance that are related to overall productivity in a straightforward manner, e.g. reading speed and time to complete assignments are considered, but not error rates. The research literature reviewed above and described in greater detail in Reference 5 reports performance changes of 2% to 20% (with one outlier value excluded—a 49% improvement). Assuming that only half of peoples' work involves tasks likely to be significantly influenced by practical variations of temperature or lighting, the range of performance improvement would be 1% to 10%. Because research has generally been based on differences in temperature and lighting about a factor of two larger than the changes likely to be made in most buildings, the estimated range of performance improvement was divided by another factor of two. The result is an estimated range for potential productivity increases in the building stock of 0.5% to 5%. Considering only US office workers, responsible for an annual gross national product of approximately $3.2 trillion (as discussed above), the 0.5% to 5% estimated performance gain translates into an annual productivity increase of roughly $20 billion to $160 billion.

The Cost of Improving Indoor Environments

In two example calculations, Fisk (5) compares the cost of increasing ventilation rates and increasing filter system efficiency in a large office building with the productivity gains expected from reductions in health effects. The estimated benefit-to-cost ratio is 14 and 8 for increased ventilation and better filtration, respectively. Similar calculations by Milton et al (15) result in a benefit-to-cost ratio of three to six for increased ventilation, neglecting the benefits of reduced health cares costs, which are about half of the total benefit. For many other measures that should increase productivity, we would expect similarly high benefit-to-cost ratios. For example, preventing or repairing roof leaks should diminish the need for building repairs in addition to reducing allergy and asthma symptoms. Also, some measures, such as excluding indoor tobacco smoking or maintaining pets outdoors of the houses of asthmatics, have negligible financial costs.

Other changes in buildings that have been associated with improved health may have higher costs than increases in ventilation rate, improved filtration, minimizing pollutant sources, and better maintenance. For example, reducing occupant density by a factor of two would increase building construction or lease costs accordingly and also considerably increase energy costs per occupant. However, even such changes to buildings may be cost effective in some situations because annual salaries are approximately 100 times larger than annualized construction costs or rent.

Limitations of Analysis

The estimated health and productivity gains discussed in this paper are based on extrapolations of the findings obtained in a relatively small number of studies to the general population. The validity of such extrapolations depends on several factors, including the degree to which the study settings are representative of the broader population and the quantity and quality of relevant scientific data. Because the published research findings are from studies of people, predominately located in real buildings or in realistic laboratory settings, these findings should apply at least qualitatively to the broader population. However, the accuracy of the quantitative extrapolations is not well understood.

One of the weaknesses of the available literature on respiratory illnesses is that 5 out of 10 studies took place in relatively atypical settings, e.g. military housing and jails with a high occupant density, and Antarctic quarters. Considering this full data set and omitting a high outlier value yielded the 9% to 20% estimate for potential reductions in respiratory illness that was used in economic calculations. If we neglect data from the atypical settings and neglect the outlier value, the reductions in respiratory illness and absence from work in the remaining studies ranges from 17% to 35% (average = 22%). Excluding absence outcomes as well yields only two data points: 17% and 20% reductions in illness. Consequently, inclusion of data from spaces with high occupant densities did not upwardly bias estimates of the potential reduction in respiratory illness. Two of the studies of respiratory illnesses might be judged atypical because they are retrospective analyses of epidemics in a jail and a nursing home. Excluding these studies eliminates two of the smaller time-adjusted data points, but does not affect the range.

The data used to estimate potential reductions in allergy and asthma symptoms have several limitations that were described previously, but most of these data are from cross-sectional studies in typical housing. Additionally, the risk factors identified—dampness and molds, tobacco smoking, pets, high levels of dust mites and cock roaches—are quite common. Thus, extrapolations to the general population are reasonable.

The available literature from SBS studies is primarily from typical office buildings. Nearly all of the major studies have selected study buildings without consideration or prior knowledge of exposures, occupants' symptom prevalences, or occupants' complaints. The analyses utilize an estimate of the proportion of occupants that experience frequent work-related symptoms obtained from a sample of 56 US office buildings that was intended to be representative of large US office buildings. The proportion of office workers with frequent SBS symptoms reported from smaller, less-representative surveys is generally similar in magnitude to that in the representative survey. The major weakness of the SBS-related estimates is a consequence of the limited information available to quantify the influence of these symptoms of worker productivity. Additional data are needed to overcome this weakness.

Publication bias, i.e. preferential publication of papers from studies that found significant associations, may have upwardly biased our estimates of potential health and productivity gains. Corrections for publication bias are difficult and may be impossible with the data currently available.

To the degree possible, double counting of potential economic benefits has been avoided. The financial savings attained from reductions in the various categories of health effects and from direct productivity gains are largely distinct. However, allergy and asthma symptoms overlap with SBS symptoms; thus, there may be some double counting associated with these two categories of health effects. The amount of double counting would be modest because the SBS-related benefits are associated exclusively with workers in offices and schools and much of the allergy and asthma costs are associated with residences.

Productivity Gains as a Stimulus for Energy Efficiency

In most nonindustrial workplaces, the costs of salaries and benefits exceeds energy, maintenance, and annualized construction costs or rent, by approximately a factor of 100 (73). Consequently, demonstrated and quantified improvements in health and productivity from better indoor environments could substantially change attitudes and practices related to building design and operation. Businesses should be strongly motivated to invest in many changes to building designs or building operation if these changes improved worker performance by even a significant fraction of a percent or reduced absence from work by a day or more per year.

The responses of employers to the growing body of information indicating that productivity improvements are possible through improvements in the indoor environment are quite uncertain; however, the nature of the response has significant energy implications. In the near term, employers may not respond significantly because of the uncertainties that remain about productivity and health improvements and because of the limited communication of research findings. However, as research is completed these uncertainties will diminish, and actions by employers seem likely. One potential near-term or longer-term response is for employers to implement the easy measures, such as a doubling of minimum ventilation rates, regardless of the energy consequences. Building energy use would increase, but the percentage increase will be modest (e.g. 5%) in most buildings because the energy used to heat or cool ventilation air is a small portion of total building energy consumption (5, 74). In buildings with a high occupant density, such as schools, energy used for ventilation is a much larger portion of total building energy use, and the percentage increases in building energy use could be considerably larger (e.g. 10%–20%).

Another possible response, and most desirable, is the preferential adoption of measures that improve productivity and simultaneously save energy, leading to energy savings. The well-established building-performance contracting industry, which finances and implements energy-efficiency measures for a share of the energy cost savings, is likely to push this option. When marketing energy-efficiency measures, energy-service companies can promise or suggest the possibility of IEQ improvements and associated productivity savings. In the ideal scenario, the productivity gains could serve as a strong stimulus for building-energy efficiency. Whereas the cost of energy is too small to garner the attention of many businesses, the promise of simultaneous productivity gains, that are financially much more significant, is less easily ignored.

Table 3 provides examples of energy efficiency measures that often improve indoor environmental quality and that may improve occupant health, satisfaction,

TABLE 3 Examples of energy efficiency measures that often improve indoor environmental quality

Energy Efficiency Measure	**Predominant Influence on Indoor Environment or Productivity**
Energy efficient lamps, ballasts, fixtures	Improved lighting quality and occupant satisfaction. Productivity may increase when work is visually demanding.
Outside air economizer for free cooling	Generally, indoor environmental quality will improve owing to increase in average ventilation rate. Potential productivity gains from reduced respiratory disease and sick building syndrome (SBS).
Heat recovery from exhaust ventilation air	If heat recovery allows increased outside air, indoor environmental quality will usually improve. Potential productivity gains from reduced respiratory disease and SBS.
Nighttime precooling using outdoor air	Nighttime ventilation may decrease indoor concentrations of indoor-generated pollutants when occupants arrive at work, leading to reduced SBS.
Operable windows substitute for air conditioning	On average, occupants of buildings with natural ventilation and operable windows report fewer SBS symptoms.
Increased thermal insulation in building envelope	Potential increase in thermal comfort because insulation helps heating/ventilation/air conditioning system satisfy thermal loads and because of reduced radiant heat exchange between occupants and building envelope.
Thermally efficient windows	Improvements in thermal comfort from reductions of drafts and radiant heat exchange between occupants and windows. Reduces condensation on windows and associated risks from growth of microorganisms.

or work performance. The information in this table is based on the conclusions of a multi-disciplinary international committee (7).

Institutions with a mission to promote energy efficiency could influence the response to the new information on productivity gains by supporting research and demonstration efforts on the suspected win-win measures that simultaneously save energy and improve productivity. Additionally, these institutions and industries can develop and demonstrate new or improved building technologies that facilitate simultaneous energy savings and productivity gains.

CONCLUSIONS

1. There is relatively strong evidence that characteristics of buildings and indoor environments significantly influence the occurrence of communicable respiratory illness, allergy and asthma symptoms, sick building symptoms, and worker performance.
2. Theoretical and limited empirical evidence indicate that existing technologies and procedures can improve indoor environments in a manner

TABLE 4 Estimated potential productivity gains from improvements in indoor environments

Source of Productivity Gain	Potential Annual Health Benefits	Potential US Annual Savings or Productivity Gain (1996 $US)
Reduced respiratory illness	16 to 37 million avoided cases of common cold or influenza	\$6–\$14 billion
Reduced allergies and asthma	18% to 25% decrease in symptoms for 53 million allergy sufferers and 16 million asthmatics	\$1–\$4 billion
Reduced sick building syndrome symptoms	20% to 50% reduction in sick building syndrome health symptoms experienced frequently at work by ∼15 million workers	\$10–\$30 billion
Improved worker performance from changes in thermal environment and lighting	Not applicable	\$20–\$160 billion
Total cost of energy in US commercial buildings[a] (for reference, in 1995)	Not applicable	\$70 billion

[a] Reference 75.

that increases health and productivity. Estimates of the potential reductions in adverse health effects are provided in Table 4.

3. Existing data and knowledge allows only crude estimates of the magnitudes of productivity gains that may be obtained by providing better indoor environments; however, the projected gains are very large. For the United States, the estimated potential annual savings plus productivity gains, in 1996 dollars, are approximately $40 billion to $200 billion, with a breakdown as indicated in Table 4. The potential savings and productivity gains are larger than the total estimated cost of energy used in buildings (75).
4. The implications of the growing knowledge about productivity gains from better indoor environments on building energy efficiency are uncertain. One scenario is that quantified and demonstrated productivity gains could serve as a very strong stimulus for the adoption of numerous energy conservation measures that simultaneously improve the indoor environment.

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APPENDIX: DEFINITIONS OF STATISTICAL TERMS

The prevalence is the fraction of the study group with a particular characteristic, e.g. the fraction that experiences a health symptom. If a and b are the prevalences of study outcomes, e.g. health symptoms, in Study Group A and Study Group B, respectively, the relative risk $RR = a/b$. Usually, a represents the higher prevalence so that the RR is greater than unity.

The odds of the outcome in Study Group A and Study Group B, respectively are $a/(1\text{-}a)$ and $b/(1\text{-}b)$, respectively. The odds ratio $OR = [(a/(1\text{-}a))/(b/(1\text{-}b))]$.

Epidemiological studies often report adjusted odds ratios or adjusted relative risks. The term adjusted indicates that a statistical model has been used to adjust or correct the odds ratio or relative risk to account for the influences of one or more potential confounding factors such as age or gender. When (adjusted) odds ratios are provided and prevalences are known or estimated, the RR can be estimated from the equation: $RR = OR\,[(1\text{-}a)/(1\text{-}b)]$. When a and b are less than ~ 0.2, the OR and RR are quite similar numerically.

The percentage increase in the outcome is determined from the RR as follows: percentage increase $= [RR\text{-}1]/RR$.

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